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Green Lending

Abstract

We develop a model of green lending to study its implications for monetary policy and environmental regulation. Banks finance firms' brown and/or green projects. The costs of brown projects increase with rising regulatory stringency or when endogenous monetary policy affects the cost of funds. Both policies can elevate the equilibrium share of green lending, resulting in greener output. Our findings remain consistent when we introduce central banks with an explicit green objective (e.g., differential interest rates based on project type), forward-looking bank behavior, and adjustment costs. Additionally, we demonstrate the relative impacts of regulatory and monetary persistent regime changes.

Keywords: Green lending; Green monetary policy; Environmental regulation

JEL Classification: G21; E44; E52; Q50

1. Introduction

The financial system is increasingly recognized as a crucial lever in the global transition to a low-carbon economy. As the effects of climate change intensify, a growing body of, mainly empirical, research has explored the exposure of financial institutions to climate-related risks, the pricing of transition risks or stranded assets, and the appropriate role of central banks in addressing these systemic threats (Battiston et al., 2017; Bolton et al., 2020; Bolton & Kacperczyk, 2021; D'Orazio & Popoyan, 2019; NGFS, 2021). Despite this emerging literature, most theoretical models of green finance remain static or treat credit allocation as exogenous, offering limited insights into how banks may adapt their portfolios over time in response to environmental signals and policy interventions. In this paper, we develop a dynamic portfolio allocation model of green and brown lending, with endogenous policy feedback, to analyze the impact of regulatory and monetary policy on credit markets and pollution dynamics.

We build on several empirical and policy insights that highlight recurring features of the green finance landscape. Brown projects continue to offer higher short-term returns but are increasingly exposed to transition risks stemming from policy tightening, market repricing, and reputational shifts (Bolton et al., 2020; Heinkel et al., 2001; NGFS, 2022). Despite the rise of green taxonomies and disclosure requirements, bank portfolios remain heavily tilted toward carbon-intensive sectors (EIB, 2021; Rainforest Action Network, 2023), and portfolio reallocation has been slow, reflecting risk perceptions, information gaps, and institutional inertia. At the same time, credible and forward-looking regulation has been shown to alter the pricing and availability of brown credit (Delis et al., 2019; ECB, 2022). Additionally, monetary authorities are increasingly debating the merits of targeted green operations, such as green Targeted Longer-Term Refinancing Operations (TLTROs) and climate-adjusted collateral frameworks (Altavilla et al., 2023; D'Orazio, 2023; Campiglio et al., 2022; van 't Klooster & van Lerven, 2020). Finally, environmental dynamics are often nonlinear, with pollution and emissions responding sharply to threshold-based policies, reinforcing the need to model discrete regime shifts and credible signaling (Lamperti et al., 2021; NGFS, 2021).

Using this feedback, we start with a stylized, yet analytically transparent, model. Banks allocate credit between green and brown projects to maximize profits. Firms use credit to invest in either clean or polluting technologies, while regulation responds endogenously to pollution by diminishing the viability of brown investments. The central bank sets a nominal interest rate according to a Taylor rule augmented by pollution sensitivity, which influences the cost of credit for both green and brown activities. The baseline model incorporates linear margins and assumes static returns, with banks responding only to current profitability differentials.

Even within this minimal structure, the baseline model generates meaningful interactions between financial decisions and environmental dynamics. Regulatory tightening in response to pollution effectively reduces brown investments by making them less profitable, while monetary policy that raises the cost of credit in polluted environments can further accelerate this shift. However, because banks adjust their portfolios discontinuously and without foresight, transitions may be inefficient or delayed. These results underscore the importance of policy design and sequencing in shaping green investment pathways.

Recognizing that bank behavior is rarely static or perfectly reactive, we enhance our baseline model to create a more flexible and empirically grounded model of dynamic portfolio allocation. In this framework, banks gradually reallocate credit between green and brown projects, based on changes in expected margins and subject to institutional frictions. This continuous adjustment mechanism reflects real-world banking practices, where shifts in strategy and capital allocation typically unfold over time rather than instantaneously. This more nuanced behavioral foundation forms the core model used in the remainder of the paper.

We next develop this dynamic structure to account for several key features of the climate-finance nexus. First, we allow project returns to evolve endogenously, with brown profitability declining under stricter regulation or increasing pollution, while green projects gain viability as policy becomes more supportive. This approach adds realism to the investment environment and captures the endogenous emergence of stranded assets. Second, we model a central bank with an explicit green mandate, enabling differential interest rates or credit subsidies that favor clean investments. Third, we consider forward-looking bank behavior, where expectations of future regulation or environmental degradation influence current allocation decisions. Fourth, we incorporate explicit adjustment costs into the credit reallocation process, capturing institutional rigidity and operational barriers. Finally, we introduce persistent regime changes in regulatory and monetary policy to model threshold effects and enhance policy credibility.

Each of these extensions is motivated by empirical evidence and enhances the model's realism in various scenarios, reflecting different assumptions. Endogenous returns link policy to financial incentives (Altavilla et al., 2023; Bolton et al., 2020; NGFS, 2021). A green central bank embodies ongoing debates about the role of monetary institutions in climate action (Campiglio et al., 2022; van 't Klooster & van Lerven, 2020). Forward-looking behavior more accurately captures the strategic planning of financial intermediaries (Bolton et al., 2020). Adjustment costs account for the observed lags in green capital flows (D'Orazio & Popoyan, 2019). Finally, regime shifts facilitate the modeling of abrupt transitions often seen in climate policy and political economy (Lamperti et al., 2021; NGFS, 2021).

Simulation results across these variants reveal how different policy tools and institutional features shape the effectiveness of green transitions. Regulation typically has a stronger and more immediate impact on credit reallocation by directly reducing the viability of brown investments. Monetary policy can complement this shift, but its effects are more gradual unless supported by strong interest rate differentiation between green and brown projects. The most effective outcomes arise when policies are coordinated and credible, and when banks anticipate future changes. In contrast, delays, myopia, or poorly signaled shifts result in higher pollution peaks and slower green reallocation.

Taken together, these findings highlight the importance of combining forward-looking, dynamic financial behavior with well-designed regulatory and monetary policies. The model offers a versatile framework for analyzing how financial systems can support the transition to a sustainable economy and for examining how policy sequencing and institutional design affect the speed and quality of this transformation.

The remainder of our paper is organized as follows: Section 2 presents the conceptual framework of our study and situates it within the existing literature. Section 3 discusses the setup of the most basic model. Section 4 provides the benchmark model of dynamic portfolio allocation. Section 5 presents several extensions to this modeling framework, including central banks with an explicit green objective. Section 6 introduces the model with explicit regime changes and its policy implications. Section 7 concludes the paper.

2. Conceptual framework

Our paper is naturally related to a large body of literature on environmental economics and an emerging field of green banking and finance. In this section, we create a conceptual framework that assists in the development of our model and its implications.

Up to the mid-2010s, foundational work on climate finance was very limited, in contrast to the extensive research on environmental economics, which does not address how the climate transition will be funded. Campiglio (2016) is one of the first to discuss, inter alia, that carbon pricing is insufficient to reduce carbon investments because banks do not necessarily reallocate funds toward green projects. Empirical evidence for this is provided by Antoniou et al. (2025), who examine the lack of response from banks to the European permits market.

Theoretical models of climate finance are scarce, and perhaps the closest to our purposes is Dafermos and Nikolaidi (2021), who introduce an ecological stock-flow consistent model. In this model, differentiated capital requirements—a "green supporting factor" (lower bank capital charges on green loans) versus a "brown penalizing factor" (higher charges on carbon-intensive loans)—alter banks' portfolio choices. Similarly, Carattini et al. (2023) and McConnell et al. (2022) study general equilibrium models with a banking sector, demonstrating that preferential treatment of green assets (through brown collateral haircuts) tilts lending toward low-carbon projects. In our model, we focus on real economy financing through project lending within a dynamic framework that includes time paths. We provide several extensions, including endogenous pollution, forward-looking bank behavior, adjustment costs, an explicit green objective, and regime changes. Thus, we consider our analysis to be broader and more foundational.

Another strand of related literature examines how central banks can incorporate green policy into their mandates. Dikau and Volz (2021) show that a limited number of central banks explicitly mention sustainability in their mandates, while a larger share supports government policies in climate objectives and recognizes that climate risks threaten financial stability. Scholars also emphasize that most central banks seek to "green" the financial system through market-friendly adjustments rather than direct intervention. For example, many central banks are tilting asset purchases or collateral haircuts based on climate scores to encourage markets to reprice green versus brown assets (Kedward et al., 2024). The obvious limitation of this strategy is that brown projects will remain profitable, and green credit allocation will remain suboptimal. Echoing this perspective, policy institutes have proposed targeted credit programs. For example, NEF (2021) advocates a green term funding scheme to provide cheaper funding for green loans, helping the Bank of England fulfill its climate-related mandate while maintaining its price and financial stability objectives.

Empirical studies are now more comprehensive and generally examine how banks, markets, and the economy respond to climate-related risks and policies (e.g., Bolton and Kacperczyk, 2021; Bolton and Kacperczyk, 2023; De Haas and Popov, 2023). In this analysis, we focus specifically on climate factors that influence credit pricing and allocation. On the risk side, banks are increasingly aware of *physical* climate risks (such as extreme weather) and *transition* risks (policy or technological shifts in the transition to a low-carbon economy) (e.g., Bua et al., 2024; de Bandt et al., 2024). Other studies have identified instances in which banks *do not* materially change lending terms following climate events (see the review by de Bandt et al., 2024).

Indeed, financial authorities worldwide, often coordinated through the NGFS, have introduced climate stress tests and disclosure frameworks to better integrate climate risk into banks' risk management (Bolton et al., 2020). The key findings indicate that in high-transition-risk scenarios, such as sudden stringent climate policies, or in severe physical risk scenarios, banks face significantly higher credit losses over the long run, reinforcing the case for early and proactive adjustments.

Our model aligns with empirical findings in the recent literature, notably Altavilla et al. (2023), who show that banks differentiate lending rates based on borrowers' carbon emissions and adjust credit risk premia under monetary policy changes. While their paper offers robust empirical evidence, our model provides a theoretical framework capturing the dynamic interaction between bank lending, pollution, and policy interventions. Specifically, our results—such as the stronger impact of regulatory shifts relative to monetary policy shocks, and the potential for green objectives within central banks to alter lending dynamics—help explain the mechanisms behind the empirical patterns observed in bank behavior.

Another relevant empirical finding comes from China's green credit guidelines (implemented in the 2010s), which explicitly encouraged banks to restrict lending to heavily polluting industries while boosting credit to cleaner sectors. Altavilla et al. (2023) empirically highlight how banks adjust lending portfolios dynamically in response to environmental factors and policy changes, supporting the inclusion of monetary policy variables in a theoretical model. He et al. (2024) exploit this policy and find that firms in polluting industries experienced a significant decline in climate risk exposure through accelerated green technological innovation, adjusted investment strategies, and improved transparency regarding environmental performance. Importantly, the literature also cautions that policy design matters (Dafermos and Nikolaidi, 2021; Kedward et al., 2024). Small incentives, such as minor capital relief for green assets, may have only limited effects on bank behavior, whereas more comprehensive or stringent regimes are likely needed to drive transformational change in lending patterns. This aligns with the notion in theoretical models that persistent regime shifts (e.g., a lasting tightening of brown-asset regulation or a long-term refinancing program for green projects) might have the greatest impact on expectations and, consequently, on banks' portfolio decisions.

In summary, both older and cutting-edge research provide a rich context for a dynamic model of green banking with endogenous policy regimes. This literature base directly informs the model's key features: profit-driven banks responding to risk-return trade-offs altered by climate policies, dynamic portfolio rebalancing as conditions and regimes shift, and the critical role of regulatory and monetary policy regimes are in flux. By drawing on these theoretical insights and empirical findings, the model can be well-calibrated to capture realistic bank responses and provide policy-relevant conclusions on the effectiveness of green banking initiatives in fostering a more sustainable financial system.

