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# The circular economy and the optimal recycling rate: A macroeconomic approach☆

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ABSTRACT

This paper studies the economic implications of the circular economy and recycling activities from a macroeconomic perspective. The paper incorporates the circular economy into an otherwise standard neoclassical dynamic general equilibrium linear economy model, in which the production function depends on capital, labor, and raw materials. Raw materials are a composite of natural resources (the linear economy) and recycled material (the circular economy). Waste is a function of consumption but can be incorporated back into production activities through recycling. We find the existence of a positive S-shaped relationship between the optimal recycling rate and economic development, indicating that increasing the circularity of the economy is a necessary condition to augment social welfare in a growing economy. The optimal recycling rate depends positively on the pollution damage and waste content of final consumption goods. Simulation of the model supports the existence of a steady-state Environmental Kuznets Curve (EKC) relationship between the stock of waste and the output in the presence of a circular economy. Finally, we find that while a permanent improvement in recycling technology has positive effects on output, expanding the circularity of the economy, an increase in the cost of natural material has harmful effects on output, increasing waste accumulation and reducing recycling.

## 1. Introduction

The debate on the "circular economy" (CE), as a new paradigm opposite to the standard "linear economy", has emerged from the necessity to deal with dwindling natural resources and the generation of waste through economic activity.[1] This issue has also attracted rising interest among scholars, although there is still a shortage of theoretical and empirical studies offering a better understanding of the consequences of incorporating the CE into the standard linear economy as a necessary step for correctly assessing the implications of CE driving policies. Several economies, such as the European Union (with Germany as the leading country), Japan and China, have incorporated the CE into their environmental and economic growth policies, considering the CE as one of the pillars of sustainable development (Geissdoerfer et al., 2017). Production and consumption activities in the economy are basically "linear", meaning that raw natural resources are used to produce final goods, and after their use in consumption or investment activities, waste is generated that needs to be managed. This is the so-called "take, make and waste" or "open-loop" approach to production. The CE is regarded as an instrument to mitigate the two main problems generated by the open-loop approach, specifically the depletion of natural resources and environmental damage, helping to "close the open-loop".

The paradigm of CE is gaining momentum as a strategy to improve the environmental quality and preserve natural resources. The role of natural resources in economics has regained prominence just when evidence of a damaged environment has emerged. Andrews (2015) situates the birth of the linear economy the "take-make-use-dispose" model of consumption in the Industrial Revolution and claims the necessity of a new economic model, in which the CE is called to play a central role in sustainability. Nowadays, there is an open debate among scholars on the relationship between the CE and sustainability, the different ways to promote the CE and the crucial sectors for implementation. Hu et al. (2018) analyze the efficiency of promoting the CE through legislation.

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[1] For a definition of the CE, see for instance, Kirchherr et al. (2018), Korhonen et al. (2018a,b), and Garc-Barraga et al. (2019).

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Other authors focus on the idea of implementing taxes as an instrument to promote the CE. For example, Bahn-Walkowiak et al. (2012) analyze the effects of taxing construction materials. Pomponi and Moncaster (2017) highlight the necessity of using CE-driving policies in those sectors that consume more raw materials. Kirchherr et al. (2018) analyze the main barriers to the CE in European countries, concluding not only that technological barriers exist but also that the main barriers seem to be cultural: the lack of awareness among consumers and a company culture of reluctance to engage in the CE. George et al. (2015) conclude that the only possible way to improve the environmental quality is to increase the recycling rate as one of the pillars of the CE. Lin et al. (2020) points out that waste has a non-zero value as it can be recycled and new material generated for new production/consumption activities.

In practice, economic activity (the production of consumption and investment goods) uses raw materials extracted from nature and produces a large variety of waste that could be reused for production purposes. Various of these waste products, such as metal, e-waste, paper, glass, plastic, batteries and so on, can be recovered and re-manufactured. Even organic residuals can be transformed into fertilizers or energy generation fuel. The awareness of environmental and natural resources issues and the elaboration of policies to embrace the idea of the CE have become fundamental in China and Europe.[2] As McDowall et al. (2017) highlight, the conception of the CE differ between the two territories, being broader in China, which includes pollution and other environmental problems in the CE perspective. By contrast, the European focus is on waste, natural resources and opportunities for business. It is not surprising that the awareness about the necessity of the CE has emerged in China where, for example, the total amount of municipal solid waste reached 191.4 million tonnes in 2015, according to the National Bureau of Statistics of and China (2015). In Europe, according to Eurostat (2021), the generation of municipal waste per capita rose to 489 kg in 2018 (municipal waste accounting for just 10% of the total waste generation).[3] Increasing the circularity of the economy is an issue that not only concerns governments, but also private firms as a managing strategy to maximize revenues. For instance, CE-related revenues represent around 15% of total revenues of the Philips company (Koninklijke Philips, 2019, 2020).

Data about waste generation and environmental exploitation highlight the necessity of an efficient recycling sector, together with a culture of negative externalities reduction and input re-use.[4] In this paper, we adopt a broad view of the concept of recycling, including several activities distinct from producing recycled material and encompassing re-manufacturing activities and the re-usage of materials as well. That is, they include the aggregate of all secondary materials whether they need a recycling process or not. Indeed, the CE is a concept far beyond the recycling sector that to be implemented, needs to be accepted in daily life by every single economic agent, including households, firms and governments. The CE has become crucial for sustainable economic growth, (see Lin et al., 2020). All firms need to re-use their inputs as much as they can and make it easy for their customers to return the waste associated with the consumption of their products so that it can be re-integrated into the productive process. Consumers have to be conscious about the necessity of reducing waste, reusing products and recycling any waste that they produce. Finally, governments should give incentives to firms to use recycled materials instead of natural resources, as well as to consumers to favor their re-using and recycling processes. Lin et al. (2020) studies sustainable growth from a CE perspective, highlighting the problems and limitations of the traditional linear economy which represents an economic growth system that is unsustainable in the long-run. Haas et al. (2015) estimate that the CE accounted for a very small fraction of the total economy in the year 2005, with a global 4 Gt/year (gigatonnes per year) of recycled waste material compared with a total of 58 Gt/year of raw natural materials. This represents around 6.5% of the total processed materials. However, we must take into account that almost half of the processed materials are energy, and, hence, are not available for recycling. Considering biomass, the circularity of the economy increases to 37%. These figures show that there is still considerable room to increase the circularity of the economy based on two pillars: an increase in recycling rates and an energy transition from fossil fuels to renewable energy sources.

Nonetheless, the CE has been neglected in standard macroeconomic analysis, which has traditionally only consider the linear economy.[5] Mainstream economics is dominated by the traditional “linear” economy, in which finite natural resources are extracted for production activities that are non-sustainable in the long-run and the generation of waste that deteriorates the environment. This paper contributes to the literature by developing a standard neoclassical Dynamic General Equilibrium (DGE) model extended by the incorporation of the CE.[6] We depart from previous analyses in ecological economics or industrial ecology, and we use the tools of traditional mainstream neoclassical economics analysis as a prism to offer a new perspective on the CE. The paper has a twofold purpose. First, we intend to study the economic and environmental implications of the CE from a macroeconomic point of view. Second, we aim to show that traditional neoclassical linear economic models can be transformed and used to study the CE to achieve a better understanding of this issue. The model considers a production function with raw materials as an additional input to capital and labor to produce final goods. Materials are a composite of natural resources (representing the linear economy) and recycled materials (the CE). The consumption of the final goods generates waste that can be recycled and reused in production. Given the presence of a negative externality (waste accumulation), the model is solved considering the socially-planned (optimal) allocation of resources. This integrated theoretical framework can be viewed as a representation of the evolution from a traditional linear economy to an economy in which the CE contributes to closing the open-loop of the former.

Consistent with the empirical evidence, quantitative simulations of the model reveal that, in the steady state, the optimal recycling rate representing the degree of circularity of the economy has a positive relationship with economic development. Furthermore, increasing the circularity of the economy is a necessary condition to increase social welfare in a growing economy. As output and consumption increase, more waste is generated, fostering the optimality of recycling activities. We find the existence of a steady-state hump-shaped relationship between the output and the stock of waste, which can be interpreted as the existence of an Environmental Kuznets Curve (EKC) in the presence of the CE. This EKC does not appear in the case of a linear economy, in

[2] Ghisellini et al. (2016) offer a measure of the concern about the CE around the world, and China emerges as the leading country. They review 89 case studies about the CE and then classify them by geographical location; 41 studies focus on China and 20 on the European Union (EU), meaning that, almost 70% of the surveyed studies about the CE refer to China.

[3] The World Bank estimates the figure to be around 2 billion tonnes of municipal solid waste annually. The United Nations estimates that the total solid waste in 2018 amounted to more than 10 billion tonnes.

