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Waste recycling policies and Covid-19 pandemic in an E-DSGE model

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1. Introduction

Waste is one of the “unresolved” environmental issues in the 21st century. Although awareness of the external effects of waste is increasing, and although in several countries capacity constraints and management problems are becoming increasingly evident, a lot of work has yet to be done. So, for example, policy initiatives undertaken by EU Member States, together with the EU level Directives on specific flows of waste, have proven to be insufficient to change the trend so far, and waste volumes keep generally increasing as a result of higher incomes and urbanization rates, increased consumption of goods and services, and more intensive use of packaging materials.

Together with the huge economic costs related to waste management practices, waste has also relevant environmental and health costs, which are strictly interrelated with each other. A widespread literature has already examined the risks to human health due to both legal (e.g. Forastiere et al., 2011) and illegal waste disposal options (Senior and Mazza, 2004; Triassi et al., 2015). Non-recyclable waste is a particularly serious problem, due to both the impossibility of recovering materials and the environmental and health impacts of disposal options, i.e. landfill and incineration. Accordingly, governments around the world have addressed the waste problem by introducing policies aimed at reducing the amount of non-recyclable, unsorted waste, and stimulating recycling, reusing and material recovery.

Waste generation and management problems are expected to even worsen in times of unexpected global shocks, such as COVID-19, which may cause negative impacts worldwide on the waste cycle (Adyel, 2020; Silva et al., 2021; Sarkodie and Owusu, 2020; Zambrano-Monserrate et al., 2020). Pandemic events contribute to strengthen the vicious cycle going from health shocks to waste related environmental impacts and back. On the one hand, pollution related to waste disposal and low environmental quality negatively impacts on individual health conditions, increasing the risk of experimenting more serious consequences from the contagion. The literature suggests that air pollution can influence the dynamics of COVID-19 contagions and deaths, due to the negative effects of long term exposures to pollutants on lungs and health