3. Baseline model

We consider a model that includes all the basic players in green lending. Firms choose their optimal production processes and generate pollution. Financiers provide funding for the firms' production processes through either green or brown lending to maximize their profits. In our setup, we refer to these financiers as banks; however, the model can apply to any credit supplier that charges interest. An environmental regulator increases the firms' production costs, which can rise either exogenously over time (as in our baseline model) or endogenously through feedback from environmental degradation. The central bank sets interest rates, influencing the cost of lending. In the baseline model, interest rate settings are exogenous, but a key objective of our end model is to explore green monetary policy.

3.1. Firm objectives and the bank's problem under environmental regulation

Firms are rational profit maximizing entities that compare the net returns across two different project types $k \in \{G, B\}$. G is a green project and B is a brown project, with corresponding returns $\boldsymbol{r_G}$ and $\boldsymbol{r_B}$. The firm decision depends both on internal operational costs $\boldsymbol{C_o}$ and external costs. The latter include credit costs $\boldsymbol{R_k = c(t) + \mu_\kappa}$, where $\boldsymbol{c(t)}$ is the cost of funds faced by banks and $\boldsymbol{\mu_\kappa}$ is the markup. The firm also faces regulatory costs $\boldsymbol{C_{reg}}$. The firms' objective is

$$\max_{\mathrm{k} \in \{G,B\}} r_k - R_k(t) - C_o - C_{reg}(\theta(t)), \tag{1}$$

where $\theta(t)$ is the current state of environmental regulation, which might include carbon taxes, cap-and-trade policy, or carbon pricing. Thus, equation 1 assumes that some firms may choose a green project despite higher costs due to more stringent future regulation (other firms can stick to the brown project despite this projection).

Banks are risk-neutral agents that provide credit L_G to firms' green projects and L_B to brown projects to maximize their own profits:[1]

$$\max_{L_G, L_B} \Pi(t) = p_G\big(R_G - c(t)\big)L_G + p_B\big(\theta(t)\big)\big(R_B - c(t)\big)L_B \, , \tag{2}$$

subject to $L_G + L_B \leq L$, for $L_G, L_B \geq 0$.

In equation 2, L is the total loan supply; R_G and R_B are the loan rates charged to green and brown firms; p_G is the success probability of green projects; $p_B\,(\theta) = p_{B0} - \lambda\Theta(t)$ is the success probability of brown projects, which decreases in regulation θ; and $c(t)$ is the cost of funds determined by central bank policy over time t.[2] Thus, loan income equals the repayment probability times the intermediation spread times the loan amount, while regulation θ affects the brown project's repayment probability.

In equations 1 and 2, we assume linear profit maximization for firms and banks, which is central to understanding bank behavior in allocating portfolios among different types of projects (for a similar choice see e.g., Holmström and Tirole, 1997; Tirole, 2006). These models are instrumental in analyzing how banks adjust their portfolios in response to changing economic

[1] Banks do not face financial frictions in our model, as this is not the focus of our research. However, we may include financial frictions in two ways. The first is through capital requirements as in Carratini et al. (2021) by limiting how much banks lend based on their equity capital. The second is through a default risk channel, where bank profit margins include expected loans from brown loans that increases with pollution. Bolton and Kacperczyk (2021; 2023) empirically show that markets now price this probability by demanding higher returns from brown stocks.

[2] The cost of funds can also be affected by deposit rates, which are influenced by central bank policy, competitive conditions in the banking market, and household savings dynamics. We refrain from introducing household behavior in our context because households do not directly influence the greening of the banking sector and rarely pressure banks to change their practices based on environmental concerns. Therefore, including households might complicate the model without providing substantial benefits.

conditions and policy interventions. While we could express the model in a more general form, this approach would not be particularly suitable for obtaining simulated solutions in the dynamic cases of the model.

Environmental regulation is not static but increases over time. For the simple case, we assume a linear increase in regulatory stringency of the form:

$$\theta(t) = \theta_0 + \kappa t, \tag{3}$$

where θ_0 is the initial regulation and $\kappa > 0$ is the speed of regulatory stringency. In this setting, the repayment probability of brown loans declines with regulation as follows:

$$p_B(\theta) = p_B^0 - \lambda\theta, \tag{4}$$

where $\lambda > 0$ is the sensitivity to regulation.

Our model is also linear in L_G and L_B, so the bank will provide all green (brown) loans if the green (brown) loan's marginal profit is higher. The green margin is $M_G(t) = p_G(R_G - c(t))$ and the brown margin is $M_B(t) = (p_B^0 - \lambda\theta(t))(R_B - c(t))$. Given the above, there are three key mechanics in place. First, without regulation (θ = 0), the brown projects are more profitable. Second, as regulation θ increases, brown project margins shrink. Third, there is a critical threshold θ^*, which solves $M_G = M_B(\theta^*)$, denoting the level of regulation where green lending becomes more profitable:

$$\theta^* = \frac{p_B^0(R_B - c) - p_G(R_G - c)}{\lambda(R_B - c)}. \tag{5}$$

In Figure 1, we present a numerical example that illustrates the key elements of the model thus far. The solid red line represents the brown margin, which decreases with increased regulation, while the green margin remains flat because regulation does not impact it. The switching point is indicated by the vertical blue line, beyond which banks transition to green lending.

[Please insert Figure 1 about here]

3.2 Endogenous regulation (environmental feedback)

In the baseline model, regulation $\theta(t)$ exogenously increases over time to fight environmental degradation. In this section, we enhance the model's realism by allowing environmental degradation to influence regulatory stringency. This creates a scenario in which the impact of firm output on the environment affects regulation, which in turn influences bank lending policy and optimal bank behavior.

We define $E(t)$ as the level of environmental degradation, which accumulates over time with the materialization of brown projects. Environmental regulation is the response to this environmental degradation. Assume that degradation evolves according to

$$\frac{dE(t)}{dt} = a_B L_B(t) - a_G L_G(t) - \delta E(t), \tag{6}$$

where $a_B > 0$, $a_G \geq 0$ are the pollution intensities for green and brown projects, and $\delta > 0$ is the natural recovery rate of the environment. In this sense, pollution accumulates over time, with brown loans worsening environmental conditions, while green loans stabilizing or improving them.

Assuming that regulatory policy reacts to environmental degradation we can write that:

$$\frac{d\theta(t))}{dt} = \gamma(E(t) - E^*), \tag{7}$$

where $\gamma \geq 0$ is the level of regulatory stringency and E^* reflects how "tolerable" is the level of environmental degradation. When $E(t) > E^*$, regulatory stringency increases over time.

Expanding our baseline model in section 2 to include endogenous regulation creates a dynamic green transition model involving banks. The feedback loop begins with lending decisions that influence the type of project (green or brown), which in turn affects the level of environmental degradation. This triggers a regulatory response that impacts the profitability of the projects, leading to new lending decisions by banks. The key insight is that if banks continue to finance brown projects, pollution levels will rise, necessitating more stringent regulations, which will make brown projects riskier. Conversely, if banks finance green projects, environmental degradation will slow, regulatory policies will stabilize, and green projects will remain competitive.[3]

Figure 2 shows the responses of key variables. Pollution dynamics decline after the implementation of the policy, which increases the regulation dynamics, and lending shifts from brown to green due to the reduced margins of brown projects. This is a baseline model that presents a discrete choice for banks between green and brown lending. While this framework is informative for the model's setup, it is relaxed under a dynamic equilibrium with portfolio allocation to reflect pragmatic considerations.

[Please insert Figure 2 about here]

3.3. Green monetary policy

Several central banks have introduced a green mandate for their monetary operations (e.g., the European Central Bank and the Bank of England). This shift is characterized by an increase in green asset purchases, the integration of climate-related policies (such as incorporating climate risk into monetary operations), and the introduction of green stress testing for banks. In this context, central banks could adjust the policy rate based on the balance between green and brown lending or implement climate-related regulatory tightening in conjunction with the banking regulator.

To this end, we assume that the central bank minimizes a loss function with respect to output, inflation, and environmental degradation, as follows:

[3] In this setting, we can also introduce policy inertia—delayed or accelerated regulatory initiatives—by affecting γ. We could extend the model further by incorporating social preferences, which would involve modeling the public opinion of households or regulators. Additionally, we could introduce technological innovation, such as green projects becoming more profitable over time. However, as we aim for an initial framework of green banking, we will leave these endeavors for future research.

$$L = \int_0^\infty e^{-\rho t}[\pi(t)^2 + \kappa y(t)^2 + \omega E(t)]dt. \quad (8)$$

In equation 8, $\pi(t)$ is the inflation rate at time t, y is the output gap, and ω is the weight the central bank places on environmental degradation E. In this setting, a greener environment can imply more accommodative monetary policy for green sectors. Thus, the cost of funds $c(t)$ depends endogenously on environmental degradation.

The monetary policy reaction function is:

$$i(t) = i^* + \varphi_\pi \pi(t) + \varphi_y y(t) + \varphi_E E(t), \quad (9)$$

where $\varphi_\pi > 0$, and $\varphi_y < 0$ are the standard responses to inflation and output stabilization. Importantly, $\varphi_E > 0$ implies that more pollution is associated with contractionary monetary policy for the brown lenders and $\varphi_E < 0$ that more pollution is associated with expansionary monetary policy for green lenders.

In the new dynamic feedback, this implies that pollution affects both regulation and the cost of funds via the equation:

$$\boldsymbol{c(t) = i(t) + \varphi}, \quad (10)$$

where φ is a constant bank-specific risk spread. The green and brown margins become:

$$M_G(t) = p_G(R_G - (i(t) + \varphi)) \quad (11)$$

$$M_B(\theta(t), t) = (p_B^0 - \lambda\theta(t))(R_B - (i(t) + \varphi)). \quad (12)$$

Both margins in equations 7 and 8 decrease with contractionary monetary policy (higher monetary policy rates). Thus, the new switching point depends on both regulation and monetary policy:

$$\theta^* = \frac{p_B^0(R_B - (i(t)+\varphi)) - p_G(R_G - (i(t)+\varphi))}{\lambda(R_B - (i(t)+\varphi))}. \quad (13)$$

The most important element of this setting is the potential for green monetary policy as a remedy for the limited funding of green projects. For example, if central banks implement contractionary monetary policy but exclude green projects from this contraction, banks will transition to green loans more quickly when interest rates rise. Therefore, monetary policy can either accelerate or delay the green transition by differentially impacting green versus brown margins.

3.4. Equilibrium

The full dynamic system comprises of equations 1 (firms), 2 (banks), 6 (pollution), 7 (regulation), 9 (policy rate), and 10 (cost of funds), while the banks' lending allocation depends on equations 11 and 12.

The equilibrium is characterized by two cases, where banks finance only brown or only green projects. The first case occurs when $M_B > M_G$. Then, $L_B = \bar{L}$, $L_G = 0$, pollution $E^* = \frac{\alpha_B L}{\delta}$, regulation $\theta^* = \frac{1}{\gamma}\left(\frac{\alpha_B L}{\delta} - \bar{E}\right)$, and interest rate $i^* = i_0 + \varphi_E E^*$ with cost of funds $c = i^* + \varphi$. We can now rewrite the margins as $M_B = (p_B^0 - \lambda\theta^*)(R_B - c)$ and $M_G = p_G(R_G - c)$, implying that as environmental stringency and / or the cost of funds increase, the brown margin decreases potentially crossing below the green margin.

In the second case, the banks finance only green projects, when $M_B < M_G$. Then, $L_G = \bar{L}$, $L_B = 0$, pollution $E^* = \frac{-\alpha_G L}{\delta}$, regulation $\theta^* = \frac{1}{\gamma}\left(\frac{-\alpha_G L}{\delta} - \bar{E}\right)$. Here the regulatory threshold will be very low or negative, so that the success probability of brown projects is high, but the green margin is higher due to low cost of funds. The equilibrium switching point is where $M_B = M_G$, and solving for θ^* we obtain:

$$\theta^* = \frac{1}{\lambda}\left[p_{B0} - p_G \frac{r_G - c}{r_G - c}\right]. \tag{14}$$

4. Dynamic equilibrium with portfolio allocation

4.1. The augmented model

The baseline model discussed in section 2 suggests that banks face a discrete choice between brown and green projects. This scenario can be realistic if regulation or monetary policy abruptly establishes the threshold described by equation 14, causing brown projects to lose their appeal. However, the transition process is typically smooth for several reasons, including transition costs (primarily related to production), slowly changing societal preferences, risks associated with stranded fossil fuel reserves, a lack of green technologies, etc. These factors are well-documented in the environmental economics literature and can be incorporated into our model by augmenting the objectives of firms or regulators, the state of the environment, or household preferences.