[4] According to a behavioral study on consumers' engagement in the CE, elaborated by the European Commission, consumers keep things that they have owned for a long time (93%), recycle unwanted possessions (78%), and repair possessions if they break (64%).

[5] See Geissdoerfer et al. (2017) and Schroeder et al. (2018a,b) for a review of the literature about the CE, its relationship with sustainability and the main topics studied in the literature related to the circularity issue.

[6] The standard neoclassical DGE model for a linear economy is introduced by Ramsey (1928) and later further developed by Cass (1965) and Koopmans (1965). Dasgupta and Heal (1974) developed a linear economy DGE model extended with the inclusion of natural resources. For a review of CE modeling approaches, see McCarthy et al. (2018).

which the relationship between the output and the stock of waste is always positive. This result shows the importance of the CE as a necessary transformation of the traditional economy to make economic growth compatible with environment preservation. The optimal social recycling rate positively depends on the damage of the stock of waste to households' utility and on the waste content of the final consumption goods. Among the potential policies to promote the CE, increasing the cost of natural resources or reducing the cost of recycled materials, we find that only the later contributes to increasing the circularity of the economy. As expected, a permanent positive technological shock reducing the cost of recycling increases recycling activities and output and reduces the stock of pollution. By contrast, simulation results from a permanent negative technological shock, increasing the cost of natural resources, are counterintuitive as this shock reduces the recycling rate and economic activity, and hence, does not contribute to the expansion of the CE.

The rest of the paper is structured as follows. Section 2 elaborates an integrated macroeconomic model in which both linear and circular economies are present. Section 3 calibrates the parameters of the model and calculates the steady state of the economy. Section 4 presents some simulation results from the model and a sensitivity analysis of the key parameters. Section 5 offers a discussion of the results and their link with the results presented in the ecological economic literature and summarizes the main conclusions.

## 2. A macroeconomic model for the circular economy

The traditional macroeconomic modeling approach relies on the study of a "linear economy", in which inputs are used to produce a final output and some negative externalities, such as waste and pollution, are generated during the production process. Standard environmental macroeconomic models usually consider raw materials as an additional input to physical capital and labor, but they constitute a model representation of a linear economy, in which raw materials are used and waste is generated without any re-use. Materials are natural resources that can be either non-renewable or renewable. In a standard linear economy, natural resources are transformed and used in production activities, and they finish as waste once the final good produced has been consumed or invested. Two key problems arise in a linear economy. First, natural non-renewable resources are depleted. Second, even when resources are renewable, a waste generation problem exists. However, the materials used in the production process, along with the existing technology, enable the recovery of a fraction of the total waste as well as its transformation into new materials. This is the case of the CE, in which waste products re-enter the production activities and, once the final goods have been consumed, are transformed again into waste, and so on. The macroeconomic model developed here encompasses the two fundamental aspects of the CE: it limits the harmful effects of the economic activity on the environment by reducing the stock of waste, and it mitigates the depletion of natural resources.

This section develops a CE model embedded in a standard neoclassical growth model for a linear economy. Waste is assumed to be generated by the consumption of final goods. Waste that is not recycled is accumulated into a stock of waste that negatively affects households' utility. The accumulation of waste can be reduced by increasing the recycling rate of waste (transforming waste into resources that can be used again in production activities). Our modeling strategy considers a view in which the CE refers to a wider set of activities leading to the re-use of materials in the economy (recycling, re-manufacturing, reusing, repairing, sharing, etc.). Given the existence of a negative externality, we consider a centralized economy in which a central planner maximizes social welfare to study the conditions for the first-best equilibrium. Given the presence of a negative externality, the planner solution will not be a decentralized equilibrium.

### 2.1. Households

We consider an economy populated by an infinitely-lived representative household with preferences regarding consumption, leisure and environmental quality. The instantaneous utility function is defined as:

$$U(C_t, L_t, Z_t) = lnC_t - \theta \frac{L_t^{1+\frac{1}{\rho}}}{1+\frac{1}{\rho}} - \phi Z_t^{\chi} \tag{1}$$

where $C_t$ is the consumption of goods and services, $L_t$ is the labor and $Z_t$ is the level of pollution generated by waste residuals from consumption activities that are assumed to be equal to the stock of waste. The parameter $\theta > 0$ represents the willingness to work, and $\rho$ is the Frisch intertemporal elasticity of the labor supply representing the change in worked hours in response to a change in the equilibrium wage, given a constant marginal utility of wealth. Waste is considered to be a negative externality, reducing households utility function. The disutility produced by the accumulated waste stock is measured by the parameter $\phi$. We assume that $U_Z < 0$ and $U_{ZZ} < 0$, indicating that, as waste is accumulated, its cost, in terms of utility, increases. The parameter $\chi > 1$ represents the elasticity of utility with respect to pollution.[7]

The resource constraint of this centralized economy is given by:

$$C_t + I_t + \Theta_n N_t + \Theta_v V_t = Y_t \tag{2}$$

where $I_t$ is investment, $N_t$ represents natural resources[8], $V_t$ denotes recycled materials, and $Y_t$ is final output. $\Theta_n$ and $\Theta_v$ are technological parameters reflecting the real cost of natural and recycled material, respectively, which are assumed to be exogenously given. This resource constraint encompasses both the linear economy, in which natural extracted resources are used in production activities, and the circular economy, in which instead of new natural resources, recycled materials are used for production. The amount of recycled material depends on the recycling rate, whereas the amount of natural resources depends on the extraction rate.

We assume the following accumulation process for physical capital, $K_t$:

$$K_{t+1} = (1-\delta_k)K_t + I_t \tag{3}$$

where $\delta_k$ ($0 < \delta_k < 1$) is the physical capital depreciation rate.

### 2.2. Waste and recycling

The model considers the existence of a negative externality in the

[7] The model has been solved for alternative specifications of the households' utility function to check the robustness of the results to the particular specification of the utility function. First, we simplify expression (Eq. (1)) eliminating leisure (labor supply). We find that the optimal labor supply decision does not affect the results. Second, we use an alternative specification for the household's utility function given by,

$$U(C_t, Z_t) = lnC_t + \theta ln(H - Z_t)$$

where the constant $H$ represents the initial endowment of environmental quality. As the stock of waste increases, the environmental quality declines and reduces utility. Again, we find that the results only change slightly using this alternative specification and, hence, the conclusions remain the same.

[8] The flow of natural material used in production, $N_t$, comes from the extraction of natural resources and the modeling strategy is close to that of André and Cerdá (2006). However, since we assume that natural resources can be both renewable and non-renewable and therefore that there is room for regeneration, we omit the modeling of this process so that our model focuses on circularity. In this sense, the fraction of income expended on both natural and recycled material is a function of the technological parameters $\Theta_n$ and $\Theta_v$, which reflect all the real cost of natural and recycled material used in production.

form of waste. We assume that waste is generated by the consumption of final goods.[9] Waste generated by consumption, $X_t$, is defined by the following function:

$$X_t = X(C_t) = \eta C_t^{\gamma} \tag{4}$$

where $\gamma$ is the elasticity of $X_t$ with respect to consumption[10], and $\eta$ is the proportion of waste as a by-product of consumption. This parameter indicates the fraction of consumption that is transformed into waste (waste content per consumption unit). A prototype model for natural resources, but without the generation of waste, is provided by Dasgupta and Heal (1974).

We assume the following accumulation process for waste:

$$Z_{t+1} = (1-\delta_z)Z_t + (1-\mu_t)X_t \tag{5}$$

where $Z_t$ is the stock of waste, $\delta_z$ is the decay rate of waste, and $0 < \mu_t < 1$ is the recycling rate. It is assumed that the cost of recycling is a constant and independent of the recycling rate. Furthermore, it is assumed that all kinds of waste can be recycled.[11] Therefore, recycled materials are produced according to:

$$V_t = \mu_t X_t \tag{6}$$

In a linear economy, the recycling rate is equal to zero ($\mu_t = 0$), and hence, also $V_t = 0$. In this scenario, waste is accumulated over time depending on the relationship between the waste decay rate and the newly generated waste. On the other hand, if $\mu_t = 1$, the stock of waste is zero, and no negative externality exists as the flow of waste disappears instantaneously.

### 2.3. Production function

We use a standard Cobb-Douglas production function with three inputs: physical capital, labor and raw materials. This technology is given by[12]:

$$Y_t = A_t K_t^{\alpha_1} M_t^{\alpha_2} L_t^{1-\alpha_1-\alpha_2} \tag{7}$$

where $Y_t$ is the aggregate output, $A_t$ is a measure of total factor productivity (TFP), $L_t$ collects labor services, $K_t$ represents physical capital and $M_t$ denotes the raw materials. $\alpha_1$ represents the elasticity of output with respect to capital and $\alpha_2$ is the elasticity of output with respect to raw materials. Materials used in production match an Armington aggregator of both virgin natural resources and recycled materials:

$$M_t = \left[\omega N_t^{\frac{\sigma-1}{\sigma}} + (1-\omega)V_t^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{8}$$

where $\omega$ is a distribution parameter and $\sigma$ is the elasticity of substitution between natural resources and recycled material.[13] The degree of substitution between natural and recycled materials is not perfect. Garc-Barraga et al. (2019) assume that natural and recycled materials are not perfect substitutes between the quality losses of recycled material in subsequent recycling rounds. We do not consider that possibility, which would require a change in the recycling technology, and we simply assume that imperfect substitution applies equally to both types of material.

