GHG Emissions Control and Monetary Policy*

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Abstract

This paper examines the optimal environmental and monetary policy mix in a New Keynesian model embodying pollutant emissions, abatement technology and environmental damage. The optimal response of the economy to productivity shocks is shown to depend crucially on the instruments policy makers have available, the intensity of the distortions they have to address (i.e. imperfect competition, costly price adjustment and negative environmental externality) and the way they interact.

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1 Introduction

In recent years climate change has been identified worldwide as one of the most challenging policy issues, attracting the interest of a number of academic researchers and pushing many governments to work out the best policy to mitigate carbon emissions. Nevertheless, some environmental policies, such as those falling in the domain of climate actions, are likely to produce pervasive effects on the economy, since the additional costs of abatement of greenhouse gas (GHG) emissions affect directly and/or indirectly the decisions of agents and their attitude toward uncertainty. GHG emissions regulations, in fact, affect the economy through two important dimensions: (i) the emissions permit price which can be variable or not, according to the regime adopted (price vs. quantity regulations); (ii) the abatement cost borne by firms. This is why many European states, especially those heavily reliant on coal, fear that a strong climate policy might be harmful for their wobbling economies, still recovering from the recent recession.[1] From this perspective, it clearly emerges the need for a full understanding of the impact of GHG emissions control policies through the lenses of macroeconomic models featuring uncertainty and other additional realistic aspects, such as imperfect price adjustments and lack of perfect competition.

For this reason, a branch of environmental economics is moving in this direction, exploring the macroeconomic implications of environmental regulations and their performance in dynamic general equilibrium model accounting for uncertainty.[2] In this respect, see the papers by Fischer and Springborn (2011), Heutel (2012), Angelopoulos et al. (2013) and Bosetti and Maffezzoli (2014) who conduct their analysis in real business cycle type models studying environmental regulation in the context of uncertainty.[3] Further, by introducing imperfect price adjustments and lack of perfect competition, Ganelli and Tervala (2011) develop a fully-fledged open economy New Keynesian model designed for the study of the international transmission of environmental policy shocks, while Annicchiarico and Di Dio (2015) develop a closed economy New Keynesian model to study the business cycle under alternative environmental policy regimes (i.e. cap-and-trade, carbon tax and intensity target) and explore the role played by nominal rigidities in shaping the macroeconomic performances of the environmental policy regime put in place.

In this work we aim at contributing to this expanding literature. Specifically, starting from the idea that different areas of interventions cannot be considered in isolation, we look at the

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[1] According to observers, in fact, the recent 2030 Climate and Energy Policy Framework of the European Union would represent a sort of compromise between countries that rely heavily on coal and those willing to push even further the process of decarbonization. See European Council (2014) and European Commission (2014).

[2] Starting from the seminal paper by Weitzman (1974) the debate on which environmental policies would best serve the goal of cutting GHG emissions has been going on in different modelling settings. See Goulder et al. (1999), Parry and Williams (1999), Dissou (2005), Hoel and Karp (2005), Kelly (2005), Newell and Pizer (2008), Quirion (2005), Jotzo and Pezzey (2007).

[3] On the macroeconomic approach to environmental policy issues, see the survey by Fischer and Heutel (2013).

implications of climate actions from a different angle and ask the following questions. How are monetary and environmental policies intertwined? What impact has the GHG emissions control policy on the optimal monetary policy response to shocks? How do different monetary policy strategies affect optimal environmental policy? These questions naturally arise having in mind the vast literature on the interactions between fiscal and monetary policy from which we have learnt the non-trivial relations between the two areas.[4] Indeed, optimal monetary policy depends on the fiscal regime adopted and *vice versa*, while the existence of a stable rational expectations equilibrium does depend on the policy mix.[5]

In this paper, we reassess this issue in a context where fiscal policy is identified with environmental policy, in that the government sells emissions permits according to a cap-and-trade scheme or simply taxes emissions, while the central bank is responsible for setting the nominal interest rate. We conduct our analysis in a simple New Keynesian model augmented to include pollutant emissions, abatement technology and environmental damage in the form of a negative externality on the production possibilities of firms, where the source of uncertainty is due to technology shocks. While the environmental part of the model follows closely Annicchiarico and Di Dio (2015) and Heutel (2012), the rest of the model is structured along the lines of a basic New Keynesian framework, with labor as a unique production factor and quadratic adjustment costs on price adjustment *à la* Rotemberg (1982), as commonly done in optimal monetary policy analysis when introducing some deviations from the baseline model (see e.g. Faia 2008, 2009). In doing so we are able to capture the two-way interaction between the ecological system and the economy together with the interaction between monetary and environmental policy in a parsimonious model, where all the relevant transmission mechanisms and the trade-offs can be easily detected.[6]

Specifically, we consider several policy combinations. First, as an interesting benchmark, we study the social planner problem. The Pareto efficient allocation, in fact, may not be implementable in this economy, because markets are imperfectly competitive and prices are sticky. Second, we move to the case of a Ramsey planner choosing jointly monetary and environmental policy. Third, we study the case of a Ramsey planner controlling monetary policy under different environmental policy instruments (i.e. carbon tax vs. cap-and-trade). Finally, we analyze the case of a Ramsey planner deciding environmental policy, but taking as given monetary policy conducted according to different types of interest-rate rule. All these different assumptions are motivated by the diverse institutional settings in which monetary and fiscal authorities do not necessarily share the same ability to commit.

Our main findings are as follows. First, in the social optimum the response of the economy

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[4] See e.g. Leeper (1991), Schmitt-Grohé and Uribe (2004) and Schmitt-Grohé and Uribe (2007).

[5] Nonetheless, the specific institutional set-up of the euro area, with centralized monetary policy and decentralized fiscal policy, renders the central bank commitment to control inflation even more challenging.

[6] For the sake of parsimony, in fact, here we deliberately abstract from capital accumulation and opt to model nominal rigidities by introducing quadratic adjustment costs as an alternative to the Calvo-pricing, as instead was done in Annicchiarico and Di Dio (2015).

to a positive productivity shock depends on the tension between two opposing forces. On the one hand, a temporary increase in productivity leads to demand a cleaner environment and, therefore, a higher abatement effort is observed, so as to mitigate pollutant emissions. On the other hand, after a positive productivity shock, labor is more productive, therefore the opportunity cost of a major abatement effort increases, making more convenient to spend more on labor inputs rather than on abatement. Under a reasonable parametrization of the model, the latter effect dominates the former, that is why we observe that emissions move procyclically.

Second, when we consider the decentralized equilibrium, with a Ramsey planner having access to monetary and environmental policy instruments, imperfect competition and nominal rigidities on prices, by shaping the dynamic response of the economy, interact with environmental variables. To put it differently, the Ramsey planner must find a compromise among all the distortions that characterize the economy, namely (i) the negative externality of pollution on the economy, (ii) costly price adjustment and (iii) imperfect competition in the intermediate goods market. Under the baseline parametrization, emissions increase, but to a lesser extent than in the absence of optimal environmental policy. Because of the negative externality of pollution on productivity, in fact, the Ramsey planner finds it optimal to diminish the procyclicality of emissions. In tackling the distortions concerning price adjustment and lack of competition, the Ramsey planner is found to tolerate some temporary deflation, in order to induce a reduction of the price markup and thus have a higher level of economic activity, necessary, in turn, to sustain major abatement costs. At the same time the price of emissions permit increases, so as to push toward emissions reduction.

Third, when the model is solved under the assumption that the Ramsey planner controls only monetary policy, the dynamic response of the economy to a positive technological shock crucially depends on the ability of the policy makers to tackle the distortions underlying the economy by using the instrument in hand under a given environmental regulation. In this respect, we show that the well-known result of the literature on optimal monetary policy, according to which strict price stability turns out to be optimal in response to technological shocks, does not always hold in this context.[7] Our findings show, in fact, that this logic needs to be modified according to the regime adopted by the government for GHG emissions control and to the strength of the negative externality of pollution. Namely, our analysis confirms the optimality of price stability only when environmental regulation is set according to a carbon tax, provided that the negative externality of pollution is small, while under a cap-and-trade scheme or with a carbon tax combined with a strong negative externality, the Ramsey dynamics imply temporary deviations from price stability in response to technology shocks. In this case, having not access to the environmental variables, the Ramsey planner creates the conditions to have more resources for abatement under a cap, and to slightly reduce the response of output

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[7] In this way, the costs introduced by price adjustments are neutralized. See e.g. Clarida et al. (2000), Woodford (2003) and Schmitt-Grohé and Uribe (2004). Exceptions are given by Faia (2008, 2009) who show that the optimality of fully inflation targeting does not hold when the basic New Keynesian model is extended along different dimensions.

to the shock, and therefore of emissions, under a tax.

Finally, when the Ramsey planner controls the level of emissions, while monetary policy is conducted according to an interest-rate rule, our findings suggest that the precise degree to which the central bank responds to output in setting the nominal interest rate plays a major role in shaping the optimal response of emissions to a positive productivity shock. If monetary policy is highly responsive to output, consumption will increase by less, thus lowering the opportunity cost of spending on abatement. In these circumstances, the Ramsey planner will find it optimal to cut emissions in response to the positive shock, thus reducing the negative externality of pollution.

As far as we know we are the first to characterize the optimal monetary and environmental policy mix. An early attempt in this direction is made by Annicchiarico and Di Dio (2015) who, among other things, study how the Ramsey environmental policy is affected by the behavioral rule adopted by the central bank for controlling inflation, but neglect to study the effects of other feedback rules responding to output, commonly considered in monetary policy analysis, and fail to consider the implications that environmental regulation has on optimal monetary policy and inflation as well as to find different solutions for the optimal policy design, depending on the distortions and the externalities the policy makers have to address, the instruments they have access to and the way they interact.

