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Applications to Inequality, Monetary Policy, and Climate Change

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RAPHAËL HULEUX

ESSAYS IN QUANTITATIVE MACROECONOMICS

Applications to Inequality, Monetary Policy, and Climate Change

CBS

Doctoral Thesis in Economics

Copenhagen Business School
Department of Economics

Essays in Quantitative Macroeconomics

Applications to Inequality, Monetary Policy, and Climate Change

Raphaël Huleux

Supervisors: David Jinkins, Birthe Larsen

COPENHAGEN BUSINESS SCHOOL
HANDELSHØJSKOLEN

Raphaël Huleux
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Acknowledgments

One taught me love
One taught me patience
And one taught me pain
Now, I'm so amazing
Say I've loved and I've lost
But that's not what I see
So, look what I got
Look at what you taught me
And for that, I say
Thank you, next (next)

Ariana Grande, Thank u next

I didn't plan to become an economist, and I am still surprised to realize I am becoming one. I was originally more drawn to philosophy, humanities, and this kind of "critical thinking". I fantasized about becoming an obscure psychoanalytic-leaning and Marxist "French intellectual". A number of random choices, mistakes, and existential crises made me realize that I was probably too neurotic to live this life. I still wanted to do some kind of intellectual work, but I wanted to be more confronted with the real world, its limitations, and its conflictuality.

This is what led me to economics. It felt like a mistake, at first, and I was surprised to see that this new field was even more theoretical and abstract than the one I had just left. I was very confused – and very bad at maths – so I splendidly failed my first exams in macroeconomics. It took me a while to understand the logic behind the models, the point of those stories written in maths, and their potential usefulness. It took me even longer to actually enjoy economics. I now believe that economics, and especially macroeconomics, is not so different from philosophy and other social sciences. There is something exhilarating in deriving social laws of aggregate behaviors that are a priori invisible to us[1].

But I didn't realize this by myself: a lot of people guided me and helped me on the way. If I am being honest, I would have never finished this thesis without them, and I would like

[1]See Ragot (2004), for parallels between structuralism and economics.

to recognize my profound indebtedness to them in this short acknowledgment.

First of all, I would like to thank my supervisors, David Jinkins and Birthe Larsen. This work would not have been possible without their helpful guidance during those four years. It is common for PhD students to complain about the lack of availability of their supervisors. I will not have this excuse: you have been constantly supporting me, setting meetings and coffee breaks, while granting me complete academic freedom.

I would also like to thank Pontus Rendahl, Katja Mann, and Karl Harmenberg who gave me some extremely useful comments and helped me during the stressful job market period. I also would like to thank Jimmy Martinez-Correa, Dolores Romero Morales, and Alexander Sebald for their continuous support and help. Dario Pozzoli, Enrico Camarda, Yajna Govind, Benjamin Serena, and Luigi Butera also gave me some critical help to prepare for the job market, and I would like to thank them again for their support. More generally, I would like to thank the whole Department of Economics at CBS for creating a space where it is a pleasure to work. And of course, I would also like to thank all my fellows PhD at the econ department for their friendship. It meant a lot.

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I am also forever grateful for my parents, Geneviève and Bernard, who granted me one of the most important things one can gift to their child: unconditional love, and a sense of self-confidence and freedom. I have always had the feeling that I could do anything and that you would continue to support and trust me no matter what. Few children get to experience this, and I will never thank you enough. Je vous aime très fort.

I would also like to thank my sister Camille and my brother Nicolas, for the love and tender memories. To Caroline, Dominique, and Eliot: visiting you always brings me joy, and you helped me see the world in a very different way. I am grateful to Thuy-Tien for letting me stay at her apartment in Paris, and for accompanying me, with Héloïse, from the very first day of my life. I admire your freedom and independence.

To Clara, I would like to say that there are very few things that I am certain of in life, but your friendship is one of them. It feels like we have known each other forever, and I know it will remain that way until the end. Thank you for being in my life. To my friends at home, in DLB, and elsewhere: Jason, Arnaud, Alex, Théo, Mathias, Laureline, Maxence, Vincent, Valentin, and Fillols, your presence means everything to me and brings me constant joy, laughter, and happiness. To Anna Pang: I would never have moved to Denmark without you, and I feel lucky for the time we spent together. To Louison, Lolo, Esther, Elise, Karin, Tessira, and Eloïse, you made me lose a few years of my life expectancy spending evenings in Bodegas, but you also made Copenhagen feel like my new home. To Yoss, I would like to thank you for those two years we spent together in Copenhagen, it meant a lot. And finally, to Emma: merci for your presence during the last weeks of this PhD, you transformed a stressful time into something beautiful and sweet.

[2]And also probably of "strongest climber in economics", even though the competition is fierce.

Summary

This thesis uses quantitative macroeconomic models to understand the relationships between inequality, monetary policy, and climate change.

Chapter 1: From Income to Wealth Inequality in the U.S.

The past 40 years have been characterized by a decrease in the rate of return on safe assets, an increase in the equity premium, an increase in the price of financial assets, and an increase in labor income and wealth inequality. Using a heterogeneous-agent model featuring permanent labor income inequality, a two-asset structure, and non-homothetic preferences, this chapter investigates the impact of an increase in permanent labor income inequality on wealth inequality. As rich households save a higher share of their permanent income than poorer ones, a more skewed permanent labor income distribution increases aggregate savings, everything else equal. However, in general equilibrium, with a realistic market structure, an increase in aggregate savings increases mostly the price of capital, not its quantity. This has little impact on the marginal productivity of capital and labor but creates capital gains that push up the top 1% wealth share.

Chapter 2: Income Inequality and Monetary Policy

This chapter studies the interplay between permanent labor income inequality and monetary policy within the framework of Heterogeneous-Agent New Keynesian (HANK) models.

This chapter studies the impact of an increase in permanent labor income inequality on the transmission of monetary shocks on the real economy. In a Heterogeneous-Agent New-Keynesian model with standard preferences, we show that the distribution of permanent labor income is neutral with respect to monetary policy shocks. However, this model cannot account for the observed relationship between permanent income and consumption-saving behavior. Including a non-homothetic taste for wealth allows us to match this relationship,

and breaks the neutrality result. The direct substitution effect from a monetary policy shock is weakened while indirect effects are stronger. The rise in permanent labor income inequality makes households hold wealth more for a present motive rather than for an intertemporal-substitution motive. As a result, the aggregate elasticity of intertemporal substitution is weakened while the aggregate static MPC is strengthened. In a realistic two-asset HANK model, we quantify the change in the composition of a monetary shock. We observe a rise in the magnitude of a monetary policy shocks as the increase in indirect effects more than outweighs the fall in the direct effect.

Chapter 3: Why is there still investment in polluting capital?

Despite governments' commitments to limit global warming to 1.5 degrees Celcius, there is still investment in carbon-intensive capital. This chapter uses a growth model featuring irreversible investment, capacity utilization, and clean and polluting capital to study this apparent paradox. It shows that current investment in polluting capital and CO_2 emissions are coherent with expectations of a future carbon tax if investors also expect a bailout of polluting capital. This result implies that governments' credibility can play an important role in reducing the cost of implementing an optimal carbon tax by committing not to bail out. However, there exists a temptation for a short-sighted government to boost output and consumption in the short run by announcing a future bailout.

Resumé

Denne afhandling bruger kvantitative makroøkonomiske modeller til at forstå forholdet mellem ulighed, pengepolitik og klimaforandringer.

Kapitel 1: Fra indkomst- til formueulighed i USA

De sidste 40 år har været præget af et fald i afkastet på sikre aktiver, en stigning i aktiepræmien, en stigning i prisen på finansielle aktiver og en stigning i uligheden i arbejdsindkomst og formue. Ved hjælp af en heterogen agentmodel med permanent ulighed i arbejdsindkomst, en struktur med to aktiver og ikke-homotetiske præferencer undersøger dette kapitel indvirkningen af en stigning i permanent ulighed i arbejdsindkomst på ulighed i formue. Da rige husholdninger sparer en højere andel af deres permanente indkomst op end fattige, vil en mere skæv fordeling af den permanente arbejdsindkomst alt andet lige øge den samlede opsparing. Men i generel ligevægt med en realistisk markedsstruktur øger en stigning i den samlede opsparing mest prisen på kapital, ikke mængden. Dette har kun ringe indflydelse på kapitalens og arbejdskraftens marginalproduktivitet, men skaber kapitalgevinster, der øger de øverste 1% af formuen.

Kapitel 2: Indkomstulighed og pengepolitik

Dette kapitel undersøger samspillet mellem permanent ulighed i arbejdsindkomst og pengepolitik inden for rammerne af nykeynesianske modeller med heterogene agenter (HANK).

Kapitlet undersøger effekten af en stigning i den permanente ulighed i arbejdsindkomst på transmissionen af monetære stød til realøkonomien. I en nykeynesiansk model med heterogene agenter og standardpræferencer viser vi, at fordelingen af den permanente arbejdsindkomst er neutral i forhold til pengepolitiske chok. Denne model kan dog ikke forklare det observerede forhold mellem permanent indkomst og forbrugsopsparingsadfærd. Ved at inkludere en ikke-homotetisk smag for rigdom kan vi matche dette forhold og bryde neutralitetsresultatet. Den direkte substitutionseffekt fra et pengepolitisk chok svækkes, mens de indirekte effekter styrkes. Stigningen i den permanente ulighed i arbejdsindkomst får

husholdningerne til at holde formue mere ud fra et nutidsmotiv end ud fra et intertemporalt substitutionsmotiv. Som følge heraf svækkes den samlede elasticitet af intertemporal substitution, mens den samlede statiske MPC styrkes. I en realistisk HANK-model med to aktiver kvantificerer vi ændringen i sammensætningen af et monetært chok. Vi observerer en stigning i størrelsen af et pengepolitisk chok, da stigningen i de indirekte effekter mere end opvejer faldet i den direkte effekt.

Kapitel 3: Hvorfor investeres der stadig i forurenende kapital?

På trods af regeringernes forpligtelser til at begrænse den globale opvarmning til 1,5 grader Celcius investeres der stadig i kulstofintensiv kapital. Dette kapitel bruger en vækstmodel med irreversible investeringer, kapacitetsudnyttelse og ren og forurenende kapital til at undersøge dette tilsyneladende paradoks. Det viser, at de nuværende investeringer i forurenende kapital og CO_2-emissioner er i overensstemmelse med forventningerne om en fremtidig CO2-skat, hvis investorerne også forventer en redning af den forurenende kapital. Dette resultat indebærer, at regeringers troværdighed kan spille en vigtig rolle i at reducere omkostningerne ved at implementere en optimal CO2-skat ved at forpligte sig til ikke at redde den. Der er dog en fristelse for en kortsigtet regering til at øge produktionen og forbruget på kort sigt ved at annoncere en fremtidig redningspakke.

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Introduction

This dissertation consists of three self-contained chapters on macroeconomics, inequality, and climate change.

The first two chapters are motivated by the same stylized fact: labor income inequality has been rising significantly in many developed countries, since the 1970s (Piketty 2018). More precisely, the permanent component of inequality has been increasing, instead of an increase in the variance of labor income risk over the lifetime (DeBacker et al. 2011; Fatih Guvenen, Kaplan, et al. 2022). This structural change matters for macroeconomics since we know that households with a higher level of permanent income also tend to save more than poorer ones (Dynan, Skinner, and Zeldes 2004; Kumhof, Rancière, and Winant 2015; Straub 2019). This means that in increase in labor income inequality redistributes income toward households with high saving rates, increasing aggregate savings.

A recent literature studies the impact of this increase in labor income inequality on the secular decline in the real interest rate, the increase in household indebtment, the increase in wealth-to-output ratios, and the increase in wealth inequality (Kumhof, Rancière, and Winant 2015; Straub 2019; Mian, Straub, and Sufi 2021). This thesis contributes to this literature in two ways. The first chapter shows that, under imperfect competition, rising permanent labor income inequality can increase the valuation of financial assets, creating capital gains for the wealthy, which in turn have an impact on the distribution of wealth. The second chapter shows how an increase in permanent labor income inequality can affect monetary policy and its transmission channels by redistributing income between households with different marginal propensities to consume and elasticity of intertemporal substitutions, as well as affecting the distribution of wealth.

Chapter 1 looks at the impact of the rise in permanent labor income inequality on the distribution of wealth in the U.S. The main question we ask is: what is the general equilibrium effect of this structural change? Indeed, if aggregate savings increase because a bigger share of national income is directed toward households with a higher marginal propensity to save, the prices of financial assets also need to change for markets to clear. This might have two effects. First, a trickle-down effect: the increase in savings might finance a higher stock of physical capital, decreasing returns, and increasing wages and output. This general equilibrium effect benefits all of society and might dampen wealth inequality by limiting the financial income at the top. However, this increase in aggregate savings might also finance a higher price of financial assets, creating some short-term capital gains that benefit households who already own wealth.

This second effect is consistent with what has been observed at the aggregate level in the U.S.: valuations of firms have been rising, the wealth-to-output ratio has increased mostly because of a valuation effect, while the aggregate saving and investment rates have remained relatively constant over the period, suggesting that households have saved mostly through capital gains. Using a quantitative model calibrated to match the relationship between permanent labor income and savings on the household side, and to match the observed valuations of firms in the U.S. on the supply side, we find that the observed increase in permanent labor income inequality mostly generated valuations effect that contributed to 10% of the observed increase in the top 1% wealth share between 1970 and 2020. Our model is also coherent with a number of stylized macro-finance facts, such as the secular decrease in the safe interest rate, the relatively constant return on equity, and an increase in the wealth-to-output ratio driven mostly by valuation effects.

The second chapter of this thesis examines the impact of rising permanent labor income inequality on monetary policy. This work contributes to the growing literature that investigates how household heterogeneity affects the strength and transmission of monetary policy. While much of the existing literature has focused on ex-post heterogeneity—primarily in the form of idiosyncratic productivity shocks—within the Heterogeneous-Agent New-Keynesian (HANK) framework, this chapter introduces ex-ante heterogeneity through differences in permanent labor income.

Our analysis shows that, under a realistic non-homothetic preference for wealth that aligns with the observed relationship between permanent labor income and savings, the distribution of permanent labor income plays a significant role in shaping monetary policy outcomes. We identify three main channels through which this impact occurs.

First, an increase in permanent labor income inequality shifts income towards households with a lower marginal propensity to consume and a higher elasticity of intertemporal substitution—a phenomenon we term the composition effect. Second, as household incomes change, their responses to interest rate or income shocks also change, an effect we refer to as the policy function effect. Third, increasing inequality in permanent labor income leads to a more unequal distribution of wealth, which raises the proportion of hand-to-mouth households. These households are highly responsive to changes in labor income but largely unresponsive to interest rate changes. Overall, our results indicate that this third effect—the increase in hand-to-mouth households—dominates, resulting in a heightened output response to monetary policy shocks as permanent labor income inequality rises.

Chapter 3 explores the persistence of investment in carbon-emitting infrastructures, such as coal power plants, despite clear evidence that the emissions from the existing stock of polluting capital already exceed the carbon budget necessary to limit global warming to

2°C. This chapter examines one possible explanation for this paradox: the uncertainty surrounding the timing of future climate policies and the potential for government bailouts of polluting infrastructures. Sen and von Schickfus 2019 demonstrates that investors might anticipate being bailed out from potential losses if their polluting investments are stranded due to future policy changes.

Using a Ramsey growth model that incorporates polluting and clean capital, irreversible investment, and capacity utilization, I analyze the consequences of this investor behavior. My findings suggest that investors' expectations regarding future climate policies significantly influence both the cost of implementing a carbon tax and the response of polluting firms' valuations once such a tax is introduced. Specifically, if investors mistakenly anticipate government bailouts, they tend to over-invest in polluting assets. Consequently, when a carbon tax is eventually imposed, these firms' valuations collapse as more assets become stranded.

The model also reveals that a firm commitment to never bail out stranded assets could reduce the future cost of implementing a carbon tax. However, there is a risk that a short-sighted government might be tempted to commit to a bailout, leading to a short-term boom in polluting investments and increased output, but at the cost of higher transition costs in the future.

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Chapter 1

From Income to Wealth Inequality in the U.S.