Although modeling these factors is beyond the scope of this paper, we can allow for gradual shifts in bank portfolios. This flexibility will enable smooth dynamic paths and steady states—likely more realistic than corner solutions—and provide a better framework for numerical simulation and the study of policy shocks.

We modify equation 2 by letting $\lambda_G = \frac{L_G}{L}$, $\lambda_B = 1 - \lambda_G$ (dropping reference to t for convenience). The objective function of the bank becomes:

$$\max_{\lambda_G} \Pi = L[p_G(R_G - c)\lambda_G + (p_{B0} - \lambda\theta)((R_B - c)(1 - \lambda_G)] \tag{15}$$

Differentiating with respect to λ_G, and setting the derivative to zero yields the interior optimum:

$$p_G(R_G - c) = (p_{B0} - \lambda\theta)((R_B - c). \tag{16}$$

If the left-hand side is larger (smaller) than the right-hand side, the bank increases its green (brown) lending share.

The differential equation for green share is:

$$\frac{d\lambda_G}{dt} = \eta[p_G(R_G - c) - (p_{B0} - \lambda\theta)((R_B - c)], \tag{17}$$

where $\eta > 0$ is the speed of adjustment. This allocation condition gives either an interior solution when the derivative equals zero or corner solutions when the derivative is strongly positive or negative.

The pollution dynamics change to:

$$\frac{dE(t)}{dt} = a_B(1 - \lambda_G)L - a_G\lambda_G L - \delta E(t). \tag{18}$$

In contrast, the regulation dynamics, the monetary policy rule and the cost of funds remain as in section 2. This model provides a unique stable equilibrium as long as $M_G \neq M_B$.

While this model allows for analytical solutions under certain steady-state conditions and threshold relationships (for example, when green lending becomes more profitable than brown), the full dynamic system of portfolio allocation and pollution feedback is non-linear and path-dependent. This complexity arises from the endogenous feedback between lending allocations, pollution, and policy responses, which means there is no analytical solution for the time paths of θ, E, and output. Therefore, we rely on numerical simulations to explore the dynamic transition paths, the effects of policy shifts, and the stability properties of the system under different parameter configurations.

4.2. Policy changes

In this section, we analyze the effects of policy changes on bank lending, firm output, and the environment.[4] We first introduce changes in the central bank response to pollution φ_E (from 0.5 to 2), and the speed of regulation tightening γ as pollution deviates from its target $\bar{E}$ (from 0.1 to 1). This means a significant increase in the reaction speed of monetary and regulatory policies to an increase in pollution, raising the cost of funds and increasing the riskiness of brown projects. The

[4] We provide Python code in Appendix A.1.

rest of the parameters are set as follows: $R_G = 0.04$, $R_B = 0.05$ (so that brown project returns are higher), $p_G = 0.95$, $p_{B0} = 0.98$ (so that the initial success probability of brown projects is higher), $p_B(\theta) = p_{B0} - \lambda\theta$, $i^* = 0.03$, $\varphi = 0.01$, $\alpha_B = 0.04$, $\alpha_G = -0.01$, $\delta = 0.02$, $L = 1$, $\eta = 1.5$, $\lambda_G = 0.5$, $E = 1$,, and $\theta = 0.1$.

We draw on these parameters from several different studies. We set the bank's speed of adjustment parameter η = 1.5 to reflect a moderately responsive yet realistic reallocation of credit portfolios in the face of profit differentials between green and brown projects. This choice is broadly consistent with estimates found in the investment adjustment literature, such as van der Ploeg and Rezai (2020), who calibrate adjustment parameters for capital reallocation in climate-economy models.[5] For the sensitivity of environmental regulation γ, we use calibrated values from Acemoglu et al. (2012) and NGFS (2024). For the pollution intensities, we use empirical findings of Battiston et al. (2017) and Monasterolo and Ramberto (2018), which suggest an approximately 4:1 benefit of green projects over brown projects (fossil fuels often emit ~0.5–1.5 tons CO_2 per \$1,000 invested, while renewable investments can reduce emissions by ~0.2–0.4 tons CO_2 per \$1,000 over time). For the natural decay rate of pollution, we use model estimations from Bovenberg and Smulders (1995) and Hoel (1992). For the sensitivity of central bank policy, we use theoretical values derived from Batten et al. (2020) and Dafermos et al. (2018). For the risk sensitivity of brown projects to regulation, we use empiric findings by Delis et al. (2024) and Bingler et al. (2021).[6]

[5] Furthermore, empirical studies like Degryse and Nguyen (2007) and Altavilla et al. (2023) document that banks adjust lending in response to credit risk and policy signals with moderate inertia, supporting the plausibility of this value. Our selection thus balances empirical realism with model tractability.

[6] In Appendix A.3, we provide several robustness tests on these parameter values, including different values for γ, ω, α_B, α_G, and η.

Figure 3 shows the green and brown lending shares over time, illustrating the impact of changes in monetary and regulatory policies. The key insight is that the initial preference for brown lending, driven by higher returns and success probabilities, diminishes following strong policy tightening, leading banks to gradually reallocate towards green projects. Notably, both policy changes must be significant; otherwise, green shares will not surpass brown shares. This observation aligns with real-world scenarios, where regulatory initiatives can be ineffective if the cost of brown funds remains low (e.g., Antoniou et al., 2025).[7] In Appendix Figure A1, we

[Please insert Figure 3 about here]

Given the above, the main proposition of our model is that green financing requires both price signals via interest rates and non-price regulation via risk weight. This implies a critical joint threshold, $\theta > \theta^*(c)$, where the transition occurs only if $\theta \uparrow$ rapidly (high γ) and $c \uparrow$ rapidly (high φ_E). Our proposition conveys a strong policy implication. Specifically, monetary policy should internalize environmental degradation by linking pollution to the cost of capital, while regulatory policy should reduce the risk-adjusted return of brown lending through speedy and forward-looking tightening.

5. Extensions

5.1. Endogenous returns

To study the transition dynamics of bank lending, we have assumed that the initial returns of green projects R_G are lower than those of brown projects R_B. This essentially implies that firm output will be lower in the future. Even though it is not our objective to study output in this model, a straightforward adjustment would be to indirectly add technological change so that R_G will

[7] For example, with the specific values of our parameters, we need $\varphi_E \geq 1$ to 2, $\gamma \geq 0.5$ to 1, $\lambda \geq 0.05$.

increase over time. Another framework can be that brown returns fall over time due to carbon pricing, stranded asset risk, regulation, etc.

One way to incorporate this into our model would be to endogenize returns, so that brown returns decline with tightening regulation or monetary policy. Alternatively, green returns can increase with innovation or economies of scale. For example, we can let net output (accounting for the external cost of pollution) be $Y_A(t) = Y(t) - wE(t)$, where $w > 0$ penalizes the economic cost of pollution. This setting produces a similar loan portfolio allocation, but allows for higher output with lower pollution (Figure 4).[8]

[Please insert Figure 4 about here]

5.2. Central banks with an explicit green objective

Despite ongoing discussions among central banks and academics (e.g., Giovanardi et al., 2023), monetary policy has yet to consider differential interest rates based on project type (e.g., preferential rates for green bonds). However, our model can be adjusted to incorporate such policy initiatives by introducing differential interest rates for green and brown projects. In this way, central banks could offer preferential rates for green loans (e.g., through targeted long-term refinancing operations).[9] We view this as a key extension of our model in section 4.

One way to update our framework is to introduce differential cost of funds by project type:

$$c_G = i + \varphi_G,\ c_B = i + \varphi_B, \tag{19}$$

[8] In this setting, one could calibrate w using data from the shadow price of carbon or endogenize it to analyze damage functions.

[9] The ECB has discussed this idea several times (e.g., van 't Klooster and van Lerven, 2020; NGFS, 2021). Other central banks in Asia (mostly in China and Bangladesh) implement "green credit guidance." See also Dafermos et al. (2020).

where i is the policy rate and $\varphi_G < \varphi_B$ are the additional refinancing costs (or discounts) for green and brown lending.[10] This setting changes the bank profit function, and thus the profit margins become:

$$M_G = p_G(R_G - c_G), \tag{20}$$

$$M_B = (p_B^0 - \lambda\theta)(R_B - c_B). \tag{21}$$

Using the same parameters as in section 3, the portfolio allocation will follow a similar path, with the green lending share expanding somewhat more quickly due to the faster rising cost of funds for brown projects. In general, this setting will enhance the strength of the impact of monetary policy on green lending shares (e.g., compared to the analysis of Figure A1). We revisit this issue when analyzing persistent changes in monetary policy regimes in section 6.

5.3. Forward-looking bank behavior

In our baseline model, banks decide on lending shares based on current expected margins. Alternatively, we could assume that banks are forward-looking by optimizing the intertemporal value of profits while accounting for future regulation and pollution levels. This implies that banks can tolerate short-run losses in brown versus green lending if green projects are expected to dominate later. This scenario is particularly interesting for projects with longer maturities. However, an argument against such an approach is that loan maturities average approximately 4 to 5 years, as shown by studies using syndicated loan data (e.g., Delis et al., 2024). During these periods, slowly changing environmental risks do not significantly impact bank behavior. This is why we do not model forward-looking bank behavior in our benchmark model.

[10] An alternative is to allow the interest rate i to also differ by project type. This would not introduce material differences in our findings.

There can be several ways to introduce forward-looking banks in our model. One way would be via dynamic optimization where banks maximize:

$$\max_{\lambda_G} \int_0^\infty e^{-\rho t}\, \Pi(\lambda_G, E, \theta, c)\, dt, \tag{22}$$

subject to the dynamic laws of motion for the environment and regulation and where ρ is the discount rate. This could be implemented via a simple approximation (adding an expectation term for $\frac{d\lambda_G}{dt}$ or via full dynamic programming (set up of a Hamiltonian system).[11]

Figure 5 reports the refined simulation results based on a one-period margin forecast. As expected, there is a quicker and earlier increase in the green lending share due to proactive bank behavior. This is accompanied by higher net output and lower pollution. If one assumes even more forward-looking bank behavior or full dynamic programming, the transition period will be even shorter.

[Please insert Figure 5 about here]

5.4. Adjustment costs

In our baseline model, we assume that banks can automatically differentiate between green and brown credit without incurring adjustment costs. We maintain this assumption because most banks in developed countries, as well as several in developing countries, have acquired the expertise necessary for risk management and understanding sector-specific constraints. However, introducing adjustment costs may still be important, particularly for financing new technologies and large-scale green transition endeavors.

[11] Another, more involved, way would be to use a rational expectations framework, where banks anticipate future paths of pollution, regulation, and even cost of funds.

Perhaps the simplest way to introduce adjustment costs is via a friction coefficient κ in the differential equation for green share:

$$\frac{d\lambda_G}{dt} = \frac{\eta}{1+\kappa}(M_G - M_B). \tag{23}$$

In this framework, the green lending share adjusts more gradually, but also more slowly, over time. Net output and pollution exhibit a similar pattern of adjustment.

6. Persistent regime changes

An important characteristic of our model is that it allows to study persistent regime changes. The key reason for this is that policy transitions are usually maintained for several years and have long-lasting effects. Consistent with our previous analysis, these may include new climate laws and potential changes in central banks' mandates to incorporate environmental monetary policy. In turn, these policy transitions help explain nonlinear or delayed responses in financial markets.