As it can be observed, the CE enters the aggregate production function in the form of materials along with the standard linear economy. The distribution parameter $1-\omega$ indicates the weight of the CE with respect to the linear economy. If $\omega = 1$, it means that the economy is fully linear, so all raw materials come directly from natural resources and all waste generated by consumption is accumulated into the existing stock of waste. For any value of $\omega < 1$, the CE comes into play, and a fraction of waste is transformed into recycled materials that can be used for production purposes. Hence, the circular part of the economy implies the existence of a material loop that contributes to a cleaner environment. Once raw materials are used in production activities, the consumption of the final goods generates waste that can be converted into new materials again and re-used for production activities.[14]

### 2.4. Central planner's welfare maximization problem

Given the existence of a negative externality, we consider the case of a planning problem, in which we assume the existence of a central planner who maximizes social welfare by choosing optimal values for the consumption, labor, capital stock, stock of waste and recycling rate. The central planner solves the following problem,

$$max_{\{C_t, L_t, K_{t+1}, \mu_t, Z_{t+1}\}} \sum_{t=0}^{\infty} \beta^t \left[ lnC_t - \theta \frac{L_t^{1+\frac{1}{\rho}}}{1+\frac{1}{\rho}} - \phi Z_t^{\gamma} \right] \tag{9}$$

subject to the restriction given by (2)– (8).[15] The full resolution of the central planner's maximization problem and the corresponding first-order conditions can be found in the technical appendix. From the first-order conditions, we find that the equilibrium condition for the optimal quantity of natural resources is given by:

[9] Alternatively, we can assume that waste is generated by consumption, investment, production activities or all of them. Nevertheless, the results presented in this paper remain unchanged for these different modeling strategies.

[10] In the calibration of the parameters of the model (see next section) we assume that $\gamma = 1$.

[11] Alternatively, the waste accumulation law of motion can be defined as,

$$Z_{t+1} = (1-\delta_z-\mu_t)Z_t + X_t$$

where the recycling rate represent the fraction of the stock of waste recovered each period. In this case, the recycling rate of the economy is not defined as the percentage of the current flow of waste recovered, but the percentage over the stock of waste. This alternative specification allows recycling not only waste of the present but also waste of the past. Nevertheless, both specifications produce similar results. Additionally, it is assumed that all kinds of waste can be recycled. However, it could be the case that not all kinds of waste are recyclable. This case could be considered by simply defining Eq. (6) in the text as

$$V_t = \mu_t \psi X_t$$

where $0 < \psi \leq 1$, represents the fraction of waste recyclable. To keep the model as simple as possible we assume that $\psi = 1$.

[12] This production function implies that the elasticity of substitution between inputs is unitary. Alternatively, we can assume a CES production function in which inputs are gross complements. However, the implications for the CE are similar, therefore, we decide to present the simplest specification.

[13] Solow and Wan (1976) investigate how the use of an exhaustible resource affects the production function and the shadow price of optimal extraction, concluding that relatively large variations in the availability of resources generate very small changes in the sustainable level of consumption.

[14] The idea of the CE is close to the carbon capture and sequestration technologies in environmental economics. Once waste or emissions are produced, some technologies can be used to mitigate the stock of pollution. They can also be reused to capture $CO_2$ for energy generation. The recycling of waste from consumption activities is based on a similar principle and implies that a fraction of the stock of waste is removed and re-used for production activities.

[15] This is the common solution approach adopted in the literature for solving environmental-economics models (see, for instance, Acemoglu et al., 2012, 2016; Golosov et al., 2014). Given the presence of a negative externality, the planner solution will not be a decentralized equilibrium. The central planning outcome only coincides with a dynamic competitive market equilibrium in the absence of relevant distortions (Hassler and Krusell, 2018).

$$\Theta_n M_t^{\frac{\sigma-1}{\sigma}} = \alpha_2 \omega Y_t N_t^{\frac{-1}{\sigma}} \tag{10}$$

The optimal investment decision is given by:

$$\frac{Y_{t+1} L_t^{\frac{1}{\rho}+1}}{Y_t L_{t+1}^{\frac{1}{\rho}+1}} = \beta\left[\left(1-\delta_k\right) + \alpha_1 \frac{Y_{t+1}}{K_{t+1}}\right] \tag{11}$$

Finally, the equilibrium condition for the optimal quantity of recycled material, indicating the optimal circularity of the economy, is given by:

$$\beta^{t+1}\phi\chi Z_{t+1}^{\chi-1} = \frac{\beta^t \theta L_t^{\frac{1}{\rho}+1}}{(1-\alpha_1-\alpha_2)Y_t}\left[\Theta_v - \alpha_2(1-\omega)\frac{Y_t V_t^{\frac{-1}{\sigma}}}{M_t^{\frac{\sigma}{\sigma-1}}}\right] - \frac{\beta^{t+1}\theta L_{t+1}^{\frac{1}{\rho}+1}}{(1-\alpha_1-\alpha_2)Y_{t+1}}\left[\Theta_v - \alpha_2(1-\omega)\frac{Y_{t+1} V_{t+1}^{\frac{-1}{\sigma}}}{M_{t+1}^{\frac{\sigma-1}{\sigma}}}\right](1-\delta_z) \tag{12}$$

Equilibrium conditions (10), (11) and (12) differ in several aspects from the equilibrium conditions resulting from the standard linear economy model. Expression (10) indicates that the optimal quantity of raw materials used in production activities is determined by the condition that equals the marginal productivity of natural material to the unit cost of raw material. Expression (11) represents the condition that equals the marginal value of consumption with the marginal value of investment, that is, the optimal consumption-saving decision. However, this equilibrium condition differs from the standard one in the fact that the intertemporal consumption marginal utility ratio is replaced by a combination of labor and output because of the introduction of the CE and that consumption generates waste. Indeed, expression (11) can be written as (see technical appendix),

$$\frac{C_{t+1} + \gamma X_{t+1}\left[\Theta_v - \alpha_2(1-\omega)\frac{Y_{t+1} V_{t+1}^{-\frac{1}{\sigma}}}{M_{t+1}^{\frac{\sigma-1}{\sigma}}}\right]}{C_t + \gamma X_t\left[\Theta_v - \alpha_2(1-\omega)\frac{Y_t V_t^{-\frac{1}{\sigma}}}{M_t^{\frac{\sigma-1}{\sigma}}}\right]} = \beta\left[1-\delta_k+\alpha_1\frac{Y_{t+1}}{K_{t+1}}\right] \tag{13}$$

notice that the equilibrium condition Eq. (13) includes the intertemporal consumption ratio as in the linear economy model when waste produced from consumption is not considered $X_t = 0$, plus a new term reflecting the fact that consumption produces waste and that the circular side of the economy transforms part of waste into recycled material reused again for production. In our model, the optimal consumption path is also affected by waste and the recycling rate reflected by the amount of recycled material. Finally, expression Eq. (12) represents the condition that equals the welfare cost of waste in terms of losses in household's utility with the difference between the marginal productivity and the cost of recycled material.

## 3. Calibration and steady state

This section presents the calibration of the parameters of the model. Since the model is composed of macroeconomic parameters and parameters related to recycling activities, we use different sources for this calibration. Macroeconomic parameters are calibrated from the real business cycle (RBC) literature, while parameters related to the waste generation process and recycling activities are obtained from different statistical sources and previous research. For some key parameters, we carry out a sensitivity analysis and simulate the model using a range of values given their uncertainty.

On the one hand, some of the parameters of the model are standard in macroeconomics. Therefore, we calibrate them by employing the standard values used in the literature. We set the intertemporal discount factor, $\beta$, to 0.97. The Frisch elasticity of labor, $\rho$, is fixed at 0.72. Given the value for labor elasticity, the willingness to work parameter, $\theta$, is calibrated at 15.6 to produce a labor steady state value of 0.33. The capital depreciation rate, $\delta_k$, is fixed at 0.07. The output-capital elasticity, $\alpha_1$, is fixed at 0.3 and the output-labor elasticity, $1-\alpha_1-\alpha_2$, at 0.65. Given the assumption of constant returns to scale, these figures result in an output-material elasticity of 0.05.