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Several countries have also experienced the massive return to using plastic shopping bags to prevent cross-contamination, contrary to policy studies show the impact of recycling subsidies on end-of-life vehicle relevant role of the subsidy policy in the recycling industry. Other Chang et al. (2016) for China, for instance, provide evidence for the several governments provide subsidies to stimulate recycling and reuse. 2021 ). On the other hand, in order to protect themselves and reduce the New habits emerging as a consequence of the lockdown have also led to the expansion of e-commerce, resulting in massive use of plastics and other materials for containment and packaging (Silva et al., 2021; Han et al., 2020). In some cases, materials cannot be sorted and recycled, like in the case of face masks or other protective equipments, due to the risk of contagion. In other cases, materials are not appropriately disposed of by final consumers, contributing to the growth of non-recyclable waste amounts. At the same time, however, all the above mentioned practices implemented to contrast the virus diffusion, despite their negative impacts on the environment, have been relevant in reducing the risk of infection and have been beneficial to people’s health. It is then interesting to evaluate in a comprehensive framework the interrelations between environmental quality and health and the impact of policies. Our contribution is rooted in a micro-founded environmental dynamic stochastic general equilibrium (E-DSGE) model incorporating waste recycling in the production and consumption processes, and also embedding recyclable and non-recyclable consumption in consumers’ preferences. We assume that recyclable consumption does not contribute to environmental harm but, rather, can be “transformed” to be utilized again in the production process, in a circular economy perspective. Non-recyclable consumption, instead, due to the need to dispose of it through landfilling and/or incineration, worsens environmental quality. Our DSGE logic is particularly suitable to understand the dynamic response of economic, waste and environmental variables in the presence of shocks related to productivity, policy and preferences. We exploit these features of our model first, to investigate the impact of two different waste policy instruments, and second, to analyze the impact of a pandemic shock, like the COVID-19 event, on the economic system, in the short term. The first part of the analysis is quite standard, but we add to the extant literature by showing the impact of two different types of waste policies: an incentive-based intervention, corresponding to either a taxation on non-recyclable consumption or a subsidy on recyclable consumption, and a behavioral, instrument, like an information or educational campaign, which stimulates a shift in consumers’ preferences towards recyclable products. The use of incentive-based instruments to reduce waste generation and stimulate recycling is becoming widespread around the world. Several countries, like the US, Japan and many EU countries, adopt Unit-Based Pricing (UBP) or pay-as-you-throw programs for residential solid waste collection, where the waste tariff is strictly related to the waste volumes (per weight or per bag of generated waste) (Bel and Gradus, 2016). Further, several governments provide subsidies to stimulate recycling and reuse. Chang et al. (2016) for China, for instance, provide evidence for the relevant role of the subsidy policy in the recycling industry. Other studies show the impact of recycling subsidies on end-of-life vehicle recycling (Yu et al., 2021) or on the power battery recycling industry (Ding et al., 2020). Behavioral policies, which try to stimulate consumption of environmental behaviors by helping them overcome their cognitive limitations, have attracted a lot of attention in recent years in the academic and policy debate. Further, it should be considered that changes in consumers’ preferences are considered as a crucial part of a circular economy transition, as very well testified by the role potentially played by consumers’ behaviors in the context of the waste related EU Green Deal objectives. The second part of the analysis represents the main contribution of our work. To the best of our knowledge, this is the first study which investigates the impact of a pandemic shock on the economic system taking into account the interrelationship between waste management and health consequences. This is clearly a highly debated issue, and we aim at assessing the waste related trade-offs that are embedded in consumers’ and policy makers’ reactions to pandemic events. Our methodological choice, the E-DSGE strategy, is also, to our knowledge, new in the literature. We calibrate our model to Italian data, but our approach can be extended to broader geographical areas (e.g. OECD countries). Our work links to three streams of the literature. The first one deals with the microeconomic analysis and the drivers of waste management and waste policies. Under a theoretical point of view, seminal contributions in this respect include Fullerton and Kinnaman (1995) as well as, more recently, D’Amato et al. (2016), among others. The received contributions show the relevance of policies in driving behaviors aimed at reducing waste production and at enhancing recycling, both under a neoclassical and under a behavioral perspective (e.g. Brekke et al., 2003). Turning to the empirical literature, several papers assess waste generation and disposal drivers, focusing on specific areas and on the role of policies (Hage and Söderholm, 2008; De Jaeger and Eyckmans, 2008; Dijkgraaf and Gradus, 2004; Kinnaman and Fullerton, 2000, among others) and, more generally, on the determinants of waste performance at the EU level (e.g. Mazzanti and Zoboli, 2009; EEA, 2007, 2009) and at the OECD level (e.g. Johnstone and Labonne, 2004). Some of these contributions specifically address the impact of waste policies on waste production and separate collection, showing how incentive-based public intervention may indeed affect waste related behaviors. In these works, the analysis is devoted to assess whether the provision of cheaper recycling facilities and/or the introduction of waste disposal fees have virtuous impacts on increased households’ recycling effort. User fees or pay-as-you-throw (PAYT) schemes are for example suggested to stimulate separate collection as well as the reduction of waste generation, although there is not a widespread agreement on their effectiveness (Bel and Gradus, 2016; Fullerton and Kinnaman, 1996; Kinnaman and Fullerton, 2000). A more recent literature on behavioral economics has suggested the use of “non-monetary” policies to correct individual incentives towards more sustainable behaviors. According to this literature, when economic agents do not make their choices as predicted by the standard neoclassical framework, due to cognitive limitations and bounded rationality, behavioral interventions can be usefully adopted to change individual behaviors. In the case of recycling practices, interventions aimed at providing information about the importance of recycling to reduce the environmental problems related to waste disposal are expected to lead to increased recycling (Schultz, 1999). The literature just summarized informs our investigation of the impact of waste policies (both traditional and behavioral) in a macroeconomic setting. The second strand of literature which is relevant for our methodological strategy is the one addressing environmental policy in explicitly dynamic economic models. Among others, the closest to our work are those by Argentiero et al. (2017), who focus on renewable energy policies, and Annicchiarico and Di Dio (2015), who develop a (New Keynesian) DSGE framework to analyse the linkages between environmental policy and business cycle fluctuations. Third, we draw on the very recent and rapidly increasing literature showing how environmental quality may significantly affect COVID-19 mortality (see, among others, Becchetti et al., 2021 and Coker et al., 2020, who find an association between PM2.5 and COVID-19 related mortality). Our work is also inspired in its structure to the work by Yang et al. (2020), that is however devoted to a completely different issue, as it investigates the impact of COVID-19, in terms of economic downturn, on the touristic sector using a DSGE model.
The corresponding production functions are:

\[ Y_r^r = A_r^r \delta \left( K_{r,t-1} \right)^{\delta_r} \left( N_r^r H_r \right)^{\delta_n} \left( RW \right)^{\delta_{rn}} \]  \hspace{1cm} (1)

\[ Y_{nr} = A_{nr}^{\rho} \delta_{nr} \left( K_{nr,t-1} \right)^{\delta_{nr}} \left( N_{nr}^r H_{nr} \right)^{\delta_{nr1}} \left( EN_{r} \right)^{\delta_{nr2}} \]  \hspace{1cm} (2)

where \( \alpha_r, \alpha_{nr}, \beta_r, \beta_{nr} \) and \( \gamma_r \) are the elasticities of output with respect to each production factor, also indicating the distributive shares of each productive factor remuneration, and \( A_r^r \) and \( A_{nr}^{\rho} \) are total factor productivities (TFP) in each sector.

The intermediate sector, i.e. the recyclable waste \( \langle RW \rangle \), sector, is a function of recyclable consumption, \( C_r^r \), \( \eta_r \) measuring the "relevance" of recycling in producing \( \langle RW \rangle \), and recycling quality provided by the Government, \( Q_r \), with \( \eta_r > 0 \) as the corresponding parameter indicating the effect of recycling quality on recyclable waste; production function for \( \langle RW \rangle \), is specified as follows:

\[ \langle RW \rangle_t = \left( \eta_r (C_r^r)^{\eta_r} + \zeta (Q_t)^{\eta_r} \right)^{1/\eta_r} \]  \hspace{1cm} (3)

where \( \varepsilon \) is the elasticity of substitution between recyclable consumption and recycling quality.