The past 40 years have been characterized by a decrease in the rate of return on safe assets, an increase in the equity premium, an increase in the price of financial assets, and an increase in labor income and wealth inequality. Using a heterogeneous-agent model featuring permanent labor income inequality, a two-asset structure, and non-homothetic preferences, we investigate the impact of an increase in permanent labor income inequality on wealth inequality. As rich households save a higher share of their permanent income than poorer ones, a more skewed permanent labor income distribution increases aggregate savings, everything else equal. However, in general equilibrium, with a realistic market structure, an increase in aggregate savings increases mostly the price of capital, not its quantity. This has little impact on the marginal productivity of capital and labor but creates capital gains that push up the top 1% wealth share.[1]

1.1 Introduction

Over the past five decades, both labor income and wealth inequality have increased rapidly in the U.S. (Saez and Zucman 2016; Piketty 2015; Piketty and Zucman 2015; Piketty, Saez, and Zucman 2018). This paper aims to explore the relationship between the distribution of permanent labor income and the distribution of wealth. A mechanism highlighted by (Straub 2019) suggests that since households with higher permanent labor income have higher saving rates than poorer households, an increase in permanent labor income inequality can result in an increase in aggregate savings. This change in aggregate savings will, in turn, affect the price of financial assets, which will have a feedback effect on the distribution of wealth.

[1] This chapter was co-written with Eustache Elina, PhD student at the Paris School of Economics.

The central question we address is: what is the general equilibrium effect of such an increase in aggregate savings on the distribution of wealth? Does the general equilibrium feedback dampen or amplify wealth inequality?

The answer to this question is theoretically ambiguous. On the one hand, an increase in aggregate savings can increase the *quantity* of physical capital, which will increase wages and decrease returns. This general equilibrium effect should have a "trickle-down" effect and dampen wealth inequality, as poor households will benefit from higher wages, while rich households will see their financial income decrease.[2] On the other hand, an increase in aggregate savings can also increase the *price* of capital. This should increase wealth inequality: wages and long-term returns would remain constant, while short-term capital gains would temporarily increase the returns of the wealthy. To assess the strength of those different channels, we build a quantitative heterogeneous agent model that can account for the relationship observed in the data between the saving rate and the level of permanent income on the household side and the valuation effects on the firm side. Using that framework, we find that the general equilibrium effect amplifies wealth inequality and represents 10% of the total increase in the top 1% wealth share.

We first present some stylized facts on the accumulation of wealth in the U.S. Using a decomposition similar to (Piketty and Zucman 2014), we find that most of the increase in the wealth-to-output ratio in the U.S. came from a valuation effect and not a quantity effect. This is consistent with the fact that the aggregate households' net saving rate has decreased over the same period: households have accumulated wealth mostly by benefiting from large unrealized capital gains on their existing wealth, not by saving a larger share of their income.[3] Instead, an increase in the value of the capital stock has taken place: the average Tobin's Q surged from around 0.6 in the 1960s to over 1 in recent times (Brun and Gonzalez 2017; Gonzalez and Trivin 2019). These aggregate macroeconomic trends also align with micro evidence on saving rates along the wealth distribution. Fagereng, Guiso, et al. (2020) found, using Norwegian register data, that the disparity in gross saving rates between the richest and the rest of the distribution is primarily explained by unrealized capital gains.

Building on those findings, we study a simple two-agent analytical model with different permanent labor income types, non-homothetic preferences, and a deterministic Lucas tree. As in Straub (2019), we find that a non-homothetic taste for wealth can account for the relationship between the saving rate and permanent income observed in the data. We also find that those non-homothetic preferences imply a positive relationship between permanent labor income inequality and the price of financial assets. This model can thus generate

[2]As shown by (Davila et al. 2012), in a standard Aiyagari-model calibrated to match the wealth and income distribution in the U.S., there is too little capital at the steady state, and a central planner would want to push the richest to save more, to increase the productivity of all workers.

[3]Net saving rates remove the impact of unrealized capital gains. Gross saving rate includes unrealized in the measure of both income (also called the Haig-Simons income) and savings. Savings in national accounts don't take into account capital gains.

large capital gains and an increase in the wealth-to-output ratio without any increase in the aggregate saving rate – which is by construction constant – as it has been observed in the U.S.

Finally, we incorporate this insight into a quantitative two-asset heterogeneous agents model featuring permanent labor income inequality, non-homothetic preferences, and imperfect competition. We calibrate this model on the U.S. economy in the 1960s and compute a transition from 1970 to 2020, where we match the observed increase in labor income inequality. Our model can match both the level of labor income and wealth inequality observed in the U.S. in 1970, generate a Tobin's Q and wealth-to-output level close to those in the data, and match both the speed and the magnitude of the observed increase in wealth inequality, a feature that most heterogeneous agents model have a hard time reproducing.

In our simulations, changes in the permanent component of labor income inequality increase aggregate savings and decrease the returns on the liquid asset, as in Straub (2019). However, due to imperfect competition and distortions coming from firm taxation, the price of financial assets increases by more than the quantity of physical capital. Those valuation effects create some short-term capital gains that maintain the high return on financial assets, and this increase in the equity premium, in turn, has a positive feedback effect on wealth inequality. The *general equilibrium effect* – the change in prices following a shock to the distribution of permanent labor income – accounts for a significant fraction of the increase in wealth inequality. We find that this general equilibrium effect accounts for 10% of the increase in the wealth share of the top 1% from 1970 to 2020.

Related Literature. Our paper adds to the large literature that attempts to study the determinants of the wealth distribution and its dynamics using quantitative models. Early attempts to analytically characterize the distribution of wealth date back to the 50s and the 60s (Champernowne 1953; Vaughan 1979; Laitner 1979; Stiglitz 1969). The development of numerical methods to solve heterogeneous agent models in the 1980s and 1990s (Bewley 1980; Imrohoroğlu 1989; Huggett 1993; Aiyagari 1994) sparked a new generation of papers quantitatively studying the factors determining the distribution of wealth (see De Nardi and Fella (2017) for a review of the literature). This literature found that the inequality in earnings alone is not able to generate the fat tail observed in the distribution of wealth but that models that include random returns or saving rates can match the data (Benhabib, Bisin, and Zhu 2011; Benhabib, Bisin, and Zhu 2015; Xavier 2021).

This paper belongs to a specific subset of this literature that aims to explain not only the long-term, steady-state distribution of wealth but also its dynamics. As found by Gabaix et al. (2016), the random returns or saving rates that create a fat tail at the steady state also generate too slow dynamics compared to the data. They suggest that models that could account for the fast increase in the top wealth share observed in the U.S. should include either a form of "type dependence" (high-savers or high-returns households) or "scale dependence" (returns and saving rates increasing with wealth). Our model follows this second strategy: the non-homothetic taste for wealth implies a positive relationship between wealth and the gross saving rate. At the same time, our portfolio choice captures the fact that rich households invest a higher share of their wealth into risky assets that yield a higher return. This is coherent with part of the empirical literature that has shown that the wealthiest households have both a higher saving rate (Dynan, Skinner, and Zeldes 2004; Fagereng, M. Holm, et al. 2019) and higher returns on their wealth (Fagereng, Guiso, et al. 2020; Bach, Calvet, and Sodini 2020; Garbinti, Goupille-Lebret, and Piketty 2021).[4]

Previous works have also studied how changes in asset returns impact the dynamics of wealth inequality. Favilukis (2013) studied the impact of increasing labor income inequality and higher returns on financial assets. In models with entrepreneurs, Gomez et al. (2016) and Cioffi (2021) also find that positive aggregate shocks pushing stock market returns increase wealth inequality. Finally, in a non-micro-founded model estimated on U.S. tax data, Blanchet (2022) finds that the two main drivers of the increase in wealth inequality have been higher saving rates at the top and capital gains. Compared to this literature, our main contribution is to focus on how an increase in labor income inequality can increase the equity premium through capital gains instead of considering higher returns driven by aggregate TFP shocks.

Hubmer, Krusell, and Smith (2021) has been one of the most successful models in matching the level and dynamics of wealth inequality, using an exogenous portfolio choice and excess returns along the wealth distribution. They find that the main drivers of wealth inequality have been a change in taxation and a change in asset returns. Our model differs from theirs along a few key dimensions: (1.) they consider an increase in the variance of earnings shocks, while we consider an increase in permanent labor income inequality, (2.) the heterogeneous saving rates come from a time-varying discount factor in their model (type-dependence), while it comes from a non-homothetic taste for wealth in ours (scale dependence). (3.) their portfolio choices and excess returns are exogenous, while they are endogenous outcomes in ours. We thus view our work as an attempt to build on their contribution by endogeneizing the excess return of wealthy households, a key factor for the dynamics of wealth inequality.

We focus on an increase in post-tax *permanent* labor income inequality, as in Straub (2019), and in line with the recent empirical literature (DeBacker et al. 2011; Bloom et al. 2017; F. Guvenen et al. 2017; Braxton et al. 2021; Fatih Guvenen, Karahan, et al. 2021). An alternative in the literature is to increase the variance of the persistent and temporary shocks instead. This can have very different effects on the wealth distribution, as found by Hubmer, Krusell, and Smith (2021). Indeed, even if idiosyncratic shocks are the primary source of wealth inequality in heterogenous-agents models, they also create a precautionary motive that pushes households at the bottom of the distribution to save

[4] In fact, Fagereng, Guiso, et al. (2020) and Bach, Calvet, and Sodini (2020) show that even within an asset class, wealthier households have higher returns than poorer ones. Our model partially captures this through random idiosyncratic returns shocks on the risky assets.

more, to reduce the likelihood of being constrained – and hence being out of their Euler equation. This precautionary motive disappears at the top of this distribution, creating a "buffer-stock" behavior (Carroll 1997). In this framework, increasing the variance of the shocks increases the precautionary motive and hence savings at the bottom of the wealth distribution, decreasing wealth inequality.

An increase in labor inequality coming from the permanent component has a very different effect. First, it reduces the total labor income risk for households with lower wages and increases the risk for households at the top of the distribution, who now face a higher risk of total wage income. As shown by Straub (2019), with standard homothetic preferences, shifts in the distribution of permanent labor income have almost no impact on aggregate savings and returns since richer households are scaled-up versions of poorer ones once they are sufficiently far away from the borrowing constraint. However, this quasi-neutrality of the distribution of permanent labor income can be broken with a non-homothetic taste for wealth. If the marginal utility of consumption decreases faster than the marginal utility of wealth, richer households will have a higher marginal propensity to save out of permanent income shocks than poorer ones, and shifts in the distribution of permanent labor income will imply shifts in aggregate savings.

Our work also builds on Straub (2019), who studies the impact of non-homothetic preferences on household behavior and wealth inequality. He proves that under homothetic preferences, individual consumption scales linearly with permanent income. In a quantitative model, he finds that when accounting for this non-homothetic behavior, the increase in permanent labor income inequality can account for a large part of the increase in wealth inequality and the decrease in real interest rate observed in the U.S. Our work differs from his on two dimensions. First, compared to his analytical result, our main contribution is to show that only a certain type of non-homothetic preferences make the distribution of permanent labor income non-linear with respect to both the distribution of wealth *and* prices. With Stone-Geary preferences, shifts in permanent labor income will increase wealth inequality but not affect prices. We also derive analytically how shifts in permanent income affect the pricing of an asset, depending on the degree of non-homotheticity. Secondly, in our quantitative model, we focus on the impact of labor inequality on asset prices and how asset prices, in turn, affect the distribution of wealth. To do so, we include a more realistic structure of the firm and a portfolio choice on the household's side. The structure of the firm allows us to study realistically the valuation effects coming from shifts in aggregate savings, while the portfolio choice implies that capital gains can shift the wealth distribution.

A key element of our model is the non-homothetic taste for wealth that allows us to match the marginal propensity to save in the data out of permanent income shocks. Carroll (1998) and Carroll (2000) are the first to study how a taste for wealth can explain both the higher saving rates of the rich and the higher share of risky assets in their portfolio. Kumhof, Rancière, and Winant (2015) shows in a two-agent model with a non-homothetic taste for wealth that an increase in permanent labor income inequality increases household debt and the endogenous risk of a debt crisis. A non-homothetic taste for wealth has also been used in the New Keynesian literature to explain the zero-lower bound and the impact of secular stagnation (Michau 2018; Mian, Straub, and Sufi 2021; Michaillat and Saez 2021).

This paper is organized as follows. In the first section, we summarise some stylized facts about the increase in labor and wealth inequality, the evolution of the wealth-to-output ratio, and the valuations of capital. In the second section, we study the impact of a labor income shock in a two-agent analytical model with non-homothetic preferences and capital gains. The third section presents our quantitative model to measure the size of the general equilibrium channel. The last section presents the main results.

1.2 Stylized facts

This section documents the main stylized facts about the U.S. that motivate this paper. At the aggregate level, we report (1.) the increase in labor income and wealth inequality, (2.) the rise in the price of capital, and (3.) an increase in the equity premium. At the cross-sectional level, we use the Survey of Consumer Finance (SCF) to document that richer households (1.) have a higher marginal propensity to save and (2.) invest a higher share of their wealth into risky assets.

This paper's main estimates of labor income and wealth inequality are from Piketty, Saez, and Zucman (2018), which combines tax, survey, and national accounts data to estimate the increase in the top labor and income shares. The primary advantage of their method is that it matches aggregate values of income and wealth in the national accounts. The values are similar, if a bit lower, to the ones obtained in the SCF (see Figure 1.1). Both document a significant increase in the top 10% and top 1% in wealth and labor income shares between 1980 and 2020.

The distribution of wealth displays a fatter right tail than the distribution of labor income, which has increased over time. The top 1% income share has risen by 6 p.p. between 1980 and 2020, according to PSZ, against 15 p.p. for the top 1% wealth share. Not only did wealth inequality increase faster than labor income inequality, but the total wealth held by households also increased faster than national income (Figure 1.2, left panel). In contrast, the personal saving rate remained relatively constant.

It is important to recall that because measures of national income do not account for capital gains, an increase in wealth does not necessarily come from increased net savings from households. Indeed, if we decompose the wealth-to-output ratio between a saving and a capital gain component, we find that almost all of the increase in the wealth-to-output ratio comes from an increase in the price of wealth and not from an increase in savings (see

Figure 1.1: Top labor income and wealth shares

Note: This figure shows the evolution of the top 1% and top 10% pre-tax labor income shares and wealth shares from the Distributional National Accounts in Piketty et al. (2018) (PSZ, blue line) and in the Survey of Consumer Finance (SCF, orange line, authors calculations).

Figure 1.2, left panel).[5] This increase in the valuation of capital is also clearly visible in the valuation of the firms: the aggregate Tobin's Q, which is the ratio of the market value and the book value of U.S. corporations, went from below 1 before the 1980s to above 1 today.

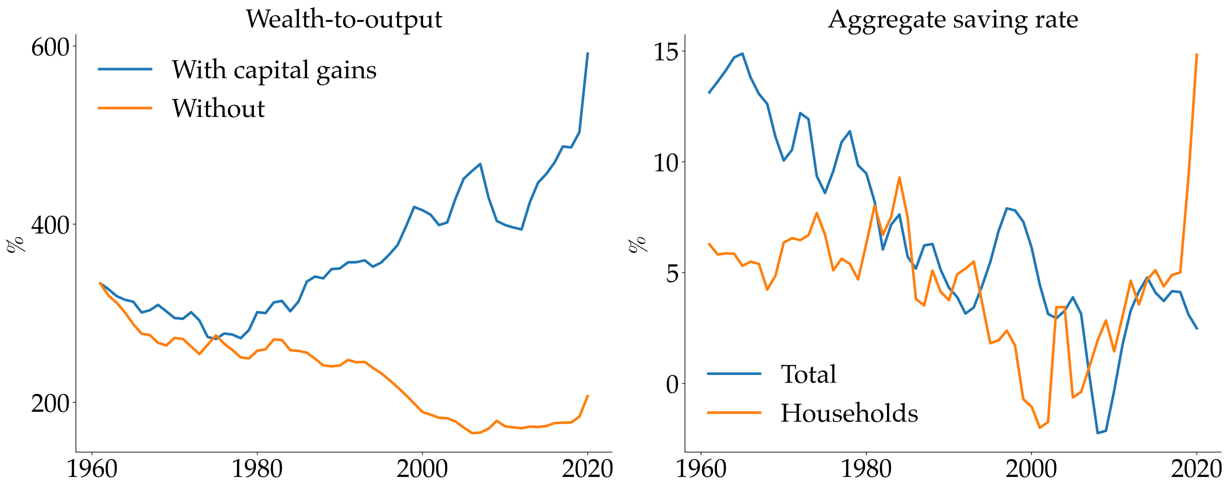

Figure 1.2: Aggregate household wealth and saving rate

Note: This figure shows the evolution of the household wealth-to-national-output ratio. The decomposition follows Piketty, Zucman (2014) by computing aggregate wealth, removing any valuation effect. This decomposition comes from the following law of motion of wealth $W_{t+1} = W_t + S_t + KG_t$ where W_t is the household aggregate wealth, S_t is aggregate savings from households and KG_t are capital gains. The figure on the right plots the net aggregate saving rate in the NIPA accounts.