On the other hand, the model includes parameters related to the waste generation process and recycling activities. The values of these parameters are not yet documented in the literature. We set the waste elasticity to consumption, $\gamma = 1$, assuming that every consumption unit involves an associated proportional waste product. The parameter $\eta$ collects the share of waste in consumption. This parameter indicates the percentage of the waste remaining from each consumption unit, that is, the waste content in consumption goods. According to Eurostat (2021), each inhabitant of the EU uses 16 tonnes of materials per year, 6 tonnes of which become waste. Thus, we can establish a relationship between consumption and waste in the model by setting $\eta$ to 6/16=0.375 and $\gamma$ to 1. We calibrate $\sigma = 1.5$ to reflect the relationship of substitution between natural resources and recycled materials, both being far from perfect substitute inputs. In accordance with the Eurostat data, we set $\omega = 0.95$, so the share of circular materials is 11.7%, matching the circularity rate of the EU-27 countries.[16] The waste damage parameter to the utility function, $\phi$, is calibrated as 0.5. The pollution damage to welfare is assumed to be a power function of the stock of pollution. Hence, the pollution elasticity parameter, $\chi$, is fixed at 2. The values of these two parameters must adequately define the fraction of waste accumulation that ends up being harmful to household's welfare (representing a variety of factors, including negative effects on health, climate change, visual effects of landfills, garbage smells, etc.). To assign these values correctly, first, we explore all the possible paths along which residue can travel once it is produced. On the one hand, this waste can be recycled or reused, entering the CE system, and we assume that it would not cause any damage to the utility. Notice that the waste that follows the CE path is not collected in the variable representing the stock of waste. On the other hand, we have the waste that is not recycled or reused, which is accumulated in $Z$. This non-recycled or non-reused waste can follow different routes to landfill or incineration. In the EU, in 2018, more than half (54.6%) of the waste was treated in recovery operations: recycling (37.9% of the total treated waste), backfilling (10.7%) or energy recovery (6.0%). The remaining 45.4% was either landfilled (38.4%), incinerated without energy recovery (0.7%) or disposed of otherwise (6.3%).[17]

Having highlighted what waste treatment data looks like, we can explore what the empirical evidence shows about how the different methods of waste treatment can affect human health (and, therefore, utility). It is very difficult to establish exactly the relative importance of consumption levels and health status for a representative individual.

[16] We must bear in mind that these data can significantly vary among countries. For example, the estimated circularity rate in France is 18.6% while it is only 1.6% in Ireland. Furthermore, it is assumed that parameters for the centralized economy are equal to those of the decentralized economy.

[17] It is also important to pay attention to the different types of waste that are produced. In particular,4.4 % of waste produced in the EU during 2018 (101.7 million tonnes) was classified as hazardous waste. According to Eurostat, in 2018, 45.1% of the hazardous waste treated in the EU was recovered: 37.5% by recycling or backfilling and 7.6% by energy recovery. The remaining 54.9% was incinerated without energy recovery (5.7%), landfilled, in other words deposited into land or through land treatment and released into water bodies (32.8%), or disposed of in another way (16.2%).

Just as we assume that higher levels of consumption result in greater utility, we also assume that greater risk to health results in lower utility. Establishing a comparison with the work of Tomita et al. (2020), we can say that, if an individual can choose between being closer to or further away from a waste deposit, he will always choose to be as far away as possible. Tomita et al. (2020) find that residing within 5 km of a waste site in South Africa is significantly associated with asthma, tuberculosis, diabetes and depression.

We can also establish a comparison with macroeconomic models that take air pollution into account, since this type of pollution is more established in the literature as a negative externality and we can find several models describing it in that way. This relationship is direct when we highlight, for example, that waste incineration may result in emissions of air pollutants. Tait et al. (2020) conduct a systematic review of the health impacts of waste incineration in which a range of adverse health effects is identified, including significant associations with some neoplasia, congenital anomalies, infant deaths and miscarriage.

As we acknowledge that the calibration of these parameters can be subjective because there are not yet any solid data or empirical evidence about this, we present our results for different values to show how the calibration of these parameters can affect the final results. Finally, we assume an annual pollution stock decay rate, $\delta_z$, of 2.5%. This corresponds to a life expectancy of 72 years. The degradation time depends on the waste material, ranging from 3 months for paper tissues, napkins or an apple core to 1–2 years for a cigarette end, 10–100 years for an aluminum can for drinks, 100–1000 years for plastic and more than 10,000 years for polystyrene (US Department of Commerce). Finally, technological components are assumed to be exogenously given and are normalized to one. A summary of the benchmark calibrated parameters of the model is presented in Table 1.

### 3.1. Steady state

For readers' convenience, we report here the system of equilibrium equations in the steady state used to simulate the model.

$$Y = AK^{\alpha_1} M^{\alpha_2} L^{1-\alpha_1-\alpha_2} \tag{14}$$

$$M = \left[\omega N^{\frac{\sigma-1}{\sigma}} + (1-\omega) V^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{15}$$

$$I = \delta K \tag{16}$$

$$C = Y - I - \Theta_n N - \Theta_v V \tag{17}$$

$$X = \eta C^{\gamma} \tag{18}$$

$$\mu = \frac{V}{X} \tag{19}$$

**Table 1**
Baseline calibration of the parameters.

| | Parameter | Definition | Value |
|---|---|---|---|
| Preferences | $\beta$ | Discount factor | 0.97 |
| | $\theta$ | Labor weight | 15.60 |
| | $\rho$ | Frisch elasticity parameter | 0.72 |
| Technology | $\alpha_1$ | Output-capital elasticity | 0.30 |
| | $\alpha_2$ | Output-material elasticity | 0.05 |
| | $\delta_k$ | Physical capital depreciation rate | 0.07 |
| | $A$ | Total factor productivity | 1.00 |
| | $\Theta_n$ | Natural resource technology | 1.00 |
| | $\Theta_v$ | Recycled material technology | 1.00 |
| Waste | $\gamma$ | Waste-consumption elasticity | 1.00 |
| | $\phi$ | Waste damage parameter | 0.50 |
| | $\chi$ | Pollution elasticity parameter | 2.00 |
| Circular economy | $\omega$ | Natural resource share | 0.95 |
| | $\sigma$ | Elasticity sources substitution | 1.50 |
| | $\eta$ | Share of recyclable consumption waste | 0.375 |
| | $\delta_z$ | Waste stock decay rate | 0.025 |

$$Z = \frac{(1-\mu)X}{\delta_z} \tag{20}$$

$$L = \left( \frac{\left( \frac{1}{C} - \frac{\phi\chi Z^{\chi-1}}{\delta_z} \eta\gamma C^{\gamma-1} \right)(1-\alpha_1-\alpha_2)Y}{\theta} \right)^{\frac{\rho}{1+\rho}} \tag{21}$$

$$K = \frac{\alpha_1 Y}{\frac{1}{\beta} - 1 + \delta} \tag{22}$$

$$N = \left( \frac{\alpha_2 \omega Y}{\Theta_n M^{\frac{\sigma-1}{\sigma}}} \right)^{\sigma} \tag{23}$$

$$V = \left( \frac{\alpha_2 (1-\omega) Y}{\left( \Theta_v - \frac{\phi\chi Z^{\chi-1}(1-\alpha_1-\alpha_2)Y}{\theta L^{\frac{1}{\rho}+1} \delta_z} \right) M^{\frac{\sigma-1}{\sigma}}} \right)^{\sigma} \tag{24}$$

where we drop the time subscripts of variables to denote steady state values. The system of Eqs. (14)–(24) contains 11 equations for 11 unknowns, ($C, I, L, K, Y, M, N, V, X, Z, \mu$). The above system of steady state equations is numerically solved using a Newton-type algorithm.[18]

## 4. Results

Using the calibrated model, three simulation exercises are performed. First, we study the steady state relationship among the key variables of the model economy for a range of values of aggregate productivity. Second, we carry out a sensitivity analysis of the key parameters related to the CE. Finally, we simulate the effects of a permanent technological shock to each type of material.

### 4.1. Optimal recycling rate and output

First, we study the determinants of the optimal recycling rate and the factors driving the circularity of the economy. In our theoretical framework, the recycling rate is determined endogenously, resulting from the maximization of social welfare once the social cost of the accumulation of waste has been internalized. This optimal recycling rate in the centralized economy would be equivalent to the target recycling rate of policies promoting the CE in a market economy. Once the waste has been produced, the recycling rate determines the fraction of waste that is transformed into recycled material to be used again in production activities, while the remaining fraction is accumulated to the previous stock of waste. Empirical evidence (OECD, 2020) suggests that recycling rates are higher in developed economies than in developing economies, indicating that economic growth can also be a factor fostering the circularity of the economy. We test this empirical evidence by calculating steady states of the model economy for a range of values of total factor productivity (TFP). In particular, we simulate the model for a range of values for TFP, from 0.2 to 1.8. The baseline calibration of the model is fixed at a value for TFP of 1, which corresponds to a steady state output of 0.390.