The paper proceeds as follows. Section 2 describes the modified New Keynesian model with pollutant emissions and abatement technology. Section 3 characterizes the social planner problem. Section 4 describes the Ramsey problem under different assumptions about the environmental and monetary policy mix. Sections 5 concludes. Technical parts are relegated to the Appendix.

2 The Model

The economy is described by a simple New Keynesian model with nominal price rigidities, including pollutant emissions, environmental policy and a negative externality of pollution on productivity. The economy presents: perfectly competitive final good producers combining differentiated intermediate goods to produce a final consumption good; monopolistically competitive polluting intermediate goods producers each of which producing a single differentiated intermediate good by using labor as the only production factor; households who consume and supply labor services; the government setting the environmental regulation for GHG emissions control and a monetary authority controlling the nominal interest rate. The assumption of separating the conduct of environmental and monetary policy between two different authorities is motivated by the fact that in many advanced and emerging countries monetary policy is conducted by independent central banks with the explicit mandate to achieve specific objectives in terms of price and/or output stabilization. The model-economy abstracts from growth, therefore our analysis just considers fluctuations around a deterministic steady state.

2.1 Production

The final good Y_t is produced by perfectly competitive firms, using the intermediate inputs with CES technology: $Y_t = \left[\int_0^1 Y_{j,t}^{(\theta-1)/\theta} dj\right]^{\theta/(\theta-1)}$, with $\theta > 1$ being the constant elasticity of substitution. The demand schedule from profits maximization is $Y_{j,t} = (P_{j,t}/P_t)^{-\theta} Y_t$, where $P_t = \left(\int_0^1 P_{j,t}^{1-\theta} dj\right)^{1/(1-\theta)}$.

There is a continuum $j \in [0,1]$ of monopolistically competitive firms. The typical firm j hires $L_{j,t}$ labor inputs to produce intermediate good $Y_{j,t}$, according to the linear technology:

$$Y_{j,t} = \Lambda_t A_t L_{j,t}, \tag{1}$$

where A_t represents the stochastic level of productivity which evolves as $\log A_t = (1-\rho_A)\log A + \rho_A \log A_{t-1} + \varepsilon_{A,t}$, with $0 < \rho_A < 1$ and $\varepsilon_{A,t} \sim i.i.d.\ N(0,\sigma_A^2)$ and Λ_t is a damage coefficient that captures the impact of climate change on output. Following Golosov et al. (2014) we assume that this damage function Λ_t has an exponential specification mapping the stock of carbon dioxide in the atmosphere to the economic damage on productivity:

$$\Lambda_t = \exp(-\chi(M_t - \tilde{M})), \tag{2}$$

where M_t is the stock of pollution in period t, $\tilde{M}$ is the pre-industrial stock level and χ is a positive parameter measuring the intensity of this negative externality.

As in Heutel (2012) and Annicchiarico and Di Dio (2015), emissions at firm level, $Z_{j,t}$, are related to output and depend on the abatement effort,

$$Z_{j,t} = (1 - U_{j,t})\,\varphi Y_{j,t}, \;\; \varphi > 0, \quad 0 \leq U_{j,t} \leq 1. \tag{3}$$

The cost of emissions abatement $\mathcal{C}_A$ is a function of the abatement effort and output:

$$\mathcal{C}_A(U_{j,t}, Y_{j,t}) = \phi_1 U_{j,t}^{\phi_2} Y_{j,t}, \;\; \phi_1 > 0, \quad \phi_2 > 1. \tag{4}$$

Emissions are costly to producers and the unit cost of emissions, p_Z, depends on the environmental regime adopted. Each producer has monopolistic power in the production of its own specific good and when setting its price faces a quadratic cost *à la* Rotemberg (1982), measured in terms of the final good, equal to $\frac{\gamma}{2}\left(\frac{P_{j,t}}{P_{j,t-1}} - 1\right)^2 Y_t$, where $\gamma > 0$ measures the degree of price rigidity.

The problem of the typical j firm is then to choose the sequence $\{L_{j,t}, U_{j,t}, P_{j,t}\}_{t=0}^{\infty}$ in order to maximize the present discounted value of expected future profits, taking as given the available technology, the real wage W_t/P_t, the emissions permit price p_Z and the demand constraint $Y_{j,t} = (P_{j,t}/P_t)^{-\theta_p} Y_t$.

At the optimum:

$$\Lambda_t A_t \Psi_t = \frac{W_t}{P_t}, \tag{5}$$

$$p_{Z,t}\varphi = \phi_1 \phi_2 U_t^{\phi_2 - 1}, \tag{6}$$

$$1 - \theta + \theta MC_t - \gamma \left(\Pi_t - 1\right) \Pi_t + \gamma E_t Q_{t,t+1}^R \left(\Pi_{t+1} - 1\right) \Pi_{t+1} \frac{Y_{t+1}}{Y_t} = 0, \tag{7}$$

where we have imposed symmetry across producers, while Ψ_t is the marginal cost component related to the extra units of labor needed to manufacture an additional unit of output, MC_t denotes the real marginal cost, $MC_t = \Psi_t + \phi_1 U_t^{\phi_2} + p_{Z,t}\left(1 - U_t\right)\varphi$, $\Pi_t = P_t/P_{t-1}$ and $Q_{t,t+1}^R$ is the stochastic discount factor.[8] Equation (5) gives the optimal choice for labor demand. Equation (6) equates the marginal product of abatement (i.e. the cost saving related to lower emissions permits expenditures, $p_{Z,t}\varphi Y_t$) to its marginal cost (i.e. $\phi_1 \phi_2 U_t^{\phi_2 - 1} Y_t$). Finally, equation (7) is the New Keynesian Phillips curve, relating current inflation to the expected future rate of inflation and to the current marginal cost, which in turn depends on the productivity level, on the available abatement technology, on the GHG emissions regulation and on the negative externality of pollution.

2.2 Households

Households derive utility from consumption C_t and disutility from labor L_t. The lifetime utility function of the representative household can be written as

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\log C_t - \mu_L \frac{{L_t}^{1+\eta}}{1+\eta} \right), \ \eta \geq 0, \ \mu_L > 0, \ 0 < \beta < 1, \tag{8}$$

where β is the discount factor, η denotes the inverse of the Frisch elasticity of labor supply, while the coefficient μ_L measures the disutility of labor. The flow budget constraint of the typical household is

$$P_t C_t + R_t^{-1} B_{t+1} = B_t + W_t N_t + D_t - P_t T_t, \tag{9}$$

where B_{t+1} are riskless one-period bonds paying one unit of the *numéraire* in period $t+1$, while B_t is the quantity of bonds carried over from $t-1$. R_t is the gross nominal return on riskless bonds purchased in period t, T_t denotes lump-sum transfers and D_t are dividends from ownership of firms.

The representative household chooses the sequence $\{C_t, \ L_t, B_{t+1}\}_{t=0}^{\infty}$ in order to maximize (8), given (9). At the optimum we have:

$$\frac{1}{R_t} = \beta E_t \frac{1}{\Pi_{t+1}} \frac{C_t}{C_{t+1}}, \tag{10}$$

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[8] See the Appendix for details.

$$C_t \mu_L L_t^{\eta} = \frac{W_t}{P_t}, \tag{11}$$

where (10) is the Euler equation and (11) gives the optimal choice for labor supply.[9]

2.3 Environmental and Monetary Policy, Resource Constraint and Competitive Equilibrium

The monetary authority controls the (gross) nominal interest rate R_t, while the government decides environmental policy. In particular, transfers to households T_t are financed by the revenues from the sales of emissions permits $p_{Z,t} Z_t$ which, in turn, depend on the environmental policy adopted. For simplicity, we assume that the net supply of bonds is zero, therefore the budget constraint of the public sector is simply $T_t = p_{Z,t} Z_t$. This assumption is motivated by the fact that we want to keep our analysis as much simple as possible by switching off the effects that monetary policy has on the real value and on the financing cost of outstanding debt along with the effects that GHG actions, by raising government revenues, can have on fiscal consolidation.[10]

Clearly, when the government levies a tax per unit of emissions, $p_{Z,t}$ is a constant. Under a cap-and-trade scheme, instead, the aggregate level of emissions is fixed and the government sells emission permits to the producers at the market price $p_{Z,t}$.

In equilibrium, factor and good markets clear, therefore we have $L_t = \int_0^1 L_{j,t} dj$, and $Y_t = \int_0^1 Y_{j,t} dj$, while the resource constraint of the economy is

$$Y_t = C_t + \phi_1 U_t^{\phi_2} Y_t + \frac{\gamma}{2} \left(\Pi_t - 1\right)^2 Y_t. \tag{12}$$

From the above equation it can be seen how the abatement cost and the price adjustment cost enter the aggregate resource constraint creating a wedge between output and consumption.

Aggregate production and total emissions are given by:

$$Y_t = \Lambda_t A_t L_t, \tag{13}$$

$$Z_t = \int_0^1 Z_{j,t} dj = \left(1 - U_t\right) \varphi \int_0^1 Y_{j,t} dj = \left(1 - U_t\right) \varphi Y_t. \tag{14}$$

Finally, we assume that pollutant emissions accumulate in the environment. Let M_t denote the pollution stock at the end of period t, then we have that the following accumulation equation

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[9] Denoting by λ_t the marginal utility of real wealth, (10) can be expressed as $\frac{1}{R_t} = \beta E_t \frac{1}{\Pi_{t+1}} \frac{\lambda_{t+1}}{\lambda_t}$. The discount factor $\beta \frac{\lambda_{t+1}}{\lambda_t}$ corresponds to $Q_{t,t+1}^R$ in (7).