Two things should be noted. First, this increase decomposition is not a counterfactual exercise: in the absence of capital gains, households might have increased their savings rate to satisfy their savings needs. It is, however, coherent with Fagereng, M. Holm, et al. (2019), who found the higher saving rates from richer households came mostly from capital gains. Secondly, this increase in the valuation of the firms is also due to other factors than the increase in labor income inequality: the decrease of the dividend and the corporate tax rate and the increase in markups also played an important role (Piketty and Zucman 2014; Brun and Gonzalez 2017).

This considerable accumulation of wealth at the aggregate level has been accompanied by an increase in the equity premium (Caballero, Farhi, and Gourinchas 2017; Reis 2022). In Figure 1.3, we plot in black the total real return on national wealth in the U.S., computed from national accounts reported by Piketty and Zucman (2014), against the real return on the 10-year Treasury Bills. Apart from medium-term fluctuations, the total real return on U.S. wealth has remained relatively constant over time while the real return has dramatically decreased. Moreover, capital gains are volatile but represent a significant proportion of the total return.

At the cross-sectional level, two stylized facts should be noted: (1.) the saving rate is an increasing function of permanent income, and (2.) richer households invest a higher share

[5] That is, $\frac{W_t}{GNP_t} = \frac{W_{t-1}+S_{t-1}+KG_{t-1}}{GNP_t}$, where W_t is the total real wealth held by households, S_t is total savings and KG_t is capital gains,

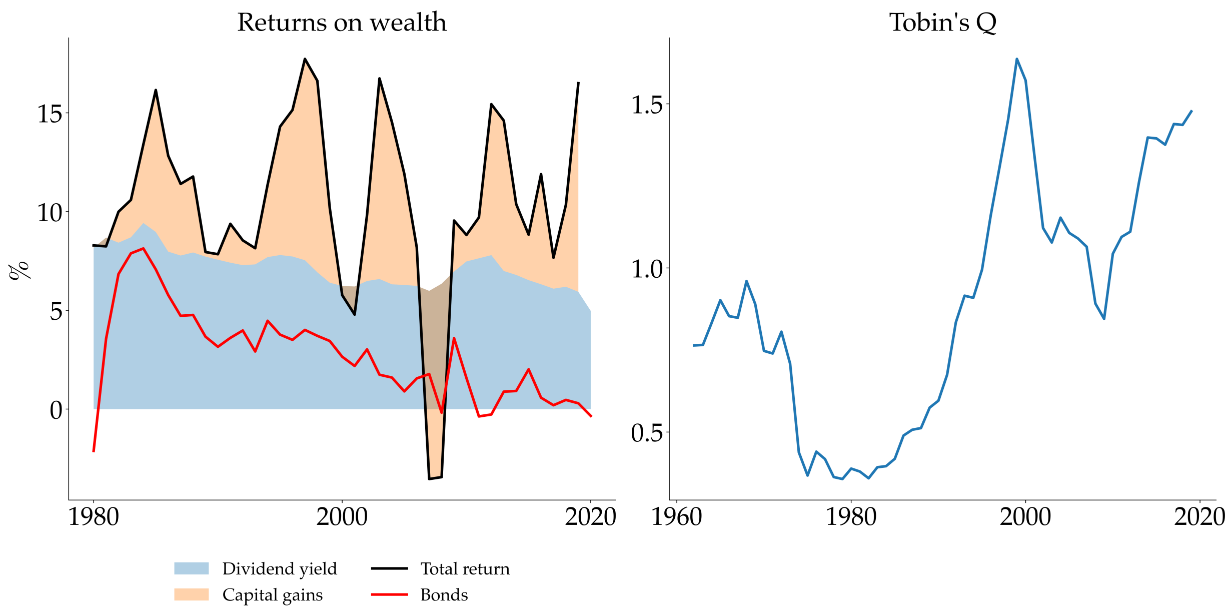

Figure 1.3: Returns on wealth and Tobin's Q

Note: This figure plots returns on total wealth in the U.S., computed from NIPA, and the Tobin's Q reported in Piketty et al. (2018).

of their wealth into risky assets (see Figure 1.4).

Those two facts are crucial to explaining the primary mechanism in our model: the difference in saving rates along the distribution of permanent income implies that an increase in labor income inequality can affect the desired aggregate savings. Those changes will, in turn, affect the valuation of capital, which will create an excess return on capital compared to the safe asset. Because richer households own a higher share of risky assets, this effect will amplify wealth inequality, creating a feedback loop between labor income and wealth inequality.

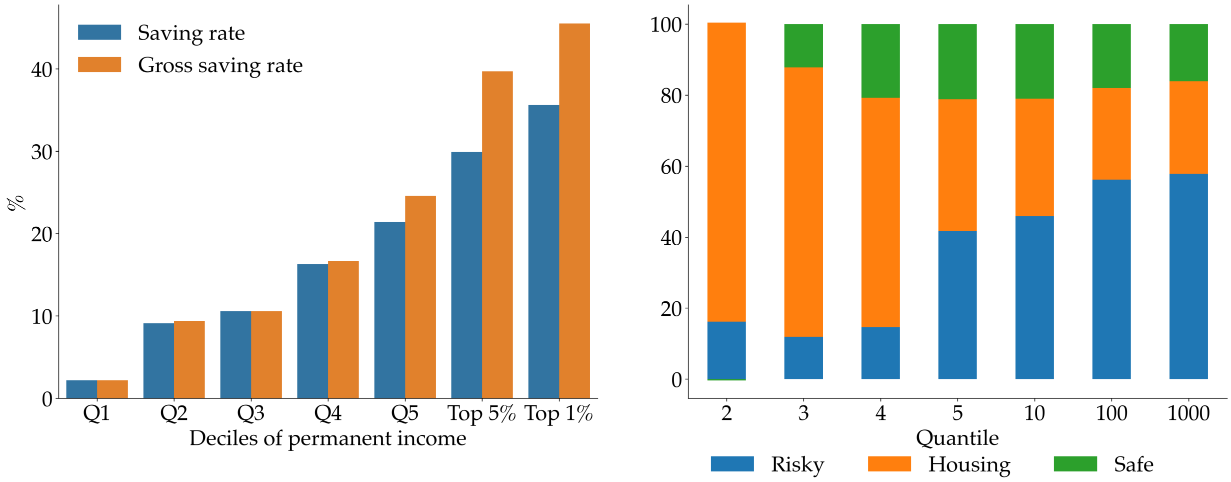

Figure 1.4: Households and saving rates portfolio in the SCF along the wealth distribution, 1989

Note: The figure on the left reproduces the saving rates computed in the SCF in 1989 by Kumhof et al. (2015). The saving rates are computed with a quantile regression and controlling for age. Gross saving rates account for unrealized capital gains.

1.3 Analytical model

In this section, we analyze what preferences can account for the positive relationship between increasing marginal propensity to save out of permanent income and permanent income in a simple analytical model with two-agent and a deterministic Lucas tree. We then explore the general equilibrium implications of an increase in permanent labor income inequality.

We show analytically that, under standard preferences for consumption, the marginal propensity to save out of permanent labor income shock is zero. When we add a homothetic taste for wealth, the marginal propensity to save is constant, and the distribution of permanent labor income has thus no impact on the price of equity. Only a particular form of non-homotheticity in the taste for wealth can generate a marginal propensity to save, which is an increasing function of permanent labor income, as we observe in the data. In this case, the distribution of labor income becomes non-neutral and shapes both the wealth distribution and the price of equity. Finally, we show that in a transition from a steady state with low inequality to a steady state with high inequality, capital gains initially increase the rise of the top 1% wealth share by increasing returns to wealth.

1.3.1 Environment

Both agents $i \in \{1, 2\}$ differ in the level of endowment z_i they receive at each period and in the initial allocation of the deterministic Lucas-tree $s_{i,0}$.[6] Without loss of generality,

[6] Endowments should be viewed as permanent labor income. Differences in endowments could reflect differences in productivity between the two agents.

$z_1 < z_2$, the total endowment is normalized to 1, and we define $z \equiv z_2$ (and so $z_1 = 1 - z$). One unit of Lucas tree delivers one unit of final good at each period.

Taking the sequence of prices for the Lucas-tree $\{q_t\}_{t=0}^{\infty}$ as given, each household i chooses a stream of consumption to maximize lifetime utility, taking into account that she values holding wealth by itself:

$$\max_{\{c_{i,t}\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta_i^t [u(c_{i,t}) + \gamma v(q_t s_{i,t})],$$

subject to the budget constraint $c_{i,t} + q_t s_{i,t+1} = (q_t + 1)s_{i,t} + z_i$ and the non-negativity constraint on equity $s_{i,t+1} \geq 0$. Consumption is CRRA with a risk aversion of σ. For the function $v(.)$, we closely follow Straub (2019) and choose:[7]

$$v(q_t s_t) = \frac{(q_t s_t + \zeta)^{1-\Sigma} - 1}{1 - \Sigma}.$$

This function has two non-homotheticity parameters: the constant term ζ and the relative risk aversion Σ.[8] Both agents can trade equity $s_{i,t+1}$ in t. The equity market must clear at all times:[9]

$$\forall t,\ s_{1,t+1} + s_{2,t+1} = 1.$$

We normalise $s = s_2$ and $s_1 = 1 - s$.

Definition 1.1. *A competitive equilibrium is an initial distribution of endowment $\{s_{1,0}, s_{2,0}\}$, sequences $\{c_{i,t}\}_{t=0}^{\infty}$, $\{s_{i,t}\}_{t=0}^{\infty}$, and $\{q_t\}_{t=0}^{\infty}$ such that households solve their problems by taking prices as given and the market for shares and the goods market clear at all times.*

1.3.2 Analytical results

We start from the benchmark case with (1.) no taste for wealth $\gamma = 0$ before (2.) adding a homothetic taste for wealth and (3.) the non-homothetic taste for wealth case.

Without a taste for wealth

Proposition 1.1. *When preferences are homothetic, the price of the equity is*

$$q_t = \left(\frac{1}{\beta} - 1\right)^{-1}.$$

$\forall t$, $s_{1,t} = s_{1,0}$ and $s_{2,t} = s_{2,0}$.

Proof. See Appendix A.1. □

[7] Our functional form only differs from Straub (2019) due to the constant term ζ.

[8] We denote that constant, the Stone-Geary parameter.

[9] Given Walras law, if the equity market clears, the goods market must also clear.

Proposition 1 tells us that the equilibrium price for the Lucas tree is such that the two agents are indifferent between saving and dissaving, and their wealth is constant over time. In this setting, the marginal propensity to save out of permanent income is zero $ds/dz = 0$ while consumption reacts one-to-one with variations in permanent income $dc/dz = 1$.

This equilibrium can be thought of as an autarky equilibrium. Because both agents value the asset at exactly the same rate β, they will never have an incentive to trade. We thus have an infinite number of possible steady states, which depends on the initial allocation the two agents start with. We have two ways to move away from this result. The most standard way is to bring in heterogeneous discount factors with $\beta_1 < \beta_2$. The other way is to move away from homothetic preferences with $\gamma > 0$.

Proposition 1.2. *When discount factors are heterogeneous $\beta_i > \beta_{-i}$, at the steady state, the non-negativity constraint of agent $-i$ is binding, $s_{-i} = 0$, and $q = \left(\frac{1}{\beta_i} - 1\right)^{-1}$.*

Proof. See Appendix A.2. □

With heterogeneous discount factors, we now have a unique steady state. The impatient household will always hit the borrowing constraint, and the patient household holds all the wealth in the economy. This result confirms a finding in the literature that heterogeneous discount factors can generate a very high level of wealth inequality (Hubmer, Krusell, and Smith 2021). However, this result does not depend on the endowment distribution $\{w_1, w_2\}$ and does not account for the relationship between marginal propensity to save and permanent labor income. In the steady state, we recover that $ds/dz = 0$ and $dc/dz = 1$.

In this case, in the steady state, the level of labor income inequality is neutral on the level of wealth inequality.[10] This is an unappealing result, given the strong correlation between the two in the data. It also generates a marginal propensity to save out of permanent income are constant and equal to 0 for all levels of wealth $ds/dz = 0$.

Adding a taste for wealth

Proposition 1.3. *When $\gamma > 0$, focusing on interior solutions, the price of equity q and the share of the Lucas tree held by agent 2, s, are implicitly defined by the following two*

[10] This result would not hold in an incomplete market setting with idiosyncratic shocks. In this case, the level of buffer stock savings will be proportional to the level of permanent income. However, as shown by Straub (2019), the linearity of the consumption function out of permanent income can be extended to a model with precautionary savings, which implies that $ds/dw > 0$ but constant as a function of permanent income.

equations:[11]

$$\frac{(qs+\zeta)^{-\Sigma}}{(z+s)^{-\sigma}} = \frac{(q(1-s)+\kappa)^{-\Sigma}}{(1-z-1-s)^{-\sigma}}, \tag{1.1}$$

$$\frac{1}{\beta} - 1 - \frac{1}{q} = \gamma \frac{(qs+\zeta)^{-\Sigma}}{(z+s)^{-\sigma}}. \tag{1.2}$$

Proof. See Appendix A.3. □

Now, both agents value holding wealth ($\gamma > 0$). Proposition 3 tells us that, at the steady state, the price of the Lucas tree depends on the level of steady-state consumption and wealth.

Equation (1) tells us that, at the equilibrium, the two agents equalize their marginal rate of substitution between the marginal utility from wealth and the marginal utility from consumption. The two agents will trade shares because they give a different value to savings depending on their permanent income. Wealth is both a way to delay consumption and a good that yields utility. Equation (2) gives that $1 + 1/q < 1/\beta$. The additional motive to accumulate wealth creates a wedge compared to the case without wealth in the utility function where there is no trade.

Proposition 1.4. *When $\sigma = \Sigma = 1$ and $\zeta = 0$, at the steady state, the value of the Lucas tree and the wealth position are given by:*

$$q = (1+2\gamma)(\frac{1}{\beta} - 1)^{-1} \textit{ and } s = z.$$

Proof. See Appendix A.4. □

Assuming log-utility, $\Sigma = \sigma = 1$, and $\zeta = 0$, we can solve analytically for the equity position s and the price of the equity q. A few comments need to be made. First, when $\gamma = 0$, we fall back to the benchmark case with $q = \left(1/\beta - 1\right)^{-1}$. Secondly, the price of the Lucas tree is an increasing function of γ. The more weight the household puts on holding wealth, the higher the equilibrium price to clear the equity market. Thirdly, inequality does not affect the price q because the marginal propensity to save out of permanent income is constant $ds/dz = 1$ for all values of income. This means that households with different levels of permanent income will have the same incentive to hold wealth. Finally, there is a one-to-one relation between wealth inequality and labor income inequality, and the general equilibrium effect neither dampens nor amplifies the direct impact.

Now, we introduce non-homotheticity by allowing for a positive ζ but keeping $\sigma = \Sigma$.[12] We can solve analytically for the value of s as a function of q.

[11] Which happens whenever w is not too close from 1.

[12] Preferences are now non-homothetic due to the ζ parameter.