Fig. 1 plots the relationship between the steady-state output and the corresponding optimal recycling rate, stock of waste, and quantities for natural and recycled material. We start by studying the relationship between the optimal recycling rate and the level of output. The relationship between the output and the recycling rate is found to be always positive, indicating that the higher the level of output, the higher the

[18] The codes are written in Matlab and are available from the authors on request.

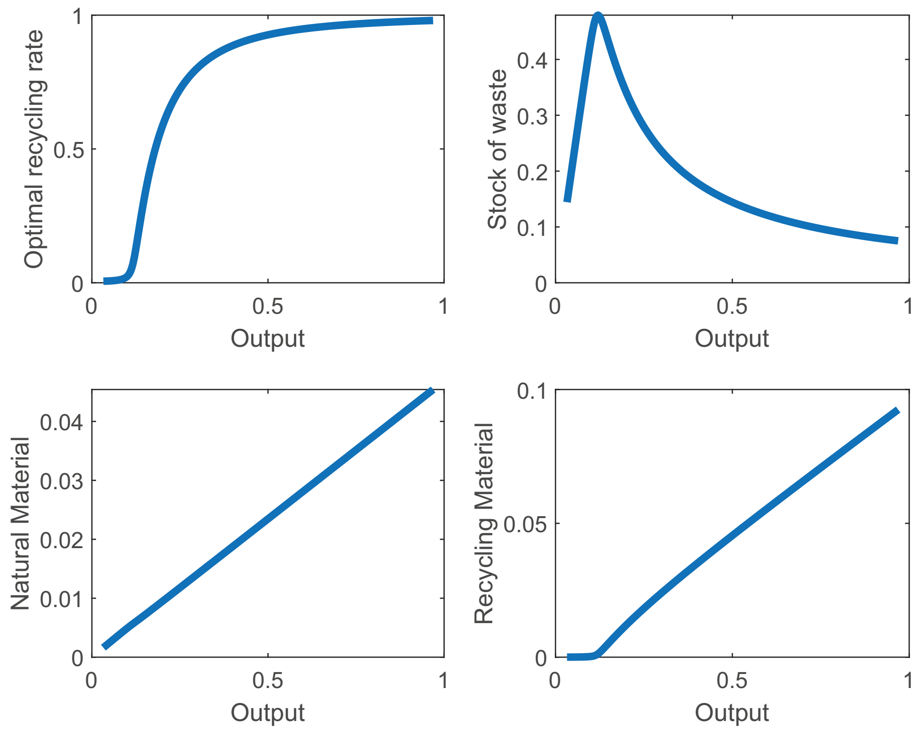


**Fig. 1.** Steady state values as a function of output.

optimal recycling rate. This steady-state relationship is obtained for alternative specifications of households' utility function. The function has an S-shaped form, reflecting that, once a certain level of output is reached, the transition from low to high recycling rates accelerates. When the output is high enough and the recycling rate is close to unity, further increases in output augment the recycling rate marginally. This result indicates that, as countries increase their output, the recycling rate that maximizes social welfare also increases and, therefore, a propensity to adopt a CE appears. Indeed, as the output grows, the waste generation increases along with the threat to the environment. Therefore, we should expect the recycling rate to be higher in developed countries than in developing countries given the greater environmental damage, with a general trend in increasing recycling activities and promoting the CE. Summing up, the model predicts a pattern of increasing circularity, as the only alternative to maximize social welfare in a growing economy to reduce the harmful effects caused by the linear economy.

Next, we study the relationship between the stock of waste and the output. Two opposite forces driving the relationship between these two variables emerge in the presence of the CE. On the one hand, as the output increases, the quantity of waste generated by consumption activities also increases, raising the stock of waste. On the other hand, as the output increases, the optimal recycling rate also increases, reducing the velocity of waste accumulation. In this context, the accumulation of waste critically depends on the circularity of the economy. We find the existence of a steady-state hump-shaped relationship between the output and the stock of waste, which can be interpreted as the existence of an Environmental Kuznets Curve (EKC) in the presence of the CE. This EKC does not appear in the case of a linear economy, in which the relationship between the output and the stock of waste is always positive. This result shows the importance of the CE as a necessary transformation of the traditional economy to make economic growth compatible with environment preservation. Bongers (2020) finds the existence of an EKC relationship between output and pollution when fossil fuel and renewable energy are considered as alternative energy sources, and a consequence of energy transition. In this theoretical framework, as the output increases, more renewable energy is used in production activities, thus reducing emissions. The mechanism from the CE found here is similar but operates through recycled material.

Finally, we find that, as the output increases, the quantity of both natural and recycled material also increases. Nevertheless, the growth in the use of recycled material is higher than that of natural material, increasing the circularity of the economy. Although recycling activities increase the available quantity of material other than natural resources for production activities, economic growth increases the total demand for material, including both recycled and natural resources, notwithstanding the lower material intensity (the number of raw materials per unit of output) of the production process given the constant returns to scale technology. This implies that the CE can partially mitigate the problems provoked by the linear economy but cannot totally close the open-loop when the output grows. The increasing circularity of the economy does not completely eliminate the pressure on natural non-renewable resources, although it is a qualified solution to the problem of waste accumulation. From this point of view, circularity is the only way to mitigate waste accumulation in a growing economy and, therefore, a necessary but not sufficient condition for sustainable growth in an environment with finite non-renewable natural resources.

### 4.2. Sensitivity analysis

The results presented in the previous section were obtained by simulating the model using the benchmark calibration of the parameters (Table 1). However, little information is available for calibrating the parameters related to the CE, and we used ad hoc parameters with plausible values for the benchmark calibration. To check the robustness of the previous results, we carry out a sensitivity analysis by varying these parameters. In particular, the model has three key parameters for the CE: the waste damage to households' utility, $\phi$, the waste content of consumption goods, $\eta$, and the elasticity of substitution between natural and recycled material, $\sigma$. For this sensitivity analysis, we solve the model by calculating steady states for a range of values of these three parameters. We use a range of values for the waste damage parameter from

0.15 to 1 (baseline value of 0.25). For the waste content of consumption, representing the fraction of consumption that transforms into waste, the selected range of values is from 0.1 to 0.5 (baseline value of 0.1). Finally, for the elasticity of substitution between natural and recycled material we choose a range of values from 1.01 to 10 (baseline value of 1.5).

Fig. 2 plots the relationship between the recycling rate and the stock of waste as a function of the waste damage parameter. The waste damage parameter represents the cost, in terms of forgone utility, of the negative externality resulting from waste accumulation. As expected, as the waste damage parameter increases, the optimal recycling rate increases to compensate for the damage to households' welfare. The waste damage parameter to households' utility can be interpreted both as a negative externality to welfare and as reflecting concerns about the environment and the exploitation of natural resources. By contrast, the stock of waste has a negative relationship with the waste damage to households' welfare. This negative relationship is only possible in a circular economy, which implies that in the case of a linear economy as the waste damage parameter increases welfare declines without a strategy for waste stock abatement. As expected, as the waste damage parameter increases, the investment, capital stock and output increase. On the other hand, variables related to circularity (recycled material and recycling rate) are positively affected when the waste damage parameter increases.

A similar sensitivity exercise is carried out with respect to the parameter representing the waste content in consumption goods. Consumption goods differ in the waste that they generate. Furthermore, the waste content of consumption goods has been increasing over time. The use of plastic, glass, electronic components, batteries and so on, spreads at the same rate that the variety of consumption goods grows. The model predicts the existence of a steady-state positive relationship between the waste content in consumption goods and the optimal recycling rate. For an initial low value of waste content, the stock of waste is higher, in spite of a rising recycling rate. This result has different interpretations. On the one hand, it indicates that reducing the waste content of consumption goods would reduce the stock of waste, even with a low recycling rate. Therefore, a strategy should be to managing consumption goods disregarding, as much as possible, elements that, after consumption, become waste. This is the case of plastic (i.e., plastic wrap can be reduced), paper, etc. On the other hand, once the waste content of consumption goods reaches a threshold, the stock of waste remains almost constant as the recycling rate is high enough. This occurs when the fraction of waste content is above 10%, and the recycling rate is above 60%. This second interpretation means that the waste content in consumption goods should not be a problem once a high enough recycling rate is reached. On the other hand, as the waste content in consumption increases, the stock of waste also increases Fig. 3.

Finally, Fig. 4 plots the results of a sensitivity analysis for the elasticity of substitution between natural and recycled material. Little change can be observed in the steady-state values when the elasticity of substitution is changed. Therefore, we conclude that the results obtained from the benchmark calibration of the model are not sensitive to the calibrated value for this parameter, and that they do not depend on the ease of substitution of natural with recycled material.