Assuming that regime changes are discrete, there are at least two ways to study them in our setup. The first method involves introducing regime switches in parameters. The second method models endogenous triggers using an environmental crisis threshold. We opt for the first approach to examine the impact of regime changes in either regulatory or monetary policy, or both, in a simpler yet still parsimonious manner.[12]

A regulatory regime change implies a discrete shift in the regulation parameter γ, to determine a potentially faster and stronger environmental regulation. The regulation dynamics change to:

$$\gamma = \begin{cases} \gamma_1 \; if \; t < T_{switch} \\ \gamma_2 \text{ if } t \geq T_{switch} \end{cases}. \tag{24}$$

[12] If we assume that regime changes are gradual, a similar setup can be achieved using a sigmoid function and a parameter indicating the speed of transition.

Similarly, a monetary policy regime change can be introduced via:

$$\varphi_E = \begin{cases} \varphi_E^{low} \; if \; t < T_{switch} \\ \varphi_E^{high} \text{ if } t \geq T_{switch} \end{cases}. \tag{25}$$

The rest of the equations remain largely similar to our baseline model.

We proceed by simulating the new model to produce the graphs in Figure 6 (we provide the code in Appendix A.4). In these graphs, we compare the responses to a regulatory regime change at time t = 10 with those to monetary policy regime changes at the same time. We find that a change in the regulatory regime triggers a faster and steeper increase in the green lending share after t = 10, while the change in the monetary policy regime results in a more modest and gradual increase. Similar results are observed for net output and pollution. Therefore, our model predicts that the impact of regulation on brown project risk is stronger than the cost differential created by the shift in the monetary regime, although the two are complementary.

[Please insert Figure 6 about here]

A key reason for this result is that in our baseline model, the monetary channel operates through the cost of funds, which indirectly affects margins via interest rates. Therefore, unless monetary policy imposes differential spreads, as discussed in section 4.2, it will likely produce smaller changes in green lending shares, unless one is willing to assume very large changes in φ_E. We illustrate this point in Figures 7 and 8, where we use a model in which central banks have an explicit green objective and simulate synchronized regime shifts at time t = 10. We compare the magnitude of the change in φ_E against the magnitude of the change in γ. The blue dashed line represents the effect of the monetary regime shift on the green lending share, while the green line represents the equivalent effect of the regulatory regime shift. The former is considerably stronger in this case, highlighting the importance of central banks having a green objective for achieving a swift and substantial increase in green lending shares.[13] Figure 8 further corroborates this finding by showing the response of the green lending share to a regime shift in monetary policy within (i) the model of central banks with an explicit green objective (blue line) and (ii) the model of central banks with uniform policy against green and brown loans (black dashed line).

[Please insert Figure 7 about here]

This comparison highlights that both regulatory and monetary tools can stimulate green lending, though their effectiveness varies in magnitude. In our model, the regulatory change (γ increase) had a larger impact per unit of intervention than the initial monetary change. This supports the idea that adjustments to capital requirements (such as a Green Supporting Factor) directly influence banks' balance sheet constraints, strongly incentivizing the reallocation of credit toward green projects. While monetary policy incentives (like cheaper funding for green loans) are directionally effective, they may need to be substantial and explicit to have a significant impact on green lending shares and pollution. It is also important to note that these policy changes could have side effects and implementation limits. For instance, significant monetary accommodation for green lending could raise concerns about market distortion or inflation, while overly strict regulation might impact bank profitability or the credit supply to other sectors.

7. Conclusions

This paper develops a theoretical framework to study the interaction between climate policy and financial decision-making, focusing on how banks allocate credit between green and brown projects. The analysis begins with a simple model where banks maximize profits by choosing between green and brown lending opportunities, influenced by endogenous regulation and

[13] This would have been the case even with milder monetary regime shifts.

monetary policy. In this setting, regulators respond to environmental degradation by tightening policies, and central banks adopt a green-sensitive monetary stance. This baseline model illustrates the fundamental trade-offs and channels through which policy can influence financial flows and environmental outcomes.

Building on this foundation, the paper introduces a dynamic model of credit portfolio allocation that serves as the benchmark for our subsequent analysis. In this richer framework, banks gradually reallocate credit in response to evolving policy signals and relative profit margins, subject to behavioral frictions. This structure allows for a more realistic and forward-looking characterization of the transition to green finance. Policy changes, both regulatory and monetary, significantly influence lending patterns and pollution dynamics. The benchmark model demonstrates how even modest policy shifts can meaningfully alter the trajectory of the financial system and environmental quality, especially when anticipated and sustained.

A series of model extensions add further depth and realism. First, project returns are allowed to evolve endogenously with environmental and policy conditions, capturing the emergence of stranded assets and the dynamic benefits of green investment. Second, the central bank is endowed with an explicit green mandate, enabling it to tilt funding costs in favor of clean projects. Third, banks are modeled as forward-looking agents who internalize future regulatory and environmental conditions, thereby accelerating the transition. Fourth, adjustment costs are introduced to reflect the inertia and frictions banks face when rebalancing their portfolios. These extensions provide a more nuanced view of policy transmission and highlight the importance of expectation management and institutional constraints.

Finally, the paper investigates persistent regime changes in the benchmark model. By comparing regulatory regime shifts to monetary policy regime shifts, the analysis shows that regulatory policy is generally more powerful in shifting bank behavior—primarily due to its direct effect on project viability. However, when the central bank has an explicit and strong green objective (modeled as a persistent increase in the green policy parameter), monetary policy can match or even exceed the regulatory impact. This finding underscores the strategic potential of central banks in supporting the green transition, especially when regulation is politically constrained or slow-moving.

Overall, the paper provides an analytically tractable framework for understanding how coordinated financial policies can drive green investment and reduce pollution. It shows that the effectiveness of policy depends not only on its type (regulatory vs. monetary) but also on its intensity, persistence, and credibility. The results highlight the importance of dynamic behavior and institutional design in shaping the success of green financial policies. As policymakers consider how to align the financial system with climate goals, these findings offer valuable guidance on sequencing, complementarity, and the calibration of regulatory and monetary interventions. An obvious extension is to include welfare implications, heterogeneous banks (i.e., with a green objective or not), and heterogeneous countries; we leave these as a desideratum for future research.

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Figure 1. Bank lending margins

The figure shows the bank lending margins for green and brown projects against the level of regulatory stringency in the most basic green lending model presented in section 3.

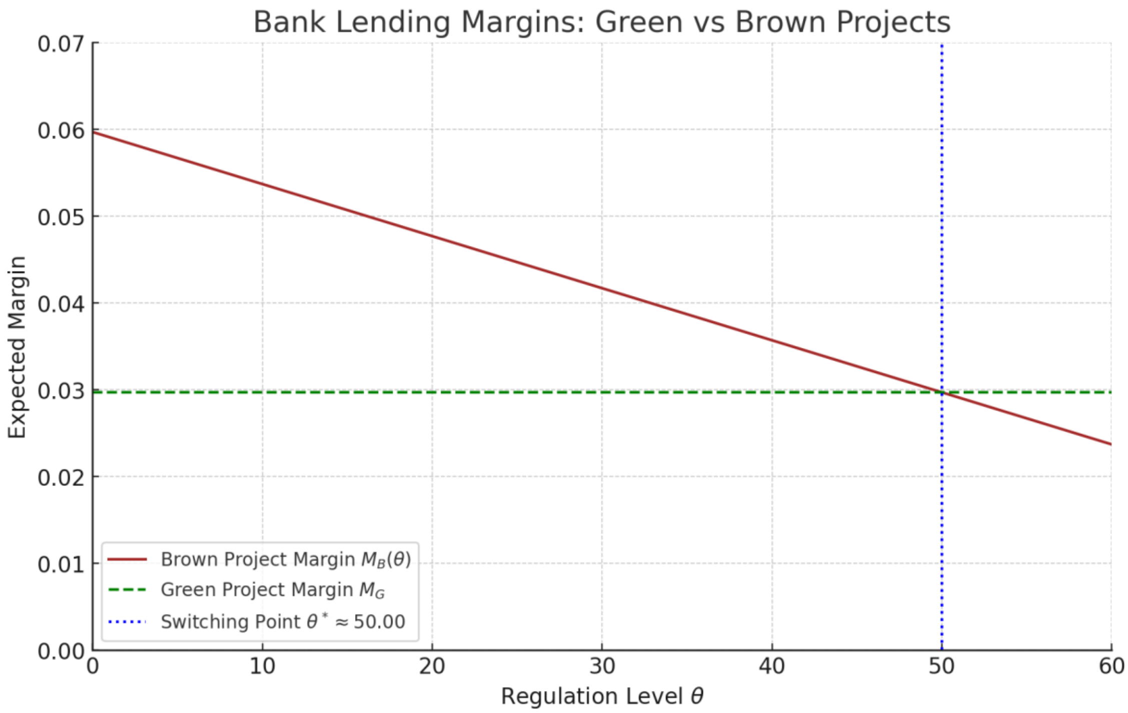


Figure 2. Dynamic responses

The figure 2 shows the dynamic responses to the regulatory policy of pollution, regulation, lending composition and project margins. The responses are obtained from the most basic model presented in section 3.

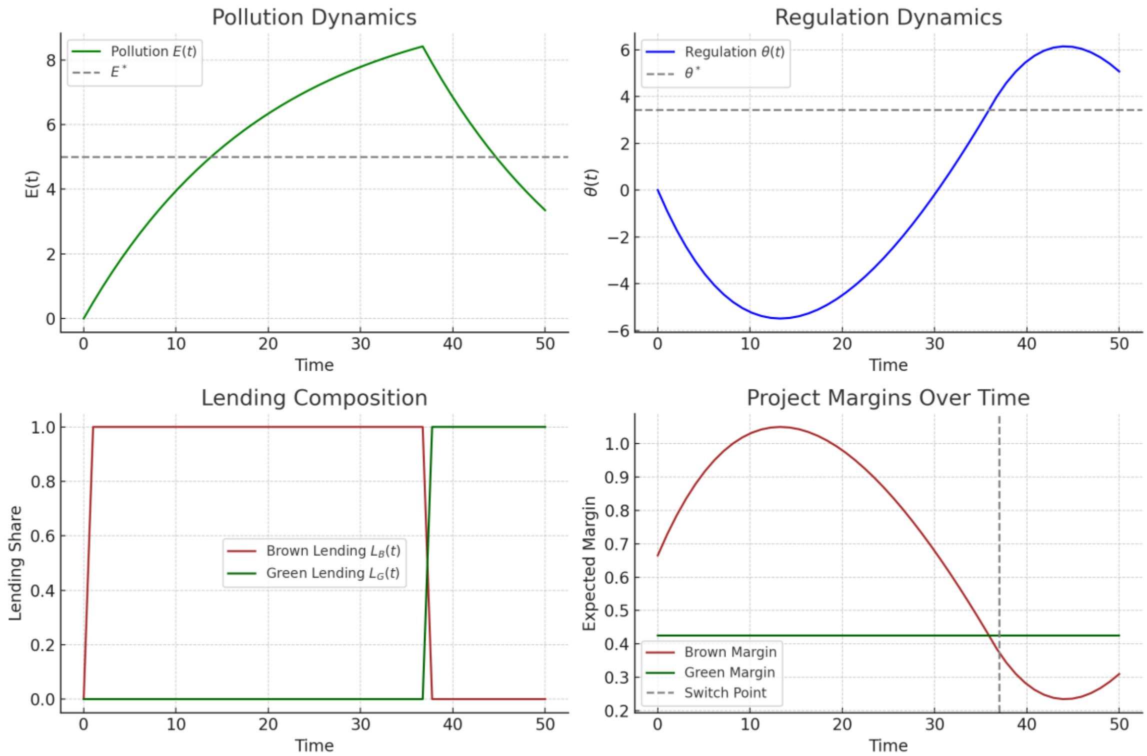


Figure 3. Bank lending shares following changes in monetary and regulatory policies

The figure shows the time paths for the green and brown lending shares from the benchmark dynamic equilibrium with portfolio allocation (presented in section 4), following changes in monetary and regulatory policies. The parameter values are provided in section 4.2.