[10] In addition, when allowing for government borrowing and in the impossibility of using lump-sum taxes, it might be optimal for the government to use fiscal deficits (i.e. adjustments in the level of public debt) as shock absorber and, therefore, the welfare implications might differ. Although this is an important issue, we leave this aspect for future research.

holds

$$M_t = (1-\delta_M)M_{t-1} + Z_t + \tilde{Z}, \tag{15}$$

where $0 < \delta_M < 1$ is the natural decay rate of the pollution stock and $\tilde{Z}$ denotes non-industrial emissions.[11]

Given environmental and monetary policy, equations (5)-(7) and (10)-(15) fully describe the competitive equilibrium of the economy. It should be emphasized that the competitive equilibrium of this economy is distorted by the presence of three sources of inefficiencies. First, monopolistic competition in the intermediate-good sector generates a positive markup on marginal cost lowering the level of economic activity. Second, the price adjustment costs reduce the overall resources available for consumption and emissions abatement. Third, the damage function introduces a negative externality of pollution on the production possibilities of firms. Clearly, the interrelation of these three distortions characterizes the interaction between environmental and monetary policy.

3 Planner Solution

Before turning to the design of the Ramsey plans under different combinations of monetary and environmental policy, it is instructive to fully characterize the social planner solution, which corresponds to the Pareto efficient equilibrium, so as to highlight the role of distortions in this economy. The planner solution is obtained by maximizing agents lifetime utility function (8) under the resource constraint (12), the available technologies for production and abatement and the equation describing the accumulation of pollution in the environment (15). The planner solution is obtained under the assumption of flexible prices. Combining all these constraints the planner problem can be described as follows:

$$\begin{aligned} & \underset{\{L_t,U_t,M_t\}_{t=0}^{\infty}}{max} E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[\log\left(\Lambda_t A_t L_t \left(1-\phi_1 U_t^{\phi_2}\right)\right) - \mu_L \frac{{L_t}^{1+\eta}}{1+\eta} \right] \right\}, && (16) \\ & s.t. && \\ M_t \; = \; & (1-\delta_M)M_{t-1} + (1-U_t)\,\varphi\Lambda_t A_t L_t + \tilde{Z}. && (17) \end{aligned}$$

Let define λ_t^M the Lagrange multiplier associated to the constraint (17). After taking the first-order conditions of the planner problem and after some manipulations, we obtain what follows:

$$\frac{1}{L_t} - \mu_L {L_t}^{\eta} - \lambda_t^M (1-U_t)\,\varphi\Lambda_t A_t = 0, \tag{18}$$

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[11] The carbon cycle described by equation (15) in assuming that all existing stock of pollution depreciates at a constant rate and abstracting from carbon-circulation models simplifies the one adopted by Golosov et al. (2014), who instead assume a permanent and a temporary component of emissions along with a specific rule regarding the evolution of pollution from both components.

$$-\frac{\phi_1\phi_2 U_t^{\phi_2-1}}{1-\phi_1 U_t^{\phi_2}} + \lambda_t^M \varphi \Lambda_t A_t L_t = 0, \tag{19}$$

$$-\chi + \lambda_t^M + \chi\lambda_t^M (1-U_t)\varphi\Lambda_t A_t L_t - \beta(1-\delta_M)E_t\lambda_{t+1}^M = 0. \tag{20}$$

Condition (18) is a static efficient condition, where the first term represents the marginal benefit of an additional unit of labor, the second negative term represents the marginal disutility of labor, while the last negative term captures the marginal environmental damage due to the increase in labor. Condition (19) is a static efficient condition, where the first negative term represents the marginal cost of additional abatement effort and the second positive effect refers to the marginal benefit derived from emission abatement in terms of a reduced level of pollution. Finally, condition (20) is a dynamic efficient condition, where the first negative term captures the marginal negative effect on consumption of an additional unit of the stock pollution, the second term refers to the fact that more pollution means that less resources are spent on abatement and thus more resources are available for consumption, the third positive term, instead, captures the fact that an additional unit of pollution, through the action of the damage function, implies lower emissions, and thus lower abatement, hence increasing the resources available for consumption; finally, the last negative term captures the marginal effect on next period's consumption. Clearly, an additional unit of pollution in this period increases the abatement effort required in the following period to achieve an equivalent level of emissions, thus diminishing the resources available for consumption.[12]

3.1 Calibration and Results

In this Section we briefly characterize numerically the dynamic properties of the first best allocation in response to a positive technology shock by showing the impulse response functions of the main economic variables. To this end we first calibrate the model and then use a 'pure' perturbation method which amounts to a first-order Taylor approximation of the model around the non-stochastic steady state as a solution strategy.[13] The calibration we present here is meant as a benchmark.[14] We will show that our results are robust to reasonable variations around this benchmark.

Time is measured in quarters. We begin with the standard parameters which are set consistently with those employed in the calibration of a basic New Keynesian model. Following Galí (2008), the discount factor β is equal to 0.99, the inverse of the Frisch elasticity, η, is

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[12] Notice that in the absence of environmental damage $\lambda_t^M = 0$ and $U_t = 0$, while condition (18) boils down into the familiar efficient condition equalizing the marginal rate of substitution between consumption an labor, $\mu_L L_t{}^{\eta} C_t$, to the marginal rate of transformation, A_t, implying that $L_t = \left(\frac{1}{\mu_L}\right)^{\frac{1}{1+\eta}}$, that is, at the optimum, labor is constant.

[13] The model has been solved in Dynare. For details see http://www.cepremap.cnrs.fr/dynare/ and Adjemian et al. (2010)

[14] For further details, see the Technical Appendix available from the authors upon request.

set equal to 1 (which represents an intermediate value for the range of macro and micro data estimates), and the price elasticity θ is set equal to 6. The parameter γ, measuring the degree of price rigidity, is consistent with a Calvo pricing setting with a probability that price will stay unchanged of 0.75 (i.e. average price duration of three quarters), namely $\gamma = 58.25$. The scale parameters A and μ_L are calibrated in order to get a steady-state value of labor hours equal to 0.2 and a level of output Y equal to unity. Finally, the persistence of the shock ρ_A is set at 0.9, which represents an intermediate value in the range 0.85-0.95 commonly used in medium-scale dynamic stochastic general equilibrium models (see e.g. Schmitt-Grohé and Uribe 2007 and Smets and Wouters 2007).

We now turn to the parameters that regard the environment. We calibrate these parameters using world-economy data and, in particular, by making reference to the RICE-2010 model (see Nordhaus 2008, Nordhaus and Boyer 2000).[15] We refer to the optimal and to the baseline runs of the model, using simulation results for the year 2015. In the optimal scenario industrial emissions amount to 8.475 gigatons of carbon (GTC), non-industrial emissions to 1.280 GTC, while output gross of abatement cost, but net of climate damage is equal to 81.056 trillion U.S. dollars. Having normalized output to unity, these data deliver our steady-state values for Z and $\tilde{Z}$ in model units. Setting a decay rate δ_M to 0.0021 as in Heutel (2012), we have the steady-state value of the overall atmospheric concentration of carbon dioxide in model units M. The pre-industrial atmospheric concentration of carbon amounts to about 600 GTC, while the overall concentration amounts to 829 GTC. These data give the pre-industrial stock concentration of pollutant expressed in model units, $\tilde{M}$. The coefficient φ, measuring emissions per unit of output in the absence of abatement, has been calibrated using data of the baseline version of the RICE-2010 model and computing emissions intensity regarding industrial emissions. These data deliver $\varphi = 0.1235$. The parameter ϕ_2 is set at 2.8, while the scale coefficient ϕ_1 is calibrated so as to have an abatement cost to output ratio equal to 0.0255%. We are so able to compute the implied optimal abatement effort in steady state along with the implied value for the parameter governing the damage caused by pollution on output, $\chi = 0.000457$.

Using this parametrization we are now able to solve numerically the model for the social planner case and study the response to productivity shocks near the steady state.

Figure 1 portrays the optimal response to a one percent shock on productivity. All variables are expressed in percentage deviations from their steady-state level. As expected, output and consumption increase immediately and their responses almost coincide, while the response of labor is only slightly negative, that is because the negative externality of pollution on output is small.[16] It can be shown, in fact, that for higher values of χ labor decreases by more. The social planner, in fact, will find it optimal to partially offset the expansion of output due to the positive shock so as to diminish the expansion of emissions and, therefore, mitigate the damage due to

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[15] The RICE-2010 model is available for download at http://www.econ.yale.edu/~nordhaus/homepage/RICEmodels.htm. For a detailed description of the model, see Nordhaus and Boyer (2000).

[16] In the absence of a damage function, in fact, under Pareto efficiency hours worked are constant, while consumption and output move proportionally to productivity.

higher pollution. Yet we observe a sharp increase in the abatement effort and in the emissions level. Consistently with previous findings, in fact, optimal emissions are procyclical.[17] On the one hand, because of the negative externality, a major emissions control is desirable in order to reduce the damage of pollution, on the other hand, abatement is a costly activity. Clearly, in this model, given the baseline parametrization, the latter effect dominates the former.

4 Ramsey Solution

In this Section we analyze the decentralized equilibrium where we consider different policy regimes. First, we conduct our analysis under the assumption of a Ramsey planner choosing jointly environmental and monetary policy. Then we assume that the Ramsey planner chooses monetary policy, while environmental policy is conducted according to a tax levied on emissions (carbon tax) or to a quantity restriction (cap-and-trade). Finally, we model the case of a Ramsey planner controlling environmental policy, while the monetary authority commits to an interest-rate rule.

It should be noted that in the decentralized equilibrium the optimal policy problem is further complicated by the existence of two additional distortions, namely the lack of perfect competition in the intermediate goods sector and costly price adjustment. These two distortions, that characterize New Keynesian models, interact with pollution damage, shaping the optimal response to shocks.

4.1 Ramsey Monetary and Environmental Policy

Consider the case of a single authority choosing monetary and environmental policy instruments, in order to maximize the expected discounted utility of households, given the constraints of the competitive economy. We assume that this authority controls the nominal interest rate R_t and sets the target on emissions Z. It can be shown that this policy is equivalent to case in which the Ramsey planner uses a tax on emissions as environmental policy instrument.