### 4.3. Technological change

Finally, we simulate a permanent change in the technology for material. In particular, we carry out two experiments: first, a permanent improvement in the technology for recycling material, which represents a permanent decline in the cost of recycling (a decline in the amount of output required per unit of recycled material), and second, a permanent deterioration in the technology for natural material, representing a permanent increase in the cost of natural material. It might be logical to think that both a decrease in the cost of recycled products and an increase in the cost of natural materials would boost the CE. However, we find that an increase in the cost of natural materials not only does not boost the CE but can even slightly slow it down.

The main results from these simulation exercises are shown in Figs. 5 and 6. Fig. 5 plots the transition dynamics from the initial steady state to the final steady state resulting from a permanent improvement in the technology for recycling material. The figure shows the transition path from the initial to the new (final) steady state, calculated as deviations

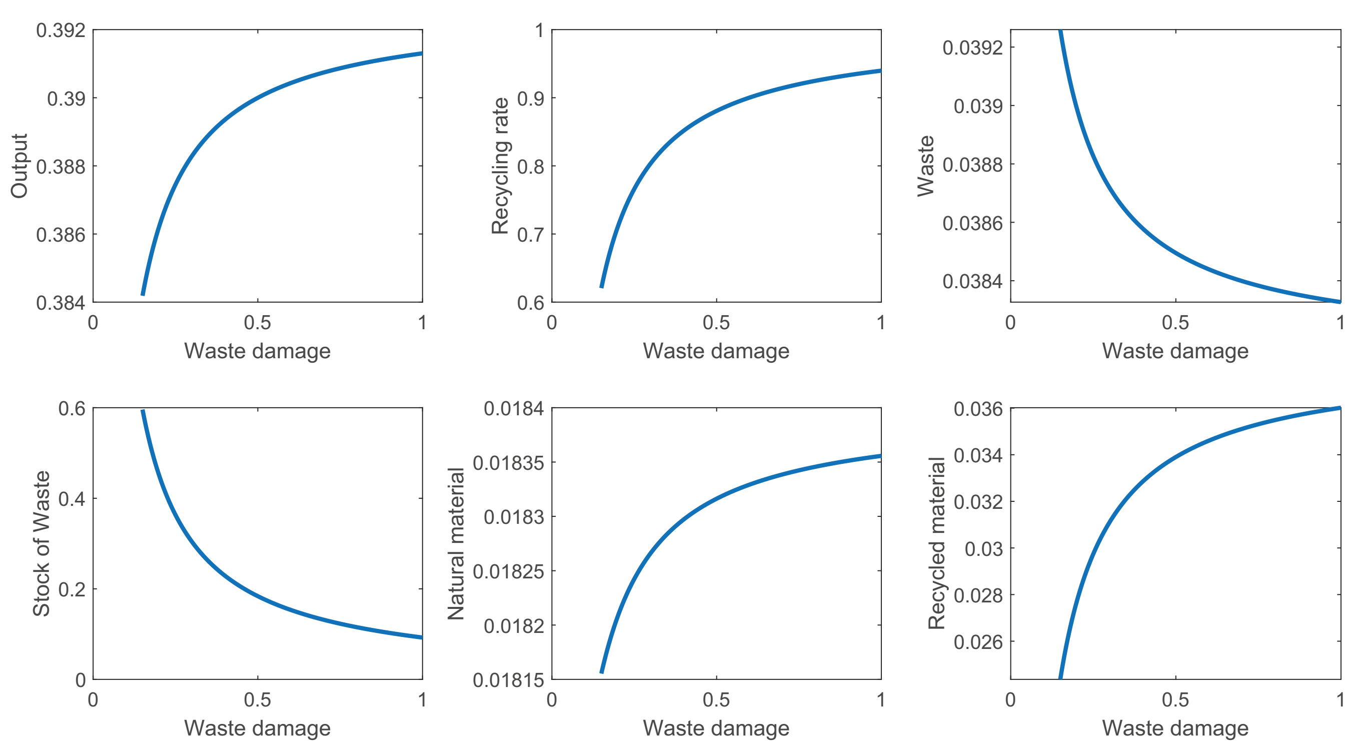


**Fig. 2.** Sensitivity analysis: steady state values as a function of the waste damage parameter.

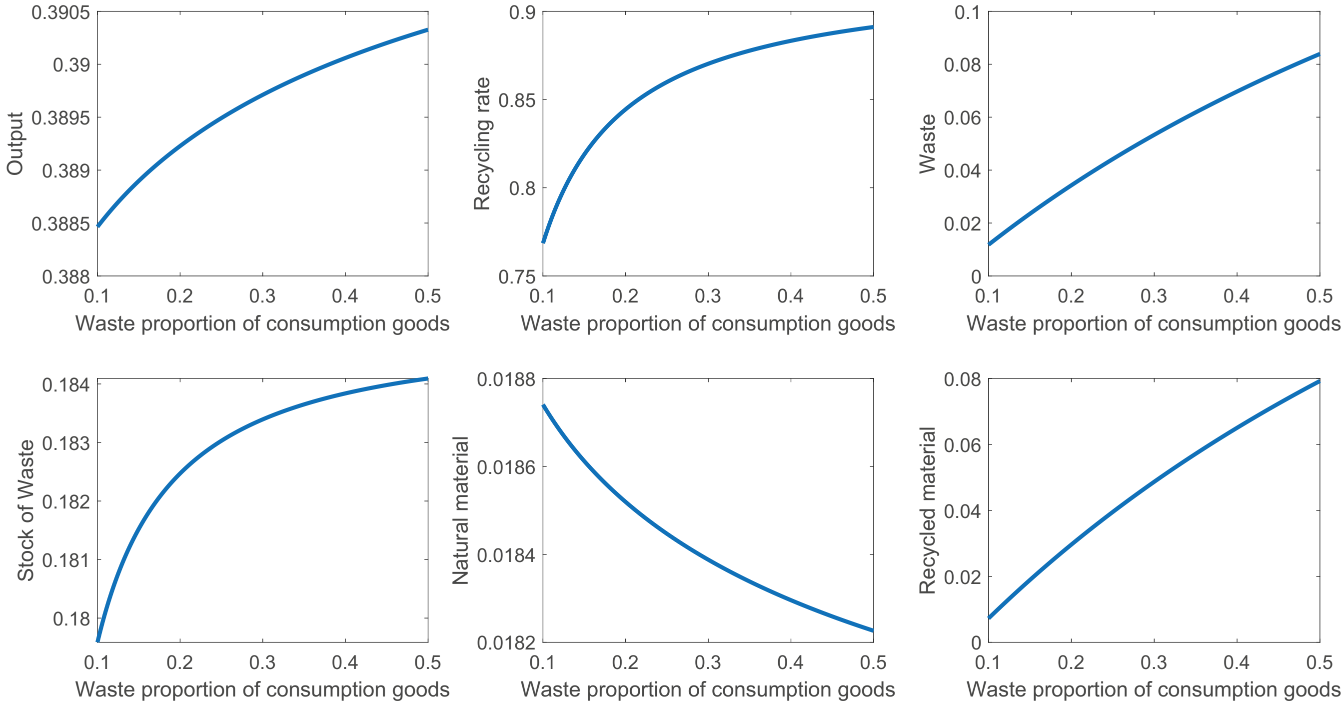


**Fig. 3.** Sensitivity analysis: steady state values as a function of the waste content in consumption parameter.

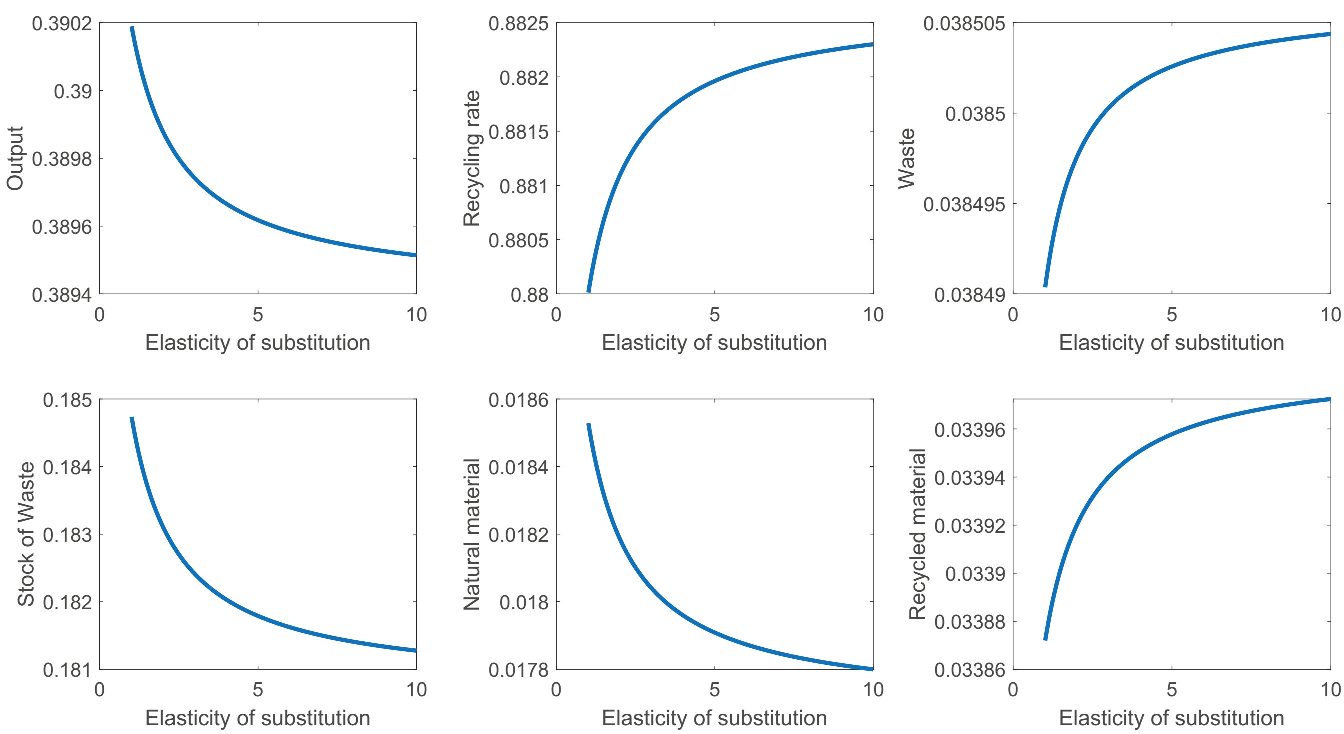


**Fig. 4.** Sensitivity analysis: Steady state values as a function of the elasticity of substitution between natural and recycled material.

from the initial steady state. This is done by computing the perfect-foresight approximate solution of the non-linear model using the Klein (2000) solution method see the technical appendix. We simulate a 5% decline in the parameter $\Theta_v$. The existence of an "overshooting" effect is observed for most of the variables