The exploitation of virgin natural resources in the two sectors, \( K_r^r \) and \( K_{nr}^{\rho} \), respectively, are related to the stock of (non renewable) natural resources. In other words, we assume that the flow of resources taken from the environment and used in the production of the two kinds of output decreases an exogenous (non-renewable) stock of natural capital.

The economy’s demand side is populated by an infinite number of infinitely living households with preferences defined over recyclable consumption goods, \( C_r^r \), non recyclable consumption goods, \( C_{nr}^{r} \), labor supply, \( N_r^r \) and \( N_{nr}^{r} \), and health status, \( H_r \).

Each agent maximizes the expected value of an intertemporal utility function, i.e.:

\[ E_0 \sum_{t=0}^{\infty} \rho U(C_r^r, C_{nr}^{r}, N_r^{nr}, N_{nr}^{r}, H_t) \]  \hspace{1cm} (4)

with \( \rho \) corresponding to the subjective discount factor.

For the period utility function, we assume the following constant relative risk aversion (CRRA) form:

3 See Appendix A for a detailed description of the model and Appendix B for the analytical derivation of the equilibrium conditions.

4 Notice that there is perfect “separability” across recyclable and non recyclable outputs. This assumption implies indeed possible losses of generality, but provides invaluable benefits in terms of ease of calculation and interpretation. The removal of this assumption is left as the subject for future research.

5 This “aggregate” representation of the stock of natural capital is rather standard, for example, in the literature on economic growth and the environment - see, among others, Smulders (2000). On the other hand, to point out the current over-exploitation of natural resources, we assume a negative exogenous stock exploitation adding to the endogenous flow of resources used in the recycling and non-recycling sectors.
\[
U_t = \nu_t \left[ \log(C_t^r) \right] + (1 - \nu_t) \left[ \log(C_t^{nr}) \right] - \left( \frac{N_r^{nr}}{1 + \psi} \right) - \left( \frac{N_r^r}{1 + \psi} \right) + H_t
\]  
(5)

where \( \nu_t \) is a taste shifter (Stockman and Tesar, 1995), whose law of motion is described by an AR(1) process with zero mean and uncorrelated residuals.

A crucial part of our modelling strategy is related to the linkages between the health status and both environmental quality and prevention measures, which are likely to affect waste related impacts. We borrow the modelling strategy from Yang et al. (2020) and define the law of motion for health status according to the following process:

\[
H_t = (1 - \delta^h)H_{t-1} + \kappa_t (\psi C_t^{nr} - G_t) - Z_t
\]  
(6)

where \( \delta^h \) indicates an exogenous health deterioration rate, while \( \kappa_t \) is an indicator variable capturing the occurrence of a pandemic; in other words, we model the presence of a pandemic shock, such as the COVID-19 crisis, assuming \( \kappa_t = 1 \). In the latter case, the negative impact is determined by an exogenous effect, \( G_t \), which can be made less harmful by adopting conservative measures, such as the use of personal protective equipment (PPEs) (e.g. face masks - as exemplified in Fig. 1) and/or the adoption of single use plastics packaging. These measures are assumed to bring an average improvement in health status by a positive parameter \( \varphi \) per unit of increase in non-recyclable consumption. The downside of this positive effect is that, in the presence of a pandemic event, the use of PPEs implies additional consumption of non-recyclable goods, by the amount \( \varphi C_t^{nr} \). In other terms, we are here assuming that PPEs and single use plastics related to the reduction of the COVID-19 contagion are part of non-recyclable consumption\(^6\). There is therefore a relationship between increases in non-recyclable consumption triggered by the pandemic shock, and the related benefits in terms of reduced health impacts. Finally, notice that in our model non-recyclable consumption related to the pandemic event is financed by a lump sum subsidy paid by the public sector to the households (\( T_t \)).

The law of motion of \( G_t \), the exogenous health impact under a pandemic event, is described by an AR(1) process with zero mean and uncorrelated residuals. Finally, health is always negatively affected by „broadly intended” environmental pollution, \( Z_t \), whose dynamics depend on the damages generated by non-recyclable goods and related to the waste disposal in landfill, incineration and waste export\(^7\).

One of the central points of our modelling strategy is therefore related to two waste-relevant impacts of the pandemic event: on the one hand, an increase in non-recyclable consumption triggers a reduction in the negative impact of the pandemic shock in terms of infections, while, on the other hand, the increase of pollution due to the same increase in non-recyclable consumption implies a worsening environmental impact. The maximization of the utility function (5) is subject to a standard budget constraint.

Finally, waste policy affects exogenously the prices of recyclable and non recyclable goods, depending on the chosen policy instrument. In particular, the Government budget is balanced on a period-by-period basis:

\[
t_r C_t^{nr} = m_r C_t^r + P_t^r Q_t + \kappa_t T_t
\]  
(7)

where taxation \( t_r \) on non recyclable consumption is levied in order to finance the value of recycling quality \( P_t^r Q_t \), to spur recyclable consumption through a subsidy \( m_r \) and to possibly finance non-recyclable consumption related to the pandemic event. Here, \( P_t^r \) is the unit 'price' of the quality of waste recycling infrastructures, which is formally borne by the Government but is effectively paid by the intermediate firm producing recyclable waste according to (3). Both the tax rate on non recyclable consumption and the subsidy follow an AR(1) process with zero mean and uncorrelated residuals.