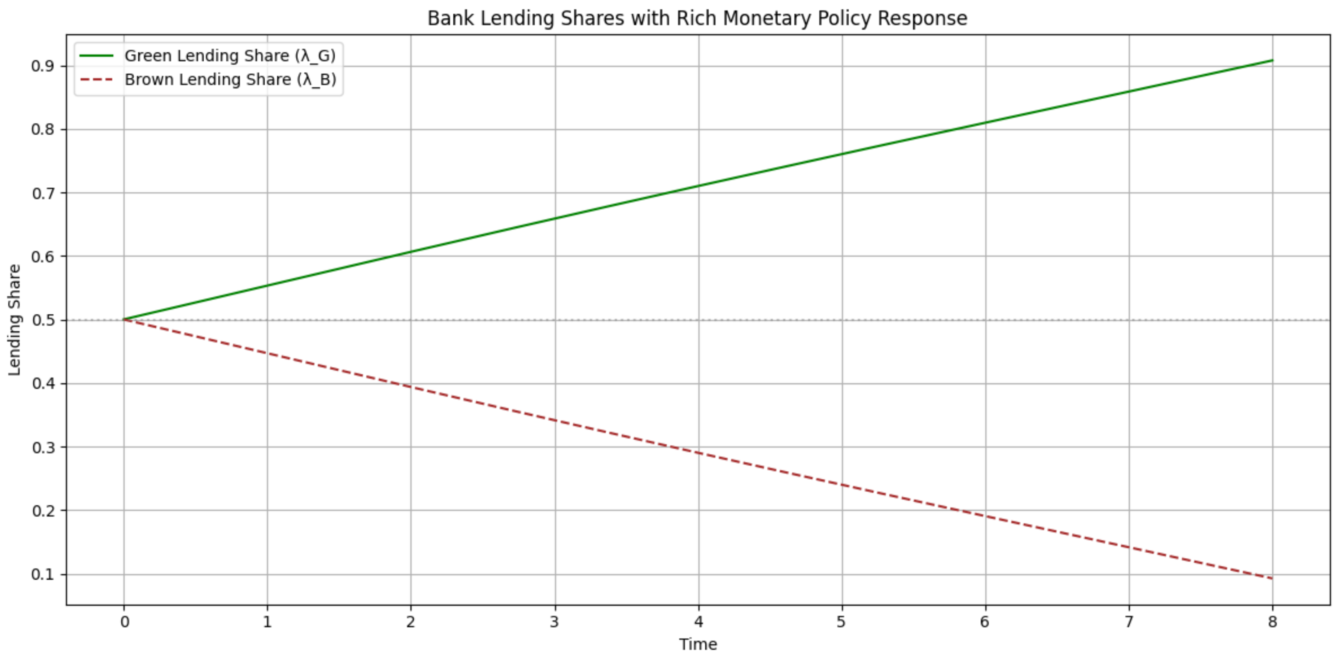


Figure 4. Endogenous returns leading to higher future firm output

The figures show the time paths for green and brown lending shares, net firm output, and pollution levels from the dynamic equilibrium with portfolio allocation and endogenous returns (presented in section 5.1), following changes in monetary and regulatory policies (as in Figure 3).

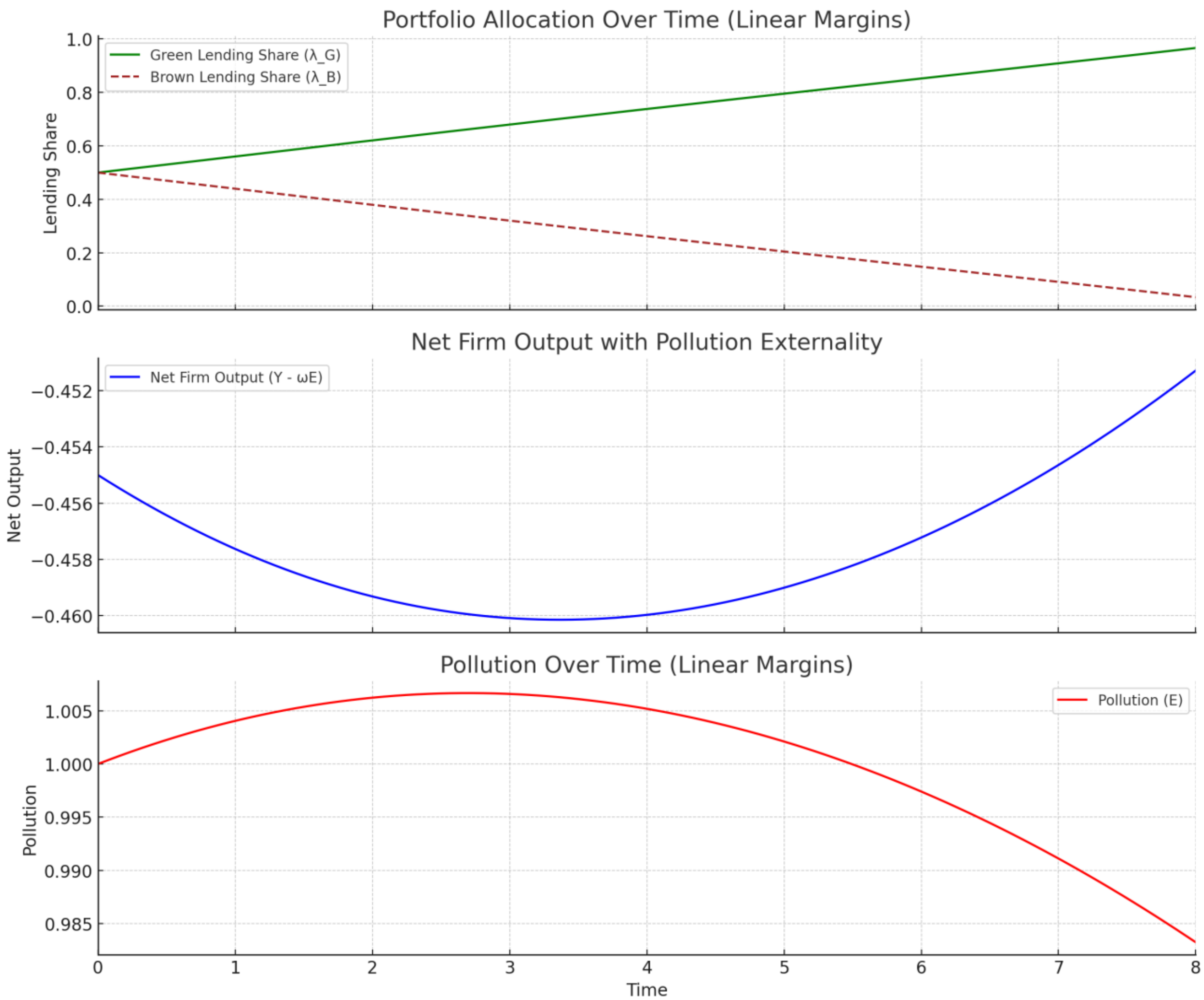


Figure 5. Forward-looking bank behavior

The figures show the time paths for the green lending shares, net firm output, and pollution levels from the dynamic equilibrium with portfolio allocation and forward-looking bank behavior (presented in section 5.3), following changes in monetary and regulatory policies (as in Figure 3).

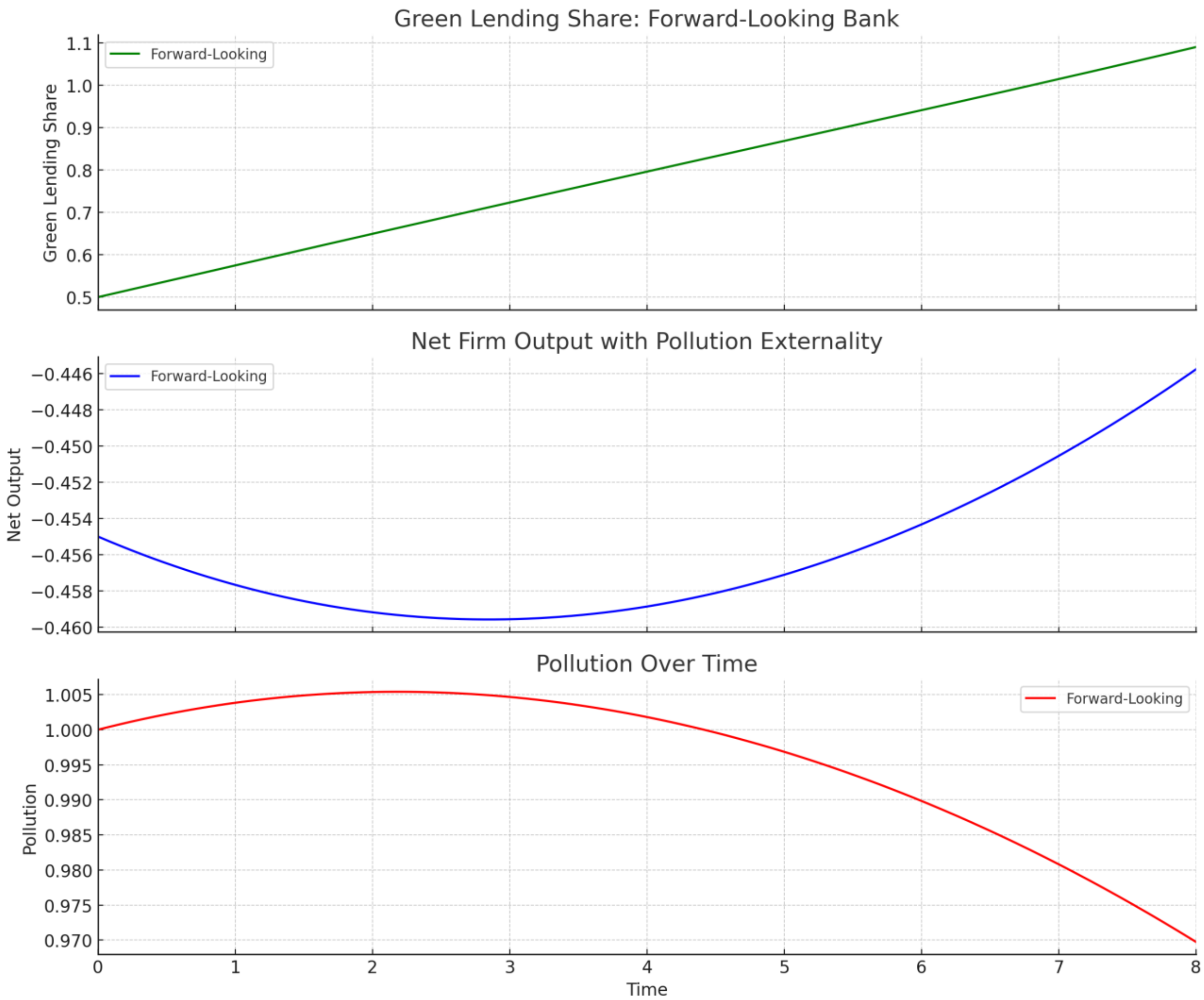


Figure 6. Regulatory policy vs. monetary policy regime changes

The figures show the time paths for green lending shares, net firm output, and pollution levels from the dynamic equilibrium with portfolio allocation under regulatory vs. monetary policy regime changes (presented in section 6). The regime changes take place at t = 10.