Proposition 1.5. *When $\sigma = \Sigma$, at the steady state, the quantity of Lucas tree held by agent 2 is given by:*

$$s = \min\left\{\frac{z(q+2\zeta)-2\zeta}{q-2\zeta}, 1\right\}.$$

Proof. See Appendix A.5. □

In partial equilibrium, keeping q as constant, the level of s (and of wealth inequality in this setting) is an increasing function of the endowment of agent 2, z. It does not depend on γ. Hence, even if the weight on the taste for wealth is small, it is sufficient to generate a non-trivial wealth distribution.[13] The wealth position of agent 2 is an increasing function of labor income inequality which is not the case with heterogeneous discount factors. We need to check if this remains valid in general equilibrium when q can adjust.

Proposition 1.6. *When $\Sigma = \sigma = 1$ and $\zeta > 0$, the price of the Lucas tree is given by :*

$$q = \frac{\beta\gamma + \beta\zeta + \frac{\beta}{2} - \zeta + \frac{\sqrt{4\beta^2\gamma^2+8\beta^2\gamma\zeta+4\beta^2\gamma+4\beta^2\zeta^2-4\beta^2\zeta+\beta^2-8\beta\gamma\zeta-8\beta\zeta^2+4\beta\zeta+4\zeta^2}}{2}}{1-\frac{1}{\beta}}.$$

And we have that: $dq/dz = 0$.

Proof. See Appendix A.6. □

Proposition 6 gives us that, in general equilibrium, the marginal propensity to save out of permanent income is positive but constant whatever the level of labor income w:

$$\frac{ds}{dz} = \frac{q+2\zeta}{q-2\zeta} > 0.$$

Even if we already introduce the non-homothetic parameter, ζ, inequality in endowments has no effect on prices. Indeed, when the distribution of permanent income gets more unequal, the dissaving at the bottom is perfectly offset by the increase in saving at the top, keeping aggregate savings equal and everything else equal. Prices thus remain constant. The result of Proposition 6 on the neutrality of the permanent labor income distribution can be extended to the non-log case as long as $\sigma = \Sigma$.

Proposition 1.7.

$$\text{When } \Sigma < \sigma,\ \frac{d^2s}{dz^2} > 0, \text{ and } \frac{dq}{dz} > 0,$$

$$\text{When } \Sigma > \sigma,\ \frac{d^2s}{dz^2} < 0, \text{ and } \frac{dq}{dz} < 0.$$

[13] Neither given by the initial allocation nor a corner solution like with heterogenous β.

Proof. See Appendix A.7. □

The first part of Proposition 7 tells us that the marginal propensity to save out of permanent income increases with permanent income whenever $\Sigma < \sigma$. In that case, the permanent labor income distribution becomes non-neutral on prices. Indeed, when the permanent labor income distribution becomes more unequal, the dissaving at the bottom is more than offset by the increase in saving at the top, so the price of wealth has to increase.

The second part of Proposition 7 tells us that the price of the Lucas tree is an increasing (decreasing) function of inequality in endowments as long as the risk aversion for consumption is greater (smaller) than the risk aversion for wealth. This result is quite intuitive. When $\sigma > \Sigma$, for low-income levels, the marginal utility with respect to consumption is relatively larger than the marginal utility with respect to wealth. The household is better off by increasing consumption compared to increasing wealth.

However, as income increases, the marginal utility with respect to consumption drops faster than the marginal utility with respect to wealth. The household wants to devote a higher share of income to accumulating wealth for higher income levels. The high-income household is willing to accumulate more wealth. In general equilibrium, total wealth must sum up to 1. Any increase in the wealth of the high-income agent must be compensated by a fall in wealth of the low-income agent. Hence, the Lucas tree's price has to increase to push the low-income agent to dis-save and the high-income agent not to over-save. The marginal propensity to save out of permanent income is positive and increases with wealth.

In this model, aggregate savings must be constant and equal to 1, by definition. Thus, changes in the distribution of permanent labor income will increase the *value* of wealth without an increase in aggregate savings. In other words, who owns the wealth will impact the price of wealth. This is a key result: the permanent labor income distribution is non-neutral on prices whenever the marginal propensity to save or consume out of permanent income is not constant. When the MPS out of permanent income is constant, any change in the distribution in permanent income leaves aggregate variables constant.

We summarise what we have seen:

1. With homothetic preferences and homogeneous discount factors, the distribution of endowment is completely neutral: it does not affect wealth distribution and prices. The wealth distribution is indeterminate and is equal to the initial distribution.

2. With Stone-Geary non-homothetic preferences (preference shifter ζ *but* the same risk aversion for consumption and wealth $\sigma = \Sigma$) and homogeneous discount factors, the distribution of the endowment is now *partially* neutral: it affects the wealth distribution, *but* it does not affect prices. The wealth distribution is an interior solution (as long as the borrowing constraint is big enough and inequality is not too high).

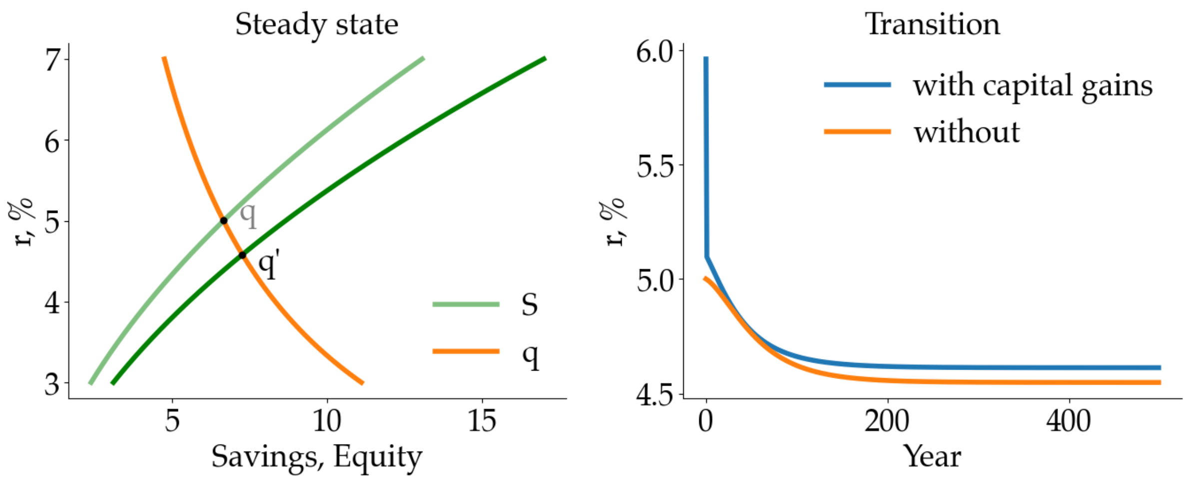

Figure 1.5: Steady-state equilibrium and evolution of returns following an increase in permanent labor income inequality

Note: The left figure shows the steady state equilibrium on the asset market. The light green curve shows the asset supply from households when inequality is low. The darker green line shows the asset supply when inequality is high. The right panel displays the equilibrium interest rate in a simulated MIT transition between those two steady states in a model with and without capital gains. See Appendix B for details.

3. With non-homothetic preferences (preference shifter ζ *and* different risk aversion for wealth $\sigma \neq \Sigma$), the distribution of endowment is not neutral: it affects the wealth distribution and prices.

The main takeaway from this discussion is that a taste for wealth is consistent with micro evidence of the positive and increasing marginal propensity to save out of permanent income. Those preferences also imply that the distribution of permanent income becomes non-neutral for asset prices. We will explore the quantitative implications it has on the pricing of assets and wealth inequality in the rest of the paper.

1.3.3 Wealth inequality dynamics

Until now, we have focused on the impact of an increase in permanent labor income inequality on the price of financial assets at the steady state. In this subsection, we focus on the impact of this increase in the price of financial assets on the dynamics of wealth inequality during the transition from a steady state with low inequality to a steady state with high inequality.

As shown in the left panel of Figure 1.5, an unexpected increase in permanent labor income inequality[14] implies that the long-term price of the financial asset q_t increases. In a

[14]In this paper, shocks are always computed as MIT shocks. That is, households unexpectedly start a new period in a new economic environment, in this case, characterized by a higher z_2 and a lower z_1. This shock was not expected by agents, but once it's realized, they expect the correct future path of prices.

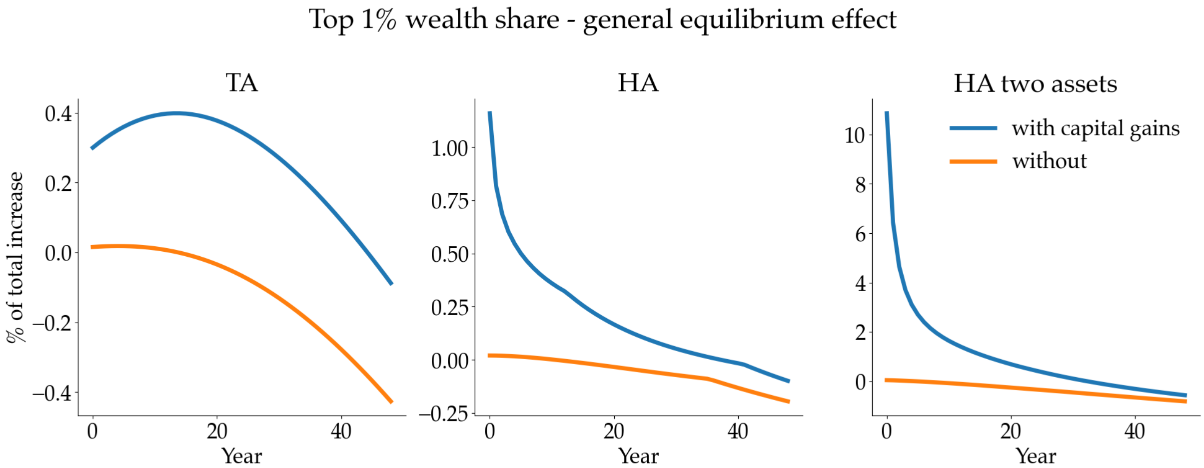

Figure 1.6: Increase in the top 1% wealth share explained by the endogenous change in returns

Note: This figure shows the general equilibrium effect on the top 1% wealth share in three different models: the two-agent models (left panel), a simple heterogeneous-agent model (center), and a two-asset heterogeneous agent model (right). See Appendix B for more details about the HA and HA-two asset models.

transition, this higher long-term price has two main effects on the return on financial assets: (1.) in the long run, the return d/q decreases, (2.) in the short run, the increase in the price creates some short term capital gains, pushing up the return. Indeed, at period 0, households bought the financial asset at the valuation of the initial steady state. However, once the shock is revealed, the price jumps to a higher value, and the return becomes

$$r_0 = \frac{d + q_1 - q_{ss}}{q_{ss}} > \frac{d}{q_{ss}} \quad \text{if} \quad q_1 > q_{ss}.$$

This one-time increase in the return on financial assets has, in turn, an impact on the distribution of wealth, since it redistributes a share of total income towards the owners of capital. Figure 1.6 shows the effect of this endogenous change in returns on the top 1% wealth share in three different models of household behavior.

In the three models, the effect follows a similar pattern: it is positive for the first periods of the transition and becomes negative over the long run. This pattern follows the two effects on the return mentioned before in the short run, rich households enjoy unexpected capital gains on their wealth, increasing their financial income and hence their wealth position. Over the long run, however, the effect reverses and the higher valuations decrease the interest rate and their financial income.

Even though the patterns are similar in the two-agent, the one-asset heterogeneous agent model, and the two-assets heterogeneous agent model, the magnitude of the effect varies importantly. In the two-agent model, the general equilibrium effect is small, only 0.4% of the total increase in the 1% wealth share at the peak. In contrast, the general equilibrium effect is two times larger in the one-asset heterogeneous agent model, reflecting the higher degree of wealth inequality. Indeed, when the steady-state top 1% wealth share is higher, an increase in financial returns accrues mostly to rich households, amplifying the effect on wealth inequality. The two-asset structure amplifies this effect further by allowing households to endogenously invest a higher share of their wealth into the illiquid asset. Since capital gains are paid only to the illiquid account, the distribution of capital gains is even more unequal than in the heterogeneous-agent model. In this setup, the general equilibrium effect is large: more than 10% of the total increase in the 1% wealth share is explained by the endogenous change in return.

This exercise shows that our analytical results on the non-neutrality of the distribution of permanent income on the price of financial assets are fairly general and still hold when we add idiosyncratic productivity shocks and a two-asset structure. However, those settings have a large impact on the magnitude of the general equilibrium effect on the top 1% wealth share, as they amplify the share of capital gains going to the top 1%. Our quantitative model in the next section will build on this insight, using a more realistic supply side.

To understand the specificity of the capital gains effect, we compare the general equilibrium effect in this baseline model to a model that allows agents to accumulate physical capital and to produce the consumption goods using a Cobb-Douglas production function[15]. In this model, the relative price of capital compared to the consumption good is one, and capital gains are thus absent by construction. The orange line in Figures 1.6 and 1.5 display the equilibrium return and the general equilibrium effect in this model. We abstract from depreciation, and the returns are thus given by

$$r_t = \alpha Z k_t^{\alpha-1}.$$

In this economy, an increase in savings has a "trickle-down" impact, as in most neoclassical models. The higher savings from households increases the stock of physical capital, which increases output and decreases returns. Since the price of physical capital is set to one compared to the consumption good, the transition never features capital gain and the general equilibrium effect is strictly negative. The higher accumulation of capital decreases the financial income of the rich, limiting their accumulation of wealth.

1.4 Quantitative model

Our analytical model suggests that changes in the distribution of permanent labor income can strongly impact asset prices if we account for the relationship between saving rates and permanent income. We propose a model incorporating this insight into an Aiyagari-style economy with two assets, imperfect competition, and a permanent income distribution.

[15]See Appendix B for more details on the calibration and the simulations of this economy.

There is no aggregate TFP risk, and aggregate shocks on the distribution of permanent labor income are modeled as MIT shocks[16].

1.4.1 Setup

Households

Demographic structure. There is a continuum of the household of mass one. Each household supplies inelastically one unit of labor with a level of permanent productivity z_i, and has a probability of dying ξ at each period[17]. Every household is also subject to persistent, idiosyncratic productivity shocks. The productivity e_t follows a log AR(1) process:

$$\log(e_t) = \rho \log(e_{t-1}) + \varepsilon_t^e \text{ with } \varepsilon_t^e \sim \mathcal{N}(0, \sigma^e).$$

Households can insure against the risk of dying with a non-optimal level of wealth by buying an insurance contract on an annuity market, as in Yaari (1965) and Blanchard (1985). When a household dies, its wealth is redistributed to surviving households by the annuity market, and another household is born with zero wealth to maintain a constant population.

Portfolios. To insure against idiosyncratic shocks and satisfy their taste for wealth, households can invest in two saving instruments with different degrees of liquidity. They can invest in a liquid asset b_{t+1} that yields a return r_t^b, or an illiquid asset a_{t+1} that yields a return r_t^a. Accumulating or decumulating illiquid assets is subject to a convex adjustment cost

$$\chi\left(a_{t+1}, a_t\right) = \frac{\chi_1}{\chi_2} \left| \frac{a_{t+1} - \left(1 + r_t^a\right) a_t}{\left(1 + r_t^a\right) a_t + \chi_0} \right|^{\chi_2} \left[\left(1 + r_t^a\right) a_t + \chi_0\right].$$

Households also face a borrowing constraint $b_{t+1} \geq \bar{b}$ on the safe asset, and risky assets cannot be borrowed $a_{t+1} \geq 0$.

Preferences. Households get utility from consumption c_t and from their total wealth level $a_t + b_t$. They have non-homothetic preferences, and the value function is given by:

$$V(a_t, b_t, e_t, z_i) = \max_{a_{t+1}, b_{t+1}} \left\{u(c_t) + v(a_t + b_t) + (1 - \xi)\beta \mathbb{E}_e V(a_{t+1}, b_{t+1}, e_{t+1}, z_i)\right\}$$

$$\text{subject to } c_t + a_{t+1} + b_{t+1} + \chi(a_{t+1}, a_t) = (1 + r_t^a)a_t + (1 + r_t^b)b_t + (1 - \tau_t)(z_i e_t w_t)^{1-\theta},$$

where $u(c_t) = \frac{c_t^{1-\sigma}}{1-\sigma}$ and $v(a_t + b_t) = \frac{(a_t + b_t + \zeta)^{1-\Sigma}}{1-\Sigma}$.