The model variables have been loglinearized at a first order around their steady state values and then they have been simulated in the presence of the stochastic shocks described above. These simulations generate the impulse response functions (IRFs) which will be discussed in Section 3.

### 2.2. Model calibration

Parameters’ values are consistent with the corresponding macro-economic great ratios and with some stylized facts related to environmental performances (e.g. sorted collection rates, waste management shares etc.). The parameters’ definitions are as reported in Table 1. The corresponding calibrated values, with the related sources, are shown in Table 2\(^8\).

The capital shares (\( \beta_r \) and \( \alpha_r \)) in the production functions (1) and (2) are calibrated on the basis of the ratios between capital rents and GDP in the EU, following Argentiero et al. (2017), whereas labor elasticities \( \beta_l \) and \( \phi_r \) are set on the basis of the average shares of gross labor incomes on GDP in the EU from 2000 to 2019 (source: Ameco dataset online). The calibration of the share of recyclable waste in the recyclable goods production function (\( \varphi_r \)) corresponds to the median value of end-of-life

### Table 1

| Parameters definitions. | Parameters |
|------------------------|------------|
| \( a_r \)              | recyclable sector elasticity of capital |
| \( \beta_r \)          | recyclable sector elasticity of labor |
| \( \gamma \)           | recyclable sector elasticity of recyclable waste |
| \( \alpha_r \)         | non recyclable sector elasticity of capital |
| \( \beta^* \)          | non recyclable sector elasticity of labor |
| \( \eta \)             | recyclable consumption share in the recyclable waste production function |
| \( \zeta \)            | recycling quality share in the recyclable waste production function |
| \( \varepsilon \)       | elasticity of substitution between recyclable consumption and recycling quality |
| \( \psi_r \)           | persistence of recyclable sector TFP |
| \( \phi^\infty \)      | persistence of non recyclable sector TFP |
| \( \xi \)              | degree of natural resource exploitation |
| \( \Psi \)             | inverse of Frisch elasticity of non recyclable sector labor supply |
| \( \nu \)              | inverse of Frisch elasticity of recyclable sector labor supply |
| \( \phi \)             | persistence of taste shifter |
| \( \vartheta \)        | persistence of Covid-19 pandemic |
| \( \delta^1 \)         | damage for the environment related to the waste disposal in landfill |
| \( \delta^2 \)         | damage for the environment related to the waste incineration |
| \( \delta^3 \)         | damage for the environment related to the waste export |
| \( d \)                | share of landfilling in total municipal waste management |
| \( e \)                | share of waste incineration in total municipal waste management |
| \( \rho \)             | intertemporal subjective discount factor |
| \( \phi^\sigma \)       | persistence of subsidy on recyclable consumption |
| \( \phi^\rho \)         | persistence of tax rate on non recyclable consumption |
| \( \phi^\nu \)         | share of non recyclable consumption to cope with Covid-19 pandemic |
| \( \delta^r \)         | non recyclable sector depreciation rate of capital |
| \( \beta^r \)          | health depreciation rate |

\(^{6}\) This is a reasonable assumption, as currently face masks and gloves cannot be disposed of in recyclable bins, and they are sent to incineration or landfill (Battagazzore et al., 2020).

\(^{7}\) For ease of calculations and computation, we assume no environmental impact from recycling.

\(^{8}\) We have increased (and decreased) the calibrated values of the parameters by +10% (and −10%) in order to evaluate the sensitivity of the results for changes in the calibration around a confidence interval. The results of this sensitivity analysis are discussed throughout section 3.1.
Table 2

| Parameters | Values | Source |
|-----------|--------|--------|
| $\alpha'$ | 0.30 | Argentiero et al. (2017) |
| $\beta'$ | 0.50 | Ameco |
| $\gamma$ | 0.10 | Eurostat |
| $\alpha''$ | 0.30 | Argentiero et al. (2017) |
| $\beta''$ | 0.50 | Ameco |
| $\eta$ | 0.613 | ISPRA (2020) |
| $\zeta$ | 0.11 | ISPRA (2020) |
| $\epsilon$ | 0.50 | Own assumption |
| $\Phi'$ | 0.90 | e.g. Argentiero et al. (2017) |
| $\Phi''$ | 0.90 | e.g. Argentiero et al. (2017) |
| $\rho$ | 3.50 | footprintnetwork.org |
| $\Psi$ | 2.00 | Smets and Wouters (2003) |
| $\nu$ | 2.00 | Smets and Wouters (2003) |
| $\phi'$ | 0.90 | Yang et al. (2020) |
| $\phi''$ | 0.90 | Yang et al. (2020) |
| $\beta^1$ | 1.35 | Forastiere et al. (2011) |
| $\beta^2$ | 1.00 | Forastiere et al. (2011) |
| $\delta^3$ | 0.00 | Own assumption |
| $\delta$ | 0.50 | ISPRA (2020) |
| $\epsilon$ | 0.45 | ISPRA (2020) |
| $\rho$ | 0.96 | European Commission (2014) |
| $\phi^3$ | 0.90 | e.g. Argentiero et al. (2017) |
| $\phi''$ | 0.90 | e.g. Argentiero et al. (2017) |
| $\varphi$ | 0.0585 | Own elaboration based on ISPRA (2020) and Adyel, 2020 |
| $\delta^3$ | 0.10 | e.g. Smets and Wouters (2007) |
| $\delta^2$ | 0.10 | e.g. Smets and Wouters (2007) |
| $\delta^1$ | 0.08 | Yang et al. (2020) |

Recycling input rates in the EU for 2016 (source: Eurostat).