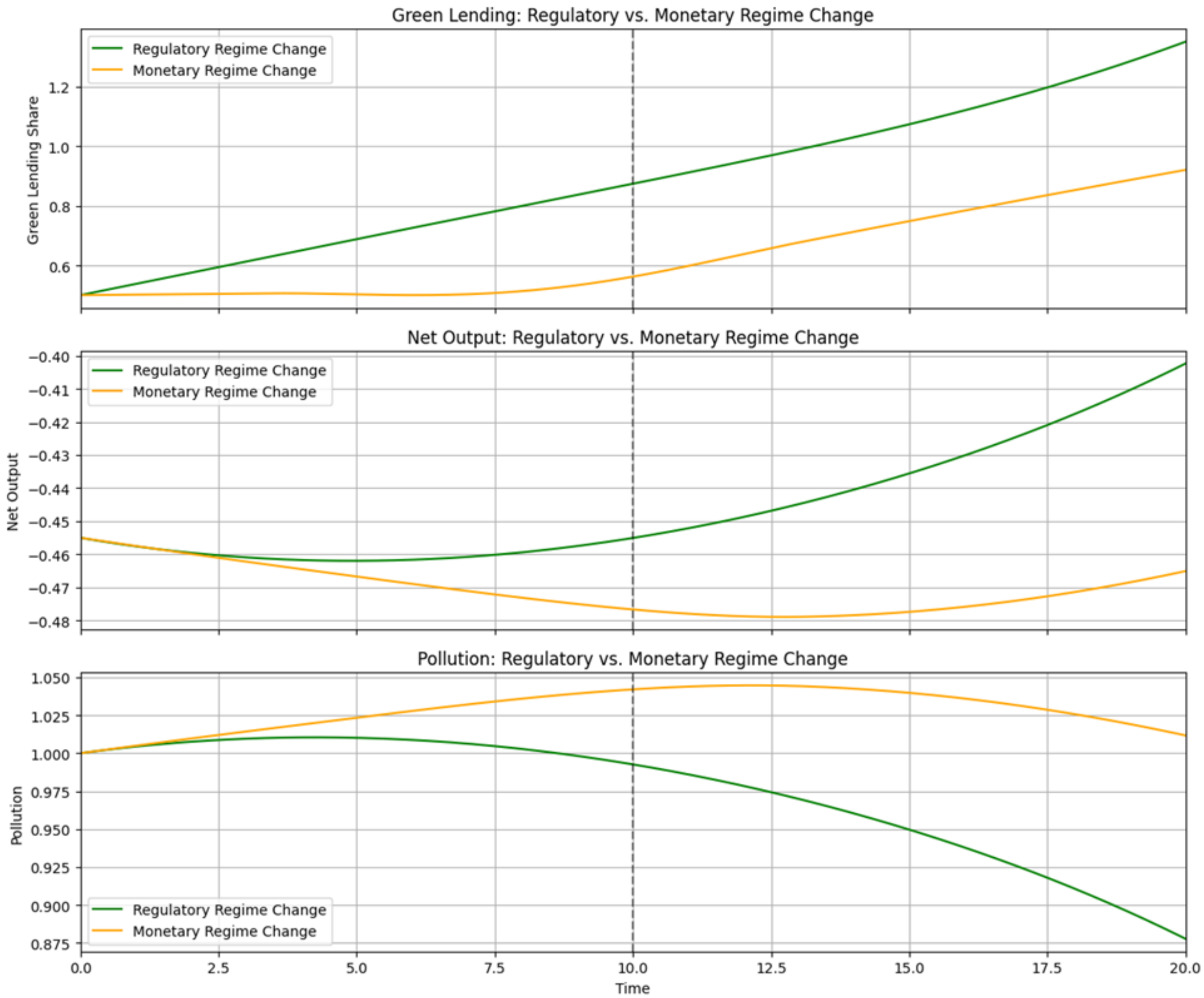


Figure 7. Regime shifts in regulatory and monetary policy for central banks with a green objective

The figure shows two different scenarios for regime shifts, one for the regulatory regime shift (green line) and one for the monetary regime shift (blue line), within the model of central banks with an explicit green objective.

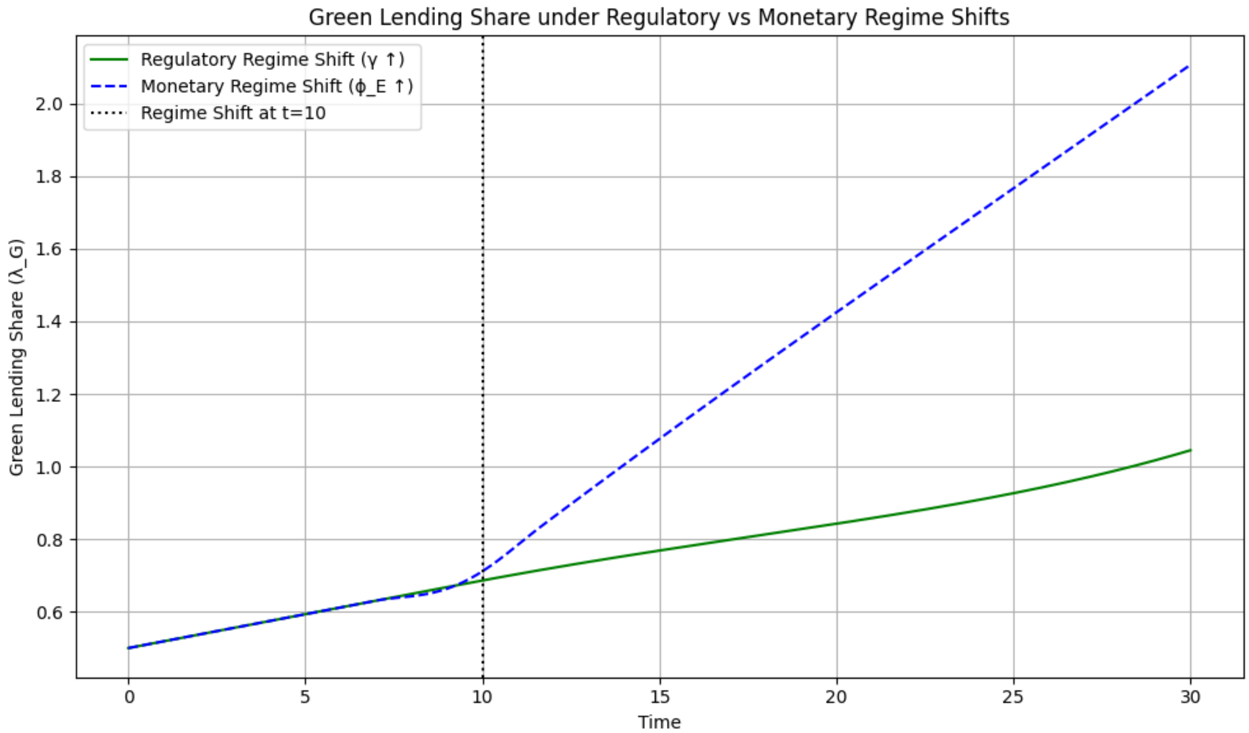
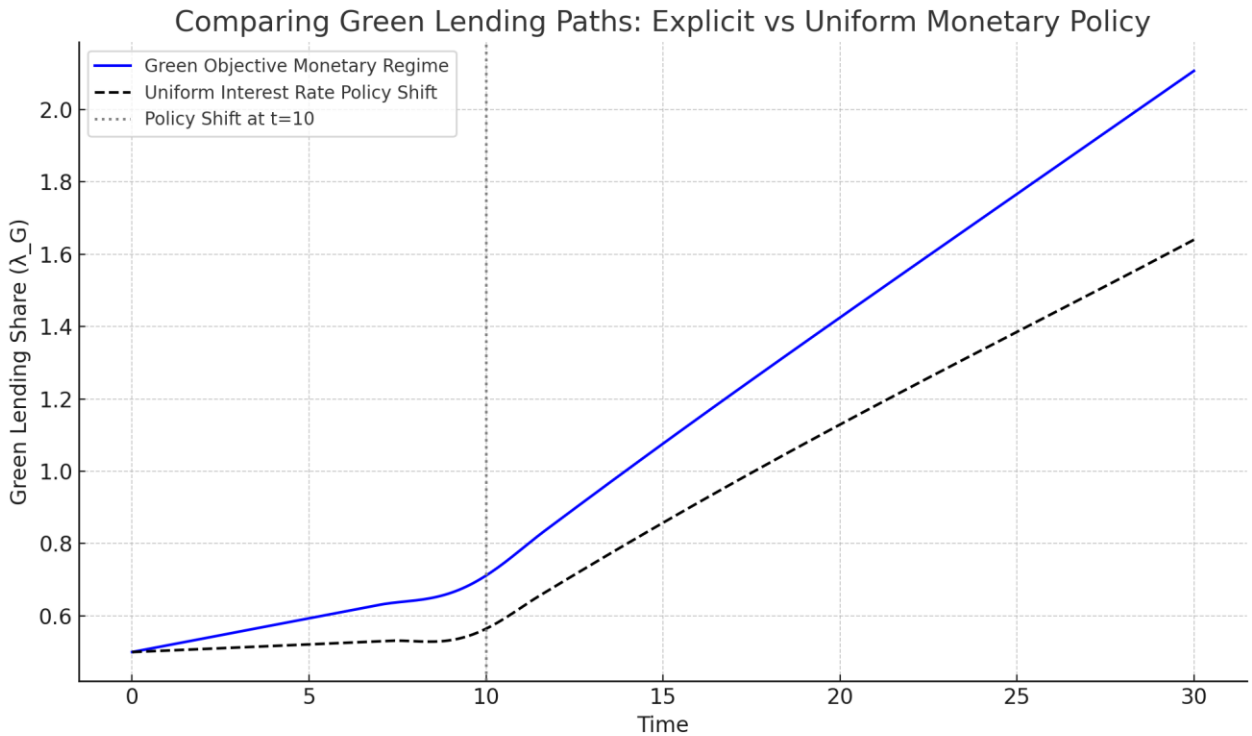


Figure 8. Regime shifts in monetary policy for central banks with explicit vs. uniform monetary policy

The figure shows two different scenarios for regime shifts, one for the monetary regime shift within the model of central banks with an explicit green objective (blue line) and one for the monetary regime shift within the model of central banks with uniform policy against green and brown loans (black dashed line).



Green Lending

Online Appendix

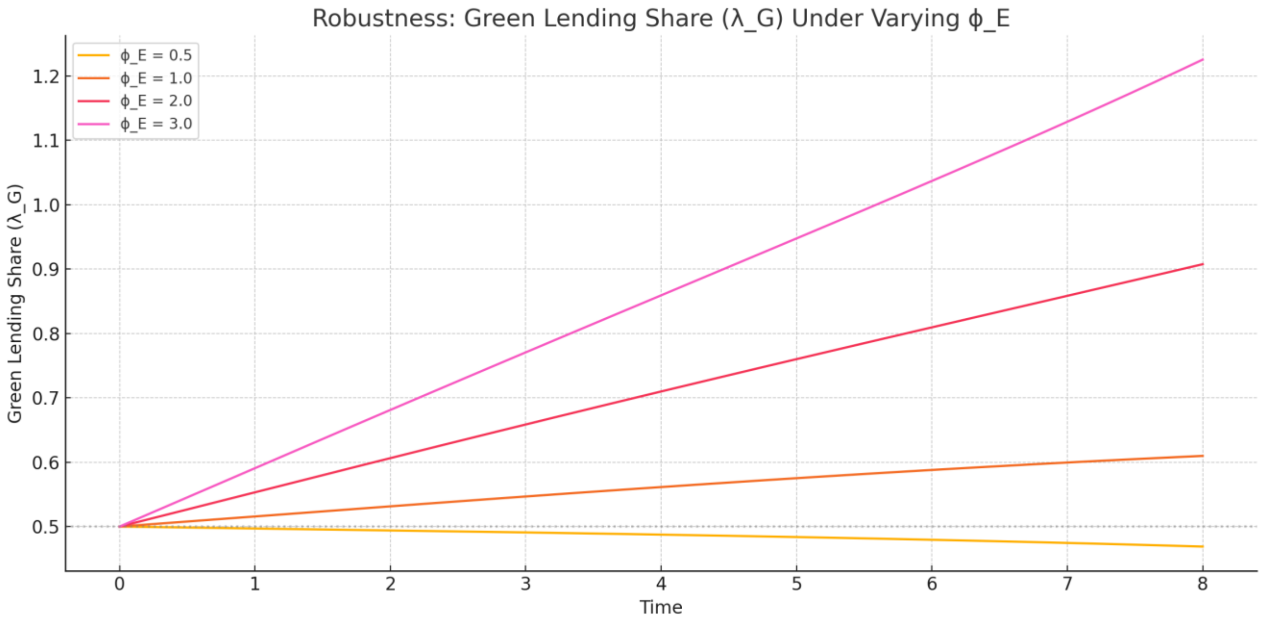
In this online appendix, we provide Python code for several of the models presented in the paper and robustness tests.