As usual, we assume that the Ramsey planner is able to commit to the contingent policy rule it announces at time 0 (i.e. ex-ante commitment to a feedback policy so as to have the ability to dynamically adapt the policy to the changed economic conditions). We start from the optimality conditions for households and firms and the resource constraint of the economy, and reduce the number of constraints to the Ramsey planner's optimal problem by substitution.

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[17] See, e.g., Heutel (2012).

The optimal allocation is obtained as solution to the following optimization problem

$$\underset{\{R_t,L_t,U_t,\Pi_t,M_t\}_{t=0}^{\infty}}{max} E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \log \left(\Lambda_t A_t L_t \left[1 - \phi_1 U_t^{\phi_2} - \frac{\gamma}{2} \left(\Pi_t - 1 \right)^2 \right] \right) - \mu_L \frac{L_t^{1+\eta}}{1+\eta} \right\}, \tag{21}$$

$$s.t.$$

$$\frac{1-\theta-\gamma\left(\Pi_t-1\right)\Pi_t}{1-\phi_1 U_t^{\phi_2}-\frac{\gamma}{2}\left(\Pi_t-1\right)^2}+\theta\mu_L L_t^{\eta+1}+\theta\frac{\phi_1 U_t^{\phi_2}+\phi_1\phi_2 U_t^{\phi_2-1}\left(1-U_t\right)}{1-\phi_1 U_t^{\phi_2}-\frac{\gamma}{2}\left(\Pi_t-1\right)^2}+$$

$$+\gamma\beta E_t\frac{\left(\Pi_{t+1}-1\right)\Pi_{t+1}}{1-\phi_1 U_{t+1}^{\phi_2}-\frac{\gamma}{2}\left(\Pi_{t+1}-1\right)^2}=0,$$

$$\frac{1}{R_t}=\beta E_t\frac{1}{\Pi_{t+1}}\frac{\Lambda_t A_t L_t\left[1-\phi_1 U_t^{\phi_2}-\frac{\gamma}{2}\left(\Pi_t-1\right)^2\right]}{\Lambda_{t+1}A_{t+1}L_{t+1}\left[1-\phi_1 U_{t+1}^{\phi_2}-\frac{\gamma}{2}\left(\Pi_{t+1}-1\right)^2\right]},$$

$$M_t=(1-\delta_M)M_{t-1}+\left(1-U_t\right)\varphi\Lambda_t A_t L_t+\tilde{Z}.$$

The first-order conditions of the above problem are listed in the Appendix.

Before turning to the analysis of the optimal response to a productivity shock, however, it is instructive to discuss the steady-state solution under Ramsey policy, where the deep parameters of the model are set according to the calibration described in the previous Section.[18] Table 1 reports the Ramsey steady state and the steady-state solution of the social planner (efficient equilibrium). We notice what follows. First, the level of economic activity is much lower in the Ramsey steady state than in the social planner solution. This is due to the fact that the decentralized equilibrium is distorted by the existence of monopolistically competitive firms in the intermediate good sector. The parameter governing this deviation from perfect competition is the elasticity of substitution between differentiated intermediate goods θ. Clearly, the higher this elasticity, the closer the Ramsey allocation will be to the social planner solution, as it is shown in the third column of Table 1, reporting the Ramsey steady-state solution for θ set at 1000. For $\theta \to \infty$ the Ramsey planner is in fact able to replicate the efficient equilibrium. Second, the lower level of output of the Ramsey solution delivers slightly lower emissions and a lower level of the stock of pollution. Of course, in steady state the optimal level of abatement is still positive since the Ramsey planner internalizes the negative externality of pollution on productivity. This result, in turn, delivers a positive value for the price on emissions permits, p_Z. By moving toward an equilibrium characterized by more competition, as in the third column of Table 1, the level of emissions flows and pollutant stock increase sharply, along with the negative externality of pollution on productivity. For this reason the optimal level of the price on emissions permits is shown to increase sharply. Third, the optimal inflation rate in the absence of shocks is zero (i.e. $\Pi = 1$). The optimality of zero inflation in steady state derives from the fact that the planner will find it optimal to neutralize the distortion induced

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[18] The steady state has been computed numerically using the ordinary least square approach proposed by Schmitt-Grohé and Uribe (2012). For further details, see the Technical Appendix.

by the cost on price adjustment which reduces the overall resources available for consumption and abatement. Finally, as expected, the achieved welfare, measured as the steady-state value of the lifetime utility function, is higher under the social planner solution which delivers the efficient allocation.

We are now ready to discuss the dynamic properties of the Ramsey equilibrium. Figure 2 presents the impulse responses of our key variables to a one percent positive technological shock. As before all variables are reported as percentage deviations from the non-stochastic steady state, except inflation, real and nominal interest rates, which are expressed as percentage-point deviations. As observed for the social planner case, output and consumption immediately increase, while labor slightly decreases. However, in this case, the response of labor is more negative for two reasons. First, because of the additional effect of price stickiness which prevents firms from adjusting their prices immediately to expand the demand necessary to absorb the higher level of production. In such circumstances, the increase in total factor productivity enables firms to produce more for a given level of inputs. However, immediately after the shock, as a result of price stickiness, aggregate demand cannot expand accordingly. In this sense, the slow price reaction to current economic conditions, due to the presence of adjustment costs, encourages firms to take advantage of the productivity increase by reducing labor demand. Second, the Ramsey planner finds it optimal to induce a reduction of labor, which is a source of disutility for households, preferring instead to free resources by temporarily reducing the distortions due to the lack of competition, as it will be clarified below. The optimal response of emissions is positive, but mitigated by the hike in the price of emissions permit which, in turn, induces a surge in the abatement effort. Again, the existence of a negative externality of pollution on production tends to mitigate the effects on emissions.

The nominal interest rate decreases and inflation falls on impact, but less than proportionally. The resulting real interest rate factor, R_t/Π_{t+1}, declines, showing that the Ramsey planner will opt to optimally respond to this shock with an accommodative monetary policy. The deviation from price stability can be explained by the fact that the Ramsey planner tends to generate the conditions under which it is optimal for firms to set lower markups, temporarily reducing the distortions due to the lack of competition and increasing the resources available for consumption and abatement. The markup, in fact, declines on impact and slowly returns to its steady-state level. We will see that this effect is particularly strong when the Ramsey planner controls only monetary policy, while environmental policy is conducted according to a cap-and-trade scheme.

In order to understand which are the forces that drive these results in Figure 3 we show the optimal response of labor, emissions permit price and markup for different parametrizations. In Figure 3a we consider different degrees of damage. The higher the strength of the negative externality, the stronger the reaction of all variables. Labor, in fact, will decline by more. In the attempt to mitigate the negative feedback of pollution on productivity, the Ramsey planner, will in fact find it optimal to induce a decline of worked hours. At the same time, the decline of markups is accentuated. More resources, in fact, are now needed to sustain the major abatement effort, which in turn will be induced by higher prices on emissions permits.

In Figure 3b we show the dynamic response of the economy for different values of ϕ_2.[19] When abatement is more costly, as expected, the price on emissions permit necessary to induce the optimal level of emissions will be higher. At the same time, markup will decline by more, since more resources are needed to cover the major abatement cost.

In Figure 3c we consider different degrees of price rigidities. The higher the level of price rigidities, the stronger the negative response of labor. This result is due to the fact that producers facing higher adjustment costs on prices are encouraged to take advantage of the positive shock on productivity by reducing labor demand. Markups, instead, decline by less, because deflation, and therefore deviations from price stability, are now more costly for the Ramsey planner.

Finally, in Figure 3d we run our simulations under different degrees of competition. Higher competition implies a stronger response of output and, therefore, of emissions to a positive technology shock. To moderate this effect and reduce the negative externality of pollution, a stronger response of the permit price is needed, together with a stronger reduction of the markups necessary to release the additional resources needed for abatement.

4.2 Ramsey Monetary Policy and Environmental Regulations

We now consider the problem of a Ramsey planner having access only to monetary policy and taking as given environmental regulation. We consider two alterative environmental policy regimes: a carbon tax and a cap-and-trade. In the first case, $p_{Z,t}$ is a constant and so the abatement effort U_t (see the optimal condition 6), while in the second case emissions Z_t are kept constant and so the level of pollution and, therefore, the negative externality on productivity.

In the case of a carbon tax the Ramsey problem can be stated as follows:

$$\underset{\{R_t,L_t,\Pi_t,M_t\}_{t=0}^{\infty}}{max} E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \log\left(\Lambda_t A_t L_t \left[1-\phi_1 U^{\phi_2} - \frac{\gamma}{2}\left(\Pi_t - 1\right)^2 \right] \right) - \mu_L \frac{L_t^{1+\eta}}{1+\eta} \right\}, \tag{22}$$

$$s.t.$$

$$\frac{1-\theta-\gamma\left(\Pi_t-1\right)\Pi_t}{1-\phi_1 U^{\phi_2}-\frac{\gamma}{2}\left(\Pi_t-1\right)^2} + \theta \mu_L L_t^{\eta+1} + \theta \frac{\phi_1 U^{\phi_2} + \phi_1 \phi_2 U^{\phi_2 - 1}\left(1-U_t\right)}{1-\phi_1 U^{\phi_2}-\frac{\gamma}{2}\left(\Pi_t-1\right)^2} +$$

$$+\gamma\beta E_t \frac{\left(\Pi_{t+1}-1\right)\Pi_{t+1}}{1-\phi_1 U^{\phi_2}-\frac{\gamma}{2}\left(\Pi_{t+1}-1\right)^2} = 0,$$

$$\frac{1}{R_t} = \beta E_t \frac{1}{\Pi_{t+1}} \frac{\Lambda_t A_t L_t \left[1-\phi_1 U^{\phi_2}-\frac{\gamma}{2}\left(\Pi_t-1\right)^2\right]}{\Lambda_{t+1} A_{t+1} L_{t+1} \left[1-\phi_1 U^{\phi_2}-\frac{\gamma}{2}\left(\Pi_{t+1}-1\right)^2\right]},$$

$$M_t = (1-\delta_M) M_{t-1} + \left(1-U\right) \varphi \Lambda_t A_t L_t + \tilde{Z}.$$

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[19] We perform this sensitivity analysis so as to keep the steady-state level of the abatement cost per unit of output constant by changing the scale parameter ϕ_1 accordingly.