[16] A MIT shock is a one-time unexpected shock on some parameter. From the model point of view, this shock is a zero-probability event, and the following transition towards the steady state is completely deterministic. Thus households don't have rational expectations with respect to the variable that is shocked, in this case, the distribution of permanent income.

[17] l stands for low, m for medium, and h for high.

Government.

The government finances its exogenous spending G_t and its debt repayment $r_t^b D_t$ by taxing four types of income: (1) a progressive tax on labor income, defined by the parameters $\tau_{t,l}$ and λ, as in HSV, (2) a tax on corporate revenues τ_c, (3) a tax on dividends τ_d, (4) a tax on capital gains τ_g. The law of motion of the public debt is :

$$D_{t+1} = D_t(1 + r_t^b) + G - \Gamma_t - \tau_d d_t - \tau_c(Y_t - Lw_t - \delta K_t) - \tau_g(p_{t+1} - p_t),$$

with $\Gamma_t = Lw_t - \sum_i (1 - \tau_l) \int (w_t e_t z_i)^{1-\lambda} d\mu_t$. We take $\tau_c, \tau_{t,d}, \tau_g$ and τ_l as exogenous. At the steady state, G adjusts to maintain a balanced budget. In the transition, the government follows a fiscal rule[18]

$$G_{ss} - G_{l,t} = \phi(D_{t+1} - D_{ss}).$$

Firms

The supply side is composed of an intermediate-good sector in imperfect competition and final-good producers in perfect competition. The capital stock is owned by the firms in the intermediate sector.

Final-good producer. The representative final-good producer aggregates a continuum of intermediate inputs indexed by j:

$$Y_t = \left(\int_0^1 y_{j,t}^{\frac{\varepsilon-1}{\varepsilon}} dj \right)^{\frac{\varepsilon}{\varepsilon-1}}.$$

The price of the final good is normalized to one. The problem of the representative final-good producer is given by:

$$\max_{\{y_{j,t}\}_{i \in [0,1]}} \left(\int_0^1 y_{j,t}^{\frac{\varepsilon-1}{\varepsilon}} dj \right)^{\frac{\varepsilon}{\varepsilon-1}} - \int_0^1 p_{j,t} y_{j,t} di.$$

Taking the first-order condition with respect to a variety $y_{j,t}$, we get the demand for each intermediary input j:

$$y_{j,t} = \left(\frac{p_{j,t}}{P_t} \right)^{-\varepsilon} Y_t.$$

With $P_t = \left(\int_0^1 p_{j,t}^{1-\varepsilon} dj \right)^{\frac{1}{1-\varepsilon}}$ being the price index. As the representative final-good producer is in perfect competition, the price of the final good will be equal to the marginal cost, P_t. We normalize the price of the consumption good to 1.

Intermediate producers. The firms in the intermediate goods sector produce those inputs using Cobb-Douglas technology, make investment decisions, and pay a corporate tax, a

[18] This fiscal rule is used only for computational purposes to help clear the liquid market during the transition. It does not affect our core results.

dividend tax, and a capital gains tax to the government. They pay a dividend

$$d_{j,t} = (1-\tau_c)\Big(y_{j,t} - \sum_i w_{i,t} l_{i,t}\Big) - k_{j,t+1} + (1-\delta)k_{j,t} + \tau_c \delta k_{j,t},$$

where

$$y_{j,t} = k_{j,t}^{\alpha} l_{j,t}^{1-\alpha}.$$

They freely set their prices to maximize intertemporal profits:

$$V(k_t, q_{t-1}) = \max_{k_{t+1}, q_t, l_t} (1-\tau_d)d_t + \tau_g q_{t-1} + (1-\tau_g)\kappa(r^a_{t+1})\frac{V_{t+1}(k_{t+1}, q_t)}{1+r^a_{t+1}},$$

subject to the technology constraint and the demand function of the final-good producer:

$$y_{j,t} = {p_{j,t}}^{-\varepsilon} Y_t.$$

The $\kappa(r^a_{t+1})$ in the Bellman equation of the firm creates a wedge between the discount factors of the owners of the firm and the discount factor that the managers of the firm will use to determine future investment in physical capital. We use this friction to match the aggregate Tobin's Q in 1970, as in Brun and Gonzalez (2017). The following subsection explains how this friction and the corporate and dividend taxes affect the equity and physical capital schedule.

The intermediate producer chooses labor and investment to maximize the firm's value. This yields the following first-order conditions:

$$\frac{1+\frac{r^a_t}{1-\tau_g}}{\kappa(r^a_t)} = \alpha(1-\tau_c)\frac{\varepsilon-1}{\varepsilon} k_{j,t}^{\alpha-1} l_{j,t}^{1-\alpha} + 1 - (1-\tau_c)\delta,$$
$$w_t = (1-\alpha)\frac{\varepsilon-1}{\varepsilon}\frac{y_{j,t}}{l_{j,t}}.$$

Since we assume that all intermediary firms are the same in our economy, that the aggregate labor supply is equal to 1, and that there is no price rigidity, $y_{j,t} = y_t$, total output is given by:

$$Y_t = \Big(\int_0^1 y_t^{\frac{\varepsilon-1}{\varepsilon}} dj\Big)^{\frac{\varepsilon}{\varepsilon-1}} = y_t = k_t^{\alpha}$$

Illiquid asset market In the illiquid asset market, in period t, equity shares are traded at a price p_{t+1}. The return on the illiquid asset is given by:

$$1 + r^a_{t+1} \equiv \frac{(1-\tau_d)d_{t+1} + q_{t+1} - \tau_g(q_{t+1} - q_t)}{q_t}.$$

Using this relationship, the price of the firm can be expressed as a function of dividends and returns, assuming no bubble:

$$q_t = \sum_{j=1}^{\infty} \left(\prod_{i=0}^{j-1} \frac{1}{1 + \frac{r^a_{t+1+i}}{1-\tau_g}} \right) \frac{1-\tau_d}{1-\tau_g} d_{t+j}.$$

Definition 1.2. *Let $\mathcal{A}$ be the space for illiquid wealth, $\mathcal{B}$ be the space for liquid wealth, $\mathcal{Z}$ the space for productivity, and $\mathcal{S}$ the space for permanent type.*

An equilibrium in this economy is defined as paths for household and firm decisions $\{a_{t+1}, b_{t+1}, k_{t+1}, c_t, d_t, l_t\}_{t=0}^{\infty}$, factor prices $\{r^a_t, r^b_t, w_t\}_{t=0}^{\infty}$, the tax policy $\{\lambda_t, \tau_{l,t}, \tau_{t,c}, \tau_{t,d}, \tau_{t,g}\}_{t=0}^{\infty}$, measures $\{\mu_t\}_{t=0}^{\infty}$, and aggregate quantities, such that, for all t: (1) households and firms solve their objective functions, (2) the sequence of distributions satisfies aggregate consistency conditions, (3) the government budget and decision rue constraint holds, and (4) all markets clear at all times:

1. *The liquid asset market clears:*

$$\int_{A\times B\times Z\times\mathcal{S}} b d\mu_t(a,b,e,z) = D.$$

2. *The illiquid asset market clears:*

$$\int_{A\times B\times Z\times\mathcal{S}} a d\mu_t(a,b,e,z) = q_{t-1}.$$

3. *The labor market clears:*

$$l_t = 1.$$

4. *The goods market clears:*

$$Y_t + (1-\delta)K_t = C_t + K_{t+1} + \int_{A\times B\times Z\times\mathcal{S}} \chi(a_{t+1}, a_t) d\mu_t(a,b,e,z).$$

1.4.2 Labor income inequalities and Tobin's Q

Valuation effects under imperfect competition

A key result of this paper is that in the presence of non-homothetic preferences and with imperfect competition, an increase in permanent labor income inequality will increase the Tobin's Q. In this section, we focus on the steady change for analytical clarity.

In the previous section, we studied two polar examples of the supply side. First, a model with a deterministic Lucas tree, where the asset supply is constant and hence all changes in asset demand from households imply an equivalent change in asset prices. This was a pure model of *valuation effects*. Then, we studied a model in which the price of financial assets is set to one and where all changes in asset demand from households imply an equivalent change in *physical quantities*. The imperfect competition setting studied in this quantitative model is an intermediate case, where changes in asset demand from households imply a change in both the price of financial assets and the quantities of physical capital. However, the price of capital reacts more to changes in asset demand than the quantity of physical capital, which means that an increase in asset demand increases the average Tobin's Q, defined as the value of the firm divided by the value of its physical capital.

The reason for this valuation effect is intuitive. With imperfect competition, the valuation of the firm at the steady state can be decomposed in two terms: the net discounted normal profits, and the net discounted excess profits stemming from the pricing power of the firm. A decrease in the real return on illiquid assets will increase the firm's valuation because excess profits will now be discounted at a lower rate. Indeed, the price of equity at the steady state can be written as[19]

$$\begin{aligned} q &= (1-\tau_d)\frac{d}{r^a} \\ &= \underbrace{\frac{1-\tau_d}{1-\tau_g}\frac{\overline{\kappa} r^a K}{r^a}}_{\substack{\text{Net discounted} \\ \textit{normal} \text{ profits}}} + \underbrace{(1-\tau_c)(1-\tau_d)\frac{Y}{r^a \varepsilon}}_{\substack{\text{Net discounted} \\ \textit{excess} \text{ profits}}}. \end{aligned}$$

Hence, when r^a falls, the firm's valuation q increases because of two effects:

$$\frac{dq}{dr^a} = \frac{1-\tau_d}{1-\tau_g}\overline{\kappa}\frac{dK}{dr^a} + \frac{(1-\tau_c)(1-\tau_d)}{\varepsilon}\frac{d(Y/r)}{dr^a}.$$

First, the fall in r^a increases the demand for capital K, and so, the value of the firm. Secondly, the fall in r^a increases the discounted excess profit from the imperfect market structure $\frac{Y}{r^a \varepsilon}$. Due to the second effect, the firm's valuation overreacts to variations in the return on the illiquid market compared to the demand for capital:

$$\left|\frac{dq}{dr^a}\right| > \left|\frac{dK}{dr^a}\right|.$$

Therefore, the average Tobin's Q increases whenever the return on the illiquid market r^a falls:

$$\begin{aligned} Q &= \frac{q}{K} \\ &= \frac{1-\tau_d}{1-\tau_g}\overline{\kappa} + (1-\tau_c)(1-\tau_d)\frac{Y}{rK\varepsilon} \quad \text{and} \quad \frac{dQ}{dr^a} < 0. \end{aligned}$$

Figure 1.7 summarizes those findings by representing the equilibrium in the illiquid asset

[19] Here, we assume that the friction takes the form $\kappa(r_t^a) = \frac{1+\frac{r_t^a}{1-\tau_g}}{1+\overline{\kappa}\frac{r_t^a}{1-\tau_g}}$. This is to ensure that the capital and price schedules are monotonic. In our calibration, $\overline{\kappa} < 1$.

market. The green line shows the supply of savings from households, while the blue line shows the value of the firm and the orange line shows the capital stock of the firm. The equilibrium is at the intersection of the supply of savings from households and the value of the firm. On the household side, as shown in Section 3, any increase in permanent labor income inequality will increase aggregate savings due to the increasing marginal propensity to save out of permanent income. The dissaving at the bottom is more than offset by the increase in savings at the top, and the supply of savings is shifted to the right. In general equilibrium, r^a should thus decrease. On the firm's side, the imperfect competition setting implies that the price of the firm will react more to changes in returns than its stock of capital, as in Brun and Gonzalez (2017). Thus, when we shift the saving curve upward, as in Figure 1.7, the value of the firm will increase by more than the stock of capital, increasing Tobin's Q.

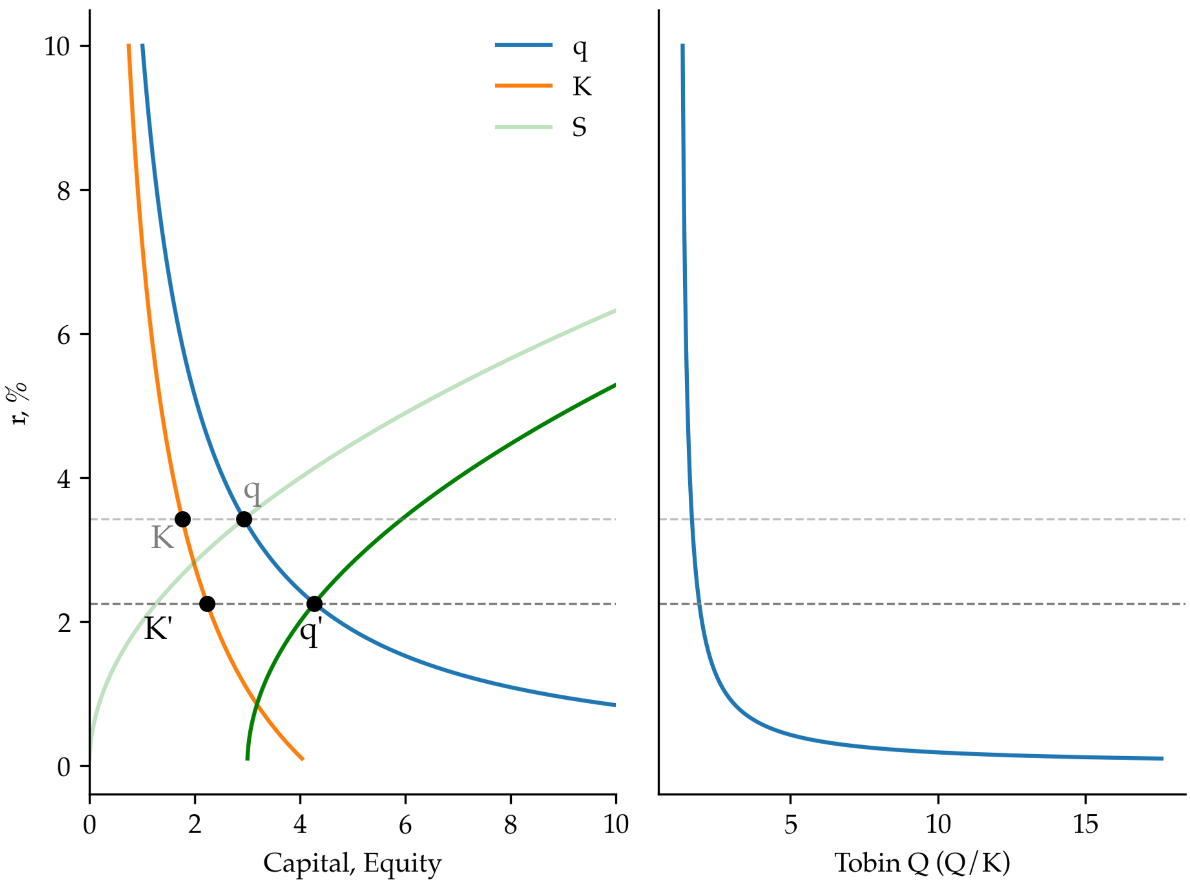

Figure 1.7: Impact of an inequality shock

Note: This figure shows the equilibrium on the illiquid market at the steady state. The blue line shows the value of the firm as a function of the return r^a, the orange line shows the capital stock of the firm and the green lines show the saving curve of households.

Note that the key element in this mechanism is imperfect competition: the price of the firm overreacts to changes in returns because of the increase in net discounted excess profits. The taxes on dividends, capital gains, and corporate revenues, along with the friction on the discount factor of the firm, are not enough to create variations in Tobin's Q when the return on the illiquid asset changes. Indeed, in the perfect competition case, when $\varepsilon \to \infty$, we have

$$Q = \frac{1-\tau_d}{1-\tau_g}\overline{\kappa} \quad \text{and} \quad \frac{dQ}{dr^a} = 0.$$

However, they allow us to match the Tobin's Q observed in the data before 1970.

Capital gains in the transition

In the previous subsection, we showed how an increase in labor income inequality impacts the firm's valuation at the steady state. In this section, we explain how this inequality shock creates some short-term capital gains.