The recyclable consumption share in the recyclable waste production function ($\rho$) is assumed to be equal to the average separate waste collection rate in Italy in 2019 (source: ISPRA, 2020); the recycling quality share in the recyclable waste production function ($\zeta$) is equal to the share of Italian municipalities that in 2019 has calculated the waste tariff on the basis of the waste produced, whereas the elasticity of substitution between recyclable consumption and recycling quality ($\epsilon$) is assumed to be equal to 0.5.

The exogenous depletion rate for natural resources is set according to the excess of ecological footprint on biocapacity measured for Italy in 2017 (properly normalized).

Following Smets and Wouters (2003), which is based on EU data, the Frisch elasticities of labor supply ($\varphi$) and ($\nu$) are calibrated to a value of 2.

The damages for the environment related to the waste disposal in landfill and waste incineration are defined on the basis of the number of people exposed to landfilling and incineration in Italy (in millions), according to Forastiere et al. (2011). On the other hand, both waste export and recycling are assumed to generate 0 damages.

The share of landfilling and the share of waste incineration in total municipal waste management is equal to the share of landfilled and incinerated not recycled waste measured in Italy in 2019 (source: ISPRA, 2020).

The share of non recyclable consumption to cope with Covid-19 pandemic ($\rho$) is calibrated to 5.85%. This is calculated by summing the share of unsorted waste from face masks, calculated on the basis of estimates by ISPRA and unsorted collection data (again from ISPRA, 2020), plus the percentage estimated increase in single use plastics from COVID-19 (from Adyel, 2020) multiplied by the share of unsorted collection (ISPRA, 2020). Following the macroeconomic literature (e.g. Smets and Wouters, 2007), the depreciation rates of capital ($\delta'$ and $\delta''$) are calibrated to an annual value of 0.1, whereas the persistence of recyclable sector TFP, the persistence of non recyclable sector TFP, the persistence of subsidy on recyclable consumption and the persistence of tax rate on non recyclable consumption are all calibrated to a value of 0.9, assuming a high degree of persistence (see e.g. Argentiero et al., 2017).

Following Yang et al. (2020), we calibrate the health depreciation rate with a value of 0.08 and the persistence of Covid-19 pandemic, intended as the persistence of disaster risk, with a value of 0.60.

The intertemporal discount factor $\beta$ has been set to a value of 0.96 (compatible with what is suggested by the European Commission, 2014).

3. Results

Results from our simulations are discussed in this section. We first evaluate the impact of a traditional waste policy shock, which we model here as an upward shock of the taxation on non-recyclable consumption or of a subsidy on recyclable consumption. As the effects are qualitatively rather similar, we here report and discuss only results for the tax related shock (see Fig. 2), omitting those generated by a recycling subsidy. As it emerges from Fig. 2, the tax shock triggers a substitution effect across non-recyclable and recyclable consumption. Coherent changes take place in the output level; as a result, and as it is reasonable, a shift of labor and capital away from the non recyclable and favouring the recyclable goods sector takes place. The use of recycled materials in production increases as well. The overall result is an improvement in environmental quality and, as a result, in the health status.

The lower part of Fig. 2 is useful to highlight the impact of the modelled waste policy shock on aggregate variables, namely total output, total consumption, investment and capital stock. As it emerges, the impact of a waste policy shock triggers an increase in consumption and output. This is however, somehow surprisingly, counterbalanced by a short run crowding out of investment and capital stock. We can nevertheless conclude that a waste policy shock has positive effects on GDP, which in our model can be explained by the higher reactivity of recyclable consumption and output, in absolute terms, as compared to non-recyclable ones.

The consequences of a behavioral intervention aimed at changing individual preferences towards recyclable products, modelled here as a taste shock, are reported in Fig. 3.

As the upper part of Fig. 3 shows, the impact of a change in tastes in favour of recyclable goods shifts consumption away from non-recyclable and towards recyclable consumption. This leads, as in the case of waste policy, to a shift of labor and capital away from the non recyclable towards the recyclable goods sector. As in the previous case of incentive-based policies, an increase in the use of recycled materials arises. Overall, this leads to improvements in environmental impacts, as well as to an improvement in health quality. Interestingly, in our model the impact of a behavioral intervention which affects directly consumers’ preferences is more effective in stimulating the consumption of recyclable products compared to a traditional incentive-based policy, which affects recyclable consumption indirectly through price changes. Looking at aggregate impacts from the lower panel of Fig. 3, results are confirmed: the positive impact on output and consumption is larger in absolute terms than the corresponding one under a waste tax (although

10 Together with the analysis discussed in this section, we also performed an assessment of the impact of total factor productivity shocks on recyclable and non-recyclable sectors. On the other hand, as results are standard, we will not detail the related discussion here. The corresponding impulse response functions are reported in Appendix C. The same Appendix reports all impulse response functions commented but not reported here.
Fig. 2. Waste policy shock - Impulse Response Functions (upper part) - Aggregate impacts (lower part).