Under a cap-and-trade scheme an additional constraint must be considered, namely: $Z = (1 - U_t)\,\varphi\Lambda_t A_t L_t$. The optimization problem immediately follows:

$$\max_{\{R_t,L_t,U_t,\Pi_t,M_t\}_{t=0}^{\infty}} E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \log\left(\Lambda_t A_t L_t \left[1 - \phi_1 U_t^{\phi_2} - \frac{\gamma}{2} (\Pi_t - 1)^2 \right] \right) - \mu_L \frac{L_t^{1+\eta}}{1+\eta} \right\}, \tag{23}$$

$$s.t.$$

$$\frac{1-\theta-\gamma(\Pi_t-1)\Pi_t}{1-\phi_1 U_t^{\phi_2}-\frac{\gamma}{2}(\Pi_t-1)^2} + \theta\mu_L L_t^{\eta+1} + \theta\frac{\phi_1 U_t^{\phi_2} + \phi_1\phi_2 U_t^{\phi_2-1}(1-U_t)}{1-\phi_1 U_t^{\phi_2}-\frac{\gamma}{2}(\Pi_t-1)^2} +$$

$$+\gamma\beta E_t \frac{(\Pi_{t+1}-1)\Pi_{t+1}}{1-\phi_1 U_{t+1}^{\phi_2}-\frac{\gamma}{2}(\Pi_{t+1}-1)^2} = 0,$$

$$\frac{1}{R_t} = \beta E_t \frac{1}{\Pi_{t+1}} \frac{\Lambda_t A_t L_t \left[1-\phi_1 U_t^{\phi_2}-\frac{\gamma}{2}(\Pi_t-1)^2\right]}{\Lambda_{t+1} A_{t+1} L_{t+1}\left[1-\phi_1 U_{t+1}^{\phi_2}-\frac{\gamma}{2}(\Pi_{t+1}-1)^2\right]},$$

$$Z = (1-U_t)\,\varphi\Lambda_t A_t L_t,$$

$$M_t = (1-\delta_M)M_{t-1} + Z + \tilde{Z}.$$

Again in order to save space, the first-order conditions are listed in the Appendix. Starting from the first-order conditions of the Ramsey plan and imposing the steady state, it can be easily shown that the optimal inflation rate in the absence of shocks is zero (i.e. $\Pi = 1$) in both cases.

Figure 4 shows the Ramsey optimal impulse response functions to a one percent positive productivity shock for our key macroeconomic variables. An increase in productivity induces output and consumption to increase and then gradually to reverse back to the steady-state state level, as expected, for both environmental regimes. In contrast, emissions expand only under a carbon tax, while with a cap-and-trade scheme the abatement effort and the permits price increase. Nonetheless, deviations from price stability are significant in response to the shock in a cap-and-trade scheme. As already mentioned in the Introduction, this is in sharp contrast with the conclusions found by previous studies on optimal monetary policy that have shown how strict price stability is optimal in response to productivity shocks. In fact, the Ramsey planner, in order to mitigate the negative effect related to the higher abatement costs, will find it optimal to induce a decrease of the inflation rate, so as to engineer a temporary negative effect on price markup, which, in fact, declines already in period one. This is why we observe that output jumps up on impact being fuelled by this reduction in the markup, despite the fact that under a cap-and-trade scheme the higher compliance costs sustained to keep emissions constant in response to the positive productivity shock would imply a reduced expansion of output. Therefore, the lower markup experienced during the adjustment process allows for a higher level of economic activity necessary to simultaneously sustain a higher consumption and the compliance costs associated with the emissions control. With a cap-and-trade scheme indeed a trade-off arises between inflation and emissions control. In presence of such trade-off the Ramsey planner would strike a balance between reducing the cost of adjusting prices and the cost of abating emissions. The Ramsey planner will then tolerate temporary deviations from strict price stability (and so higher adjustment costs on prices) as a way of reducing the markup and so the inefficiency related to the lack of perfect competition, so freeing extra resources to be used for the higher compliance costs and sustain a higher response of consumption. We also observe a negative response of labor with a cap-and-trade, which is consistent with the fact that output cannot fully expand in response to a positive technological shock, given the existence of the cap and despite the moderation of the markup. This is also consistent with the fact that the Ramsey planner will choose the allocations which maximize the welfare. The slightly lower response of consumption observed under a cap scheme is compensated by the reduced utility loss to be attributed to labor effort.

Under a carbon tax, instead, the Ramsey planner will only induce a slight deflation combined with a higher markup. In Figure 5 we show that the intensity of these effect depends on the damage function. A higher χ implies, in fact, a stronger damage of pollution on productivity, inducing the Ramsey planner to partially offset the size of this negative externality by reducing the expansion of output in response to the positive shock through an increase in the markup, partially moderated by deflation. In these circumstances the Ramsey planner will respond to this shock, by balancing the three distortions optimally. Clearly, for χ that tends to zero, the monetary Ramsey planner will find it optimal to bring about price stability, so avoiding the extra costs deriving from price adjustment. In this case the productivity gain is fully absorbed by the nominal wage rate, so leaving the real marginal cost and so the markup at their steady-state level.

In what follows we offer some sensitivity analysis to explore further the mechanism at work leading to the results just observed when GHG emissions regulation is set according to a cap-and-trade scheme and optimal monetary policy is decided by a Ramsey planner. As we have seen, in fact, in this case the Ramsey planner faces a trade-off between inflation and emissions control. The crucial determinants of the size of this trade-off are given by the available abatement technology, the adjustment costs on prices and the degree of competition. To appreciate the quantitative significance of these two parameters we compare the impulse response functions of some of the relevant variables for different parameterizations. See Figure 6.

In Figure 6a we consider different values of the degree of damage of pollution on output. We see that at least for these variables the results do not change.

Figure 6b reports the response of the same variables to the same shock for three different values of the parameter ϕ_2 governing the convexity of the available abatement technology. We notice that the higher ϕ_2, the higher the environmental regulation compliance cost borne by firms per unit of output in response to an expansionary shock. In such circumstances, the Ramsey planner tolerates a larger drop of prices to engineer a substantial drop of the markup, so temporarily reducing the inefficiency deriving from imperfect competition and generate the extra resources needed to cover the compliance cost and sustain consumption. When ϕ_2 is lower, instead, we have a limited variation in the price of the emissions permit and so of the abatement cost per unit of output in response to the expansionary shock, therefore the Ramsey planner allows only for minor deviations from price stability, since less resources are now needed to cover the compliance cost.

Figure 6c plots the optimal response to a positive productivity shock of inflation, the abatement cost per unit of output and the markup for different degrees of adjustment costs on prices. In particular, we assign three different values to the parameter γ determining the size of the cost of adjusting prices. A higher γ makes deviations from price stability more costly, that is why the Ramsey planner will tolerate less deflation in response to the shock, then producing a diminished effect on the markup. On the contrary, a lower γ allows the Ramsey planner to profitably use lower prices to reduce the markup and expand production further.

Finally, Figure 6d explores the implications of having different degrees of competition. A lower level of competition calls for a stronger response of inflation and then to a stronger, although delayed, fall of the markup. Less competition implies, in fact, that major distortions arise in response to a productivity shock. To reduce this distortion, the optimal Ramsey will find it optimal to tolerate higher adjustment cost on prices.

4.3 Ramsey Environmental Policy and Interest-Rate-Rules

We conclude our analysis by exploring the Ramsey solution under the assumption that the fiscal authority is able to optimally set environmental policy, taking as given monetary policy, conducted according to an interest rate rule, according to which the nominal interest responds to deviations of inflation and output from their stead-state levels. Following the literature on monetary policy we assume a rule which allows for a smoothing component, that is

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\frac{\Pi_t}{\Pi}\right)^{\rho_\Pi} \left(\frac{Y_t}{Y}\right)^{\rho_Y}\right]^{1-\rho_R}, \tag{24}$$

where ρ_R, ρ_Π, ρ_Y are all policy parameters and R, Π and Y are the steady-state value for the nominal interest rate, the inflation rate and output. The above rule prescribes that the interest rate responds to current inflation deviation from its steady state and to current deviation of output from its steady state. For $\rho_R \in (0,1)$ the rule allows for a certain degree of smoothing. The higher ρ_R, the lower the weight attached to current events in explaining variations in R_t.