As we showed in the analytical model, an unexpected shock in the distribution of permanent labor income – i.e., a shock on (z_h, z_m) – increases desired aggregate savings. This increase in aggregate savings decreases the long-term real returns (r^a, r^b). As households are surprised by the change in the path of variables, the ex-ante anticipated equity price does not equal the ex-post equity price, increasing the realized return on illiquid assets in period 0 of the transition. The expected return at the steady state was

$$r^a_{ss} = \frac{(1-\tau_c)d_{ss}}{q_{ss}},$$

but the realized return is

$$r^a_0 = \frac{(1-\tau_c)d_{ss} + (1-\tau_g)(q_1 - q_{ss})}{q_{ss}} > r^a_{ss} \quad \text{if} \quad q_1 > q_{ss},$$

where q_1 is the price at the first period of the transition. Only this initial return on the illiquid asset following a permanent labor income shock differs from the expected return, and there is perfect foresight for the remaining periods of the transition. However, because we model the increase in permanent labor income inequality as a sequence of unexpected MIT shocks between 1980 and 2020, households are consistently surprised by the higher return on the illiquid asset for the initial 50 years of the transition.

This myopic behavior of households in the transition is obviously a strong simplifying assumption, but we argue that it captures some realistic features of household behavior that have been recently developed in works that include some behavioral frictions in heterogeneous models. Our model can be seen as a reduced-form implementation of the behavioral friction introduced by Auclert, Bardóczy, et al. (2021). In their model, households infrequently update their information sets about aggregate shocks and the price of illiquid assets.

An alternative would be to assume that households had perfect knowledge of the future increase in permanent labor income in 1980. This would be unrealistic, as it implies that households forecasted the entire evolution of the distribution of permanent labor income accurately to predict changes in returns, whereas economists themselves have only recently understood this increase in inequality. Another counterfactual implication of this alternative is that since rich households expect their wage to increase in the future, they would decrease savings today to smooth their consumption, whereas poor households would do the opposite. This consumption smoothing behavior would imply that an increase in permanent labor income inequality decreases wealth inequality.

A last possibility is to compute a one-time shock on permanent labor income inequality. The capital gains would thus be concentrated on the first period of the transition, which speeds up the increase in wealth inequality. This solution has the benefit of being orders of magnitude faster computationally than our benchmark results but doesn't change the main results that we describe in the next subsection. The main results of this one-time-shock transition can be found in the Appendix.

1.4.3 Calibration

We calibrate our initial steady state on U.S. data between 1960 and 1970.

Permanent income distribution. We calibrate the distribution of permanent labor income inequality, characterized by the parameters $\{z_l, z_m, z_h\}$ on the labor income share observed in the U.S., as measured by Piketty (2018). To move from the empirical labor share to the parameters z_s, we use the following formula

$$z_s = \frac{\omega_s}{\mu_s},$$

where ω_s is the labor income share observed in the data and μ_s is the mass of agents with permanent income z_s in the model.

Households. As standard in the literature, we fix $\sigma = 2$ and internally calibrate the rest of the preference parameters of the household to jointly match the wealth distribution in 1970 and the marginal propensity to save computed on the SCF in 1983 (see Appendix for details). We calibrate the illiquidity parameters on the portfolios observed in the SCF in 1989. We use the year 1989 as it is the oldest vintage available in the SCF with detailed information about portfolio composition. For the idiosyncratic productivity shocks, we follow Straub (2019) and set $\rho = 0.9$ and $\sigma_e = 0.2$.

Table 1.1: Wealth distribution at the initial steady state

	Bottom 50%	Middle 40%	Top 10%	Top 1%	Top 0.1%
Data PSZ (1970)	1	29	69	26	9
Model	3	29	67	27	9

Government. We fix $(\tau_{1980,c}, \tau_{1980,d}, \tau_{1980,g})$ to $(0.35, 0.4, 0.19)$, as reported by Brun and Gonzalez (2017), and we adjust B to match an aggregate ratio $\frac{B}{q+B} = 30\%$ to match the illiquid-to-liquid ratio reported in the national accounts. λ_{1980}, the progressivity parameter in the HSV tax function is equal to 0.18, as in Ferriere, Grübener, et al. (2023). We then set $\frac{G}{Y} = 10\%$ and use the labor tax rate $\tau_{l,t}$ to solve the budget constraint of the government.

Table 1.2: Share of illiquid assets along the wealth distribution

	Q1	Q2	Q3	Q4	Q5	D10	P100
Data SCF (1989)	31	58	71	71	78	79	83
Model	10	39	45	55	76	77	91

Firms. We target a labor share of $\frac{2}{3}$, as is standard in the literature, and fix the elasticity of substitution between inputs $\varepsilon = 6$ to obtain a markup of 20% and adjust the capital share α to match a labor share of $\frac{1}{3}$. We adjust the depreciation rate δ to obtain a ratio $\frac{K}{Y} = 250\%$. We then adjust the firm's patience κ to obtain a Tobin's Q of 0.7.

Table 1.3: Marginal propensity to save along the permanent labor income distribution

	MPS low	MPS mid	MPS high	MPS Agg
SCF (1983)	0.28	0.45	0.68	0.3
Model	0.25	0.46	0.52	0.27

Table 1.1, Table 1.3, and Table 1.2 report the wealth distribution, the marginal propensity to save along the distribution of permanent labor income, and the portfolio shares at the initial steady state. We use the SCF in 1983 to estimate the marginal propensity to save out of permanent income since it is the only year where the SCF had a true panel[20]. Our model fits well the very top of the wealth distribution, up to the 0.1% share, but slightly underestimates the top 10% wealth share and overestimates the share of the bottom 50%. Our calibration also reproduces the stylized facts of the marginal propensity to save along the distribution of permanent income, and we obtain an aggregate MPS of around 0.3, a calibration similar to the one of Straub (2019). Finally, our portfolio shares match the increasing nature of illiquid assets along the distribution of wealth but underestimate the share of illiquid assets owned by the middle of the distribution.

[20]We follow Kumhof, Rancière, and Winant (2015) to estimate the marginal propensity to save, using the same dataset. Note that a panel is also available for the SCF in 2008, but given the specificity of this year in the U.S., we choose not to use it to calibrate our model.

Table 1.4: Calibration of the model

Parameters	Description	Value	Source
Preferences			
β	Discount rate	0.92	Internally calibrated
γ	Weight on taste for wealth	2	Internally calibrated
σ	CRRA coefficient for consumption	2	
Σ	CRRA coefficient for wealth	1.7	Internally calibrated
ζ	Stone-Geary parameter for wealth	6	Internally calibrated
Illiquidity cost			
χ_0		0.8	Internally calibrated
χ_1		3	Internally calibrated
χ_2		2	Internally calibrated
Production			
α	Capital share	0.2	Capital share of 0.33
z_s	Permanent labor income		Piketty et al (2018)
ε	Inverse markup	6	
δ	Depreciation rate	0.07	Capital-output ratio of 2
$\overline{\kappa}$	Friction in the firm's discount rate	0.1	Target a Tobin's Q of 0.5
labor income process			
ρ	Auto-correlation of idiosyncratic shocks	0.9	Straub (2019)
σ_e	Variance of idiosyncratic shocks	0.2	Straub (2019)
Government			
D	Government debt	0.9	Internally calibrated
ϕ_τ	Elasticity of public debt	0.1	
λ_{1980}	Tax progressivity	0.17	Ferriere et al (2018)
τ_l	Labor income tax	0.12	
$\tau_{1980,c}$	Corporate income tax, 1980	0.35	Brun, Gonzales (2017)
$\tau_{1980,d}$	Dividend tax, 1980	0.4	Brun, Gonzales (2017)
$\tau_{1980,g}$	Capital gains tax, 1980	0.19	Brun, Gonzales (2017)

1.5 Impact of an increase in permanent labor income inequality

As shown in the previous section, our quantitative model captures the key relationships between labor income inequality, the marginal propensity to save, and households' portfolios while generating a realistic distribution of wealth. We now ask two questions. First, what is the role of each element in our model in determining the distribution of wealth at the steady state? Secondly, how and through which channel did the increase in post-tax permanent labor income inequality affect the distribution of wealth? We answer these questions by (1.) proposing a simple decomposition of the distribution of wealth at the steady state, as in Hubmer, Krusell, and Smith (2021), and (2.) by running a transition matching the observed increase in labor income inequality in the data in partial equilibrium and general equilibrium.

1.5.1 Steady-state decomposition

Table 1.5: Contribution of different channels for steady state inequality

#		Bottom 50%	Middle 40%	Top 10%	Top 1%
1	No permanent labor income inequality ($z_s = 1$)	5	18	-23	-16
2	No transitory shocks ($\sigma_e = 0$)	-1	-7	7	5
3	No tax redistribution ($\lambda = 0$)	-1	-6	7	4
4	One-asset ($\chi_1 = 0$)	0	2	-2	-3
5	Perfect competition ($\varepsilon = \infty$)	5	9	-15	-14
6	No capital tax ($\tau_g = 0$)	0	-1	1	6
7	No labor tax ($\tau_l = 0$)	1	6	-7	-6

Note: This table displays the p.p. change in the wealth distribution for each quantile after removing a given feature of the model, keeping the calibration constant. For example, the first row says that removing heterogeneity in permanent labor income decreases the top 1% wealth share by 16 p.p.

Table 1.5 decomposes the factors behind the distribution of wealth in our full model. The main drivers of inequality at the steady state are the distribution of permanent labor income (line 1), the imperfect competition setting (line 5), and the tax on capital (line 6). Note that because of the non-linear nature of the model, the different effects don't sum to the total wealth shares.

The major role of the distribution of permanent labor income is not surprising. As we have seen in Section 3, with a non-homothetic taste for wealth, households with higher levels of permanent labor income have a higher marginal propensity to save and will thus accumulate more wealth than poorer ones. In contrast, the idiosyncratic transitory shocks have a smaller impact on the distribution of wealth, which explains why standard heterogeneous-agent models usually have a hard time generating high degrees of wealth inequality. As in Hubmer, Krusell, and Smith (2021), the idiosyncratic transitory productivity shocks *dampen* wealth inequality due to the precautionary motive.

Secondly, the imperfect competition setting also generates a high level of wealth inequality. In our simulations, we set ε to a very high value and adjust α to keep the labor share constant. Thus, the impact of switching to perfect competition displayed here does not come from a change in the labor share but from two different effects on the firm side: an increase in the demand for capital of the firm and a decrease in the equilibrium profits and valuation of the firm. Those two effects increase the capital stock in equilibrium and, hence, the total output, increasing wages and decreasing wealth inequality.

Thirdly, removing the taxes on dividends, capital gains, and corporate revenues also decreases wealth inequality in equilibrium. This comes from two effects. First, for a given level of physical capital, removing those taxes increases dividends and, thus, the return on equity, benefiting households already owning a lot of wealth. Secondly, removing those taxes also changes the firm's demand for capital and its valuation in equilibrium. In our calibration, this increases the Tobin's Q and decreases the quantity of physical capital in the economy, decreasing output and wages and amplifying wealth inequality.

Finally, the two-asset structure endogenously creates the type of "scale-dependence" described by Gabaix et al. (2016); that is, the return becomes an increasing function of wealth. Indeed, due to the transaction cost associated with illiquid assets, portfolios are not homogenous across the wealth distribution. At the bottom of the wealth distribution, the probability of hitting the borrowing constraint makes households risk averse, and, as a result, poor households prefer to hold liquid assets. As households get richer, the probability of hitting the constraint falls, and the fraction of risky assets in their portfolio increases, increasing the total returns they enjoy on their wealth. This mechanism remains relatively small since the illiquidity premium is small in our model. It is, however, important in determining the strength of the general equilibrium effect, as we will show in the next section.

1.5.2 Transition

We now focus on the main quantitative exercise of this paper: the simulation of this economy following a shock on the distribution of permanent labor income. More precisely, we simulate a sequence of unexpected MIT shocks on the sequence of (z_h, z_m, z_l) and on the tax progressivity parameter λ_t, using the Sequence Space Jacobian method (Auclert, Bardóczy, et al. 2021). A description of the algorithm is available in the Appendix. We set the $(z_{l,t}, z_{m,t}, z_{h,t})$ to the pre-tax labor income shares observed in the data in Piketty, Saez, and Zucman (2018) from 1970 to 2020. As shown in Figure 1.8, we have a perfect match for the top 10% and top 1% labor income shares since there is a one-to-one mapping between those empirical targets and our parameters. For the progressivity parameter λ_t, we use estimates from Ferriere and Navarro (2018).

Prices. Let us first focus on the change in prices. Figure 1.9 plots the evolution of the wealth-to-output, Tobin's Q, and returns during the transition. First, the wealth-to-output increases by 10 p.p. compared to the initial steady state. Due to imperfect competition, most of the increase in wealth comes from a price effect instead of a quantity effect, and we thus capture the qualitative evolution of wealth in the U.S. Secondly, the Tobin's Q moves from 0.84 in 1970 to 0.9 in 2020, due to those valuation effects. Finally, the illiquidity premium increases as the return on the safe asset decreases while the return on the illiquid assets increases slightly due to the unexpected nature of capital gains. The path followed by returns is consistent with the main finding of Reis (2022), who empirically observed a relatively stable return on capital over the last 20 years, combined with a fall in the return on the liquid asset.

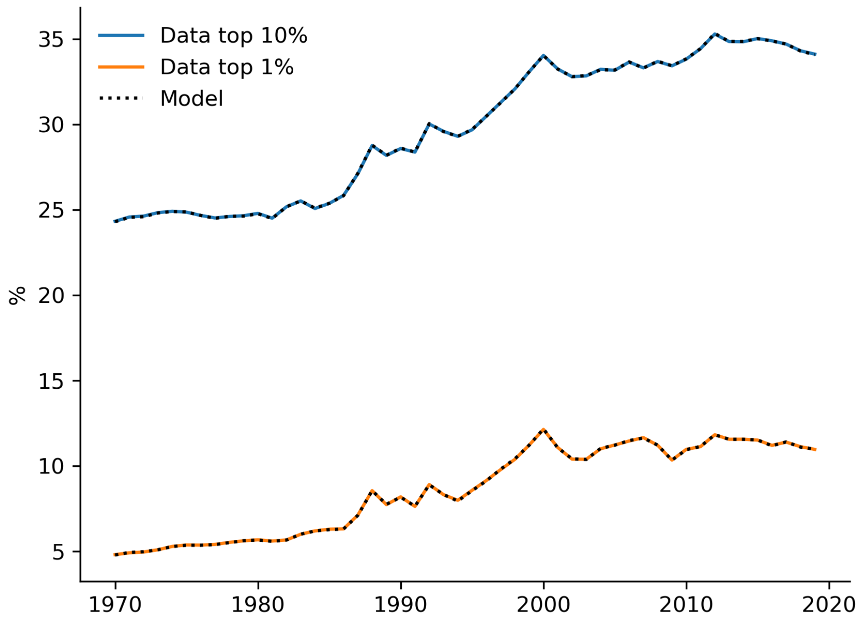

Figure 1.8: Top labor income shares in the data and in the model

Note: This figure shows the top pre-tax labor income shares in the data (Piketty et al. 2018) and in our model.

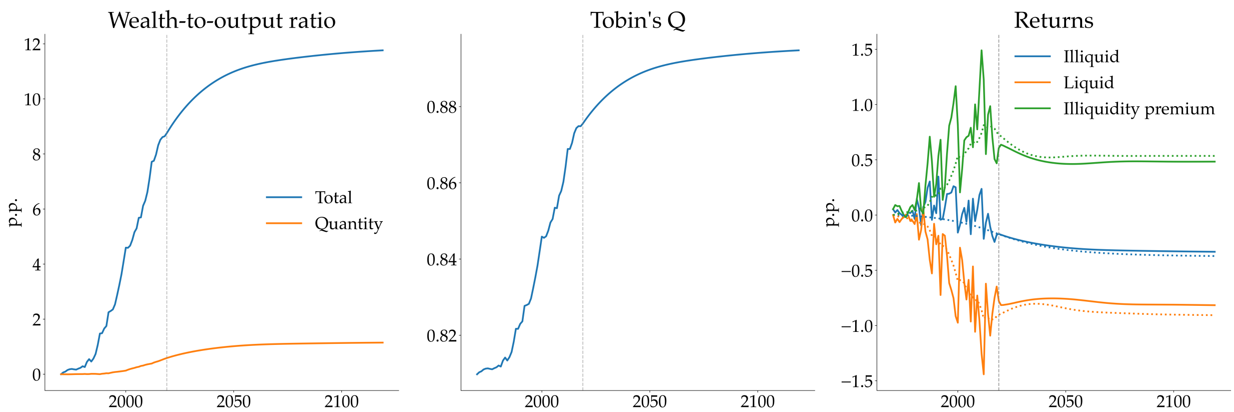

Figure 1.9: Evolution of prices in the model

Note: The figure on the left shows the p.p. increase in the wealth-to-output ratio in blue and the increase in the physical capital stock to output in orange. The middle graph shows the evolution of the Tobin's Q. The right figure plots the evolution of the returns, with the dotted line showing the evolution of returns in the perfect competition case. Note that the changes are volatile until 2020 because we use the actual changes in permanent labor income observed in the data. They are smooth afterward because of the lack of additional shocks.