A.1. Code for simulations of the dynamic model

```
# Re-import libraries due to kernel reset
import numpy as np
import matplotlib.pyplot as plt
from scipy.integrate import solve_ivp

# Parameters
p_G = 0.95
p_B0 = 0.98
lambda_reg = 0.05
r_G = 0.04
r_B = 0.05
i_star = 0.03
phi_pi = 0.5     # Central bank response to inflation
phi_y = -0.2     # Central bank response to output
phi_E = 2.0      # Central bank response to pollution
phi = 0.01       # Risk spread
L = 1.0
alpha_B = 0.04
alpha_G = -0.01
delta = 0.02
gamma = 1.0
bar_E = 1.0
eta = 1.5

# Constant inflation and output values for simulation
pi_const = 0.02
y_const = 1.0

# Time span and initial conditions
t_span = (0, 8)
t_eval = np.linspace(*t_span, 300)
y0 = [0.5, 1.0, 0.1]  # [lambda_G, E, theta]

# Define system with richer monetary rule
def system_monetary_regulation(t, y):
    lambda_G, E, theta = y
    i = i_star + phi_pi * pi_const + phi_y * y_const + phi_E * E
    c = i + phi

    p_B = p_B0 - lambda_reg * theta
    d_lambda_G = eta * (p_G * (r_G - c) - p_B * (r_B - c))
    dE = alpha_B * (1 - lambda_G) * L - alpha_G * lambda_G * L - delta * E
    dtheta = gamma * (E - bar_E)
```

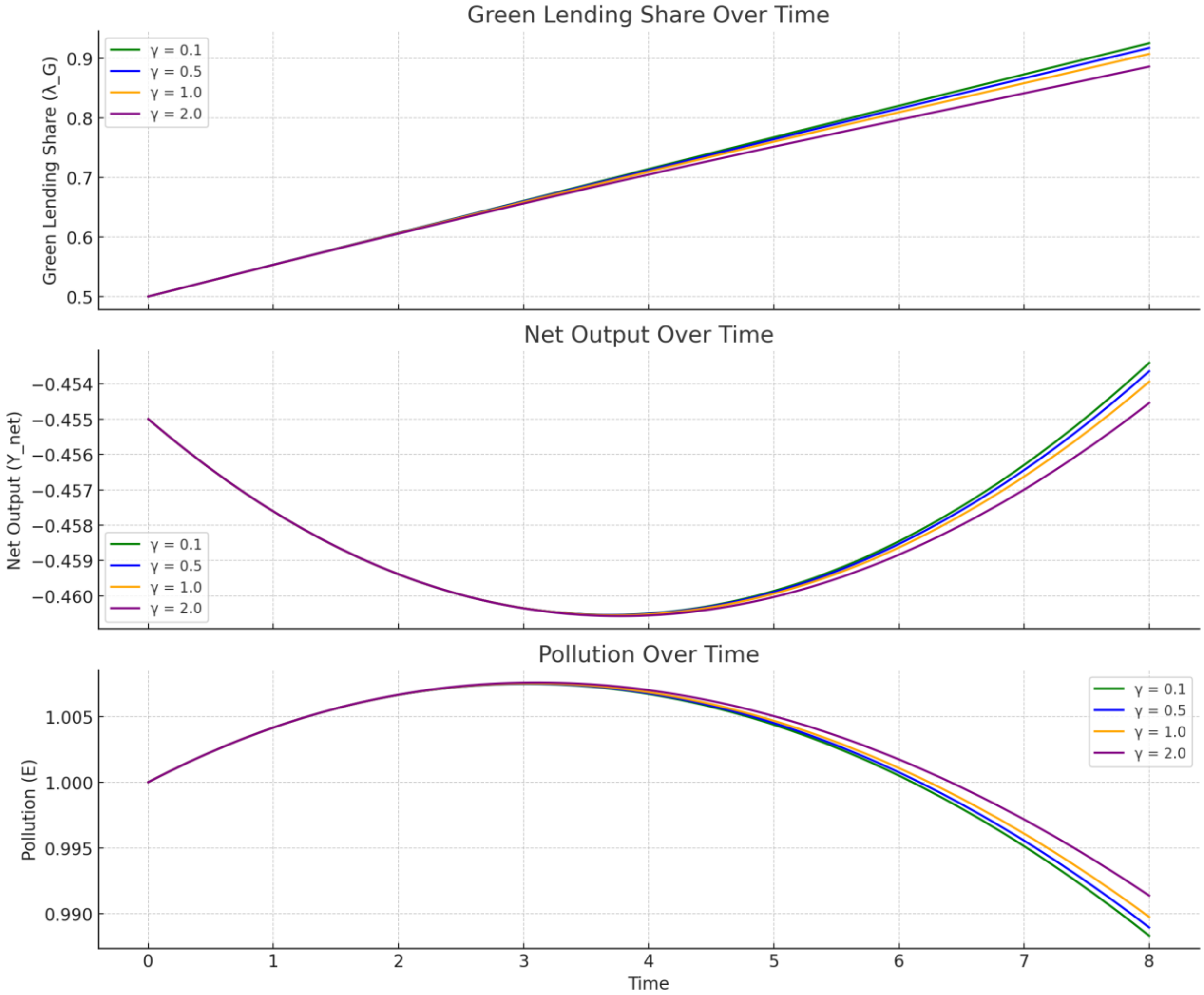
```
    return [d_lambda_G, dE, dtheta]

# Solve the system
sol = solve_ivp(system_monetary_regulation, t_span, y0, t_eval=t_eval)

# Plot the results
plt.figure(figsize=(12, 6))
plt.plot(sol.t, sol.y[0], label='Green Lending Share (λ_G)', color='green')
plt.plot(sol.t, 1 - sol.y[0], label='Brown Lending Share (λ_B)', color='brown', linestyle='--')
plt.axhline(0.5, color='gray', linestyle=':', alpha=0.5)
plt.title('Bank Lending Shares with Rich Monetary Policy Response')
plt.xlabel('Time')
plt.ylabel('Lending Share')
plt.legend()
plt.grid(True)
plt.tight_layout()
plt.show()
```