The problem of the environmental Ramsey problem immediately follows:

$$\underset{\{L_t,U_t,\Pi_t,M_t\}_{t=0}^{\infty}}{max} E_0\sum_{t=0}^{\infty}\beta^t\left\{\log\left(\Lambda_t A_t L_t\left[1-\phi_1 U_t^{\phi_2}-\frac{\gamma}{2}\left(\Pi_t-1\right)^2\right]\right)-\mu_L\frac{L_t^{1+\eta}}{1+\eta}\right\}, \tag{25}$$

$$s.t.$$

$$\frac{1-\theta-\gamma\left(\Pi_t-1\right)\Pi_t}{1-\phi_1 U_t^{\phi_2}-\frac{\gamma}{2}\left(\Pi_t-1\right)^2}+\theta\mu_L L_t^{\eta+1}+\theta\frac{\phi_1 U_t^{\phi_2}+\phi_1\phi_2 U_t^{\phi_2-1}\left(1-U_t\right)}{1-\phi_1 U_t^{\phi_2}-\frac{\gamma}{2}\left(\Pi_t-1\right)^2}+$$

$$+\gamma\beta E_t\frac{\left(\Pi_{t+1}-1\right)\Pi_{t+1}}{1-\phi_1 U_{t+1}^{\phi_2}-\frac{\gamma}{2}\left(\Pi_{t+1}-1\right)^2}=0,$$

$$\frac{1}{R_t}=\beta E_t\frac{1}{\Pi_{t+1}}\frac{\Lambda_t A_t L_t\left[1-\phi_1 U_t^{\phi_2}-\frac{\gamma}{2}\left(\Pi_t-1\right)^2\right]}{\Lambda_{t+1}A_{t+1}L_{t+1}\left[1-\phi_1 U_{t+1}^{\phi_2}-\frac{\gamma}{2}\left(\Pi_{t+1}-1\right)^2\right]},$$

$$M_t=(1-\delta_M)M_{t-1}+\left(1-U_t\right)\varphi\Lambda_t A_t L_t+\tilde{Z},$$

$$\frac{R_t}{R}=\left(\frac{R_{t-1}}{R}\right)^{1-\rho_R}\left[\left(\frac{\Pi_t}{\Pi}\right)^{\rho_\Pi}\left(\frac{Y_t}{Y}\right)^{\rho_Y}\right]^{\rho_R}. \tag{26}$$

As usual the first-order conditions are listed in the Appendix.

We solve the model under three different parametrizations of the interest rate rule ensuring the existence of a unique stable equilibrium, namely we consider an interest rate peg ($\rho_R = \rho_\Pi = \rho_Y = 0$), an interest rate rule with smoothing ($\rho_R = 0.8$, $\rho_\Pi = 0.9$, $\rho_Y = 0.125$) and interest rate rule without smoothing ($\rho_R = 0$, $\rho_\Pi = 0.9$, $\rho_Y = 0.125$).[20] Figure 7 shows the optimal environmental Ramsey response to a positive productivity shock.

We notice the following. First, the response of output, consumption and then emissions is much lower than that experienced in the previous policy experiments, where the Ramsey planner has access to the monetary instrument. Also the abatement effort is lower than under a Ramsey monetary policy with a cap-and-trade or than under a Ramsey environmental and monetary policy. The observed diminished effect on these variables is due to the fact that the markup now increases in response to the shocks. Since the Ramsey planner has no access to monetary policy, it is not able to directly influence the response of the markups which, in these circumstances, turn out to be procyclical. In addition, price stickiness combined with the lack of control of monetary policy on the part of the Ramsey planner, induces a reduction of labor. As already explained, in fact, in the impossibility of changing prices without cost, firms will reduce their labor inputs.

Second, the monetary policy conduct is shown to influence intensively the way in which the Ramsey planner sets environmental policy. In particular, when the nominal interest rate is pegged (i.e, $\rho_R = \rho_\Pi = \rho_Y = 0$), the monetary policy is accommodative (the real interest rate declines, accommodating the expansion of output by boosting demand and so requiring a

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[20] In this setting, under a Ramsey environmental policy, the existence of a unique stable equilibrium requires that the policy parameter governing the reaction of the nominal interest rate to inflation, ρ_Π, is less than one. For values larger than one, in fact, the model becomes unstable.

lower reduction of labor), therefore the shock is more expansionary and emissions will increase by more. In other words, following the positive supply shock, under a peg, output goes up and this increase is matched by a surge in consumption, due to the fact that monetary policy is accommodative. In such circumstances, the opportunity cost of abatement is higher. Therefore, the environmental Ramsey planner will intervene to a lesser extent to reduce the negative externalities stemming from the damage function.

When there is a positive reaction of the interest rate to output and inflation, instead, these effects are less intense, since now monetary policy is less accommodative, reducing the positive impact on consumption. In such circumstances, the optimal environmental policy induces a major increase in the permit prices, so as to push toward a major abatement effort, further mitigating the effect on emissions. The opportunity cost of a major abatement, in fact, reduces when the interest rate rule is responsive to current variables, slowing down consumption. This effect is particularly evident when the interest rate only reacts to inflation and output, with no smoothing (i.e., $\rho_R = 0$, $\rho_\Pi = 0.9$, $\rho_Y = 0.125$). Emissions in fact, initially increase and then temporarily decline to slowly revert back to their initial steady-state level. When the interest rate only responds to current variables, in fact, monetary policy is less accommodative, consumption increases by less in response to the positive shock and so the opportunity cost of abatement reduces. This is why the Ramsey planner finds it optimal to set a lower level of emissions which become countercyclical, reducing even further the damage of pollution on productivity. To induce a decline of emissions the price on emissions permit will hike and so the abatement effort. It can be shown that the countercyclical response of the emissions is due to the reaction of the interest rate rule to the current level of output, ρ_y. By increasing this parameter from 0 to 0.5, for instance, while keeping ρ_Π at 0.9 and $\rho_R = 0$, the correlation between the technological level A and emissions Z moves from 0.7155 to -0.7818. These results shed light on the non-trivial implications of the monetary policy conduct on optimal environmental policy.

5 Conclusions

This paper studies the optimal environmental and monetary policy mix in a New Keynesian model extended to account for pollutant emissions, abatement technology and environmental damage. The model features three main distortions (i.e. imperfect competition, costly price adjustment and negative externality of pollution on productivity) that shape the optimal response of the policy makers to productivity shocks, conditional on the instruments they have access to and on the way they interact.

Our main results can be summarized as follows. First, we find that, in general, emissions turn out to be procyclical, although to a lesser extent than in the absence of optimal policy and depending on the intensity of the environmental damage of pollution. However, when the Ramsey planner only controls environmental policy and the interest rate rule describing monetary policy is strongly responsive to output, then emissions may turn out to be countercyclical. On the contrary, when the reactivity to output is low or nihil, then emissions are again procyclical. A meaningful characterization of environmental policy is then found to be conditional on the way monetary policy reacts to shocks.

Second, when the Ramsey planner controls both environmental and monetary policy by setting aggregate emissions target and the nominal interest rate, the optimal level of emissions, given the negative externality, is achieved through a mix of low markups and high emissions permit prices, so as to increase the flow of available resources for abatement cost and induce a mitigation of emissions. The intensity of the distortions that characterize the economy as well as the available abatement technology, influence the magnitude of the reaction of these variables.

Finally, when the Ramsey planner has only access to the monetary instrument and environmental policy is conducted according to cap-and-trade scheme or to a carbon tax, we show that GHG emissions regulation is not neutral for monetary policy. In particular, we find that the typical result of the literature on the optimal design of monetary policy prescribing the optimality of strict inflation targeting does not hold in this context. We show, in fact, that strict inflation targeting is found to be optimal only under a carbon tax regime and in the absence of environmental damage. With an emissions cap or with a carbon tax combined with a non-negligible environmental damage, instead, prices are allowed to change so as to address the inefficiencies related to the lack of perfect competition and the negative feedback of pollution on productivity. In this sense GHG emissions regulation is not neutral for monetary policy.

Overall, we think that the issue of the interaction between different policy domains requires much further research, in particular when environmental issues come into play. Climate actions are likely to have pervasive effects on the conduct of agents and on the compliance costs borne by firms, as well as economic variables tend to affect the quality of the environment and therefore the performance of mitigation policies. These aspects should be taken into account by policy makers when acting in other areas of interventions, which are likely to affect directly and/indirectly agents choice and so their response to exogenous shocks.

We argue that if the dependence between different domains is not made explicit, policy recommendations may be misleading. From this perspective, our analysis prepares the ground for future explorations in this direction in the context of fully-fledged models designed for policy analysis.

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Table 1: Steady-State Solutions

	Social Planner	Ramsey	Ramsey $\theta = 1000$
Y	1	0.9141	1.000
C	0.9997	0.9140	0.9997
L	0.2	0.1828	0.2000
Z	0.1046	0.1039	0.1046
U	0.1534	0.0798	0.1534
p_z		0.01162	0.0377
Π		1	1
M	57.3089	56.9879	57.3089
$Welfare$	-49.8285	-50.5881	-49.8285

Figure 1: Dynamic Responses to a One Percent Increase in Productivity - Social Planner