All those trends continue even after permanent labor income inequality stops increasing. Specifically, our model then predicts a long-term decrease in the return on capital that will remain modest compared to the decrease in the safe asset, increasing the illiquidity premium. This happens for two reasons. First, while capital gains push up the short-term return on the illiquid assets, the long-term return on the illiquid asset is determined by the marginal productivity of capital. As we have shown before, with imperfect competition, most of the increase in wealth comes from a valuation effect, and the economy accumulates very little physical capital. The long-term marginal productivity of capital will thus decrease very little, and the same will be true of the return on the illiquid asset. Secondly, the elasticity of the demand for safe assets from the government with respect to the interest rate r^b is zero, while the elasticity of the demand for risky assets of the firms with respect to the interest rate r^a is negative. Hence, when the return on the risky market falls, the demand from firms increases, which limits the fall in the return on the risky market. On the safe market, the demand from the government does not increase with the fall in return on the safe market. Therefore, the return on the safe market falls by more than the return on the risky market.[21]

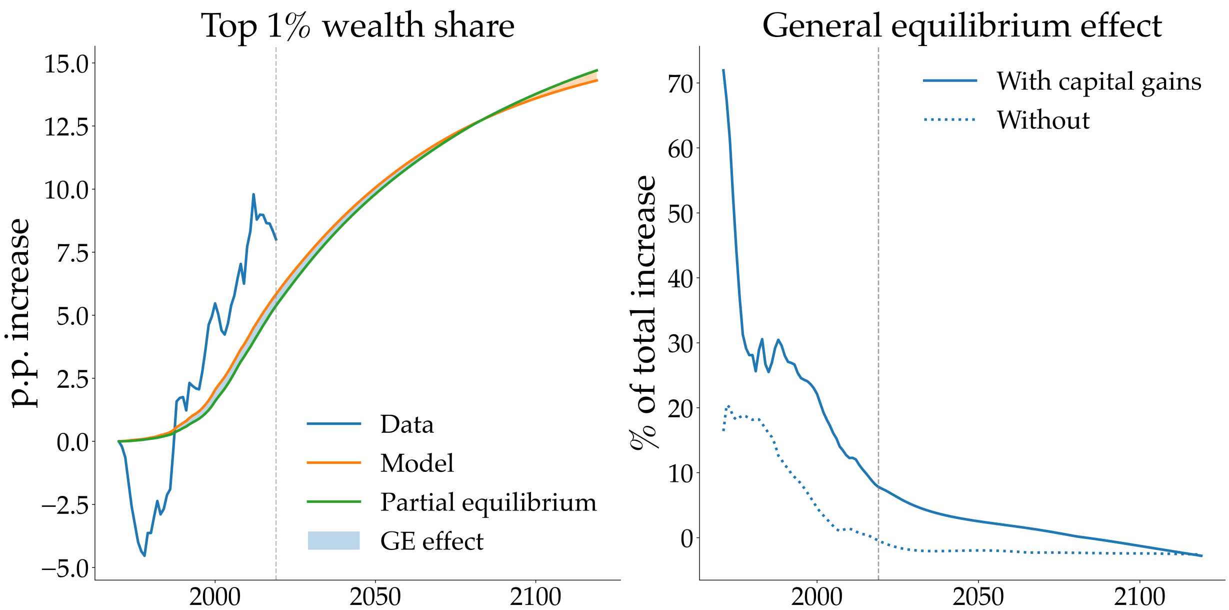

Figure 1.10: Increase in the top 1% wealth share and general equilibrium effect

Note: The figure on the left shows the p.p. increase in the top 1% wealth share in the model and the data. The orange line shows the increase in general equilibrium, and the green line shows the increase in partial equilibrium, keeping returns and wages constant. The shaded area between the two is the general equilibrium effect. The figure on the right displays this general equilibrium effect as a percentage of the total increase in wealth inequality in the model. The dotted blue line shows the same general equilibrium effect in a model with perfect competition and no capital gains.

Wealth inequality. We can now focus on the response of wealth inequality, which we

[21]This is driven by the fact that our model's supply of safe assets consists exclusively of public debt and that we assume that public debt remains constant in the transition. This is obviously a simplifying assumption but is in line with the fact that the share of risky assets in households' portfolios has increased significantly over the past 50 years.

decompose in a partial equilibrium and a general equilibrium effect. To isolate the general equilibrium effect, we run a transition in partial equilibrium, keeping prices constant and only allowing the parameters $\{z_s\}$ to change. We then run a transition in general equilibrium, adjusting all prices to maintain market clearings. We then define the general equilibrium effect on the top wealth share as

$$GE_t = \frac{\text{Top wealth share}_t^{\text{general}} - \text{Top wealth share}_t^{\text{partial}}}{\text{Top wealth share}_t^{\text{general}} - \text{Top wealth share}_{ss}^{\text{general}}}.$$

Figure 1.10 displays the main result of our model. The left panel shows the increase in the top 1% wealth share due to the increase in permanent labor income, while the right panel shows our measure of the general equilibrium effect.

As shown in the left panel, our model matches both the speed and the magnitude of the increase in the top 1% wealth share and predicts that this trend will continue in the future. Most of this increase is driven by a partial equilibrium effect, represented by the green line in the left panel of Figure 1.10. High-productivity households receive higher wages and can thus accumulate more wealth. This effect is amplified by the fact that their marginal propensity to save increases as they become richer. At the bottom of the labor income distribution, the opposite effect occurs: poorer households dissave following a shock on their permanent level of labor income, and their marginal propensity to save decreases as well.

However, as we mentioned before, because of the non-homothetic nature of the taste for wealth, the increase in wealth from the high-productivity households is larger than the dissaving from the poorer households, which increases aggregate savings and changes the equilibrium prices. The effect of this price change on the top 1% wealth share is displayed by the blue-shaded area in the left panel of Figure 1.11 and by the blue line in the right panel. In 2020, the general equilibrium effect contributed 10% of this increase in the top 1% wealth share and stayed positive until approximately 2100. This means that the change in prices due to a change in permanent labor income inequality increases the speed at which the model's top 1% wealth share increases. It becomes negative after that point, meaning that, over the very long term, the price change actually decreases wealth inequality, as the lower returns negatively impact the wealthy.

Decomposition of the GE effect. We can further decompose this general equilibrium effect between a return and wage effect. Figure 1.11 shows the result of this decomposition. First, the change in returns increases wealth inequality initially, as richer households, who own mostly illiquid assets, enjoy the capital gains, while poorer households, who own mostly liquid wealth, dissave more as the returns they face decrease quickly. Over the long term, however, both returns decline, and this return effect becomes negative.

Secondly, the increase in the stock of physical capital also increases wages, creating a "trickle-down" effect that dampens the top 1% wealth share slightly over the long term.

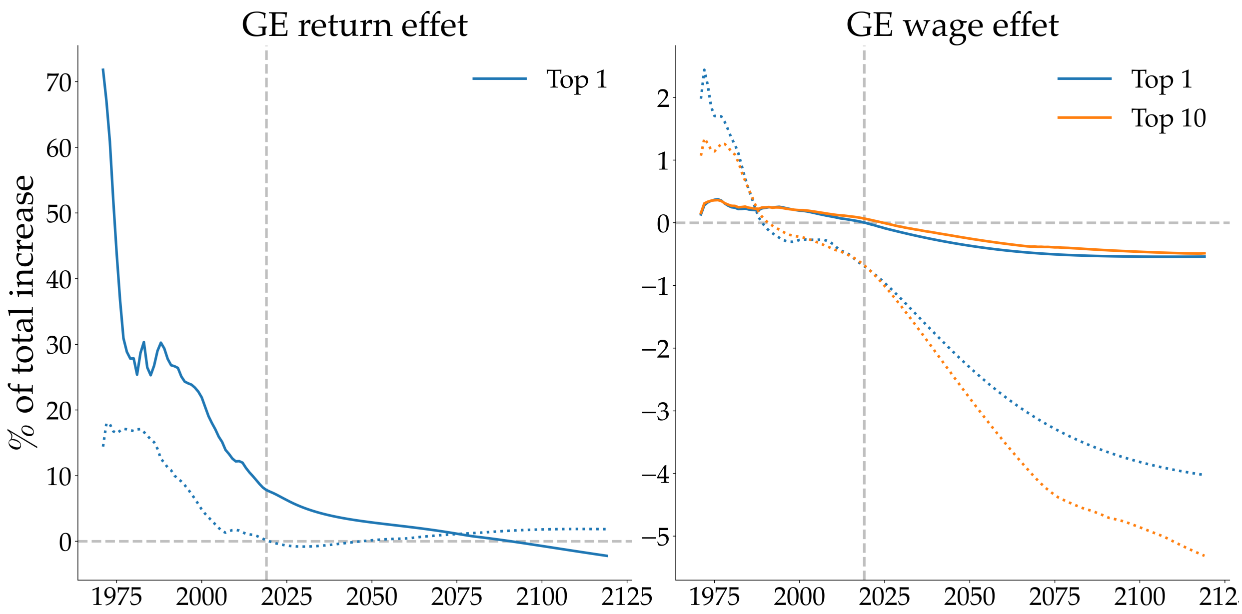

Figure 1.11: Decomposition of the general equilibrium effect on the top wealth shares

Note: This figure decomposes the general equilibrium effect between a wage effect and a return effect.

This effect is negative, as it mostly benefits the poorest households, who get most of their income from labor. However, because the stock of capital increases very little, this effect is quantitatively very small and does not significantly decrease the top 1% wealth share. In contrast, the dotted line shows the effect of this channel in a model with perfect competition. In this model, there is a one-to-one increase in aggregate savings and the stock of physical capital: wages increase by more, and this channel decreases the top 1% wealth share by 5% in the long run.

1.6 Conclusion

In this paper, we have studied the specific role of capital gains to account for the rise in wealth inequality in the US since 1970. Our contribution is threefold. (1) In a simple analytical model, we identify the preferences consistent with micro evidence on marginal propensity to save out of a permanent income shock. (2) In a quantitative model calibrated on US data, we endogenously generate valuation effects that create an excess return on the equity market. (3) We quantify the size of this capital gain channel by wealth groups and over time.

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A Appendix: Analytical model

A.1 Proposition 1

The Lagrangian of our maximization problem is the following:

$$\mathcal{L}(\{s_{i,t+1}\}, \{\lambda_{i,t}\}) = \sum_{t=0}^{\infty} \beta_i^t [u(z_i + (1+q_t)s_{i,t} - q_t s_{i,t+1}) + \lambda_{i,t} s_{i,t+1}]$$

Taking the FOC with respect to $s_{i,t+1}$, we get:

$$q_t u'(c_{i,t}) = \beta_i (1 + q_{t+1}) u'(c_{i,t+1}) + \lambda_{i,t}$$

We will ignore the borrowing constraint and check ex-post that the sequence $\{a^i_{t+1}\}$ does indeed satisfy the borrowing constraint.

The Euler equation of the household problem gives us $c_{i,t}$ as a function of $c_{i,t-1}$:

$$\forall t,\, c_{i,t} = \left(\beta \frac{1+q_{t+1}}{q_t}\right)^{\frac{1}{\sigma}} c_{i,t-1}$$

As it holds for the two agents, taking the ratio of the two Euler equations, we get that:

$$\forall t,\, \frac{c_{1,t}}{c_{1,t-1}} = \frac{c_{2,t}}{c_{2,t-1}}$$

Since we have that $c_{1,t-1} + c_{2,t-1} = c_{1,t} + c_{2,t} = 2, \quad \forall t$, consumption is necessarily constant over time. This is only possible if:

$$\forall t,\, \beta \frac{1+q_{t+1}}{q_t} = 1$$

As consumption is constant over time, the asset position remains the same, and we have that:

$$s_{i,t+1} = s_{i,0} \forall i \in \{1,2\},\, \forall t \geq 0.$$

Hence, the borrowing constraint is indeed satisfied at all times.

A.2 Proposition 2

At the steady state, consumption is constant and the equilibrium allocation $\{r, s_1, s_2, \lambda_1, \lambda_2\}$ is characterized by the following four equations:

$$1 = \beta_1 \left(1 + \frac{1}{q}\right) + \lambda_1 / u'(1 - z + 1 - s),$$

$$1 = \beta_2 \left(1 + \frac{1}{q}\right) + \lambda_2 / u'(z + s),$$

$$\lambda_1(1 - z + 1 - s) = 0,$$

$$\lambda_2(z + s) = 0.$$

We are going to prove proposition 2.2 by contradiction:

First case: assuming that the borrowing constraint does not bind for the two agents. It must be the case that $\lambda_1 = \lambda_2 = 0$. Equations (3) and (4) imply that :

$$1 + \frac{1}{q} = \frac{1}{\beta_1} = \frac{1}{\beta_2}$$

This is not possible since we assumed that $\beta_1 \neq \beta_2$.

Second case: the non-negativity constraint holds for agent 2 and not for agent 1. In that case, $\lambda_2 > 0$ and $\lambda_1 = 0$. Putting equations (3) and (4) together, we have that:

$$\beta_1 \left(1 + \frac{1}{q}\right) = \beta_2 \left(1 + \frac{1}{q}\right) + \lambda_2 / u'(c_2)$$

This is not possible since $\lambda_2 / u'(c_2) > 0$ as marginal utility is always positive and we assumed that $\beta_2 > \beta_1$.

Third case: the borrowing constraint holds for the two agents. This is trivially impossible, as the market clearing condition on the equity market would not hold.

The only possibility is that $s_1 = 0$, and $1 + \frac{1}{q} = \frac{1}{\beta_2}$ □

A.3 Proposition 3

When we include a taste for wealth $\gamma > 0$, the Lagrangian of our maximization problem is the following:

$$\mathcal{L}(\{s_{i,t+1}\}, \{\lambda_t^i\}) = \sum_{t=0}^{\infty} \beta^t [u(z_i + (1 + q_t)s_{i,t} - s_{i,t+1}) + \gamma v(q_t s_{i,t}) + \lambda_{i,t} s_{i,t+1}].$$

Taking the FOC with respect to $s_{i,t+1}$, we get:

$$q_t u'(c_{i,t}) = \beta[(1 + q_{t+1}) u'(c_{i,t+1}) + \gamma v'(a_{i,t+1}) + \lambda_{i,t}].$$

At the steady state for agent 1:

$$u'(1 - z + 1 - s) = \beta(1 + \frac{1}{q}) u'(1 - z + 1 - s) + \beta\gamma v'(q(1 - s)) + \lambda_1,$$

$$\iff \frac{1}{\beta} = 1 + \frac{1}{q} + \gamma\frac{v'(q(1-s))}{u'(1-z+1-s)} + \frac{\lambda_1}{u'(1-z+1-s)}.$$

For Agent 2:

$$u'(z+s) = \beta(1+\frac{1}{q})u'(z+s) + \beta\gamma v'(qs) + \lambda_2,$$

$$\iff \frac{1}{\beta} = 1 + \frac{1}{q} + \gamma\frac{v'(qs)}{u'(z+s)} + \frac{\lambda_2}{u'(z+s)}.$$

Our steady-state allocation $\{s, q, \lambda_1, \lambda_2\}$ is characterized by the following system of four equations:

$$\begin{cases} \frac{1}{\beta} = 1 + \frac{1}{q} + \gamma\frac{v'(q(1-s))}{u'(1-z+1-s)} + \frac{\lambda_1}{u'(1-z+1-s)}, \\ \frac{1}{\beta} = 1 + r + \gamma\frac{v'(qs)}{u'(z+s)} + \frac{\lambda_2}{u'(z+s)}, \\ \lambda_1 s = 0, \\ \lambda_2(1-s) = 0. \end{cases}$$

When there is an interior solution, putting the first two equations together gives the equilibrium level of equity holdings s as a function of q :

$$\frac{v'(q(1-s))}{u'(1-z+1-s)} = \frac{v'(qs)}{u'(z+s)}.$$

A.4 Proposition 4

When $\sigma = \Sigma$ and assuming that the non-negativity constraint on equity holdings, the equation equating the two marginal rates of substitution becomes:

$$\frac{qs+\zeta}{s+z} = \frac{q(1-s)+\zeta}{1-s+1-z}$$

$$s = \frac{zq+2z\zeta-2\zeta}{q-2\zeta}$$

In the general case (incorporating binding constraints), equity holdings are given by:

$$s = \min\left\{\frac{zq+2z\zeta-2\zeta}{q-2\zeta}, 1\right\}$$

A.5 Proposition 5

In the case of log utility $\sigma = \Sigma = 1$ and $\zeta = 0$, equity holding becomes:

$$s = z$$

Plugging that in the Euler equation of one of the two agents, we recover the price of the equity share:

$$1+\frac{1}{q}=\frac{1}{\beta}-\gamma\frac{s+z}{sq}$$

Plugging the solution for s:

$$1+\frac{1}{q}=\frac{1}{\beta}-\gamma\frac{2}{q} \iff \frac{1+2\gamma}{q}=\frac{1}{\beta}-1 \iff q=\frac{1+2\gamma}{\frac{1}{\beta}-1}$$

$$\frac{\partial q}{\partial \beta}>0,\ \frac{\partial q}{\partial \gamma}>0, \text{ and } \frac{\partial q}{\partial z}=0$$

The price of the Lucas tree is not a function of labor income inequality.