Fig. 3. Taste shock - Impulse Response Functions (upper part) - Aggregate impacts (lower part).
the corresponding crowding out of investment is larger as well). Overall, this suggests that, at least in terms of output impacts, a behavioral campaign may indeed improve upon standard waste policy tools. From our results it seems to emerge a clear "demand oriented" reactivity of our modelled economy. Finally, the consequences of a pandemic shock in our model are reported in Fig. 4. For each variable of interest, the upper part in the Figure represents the overall impact of the pandemic, while the lower part shows the consequences of the shock in the absence of the sanitary equipments, e.g. PPEs, and of the related change in non-recyclable consumption. As it clearly emerges, a pandemic shock has a short run negative impact on output in both recyclable and non-recyclable sectors, with resulting negative impacts on capital and possibly substitution effects across sectors in terms of labor force. Recycled materials decrease as well, as it is reasonable. The impact of the shock on non-recyclable consumption is worth further attention; indeed, the need for non-recyclable consumptions due to the pandemic event implies that non-recyclable consumption drops less when the latter need is accounted for in the simulations. As a result, the short run beneficial impact on environmental quality resulting from the output reduction in the non-recyclable sector due to the pandemic event is lower, in absolute value, if we account for the reaction of non-recyclable consumption to the shock. This appears as the price to pay to face the health impact of the pandemic event, which is clearly less harmful when non recyclable consumption increases to face it. These conclusions from Fig. 4 seem to suggest the existence of a potential health/environment trade-off: an increase in non recyclable consumption is needed to face the pandemic event, but there is a "price" to pay in terms of a negative impact on environmental quality, triggered by non recyclable consumption.

### 3.1. Sensitivity Analysis

In order to evaluate the robustness of our results, we carried out a sensitivity analysis over some key parameters that are relevant for recycling and environmental impacts. In particular here we discuss our robustness check exercise by focusing on the elasticities of recyclable output with respect to labor and capital ($\alpha_r$ and $\beta_r$), the recycling quality share in the recyclable waste production function ($\zeta$), the elasticity of substitution between recyclable consumption and recyclable quality ($\epsilon$), the share of non recyclable consumption allocated to PPEs ($\varphi$) and the persistence coefficients of the AR(1) processes for taxation on non recyclable consumption and subsidy on recyclable one.

Our robustness analysis is based on the comparison of steady state values resulting from the baseline calibration with the same values generated by increasing (and decreasing) each calibrated value, ceteris paribus, by $\pm10\%$. We base our comparison on the assessment of changes of the ratio of recyclable to non recyclable consumption and the corresponding ratio for output - $\frac{C_r}{C}$ and $\frac{Y_r}{Y}$ respectively - environmental impact per capita $\frac{H}{N}$ - where $N$ is the number of Italian citizens in 2019 (source ISTAT), and $\frac{H}{Y}$ - the health impact per unit of output. This is done in order to evaluate the sensitivity of the results to changes in the calibration around the aforementioned confidence interval. The results are

| Parameter | $\frac{C_r}{C}$ | $\frac{Y_r}{Y}$ |
|-----------|----------------|----------------|
| $\alpha_r$ | 1.50; 1.50; 1.50 | 2.10; 2.20; 2.10 |
| $\beta_r$ | 1.50; 1.63; 1.50 | 2.10; 2.30; 2.00 |
| $\zeta$ | 1.50; 1.61; 1.45 | 2.10; 2.40; 2.00 |
| $\epsilon$ | 1.50; 1.50; 1.50 | 2.10; 2.10; 2.10 |
| $\varphi$ | 1.50; 1.42; 1.50 | 2.10; 2.00; 2.10 |

| Persistence for $\tau$ | 1.50; 1.50; 1.50 | 2.10; 2.10; 2.10 |
| Persistence for $\mu_r$ | 1.50; 1.64; 1.50 | 2.10; 2.00; 2.10 |

| Parameter | $Z$ | $H$ |
|-----------|-----|-----|
| $\alpha_r$ | 6.35; 6.33; 6.34 | 0.08; 0.09; 0.08 |
| $\beta_r$ | 6.35; 6.34; 6.35 | 0.08; 0.09; 0.08 |
| $\zeta$ | 6.35; 6.34; 6.35 | 0.08; 0.10; 0.08 |
| $\epsilon$ | 6.35; 6.35; 6.35 | 0.08; 0.08; 0.08 |
| $\varphi$ | 6.35; 6.40; 6.33 | 0.08; 0.12; 0.07 |

| Persistence for $\tau$ | 6.35; 6.35; 6.35 | 0.08; 0.08; 0.08 |
| Persistence for $\mu_r$ | 6.35; 6.34; 6.35 | 0.08; 0.09; 0.08 |

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11 The results for the waste subsidy are midway between those of a waste tax and those stemming from a taste shock. This implies that the impact on aggregate production and consumption, as well as the impact in terms of recyclable consumption, is larger under a taste shock than under any kind of modelled policy.
summarized in Table 3:

As it seems to emerge from the two parts of Table 3, none of the relevant ratios at stake appear to be significantly affected by the introduction of the proposed small parameters changes. This confirms the robustness of our analysis to small perturbations in the chosen calibration setting. Few notable, but reasonable, variations arise when the share of non recyclable consumption allocated to PPEs \((\zeta)\) increases as compared to the baseline, increasing health per unit of output as well as reducing the ratio of recyclable over non recyclable consumption. The same ratio increases instead when we increase the elasticity of the parameter in recyclable consumption \((\beta_r)\) and the recycling quality share in the recyclable waste production function \((\zeta)\), leading to similar changes in recyclable to non recyclable output ratio.