as they increase on the impact, but later they adjust to the new steady state. The long-run effect on the output is positive, as expected. Indeed, the initial overshooting effect is explained by the fact that the increase in output leads to a rise, in the long-run, in the utilization of more natural resources. Natural resources decrease in impact as their cost relative to recycled material increases. However, the expansion of economic activity resulting from the shock leads to a greater demand for both recycled and natural material. Summing-up, the shock has positive effects on the CE side of the economy. As observed in Fig. 5, both the recycling ratio and the use of

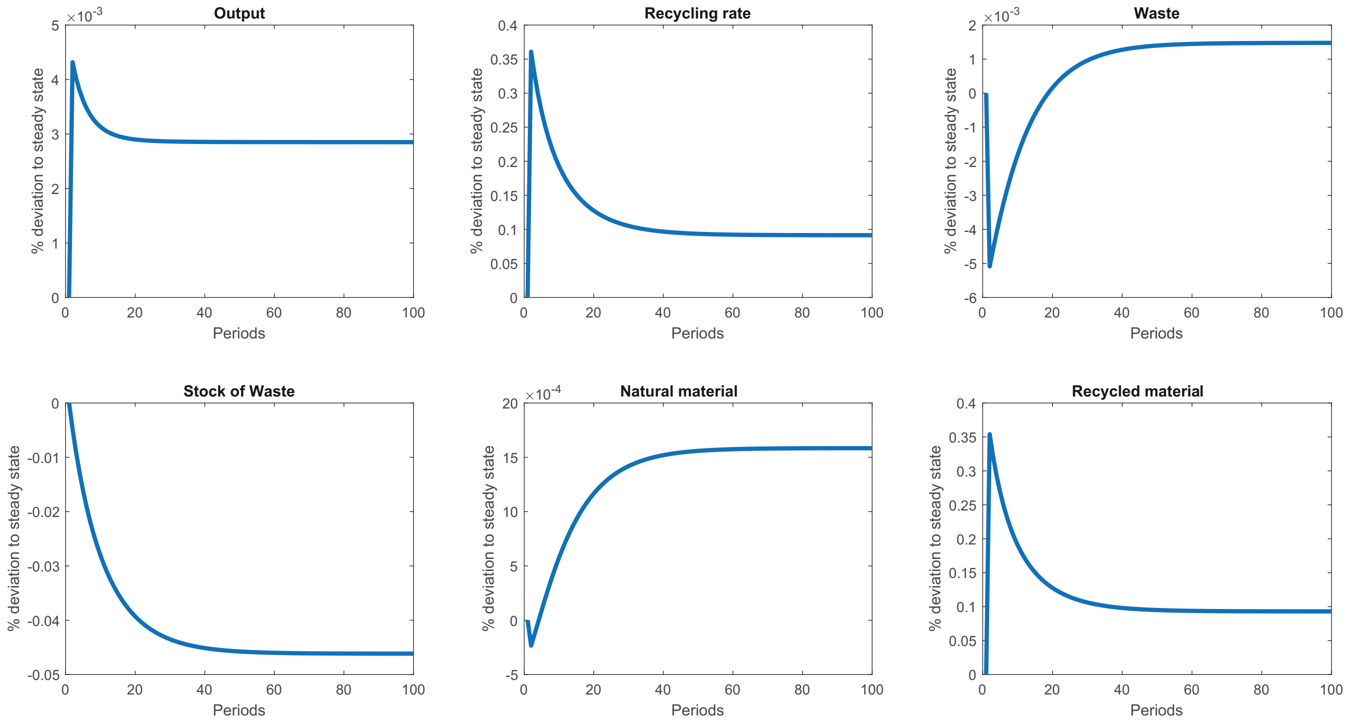


**Fig. 5.** Technological change in recycling material: a permanent decline in $\Theta_v$. Transition path to the new steady state as percentage deviation to the initial steady state.

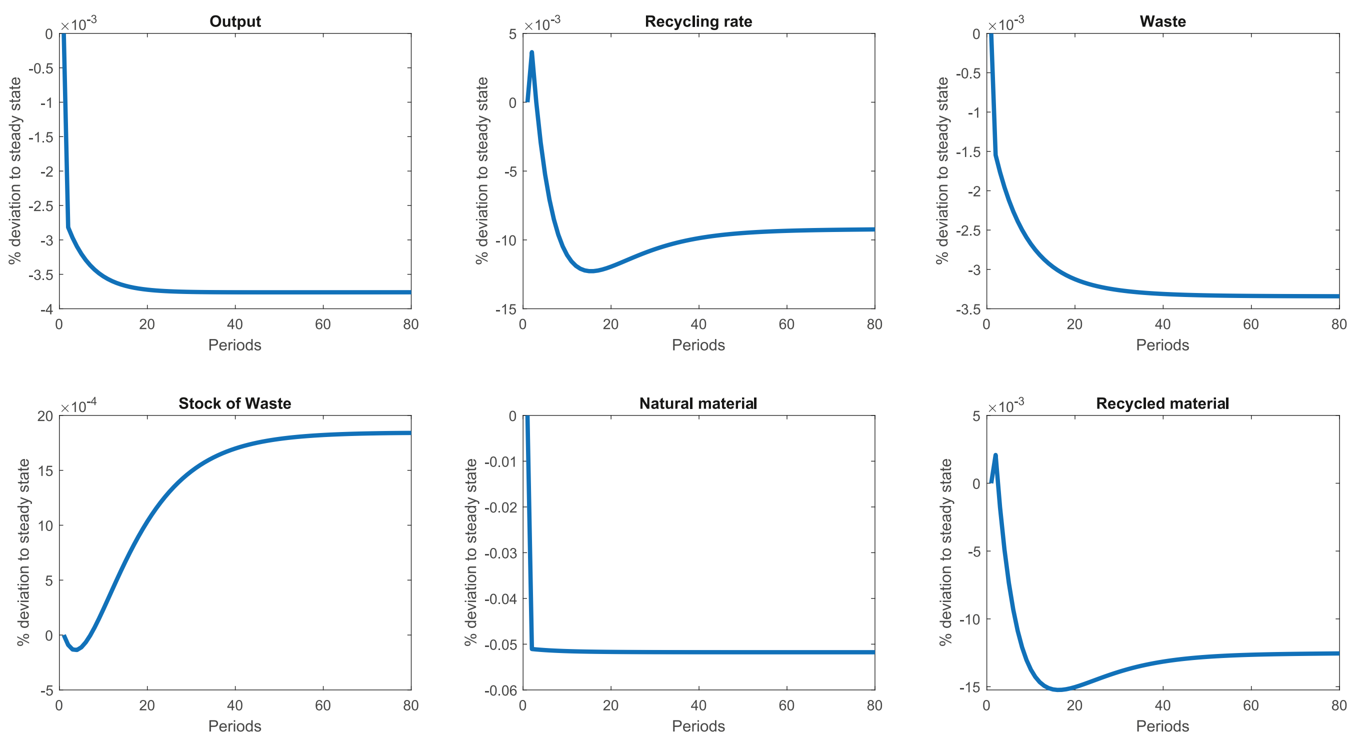


**Fig. 6.** Technological change in recycling material: A permanent increase in $\Theta_n$. Transition path to the new steady state as percentage deviation to the initial steady state.

recycled materials in production increase, while the stock of waste decreases. The generation of waste also declines in the impact, as the shock changes the optimal consumption/saving decision, increasing investment. However, after the initial decline, more waste is generated as consumption increases.[19] As recycled materials become less costly, a substitution effect of primary natural materials to recycled material in production activities is expected. However, there is also an income effect as reducing the cost of recycling increases the economic activity, expanding the demand for raw materials. Simulations show that, in the long-run, the income effect is larger than the substitution effect and, hence, the use of policies for expanding the CE does not guarantee a decay in the depletion rate of virgin natural resources.