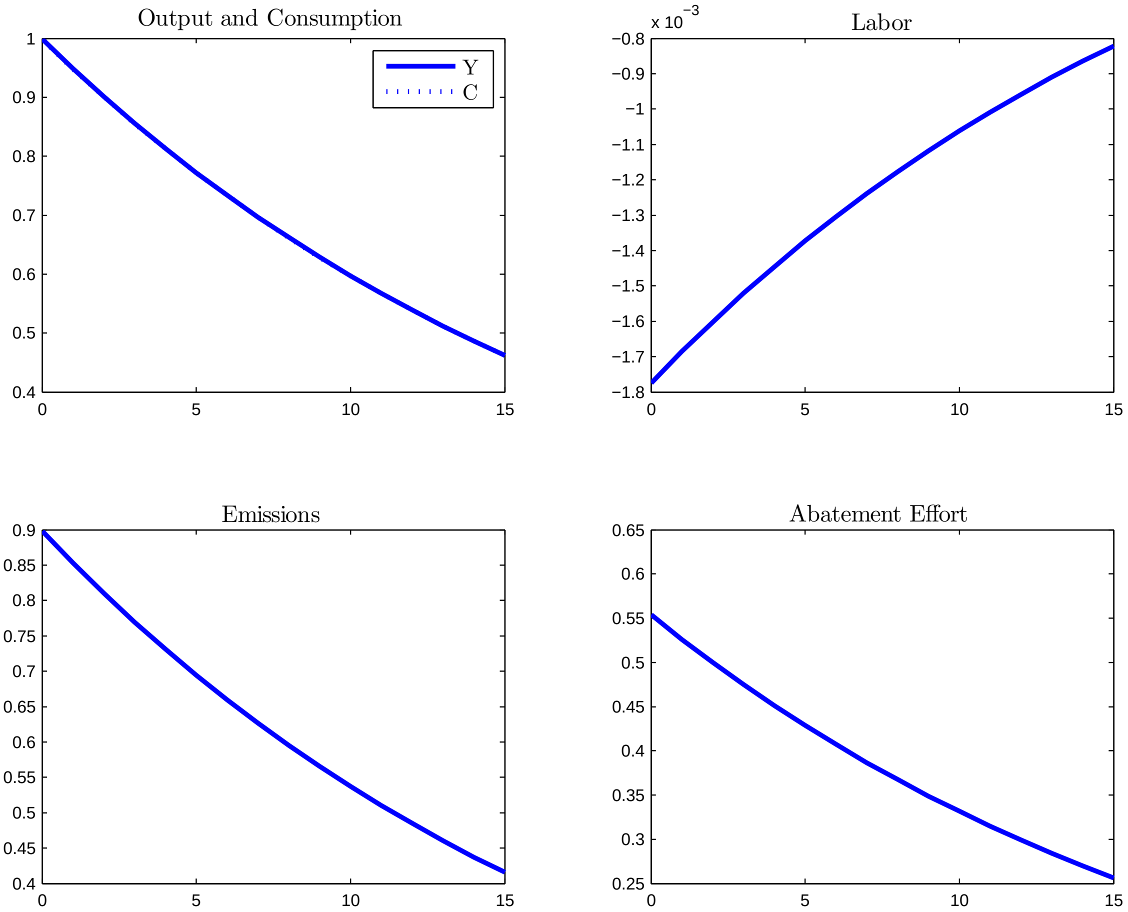


Figure 2: Dynamic Responses to a One Percent Increase in Productivity - Ramsey Monetary and Environmental Policy

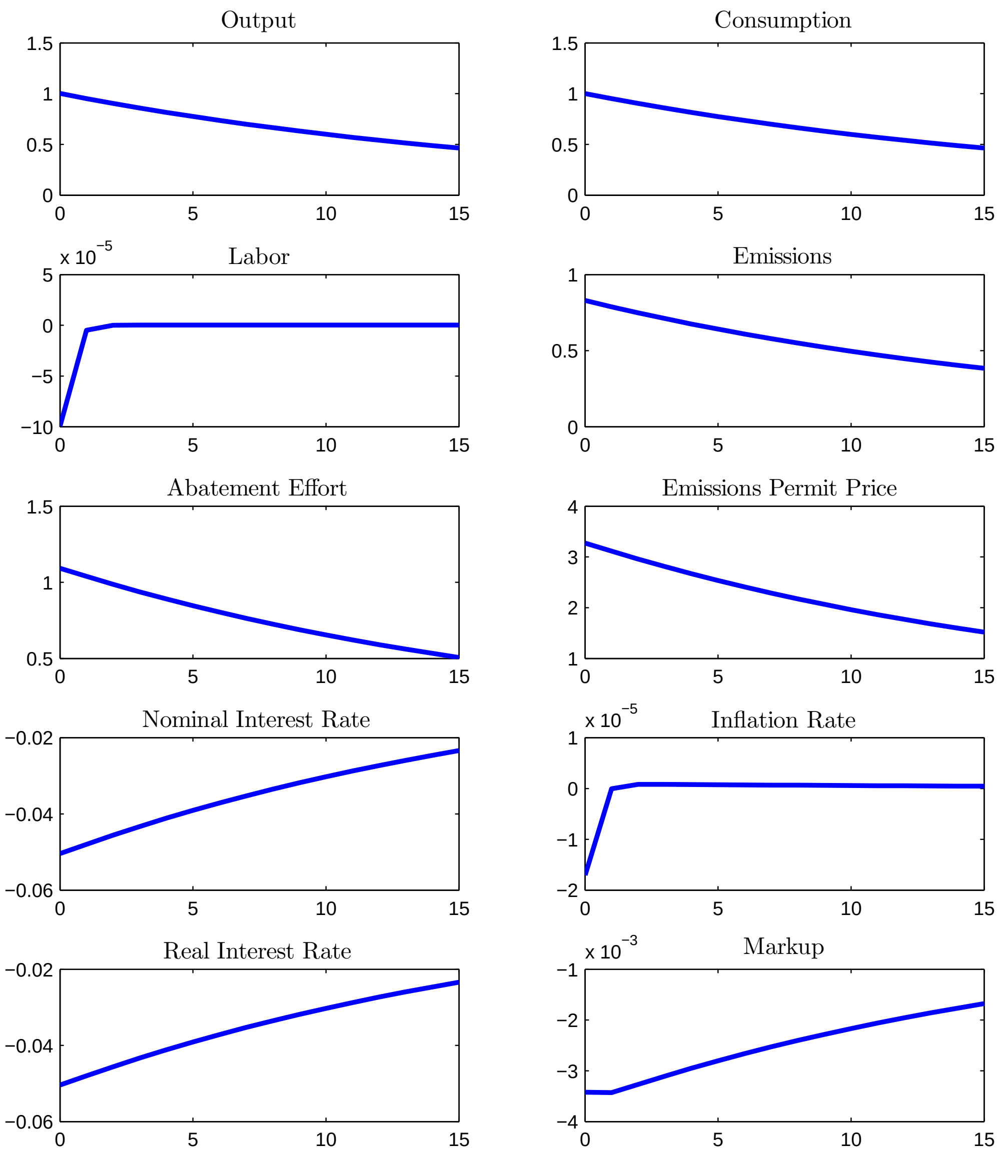
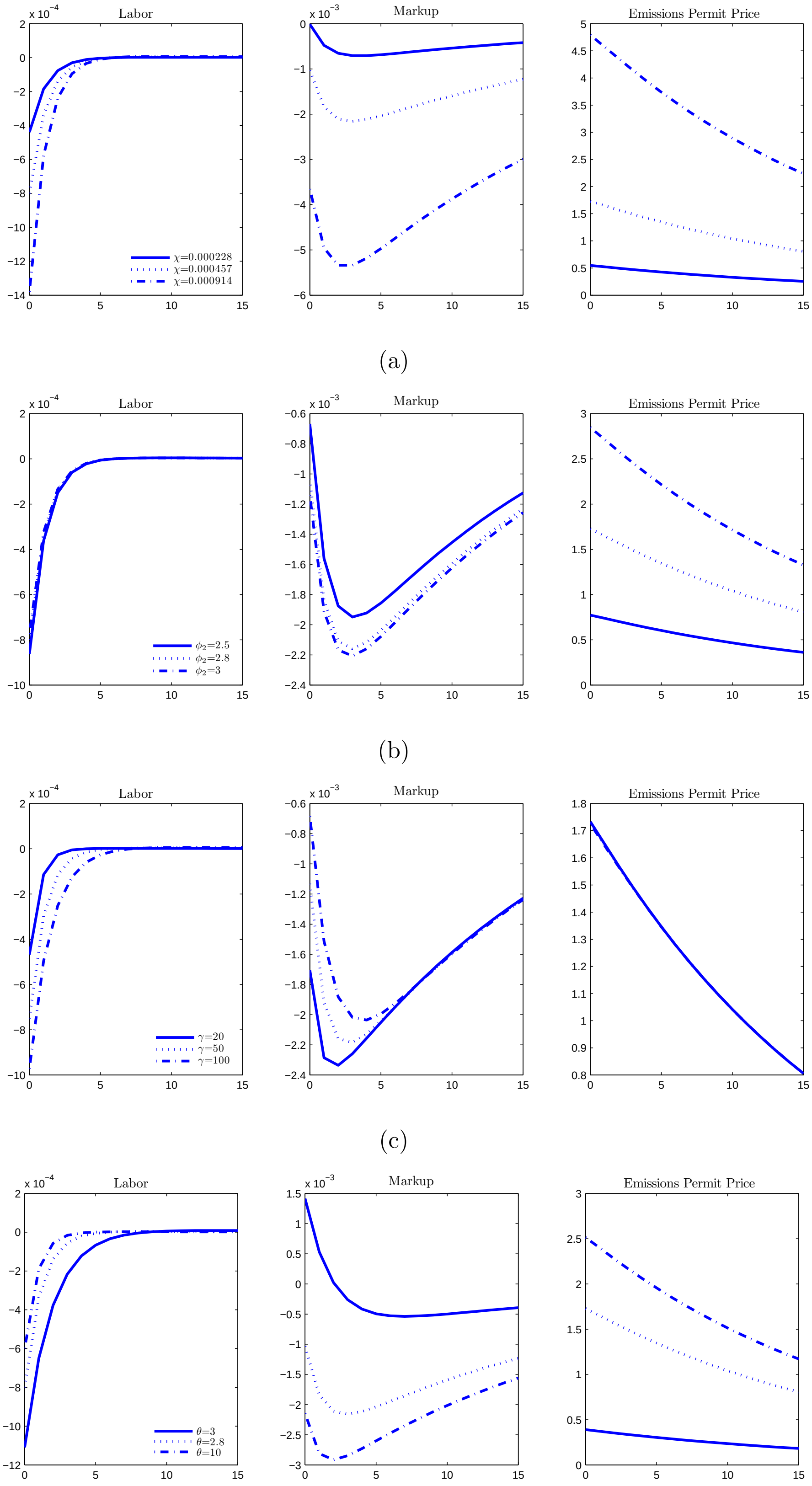


Figure 3: Dynamic Responses to a One Percent Increase in Productivity - Ramsey Monetary and Environmental Policy - Sensitivity



(a)

(b)

(c)

(d)

Figure 4: Dynamic Responses to a One Percent Increase in Productivity - Ramsey Monetary Policy