A.2. Different monetary policy shocks

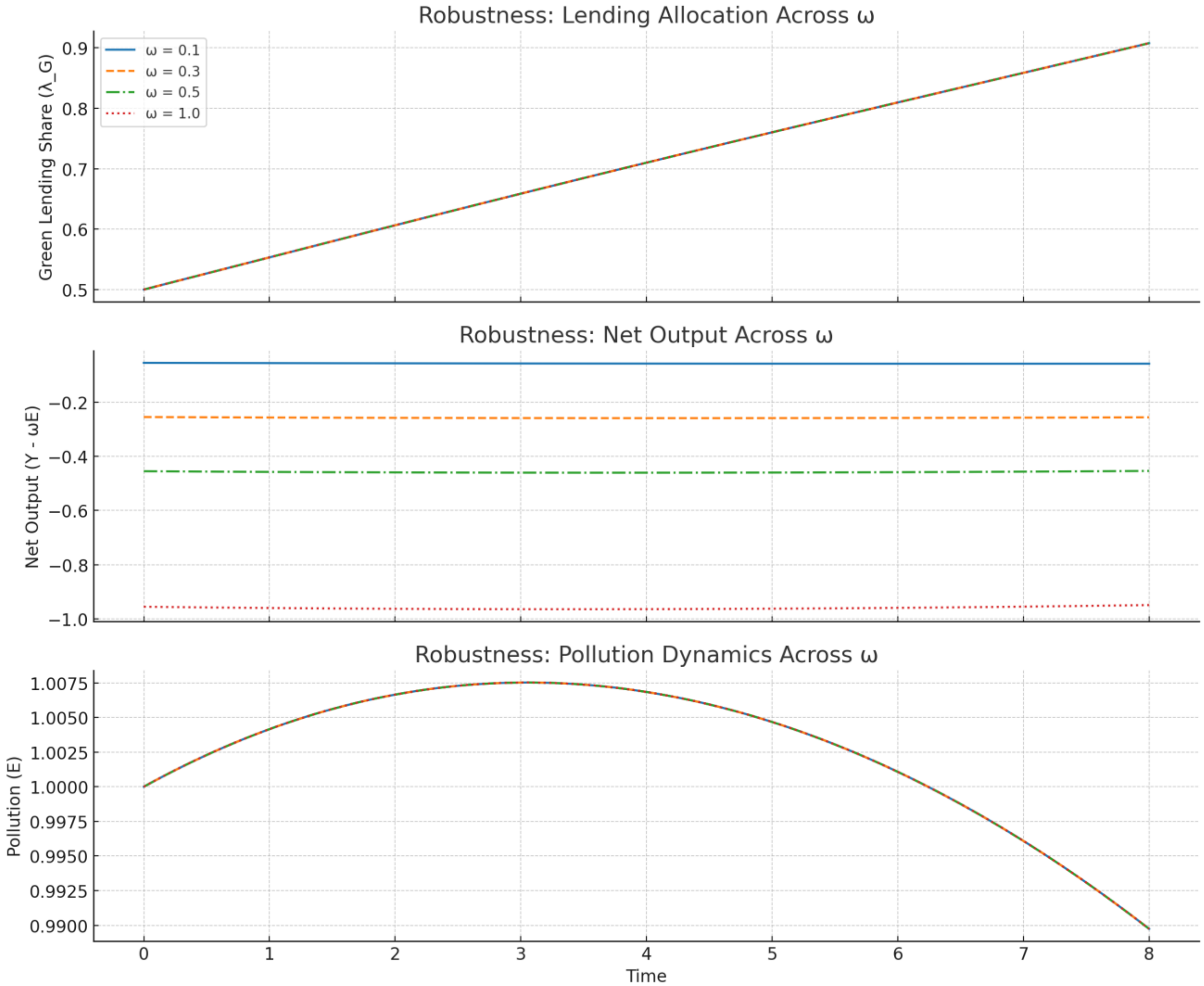


A.3. Different parameter estimates

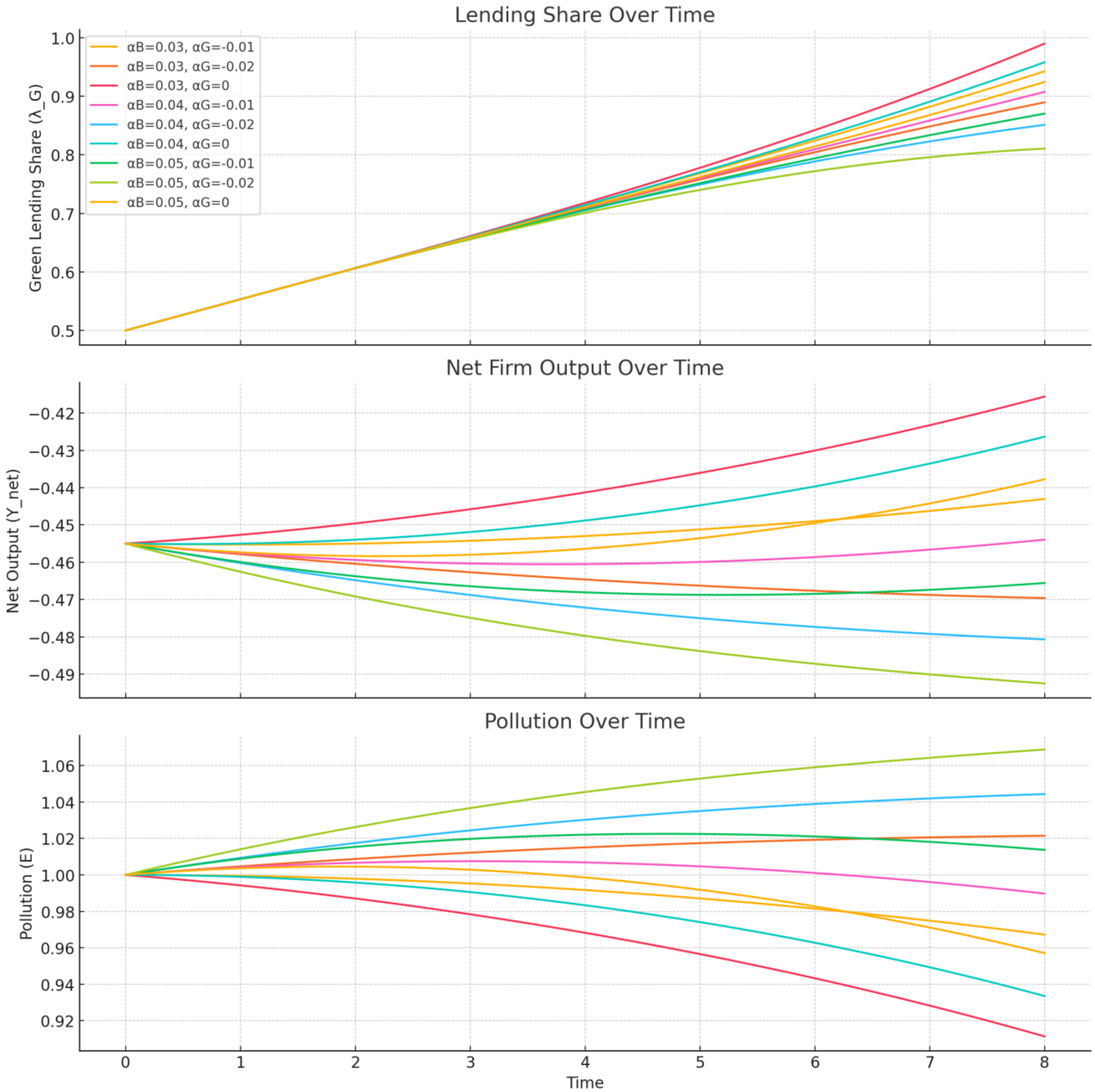
Robustness for γ



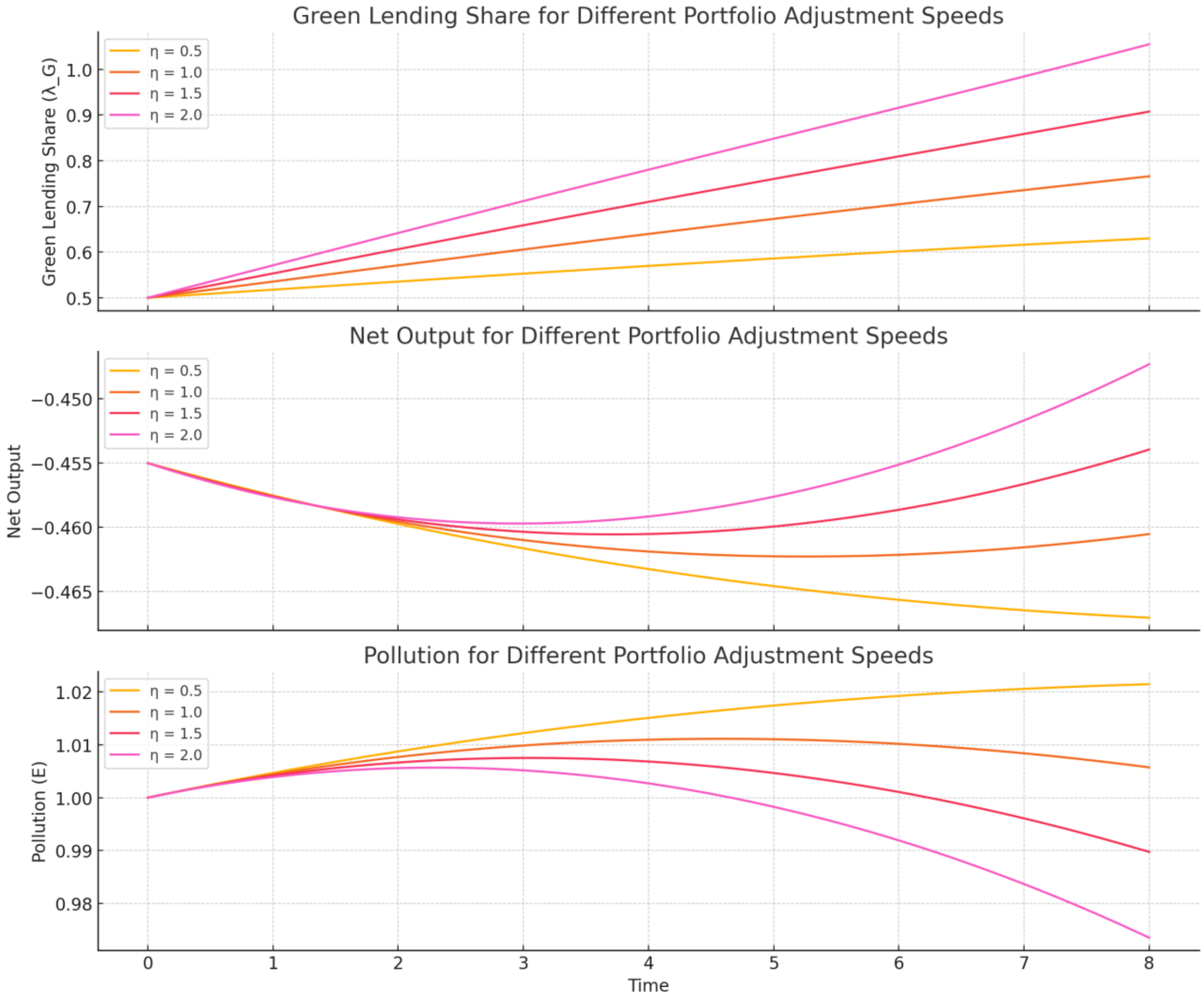
Robustness for ω



Robustness for α_B, α_G



Robustness test on η



A.4. Regulatory regime changes

```
# Re-import necessary libraries and redefine all parameters after reset
import numpy as np
import matplotlib.pyplot as plt
from scipy.integrate import solve_ivp

# Parameters
p_G = 0.95
p_B0 = 0.98
r_G = 0.04
r_B = 0.05
i_star = 0.03
phi_E_strong = 2.0
phi_G = 0.005
phi_B = 0.015
lambda_reg = 0.05
eta = 1.5
kappa = 1.0
alpha_B = 0.04
alpha_G = -0.01
delta = 0.02
gamma_1 = 0.1
gamma_2 = 1.0
bar_E = 1.0
omega = 0.5
L = 1.0

# Time span and initial conditions
t_span = (0, 20)
t_eval = np.linspace(*t_span, 300)
y0 = [0.5, 1.0, 0.1]  # initial [lambda_G, E, theta]
T_switch = 10  # time of regime change

# Define system with discrete regime change in regulation responsiveness
def system_regime_change(t, y):
    lambda_G, E, theta = y

    i = i_star + phi_E_strong * E
    c_G = i + phi_G
    c_B = i + phi_B

    M_G = p_G * (r_G - c_G)
    p_B = p_B0 - lambda_reg * theta
    M_B = p_B * (r_B - c_B)
```

```
    d_lambda_G = (eta / (1 + kappa)) * (M_G - M_B)

    gamma = gamma_1 if t < T_switch else gamma_2
    dE = alpha_B * (1 - lambda_G) * L - alpha_G * lambda_G * L - delta * E
    dtheta = gamma * (E - bar_E)

    return [d_lambda_G, dE, dtheta]

# Solve the system
sol_regime = solve_ivp(system_regime_change, t_span, y0, t_eval=t_eval)

# Extract results
lambda_G_reg = sol_regime.y[0]
lambda_B_reg = 1 - lambda_G_reg
E_reg = sol_regime.y[1]
Y_reg = lambda_G_reg * r_G + lambda_B_reg * r_B
Y_net_reg = Y_reg - omega * E_reg

# Plot results
fig, axs = plt.subplots(3, 1, figsize=(12, 10), sharex=True)

axs[0].plot(sol_regime.t, lambda_G_reg, label='Green Lending Share', color='green')
axs[0].axvline(T_switch, color='black', linestyle='--', alpha=0.5, label='Regime Change')
axs[0].set_xlim(0, 20)
axs[0].set_ylabel('Lending Share')
axs[0].set_title('Green Lending with Regulation Regime Change')
axs[0].grid(True)
axs[0].legend()

axs[1].plot(sol_regime.t, Y_net_reg, label='Net Output', color='blue')
axs[1].axvline(T_switch, color='black', linestyle='--', alpha=0.5)
axs[1].set_ylabel('Net Output')
axs[1].set_title('Net Firm Output with Pollution Externality')
axs[1].grid(True)
axs[1].legend()

axs[2].plot(sol_regime.t, E_reg, label='Pollution (E)', color='red')
axs[2].axvline(T_switch, color='black', linestyle='--', alpha=0.5)
axs[2].set_xlabel('Time')
axs[2].set_ylabel('Pollution')
axs[2].set_title('Pollution Over Time')
axs[2].grid(True)
axs[2].legend()

plt.tight_layout()
plt.show()
```

```
# First, define the monetary policy regime change system
T_switch = 10  # time of regime change

# Define system with monetary regime change (change in phi_E)
phi_E_low = 0.1
phi_E_high = 2.0

def system_monetary_regime_change(t, y):
    lambda_G, E, theta = y

    # Regime-dependent monetary policy sensitivity
    phi_E = phi_E_low if t < T_switch else phi_E_high
    i = i_star + phi_E * E
    c_G = i + phi_G
    c_B = i + phi_B

    M_G = p_G * (r_G - c_G)
    p_B = p_B0 - lambda_reg * theta
    M_B = p_B * (r_B - c_B)

    d_lambda_G = (eta / (1 + kappa)) * (M_G - M_B)
    dE = alpha_B * (1 - lambda_G) * L - alpha_G * lambda_G * L - delta * E
    dtheta = gamma_1 * (E - bar_E)  # fixed regulation

    return [d_lambda_G, dE, dtheta]

# Solve the monetary policy regime change system
sol_monetary = solve_ivp(system_monetary_regime_change, t_span, y0, t_eval=t_eval)

# Extract monetary regime results
lambda_G_mon = sol_monetary.y[0]
lambda_B_mon = 1 - lambda_G_mon
E_mon = sol_monetary.y[1]
Y_mon = lambda_G_mon * r_G + lambda_B_mon * r_B
Y_net_mon = Y_mon - omega * E_mon

# Plot comparison of regulatory vs monetary regime shifts
fig, axs = plt.subplots(3, 1, figsize=(12, 10), sharex=True)

# Green lending share
axs[0].plot(sol_regime.t, lambda_G_reg, label='Regulatory Regime Change', color='green')
axs[0].plot(sol_monetary.t, lambda_G_mon, label='Monetary Regime Change', color='orange')
axs[0].axvline(T_switch, color='black', linestyle='--', alpha=0.5)
axs[0].set_xlim(0, 20)
axs[0].set_ylabel('Green Lending Share')
axs[0].set_title('Green Lending: Regulatory vs. Monetary Regime Change')
axs[0].grid(True)
```

```
axs[0].legend()

# Net output
axs[1].plot(sol_regime.t, Y_net_reg, label='Regulatory Regime Change', color='green')
axs[1].plot(sol_monetary.t, Y_net_mon, label='Monetary Regime Change', color='orange')
axs[1].axvline(T_switch, color='black', linestyle='--', alpha=0.5)
axs[1].set_ylabel('Net Output')
axs[1].set_title('Net Output: Regulatory vs. Monetary Regime Change')
axs[1].grid(True)
axs[1].legend()

# Pollution
axs[2].plot(sol_regime.t, E_reg, label='Regulatory Regime Change', color='green')
axs[2].plot(sol_monetary.t, E_mon, label='Monetary Regime Change', color='orange')
axs[2].axvline(T_switch, color='black', linestyle='--', alpha=0.5)
axs[2].set_xlabel('Time')
axs[2].set_ylabel('Pollution')
axs[2].set_title('Pollution: Regulatory vs. Monetary Regime Change')
axs[2].grid(True)
axs[2].legend()

plt.tight_layout()
plt.show()
```