4. Conclusions and policy implications

The crisis related to the COVID-19 pandemic event implies significant systemic impacts on the environment and on the economic system. Waste production and management are not an exception in this respect, and the related trade-offs are adding to an existing waste issue which is already extremely serious for policy makers. We based our paper on these considerations and tried to address first, the impact of changes in waste policy design and of consumers’ preferences on economic and environmental phenomena and second, the impact of a pandemic event which exacerbates waste problems. We use a DSGE approach that has the merit to highlight the impact of shocks on consumption and output, as well as on environmental quality and health. Our modelling strategy allows us to also include in our analysis considerations related to recyclable and non-recyclable consumption and to the amount of recycled materials used in production. Our analysis highlights positive effects of both incentive based and behavioral policies, like information or educational campaign, even though the effectiveness of the second type of policies seems to be larger in stimulating recyclable consumption and then in moving the economy towards a more circular path. The novelty of our paper rests, however, in the possibility of identifying a waste-triggered health-environment trade off related to the reaction of the economy to an exogenous pandemic shock: an economy that increases non-recyclable consumption in reaction to a shock pays a price in terms of environmental quality. This suggests the need to invest in preparedness, for example promoting research to increase the recyclability of products like PPEs in order to break the vicious health-environment link.

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

A.1. The detailed model

The supply side of our model can be summarized in the following block of equations:

\[
Y_t = A_t^s (K_{t-1}^s)^{\alpha_s} (N_t^r H_t)^{\alpha_r} (RW_t)^{\alpha_r} (E_t)^{1-\alpha_s-\alpha_r-\gamma} \\
Y^r_t = A_t^{r,s} (K_{t-1}^{r,s})^{\alpha_s} (N_t^r H_t)^{\alpha_r} (E_t)^{1-\alpha_s-\alpha_r-\nu} \\
(RW)_t = (\rho (C_t)^{-\psi} + \zeta (Q_t)^{-\xi})^{1/2}
\]

The laws of motion of TFPs \(A_t^s\) and \(A_t^{r,s}\) in production functions (2) and (1) are described by the following AR(1) processes with zero mean and uncorrelated residuals \(\epsilon_t^s\) and \(\epsilon_t^{r,s}\):

\[
\log A_t^s = (1 - \phi^s) \log \bar{A}^s + \phi^s \log A_{t-1}^s + \epsilon_t^s
\]

and

\[
\log A_t^{r,s} = (1 - \phi^{r,s}) \log \bar{A}^{r,s} + \phi^{r,s} \log A_{t-1}^{r,s} + \epsilon_t^{r,s}
\]

where \(\bar{A}^s\) and \(\bar{A}^{r,s}\) indicate the steady state value of the TFP in each sector and \(\phi^s\) and \(\phi^{r,s}\) the persistence components.

Virgin natural resources, \(E_t^r\) and \(E_t^{r,s}\), are subject to the following dynamic constraints:

\[
S_{r, t+1} - S_r^t = - \xi S_r^t - E_r^t
\]

\[
S_{r, t+1} - S_r^t = - \xi S_r^t - E_r^{r,s}
\]

where \(S_r^t\) and \(S_r^{r,s}\) are the respective stocks of natural resources in time \(t\) and \(\xi\) represents an exogenous degree of exploitation of environmental resources taking place outside of our model boundaries.

The constant relative risk aversion (CRRA) utility function that the representative agent maximizes with respect to \(C_{t-1}, C_t^{r,s}, N_t^r\) and \(N_t^r\) reads as

\[
U_t = \nu_r \left[ \log (C_{t-1}) \right] + (1 - \nu_r) \left[ \log (C_t^{r,s}) \right] - \frac{(N_t^r)^{1+\psi}}{1+\psi} - \frac{(N_t^r)^{1+\upsilon}}{1+\upsilon} + H_t
\]

\[12\] The first column contains the parameters considered for the sensitivity analysis, whereas the other columns indicate the simulated steady state values for some relevant great ratios: the first value is the one simulated under the baseline calibration, the second one is generated when the parameter value is increased by 10% and the third one when the parameter value is decreased by 10%.
where $H_t$ is the health status affecting utility and $\epsilon_t$ is a taste shifter (Stockman and Tesar, 1995), whose law of motion is described by the following AR (1) process with zero mean and uncorrelated residuals $\epsilon_t^r$:

$$\log u_t = (1 - \phi^r) \log \pi + \phi^r \log u_{t-1} + \epsilon_t^r$$  \hspace{1cm} (9)

with $\pi$ indicating the steady state value of the taste shifter and $\phi^r$ is the corresponding persistence component. We model taste shock as an increase (decrease) in parameter $\phi^r$ to model changes in preferences favouring recyclable (non recyclable) consumption.