Second, we study the case of a deterioration of technology (an increase in the cost) for natural resources. Fig. 6 plots the transition dynamics from the initial steady state to the final steady state resulting from a permanent deterioration in the technology of natural material. We simulate a 5% increase in the parameter $\Theta_n$. This shock has a negative effect on the output as the cost of using natural material becomes higher, reducing the demand for raw material. However, we find that any policy increasing the cost of natural resources does not have positive effects on the circular economy but the opposite, increasing the deterioration of the environment. Indeed, the shock reduces the optimal recycling rate, increasing the stock of waste. It is true, that this shock reduces consumption and hence, the generation of waste. However, the decline in the recycling rate demonstrates that shocks that increase the cost of natural material do not help the circularity of the economy.

The economic intuition behind this counterintuitive result is the following. As we notice, the higher cost of natural resources increases production cost. As a consequence, output declines in the new steady state, resulting in a negative income effect. This negative income effect is larger than the substitution effect of natural resources by recycled material, resulting in a lower demand of both natural resources and recycled material compared to the initial steady state. The lower demand of recycled material decreases the recycling rate more than the observed decline in waste, leading to an increase in the accumulation of waste.

## 5. Discussion and conclusions

This paper studies the optimal recycling rate in an economy with linear and circular production technologies from a macroeconomic perspective using standard tools in mainstream economics. The CE has traditionally been neglected in the construction of macroeconomic models, including those models that integrate environmental pollution and natural resource issues. This paper fills this gap and incorporates the CE into an otherwise standard neoclassical optimal growth model. The CE enters the model in two different ways: mitigating the negative externality arising from waste accumulation, which has a negative impact on households' utility, and as an input-augmenting technology. We define a three-input production technology: capital, labor, and raw materials. Raw materials can be generated by the extraction of natural resources or by recovering and recycling waste. The first case represents a linear economy, whereas the second is representative of a CE. In our model, the two economies coexist, the aim of our research being to build a theoretical framework in which both the linear and the circular economy are present and interact with each other. The integration of the CE into an otherwise standard traditional linear economy model proves to be fruitful and leads to a number of interesting results about the implications of the CE in terms of social welfare, economic activity and the environment. Moreover, it is useful to identify proper policies to encourage the development of the CE and the relationship between the CE and economic growth. The analysis performed in the previous sections allows a direct comparison between the CE and the standard linear economy using the tools of mainstream economics. This integrated theoretical framework provides a number of insights.

First, we identify a positive relationship between the circularity of the economy and economic development, measured by output. This result indicates that the CE will expand as the level of output increases, as growing economies require the expansion of the CE as a necessary condition to turn economic growth into social welfare gains and to mitigate environmental deterioration (see Schroeder et al., 2018a). The model indicates that welfare maximization requires an increase in the circularity of the economy when the output is expanding. Otherwise, an increase in the output does not guarantee improved social welfare as the linear economy causes the environment to deteriorate. Therefore, the model reveals that the CE is fully consistent with sustainable development, contributing to the three pillars: economic, social, and environmental. Millar et al. (2019) argue that the CE cannot be understood as an optimal tool for sustainable development. While this is true, the CE can be viewed as a production model supporting sustainable development. This is consistent with the model's results, which show that the CE is a necessary but not sufficient condition for sustainable growth. The CE is adopted, not to solve all environmental and natural resource problems, derived from a linear conception of the economy, but as a strategy to mitigate those problems, by partially closing the open-loop of the standard linear production model. Schroeder et al. (2018a,b) argue that the CE can contribute directly to attaining a high number of UN Sustainable Development Goals, while Geissdoerfer et al. (2017) highlight the differences and similarities between the CE and sustainability concepts. Millar et al. (2019) review the concepts of the CE and sustainable development and their relationship. The macroeconomic approach in this paper contributes to that debate and shows that the economic, welfare, environmental and sustainable development implications of the CE are radically opposite to those of the linear economy. Lin et al. (2020) points out the relationship between sustainable growth and CE and the importance of CE achieving the goal of sustainability, arguing that sustainable growth can be understood as an institutional arrangement of regenerating circular output in a sustainable way.

Second, the CE cannot solve all the environmental and natural resources exploitation problems generated by the linear economy. As pointed out by Millar et al. (2019), the CE can be interpreted as a positive contribution to a more environmentally sustainable model mitigating some of the problems produced by the linear economy. The CE can contribute to closing the "open-loop" on which the linear economy is based and, hence, promote economic growth by reducing its negative consequences for the environment and natural resources. Even in the case of 100% of energy being renewable and a recycling rate of 100%, the pressure on natural resources would exist in a growing economy. That is, full circularity of the economy would eliminate environmental quality damage but would not totally eliminate the pressure on the natural system. On the other hand, it is widely accepted that there is a relationship between the history of waste and climate change, and that CE policies should not only concern nowadays waste, but also the already accumulated waste in Earth, considering them as useful (new) factors of production and consumption. Korhonen et al. (2018a) identified six limits for the CE, including thermodynamics, spatial and temporal system boundaries, the limits posed by the physical scale of the economy, and the limits posed by path-dependency. These limits are also present in our model, in which the CE cannot be a substitute for the linear economy. Nevertheless, we show that the CE is essential for reducing the stock of waste and preserving the environment as output grows. Only in the presence of the CE is an EKC represented by a hump-

[19] These results prove that, in principle, any policy designed to reduce the cost of recycling will have positive effects on the level of circularity of the economy and on social welfare. These results can be related to some extent with the case of a subsidy for recycling activities, although the use of taxes/subsidies provokes other effects on the economy not considered in our model. Kirchherr et al. (2018) take, as an example of this kind of intervention, the proposal of reducing the value-added tax (VAT) from 19% to 7% for any reparations as a measure to make reparations more attractive in Germany. This proposal was launched by Alliance 90/The Greens, a German environmental party.

shaped relationship between the output and the stock of waste obtained. Without increasing the circularity of the economy, economic growth leads to the accumulation of waste with adverse effects on social welfare from environmental deterioration. Lin et al. (2020) proposes a Circular Economy National Income Accounting (CENIA) framework for measuring the contribution of CE to sustainable growth, where circular output representing the domestic demand for sustainable development is incorporated as a new component to the traditional definition of GDP.

Third, technological change, accounting for a reduction in the cost of recycling activities, improves the circularity of the economy and reduces the stock of pollution. Korhonen et al. (2018b) warn about the possibility of a "rebound" effect provoked by the expansion of the CE. The "rebound" effect is well-known in the energy literature and states that an increase in energy efficiency leads to an increase in energy consumption, reversing the initial positive effects of efficiency gains. The model developed here predicts no rebound effect from the CE, clearing the way for expanding the circularity of the economy. We find that expanding the CE has a positive effect on output, enhancing income growth without adverse effects on natural resource exploitation. This paves the way to the active use of this type of policies which augment the circularity of the economy as a strategy for sustainable long-run growth.

Finally, we find that any shock that increases the cost of natural material without directly affecting the rest of the economy is counterproductive for the CE and involves many adverse economic consequences for the economy. Although the relative price of recycled versus natural material declines, the optimal the optimal recycling rate decreases in response to the negative effects of this policy on output and consumption. Paradoxically, the decline in waste generation leads to an accumulation of the stock of waste, given the counter-reaction of the recycling rate. Therefore, while a shock increasing the cost of natural material would limit the natural resource depletion rate, it would provoke a deterioration of the environment by accumulating more waste at the same time as limiting the circularity of the economy.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2022.107504.

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# Corrigendum to "The circular economy and the optimal recycling rate: A macroeconomic approach" [Volume 199, September 2022, 107504]

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The authors regret as the in-text citation Lin et al. (2020) should be Lin (2020).

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