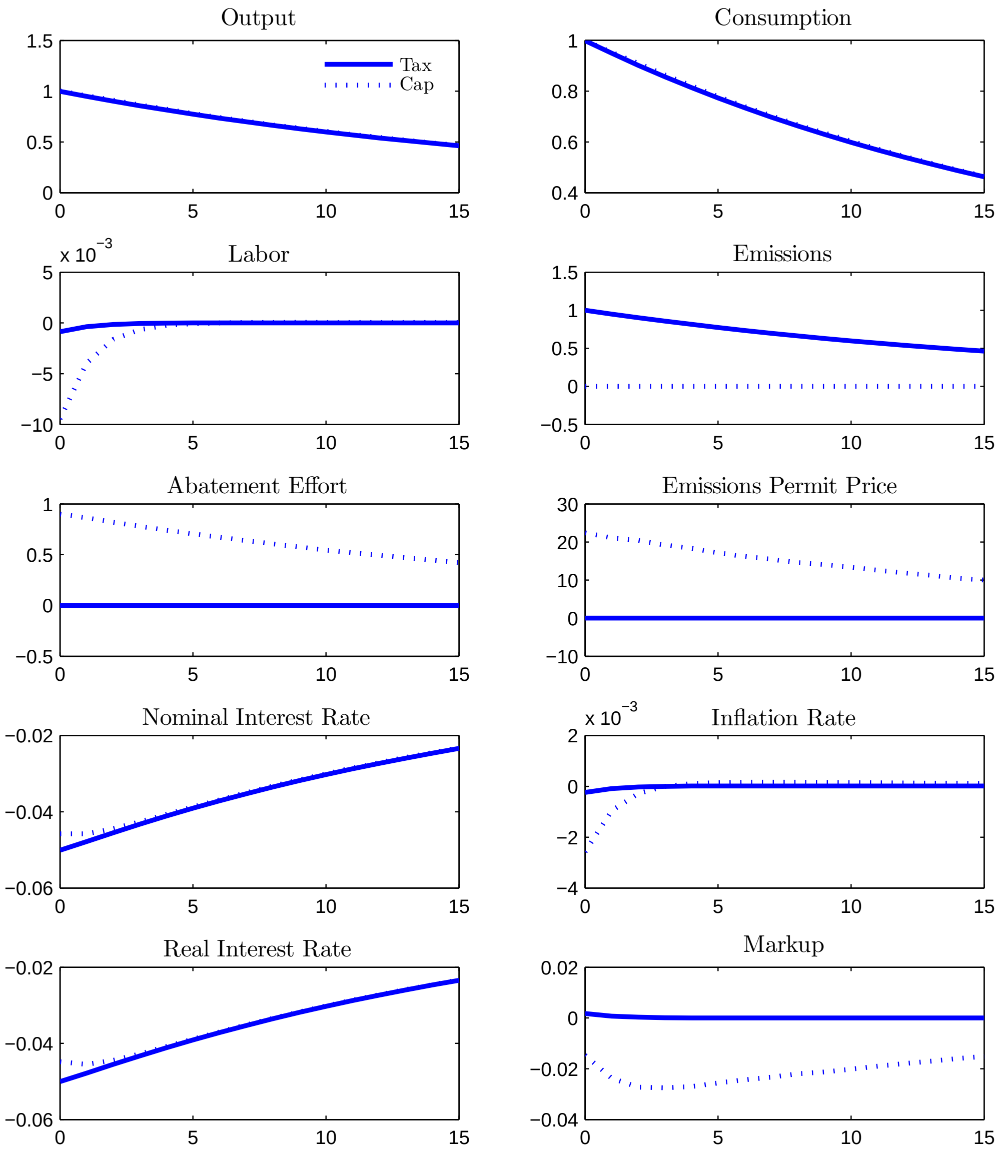


Figure 5: Dynamic Responses to a One Percent Increase in Productivity - Ramsey Monetary Policy with Carbon Tax

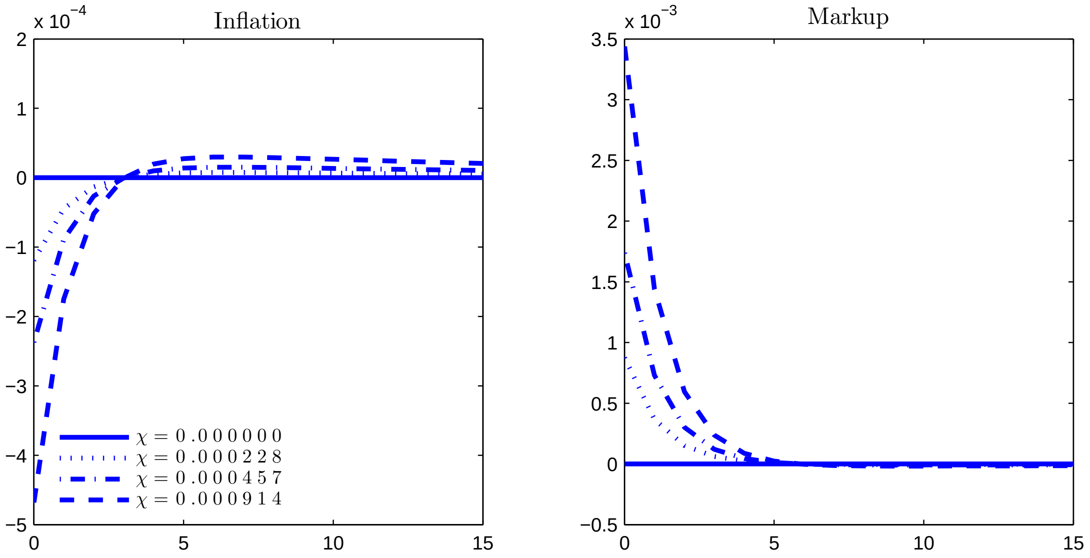
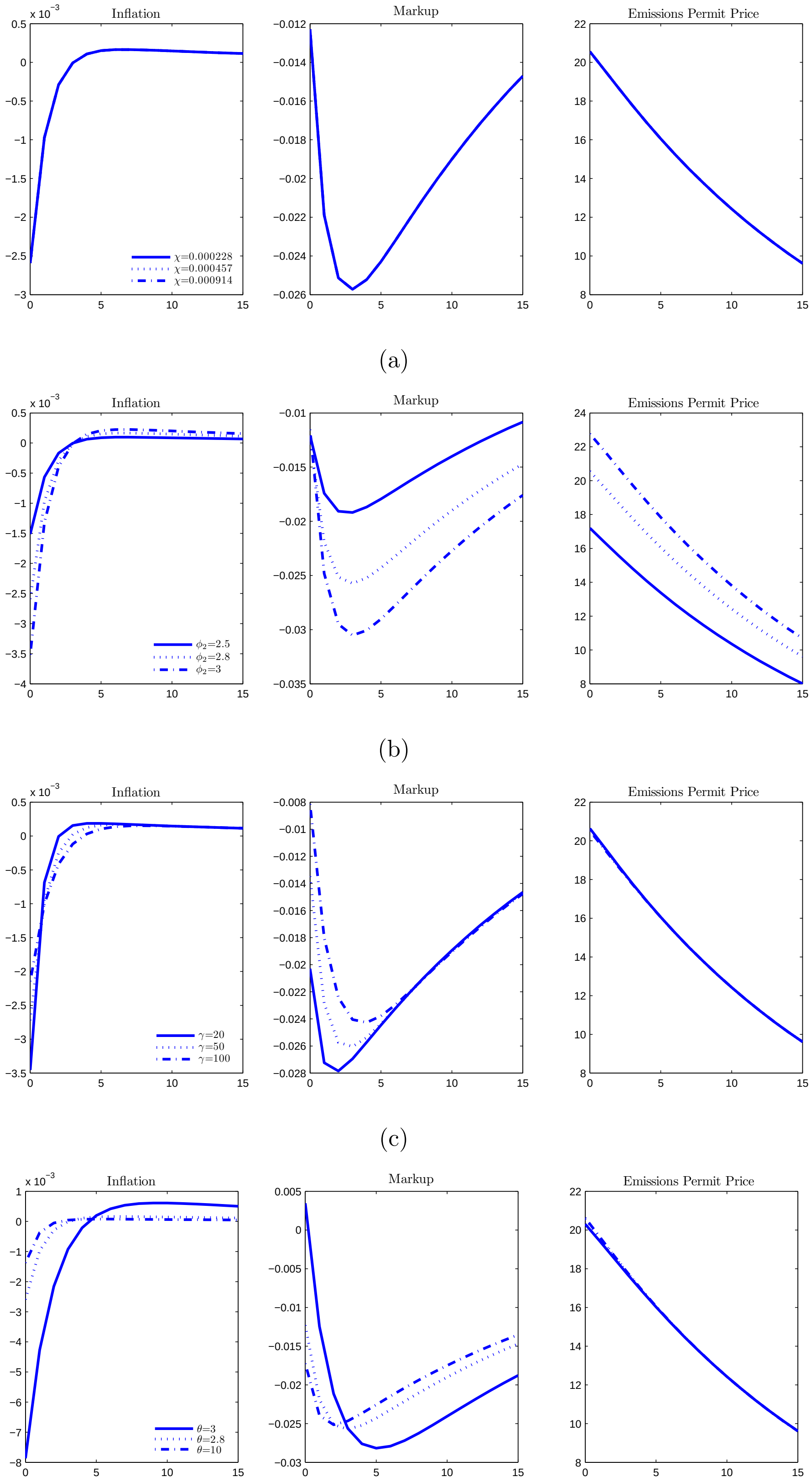


Figure 6: Dynamic Responses to a One Percent Increase in Productivity - Ramsey Monetary Policy with Cap - Sensitivity



(a)

(b)

(c)

(d)

Figure 7: Dynamic Responses to a One Percent Increase in Productivity - Ramsey Environmental Policy