Health dynamics evolves according the following process:

$$H_t = (1 - \delta) H_{t-1} + \kappa \left( \phi C^r_t - G_t - Z_t \right)$$  \hspace{1cm} (10)

Non recyclable consumption related to the pandemic event ($\kappa = 1$) is financed by a lump sum subsidy paid by the public sector to the households:

$$T_t = P^0 \phi C^r_t$$  \hspace{1cm} (11)

where $T_t$ is the lump sum subsidy and $P^0$ is the constant price of non recyclable consumption triggered by the pandemic event (e.g. PPEs) \(^{13}\).

The law of motion of $G_t$, i.e. the exogenous health impact under a pandemic event, is described by the following AR(1) process with zero mean and uncorrelated residuals $\epsilon_t^g$:

$$\log G_t = (1 - \phi^g) \log \pi + \phi^g \log G_{t-1} + \epsilon_t^g$$  \hspace{1cm} (12)

where $\phi^g$ indicates the persistence component and $\pi$ the steady state value of the health disaster linked to Covid-19 pandemic. Finally, health is always negatively affected by "broadly intended" environmental pollution, $Z_t$, whose dynamics reads as follows:

$$Z_t = Z_{t-1} + \left( 1 + \kappa \tau \right) C^r_t \left( d^r \delta_1^r + e^r \delta_2^r + (1 - d - e) \delta_3^r \right)$$  \hspace{1cm} (13)

where $\delta_1^r$, $\delta_2^r$ and $\delta_3^r$ indicate the damages related to the waste disposal in landfill, to waste incineration and waste export, respectively, according to the weights $d$, $e$ and $1 - d - e$.

The maximization of the utility function (5) is subject to the following budget constraint:

$$(P_t^r - \mu_t) C_t^r + C_t^r (1 + \tau + \kappa \phi^r P^0)$$

$$+ K_t^r + K_t^r = R_t^c K_t^c + R_t^r K_t^r + W_t^r N_t^r +$$

$$+ W_t^r N_t^r + P_t^r E_t^r + P_t^r E_t^r + \kappa T_t$$  \hspace{1cm} (14)

where $P_t^r$ is the price of the recyclable consumer goods, the price of the non recyclable consumer goods is normalized to 1, $P_t^r$ and $P_t^r$ are the prices of the natural resources, $\mu_t$ is a subsidy on recyclable consumption $C_t^r$, $\tau$ is a tax on non recyclable consumption $C_t^r$, $W_t^r$ and $W_t^r$ are the nominal wages paid, $R_t^c$ and $R_t^c$ are the gross rates of return on capital stocks:

$$R_t^c = r_t^c + 1 - \delta^c$$  \hspace{1cm} (15)

$$R_t^c = r_t^c + 1 - \delta^c$$  \hspace{1cm} (16)

with $\delta^c$ and $\delta^r$ indicating the corresponding capital depreciation rates, while $r_t^c$ and $r_t^c$ are the net rates of return on capital stocks.

The Government budget constraint reads as:

$$\tau C_t^r = \mu, C_t^r + P_t^r Q_t + \kappa T_t$$  \hspace{1cm} (17)

Both the tax rate on non recyclable consumption and the subsidy follow an AR(1) process with zero mean and uncorrelated residuals $\epsilon_t^\tau$ and $\epsilon_t^\mu$:

$$\log \tau_t = (1 - \phi^\tau) \log \pi + \phi^\tau \log \tau_{t-1} + \epsilon_t^\tau$$  \hspace{1cm} (18)

$$\log \mu_t = (1 - \phi^\mu) \log \pi + \phi^\mu \log \mu_{t-1} + \epsilon_t^\mu$$  \hspace{1cm} (19)

where $\phi^\tau$ and $\phi^\mu$ are the persistence components and $\pi$ and $\pi$ the respective steady state values. When focusing on policy shocks, we model them as an increase in $\phi^\tau$ or $\phi^\mu$ respectively.

Total capital stock and labor are allocated to the economic sectors:

$$K_t = K_t^r + K_t^c$$  \hspace{1cm} (20)

$$N_t = N_t^r + N_t^c$$  \hspace{1cm} (21)

The corresponding capital accumulation constraints read as:

\(^{13}\) For example, we can think of $P^r$ as the administered price for the PPEs.
$r_{tt} = (1-\delta)K_{t-1}^{r} + \Gamma_{r}$

$K_{tt}^{r} = (1-\delta r)K_{t-1}^{r} + \Gamma_{r}$

and $\Gamma_{r}$ and $\Gamma_{r}^{w}$ are the corresponding investment flows.

Finally, for each sector the following relationships hold:

$Y_{t}^{r} = C_{t}^{r} + I_{t}^{r}$

$Y_{t}^{w} = C_{t}^{w}(1+\xi_{t}q) + \Gamma_{r}^{w}$

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.wasman.2021.12.036.

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