A.6 Proposition 6

Assuming an interior solution:

$$s=\frac{zq+2y\zeta-2\zeta}{q-2\zeta}$$

Plugging that in the Euler equation of one agent:

$$1+\frac{1}{q}=\frac{1}{\beta}-\gamma\frac{\frac{zq+2z\zeta-2\zeta}{q-2\zeta}+z}{q\frac{zq+2z\zeta-2\zeta}{q-2\zeta}+\zeta}$$

$$(\frac{1}{\beta}-1)zq^3+\left[(\frac{1}{\beta}-1)\zeta(2z-1)-2\gamma z-z\right]q^2+\left[2\gamma-2z+1-2(\frac{1}{\beta}-1)\zeta\right]\zeta q+2\zeta^2=0$$

Notice that this third-order polynomial has a root equal to $\frac{\zeta}{y}$. This root is not a solution to our problem as it is inconsistent with the non-negativity constraint on equity holding. To see that:

$$s=\frac{\zeta+2z\zeta-2\zeta}{\frac{\zeta}{z}-2\zeta}=\frac{2z-1}{\frac{1}{z}-2}<0$$

Hence, we can rewrite the last equation as being equal to:

$$(q-\frac{\zeta}{y})((1-\beta)q^2+[2\zeta-(2\beta\gamma+2\beta\zeta+\beta)]q-2\beta\zeta)=0$$

And we can ignore the first term and only solve the following second-order polynomial:

$$(1-\beta)q^2+[2\zeta-(2\beta\gamma+2\beta\zeta+\beta)]q-2\beta\zeta=0$$

Computing the discriminant:

$$\Delta=[2\zeta-(2\beta\gamma+2\beta\zeta+\beta)]^2+8(1-\beta)\beta\zeta>0$$

The second-order polynomial takes two roots:

$$q_1 = \frac{-b - \sqrt{\Delta}}{2a} \text{ and } q_2 = \frac{-b + \sqrt{\Delta}}{2a}$$

The root q_1 is strictly lower than 0. Indeed: $(1-\beta)\beta\zeta > 0$, and so

$\Delta > [2\zeta - (2\beta\gamma + 2\beta\zeta + \beta)]^2$.

Hence:

$$q_1 = \frac{-b - \sqrt{\Delta}}{2a} < \frac{-[2\zeta - (2\beta\gamma + 2\beta\zeta + \beta)] - \sqrt{[2\zeta - (2\beta\gamma + 2\beta\zeta + \beta)]^2}}{2(1-\beta)} = 0$$

Hence, we do have that $q_1 < 0$ and we know that q_1 is not a solution to our problem.

The equilibrium solution price is hence given by:

$$q^* = \frac{\beta\gamma + \beta\zeta + \frac{\beta}{2} - \zeta + \frac{\sqrt{4\beta^2\gamma^2 + 8\beta^2\gamma\zeta + 4\beta^2\gamma + 4\beta^2\zeta^2 - 4\beta^2\zeta + \beta^2 - 8\beta\gamma\zeta - 8\beta\zeta^2 + 4\beta\zeta + 4\zeta^2}}{2}}{1 - \frac{1}{\beta}}$$

Crucially, $dq^*/dy = 0$ and the labor income distribution does not affect the equilibrium price of equity.

A.7 Proposition 7

Taking the Euler equation of agent 2:

$$\frac{1}{\beta} - 1 - \frac{1}{q} = \gamma \frac{(z+s)^\sigma}{(qs+\zeta)^\Sigma}$$

And differentiating with respect to z:

$$\frac{\frac{dq}{dz}}{q^2} = \gamma \frac{\sigma(1 + \frac{ds}{dz})(z+s)^{\sigma-1}(qs+\zeta)^\Sigma - \Sigma(s\frac{dq}{dz} + q\frac{ds}{dz})(qs+\zeta)^{\Sigma-1}(z+s)^\sigma}{(qs+\zeta)^{2\Sigma}}$$

$$\iff \frac{\frac{dq}{dz}}{q^2} = \gamma \frac{\sigma(1 + \frac{ds}{dz})(qs+\zeta) - \Sigma(s\frac{dq}{dz} + q\frac{ds}{dz})(z+s)}{(qs+\zeta)^{2\Sigma}}(z+s)^{\sigma-1}(qs+\zeta)^{\Sigma-1}$$

$$\iff 0 = a_1 + b_1\frac{ds}{dz} - c_1\frac{dq}{dz}$$

With $a_1 \equiv \sigma(qs+\zeta)$, $b_1 \equiv \sigma(qs+\zeta) - \Sigma(z+s)q$, $c_1 \equiv \Sigma(z+s)s + \dfrac{(qs+\zeta)^{\Sigma+1}}{\gamma q^2(z+s)^{\sigma-1}}$

We need a second equation as we no longer have a closed-form solution for s. Taking the Euler equation of agent 1:

$$\frac{1}{\beta} - 1 - \frac{1}{q} = \gamma \frac{(2-z-s)^{\sigma}}{(q(1-s)+\zeta)^{\Sigma}}$$

And differentiating with respect to z:

$$\frac{\frac{dq}{dz}}{q^2} = \gamma \frac{\sigma(-1-\frac{ds}{dz})(2-z-s)^{\sigma-1}(q(1-s)+\zeta)^{\Sigma} - \Sigma((1-s)\frac{dq}{dz} - q\frac{ds}{dz})(q(1-s)+\zeta)^{\Sigma-1}(2-z-s)^{\sigma}}{(q(1-s)+\zeta)^{2\Sigma}}$$

$$\iff \frac{\frac{dq}{dz}}{q^2} = \gamma \frac{\sigma(-1-\frac{ds}{dz})(q(1-s)+\zeta) - \Sigma((1-s)\frac{dq}{dz} - q\frac{ds}{dz})(2-z-s)}{(q(1-s)+\zeta)^{2\Sigma}}(2-z-s)^{\sigma-1}(q(1-s)+\zeta)^{\Sigma-1}$$

$$\iff 0 = a_2 + b_2\frac{ds}{dz} - c_2\frac{dq}{dz}$$

With $a_2 \equiv -\sigma(q(1-s)+\zeta),\ b_2 \equiv \Sigma q(2-z-s) - \sigma(q(1-s)+\zeta),$ and
$c_2 \equiv \Sigma(1-s)(2-z-s) + \dfrac{(q(1-s)+\zeta)^{\Sigma+1}}{\gamma q^2(2-z-s)^{\sigma-1}}$

The last expression gives us $\frac{ds}{dz}$ as a function of $\frac{dq}{dz}$:

$$\iff \frac{ds}{dz} = \frac{c_2\frac{dq}{dz} - a_2}{b_2}$$

Plugging that in the first equation:

$$0 = a_1 + b_1\frac{c_2\frac{dq}{dz} - a_2}{b_2} - c_1\frac{dq}{dz}$$

$$\frac{dq}{dz} = \frac{a_1 - \frac{a_2 b_1}{b_2}}{\frac{b_1 c_2}{b_2} - c_1} = \frac{a_1 b_2 - a_2 b_1}{b_2 c_1 - b_1 c_2}$$

Or:

$$\frac{dq}{dz} = \frac{\sigma(qs+\zeta)(\Sigma q(2-z-s) - \sigma(q(1-s)+\zeta)) + \sigma(q(1-s)+\zeta)(\sigma(qs+\zeta) - \Sigma(z+s)q}{(\Sigma q(2-z-s) - \sigma(q(1-s)+\zeta))(\Sigma(z+s)s + \frac{(qs+\zeta)^{\Sigma+1}}{\gamma q^2(z+s)^{\sigma-1}}) - (\sigma(qs+\zeta) - \Sigma(z+s)q)(\Sigma(1-s)(2-z-}$$

Evaluating this expression around the $\sigma = \Sigma = 1$ case:

$$a_1 b_2 = \sigma(qs+\zeta)(\Sigma q(2-z-s) - \sigma(q(1-s)+\zeta))$$

$$\iff a_2 b_1 = -(q(1-s)+\zeta)(2qs+\zeta+zq)$$

Computing the numerator:

$$a_1 b_2 - a_2 b_1 = (qs+\zeta)(q(1-z)-\zeta) + (q(1-s)+\zeta)(2qs+\zeta+zq)$$

$$\iff a_1 b_2 - a_2 b_1 = (qs+\zeta)q(1-z) + q(1-s)(2qs+\zeta+zq) + \zeta(qs+zq) > 0$$

Now, moving to the denominator:

$$b_1c_2 = [\sigma(qs+\zeta) + \Sigma(z+s)q][\Sigma(1-s)(2-z-s) + \frac{(q(1-s)+\zeta)^{\Sigma+1}}{\gamma q^2(2-z-s)^{\sigma-1}}]$$

$$\iff b_2c_1 = [q(1-z)-\zeta][(z+s)s + \frac{(qs+\zeta)^2}{\gamma q^2}]$$

Computing the denominator:

$$b_1c_2 - b_2c_1 = [2qs+\zeta+zq][(1-s)(2-z-s)+\frac{(q(1-s)+\zeta)^2}{\gamma q^2}] - [q(1-z)-\zeta][(z+s)s+\frac{(qs+\zeta)^2}{\gamma q^2}]$$

Left to show that it is positive which implies that $\frac{dq}{dz} > 0$.

Computing the denominator:

$$(\Sigma q(2-z-s)-\sigma(q(1-s)+\zeta))(\Sigma(z+s)s+\frac{(qs+\zeta)^{\Sigma+1}}{\gamma q^2(z+s)^{\sigma-1}})-(\sigma(qs+\zeta)-\Sigma(z+s)q)(\Sigma(1-s)(2-z-s)+\frac{(q(1}{\gamma q^2(}$$

Using the fact that:

$$\frac{(z+s)^\sigma}{(qs+\zeta)^\Sigma} = \frac{1}{\gamma}[\frac{1}{\beta}-1-\frac{1}{q}] \iff \frac{(qs+\zeta)^\Sigma}{(z+s)^\sigma} = \gamma[\frac{1}{\beta}-1-\frac{1}{q}]^{-1}$$

And :

$$\frac{(2-z-s)^\sigma}{(q(1-s)+\zeta)^\Sigma} = \frac{1}{\gamma}[\frac{1}{\beta}-1-\frac{1}{q}] \iff \frac{(q(1-s)+\zeta)^\Sigma}{(2-z-s)^\sigma} = \gamma[\frac{1}{\beta}-1-\frac{1}{q}]^{-1}$$

Plugging that in the denominator:

$$(\Sigma q(2-z-s)-\sigma(q(1-s)+\zeta))(\Sigma(z+s)s+\gamma[\frac{1}{\beta}-1-\frac{1}{q}]^{-1}(qs+\zeta)(z+s))-(\sigma(qs+\zeta)-\Sigma(z+s)q)(\Sigma(1-s)(2-$$

$$= (z+s)(\Sigma q(2-z-s)-\sigma(q(1-s)+\zeta))(\Sigma s+\gamma[\frac{1}{\beta}-1-\frac{1}{q}]^{-1}(qs+\zeta))-(2-z-s)(\sigma(qs+\zeta)-\Sigma(z+s)q)(\Sigma(1-$$

B Appendix: Heterogeneous-agent model in the analytical section

This section describes the one-asset and two-asset models in Section 2.

B.1 Households

The problem of the household with one-asset writes

$$
\begin{aligned}
V(a_t, e_t, z) = \max_{a_{t+1}} &\{u(c_t) + v(a_t) + \beta \mathbb{E}_e V(a_{t+1}, e_{t+1}, z)\}; \\
\text{subject to } & c_t + a_{t+1} = a_t(1 + r_t) + z e_t w_t; \\
& a_{t+1} \geq 0.
\end{aligned}
$$

The two-asset version of the problem writes

$$
\begin{aligned}
V(a_t, b_t, e_t, z) = \max_{a_{t+1}, b_{t+1}} &\{u(c_t) + v(a_t + b_t) + \beta \mathbb{E}_s V(a_{t+1}, b_{t+1}, e_{t+1}, z)\} \\
\text{subject to } & c_t + a_{t+1} + b_{t+1} + \chi(a_{t+1}, a_t) = (1 + r_t^a) a_t + (1 + r_t^b) b_t + e_t z w_t \\
& a_{t+1} \geq 0, \quad b_{t+1} \geq \bar{b}.
\end{aligned}
$$

In this two-asset version of the model, we assume that capital gains are paid only to the illiquid account. That is, the excess returns at period 0 $\frac{q_1 - q_{ss}}{q_{ss}}$ are paid only to the owners of illiquid assets.

B.2 Firms

Deterministic Lucas tree. There is a Lucas tree in unit-net supply that provides one unit of consumption good every period:

$$y_t = s_t = 1.$$

We assume that a share α is paid to the owners of the Lucas tree, so that

$$d_t = \alpha y_t.$$

The return on the Lucas tree is given by

$$r_t = \frac{d_t + q_{t+1}}{q_t} - 1.$$

The rest of the output is paid to households through wages

$$w_t = (1 - \alpha) y_t.$$

Neoclassical model. The supply side of this section is kept intentionally stylized. In the model with a neo-classical production function and without capital gains, output is given by

$$y_t = c k_t^{\alpha}.$$

We assume zero depreciation of capital so that returns and wages are given by

$$r_t = \alpha c k_t^{\alpha-1},$$

$$w_t = (1-\alpha) c k_t^{\alpha}.$$

Calibration. We set $\alpha = 1/3$, and calibrate c so that the initial steady state when inequality is low are the same in the economy with a Lucas tree and with a neo-classical production function. We set β in the household problem so that the initial steady state return r is equal to 5%. γ, ζ and Σ are set to the same values as in the quantitative model described in Section 3.

C Appendix: Computational method

This section describes how we solve the quantitative model of Section 3.

C.1 Household maximization

Given parameters and given a path for $\{r_t^a, r_t^b, w_{i,t}, \tau_{l,t}\}$, a household solves the following dynamic programming problem

$$\begin{aligned} V(a_t, b_t, e_t, z_i) = \max_{a_{t+1}, b_{t+1}} & \{u(c_t) + v(a_t + b_t) + (1-\xi)\beta \mathbb{E}_s V(a_{t+1}, b_{t+1}, z_{t+1}, z_i)\} \\ \text{subject to } & c_t + a_{t+1} + b_{t+1} + \chi(a_{t+1}, a_t) = (1 + r_t^a) s_t \tilde{a}_t + (1 + r_t^b) b_t + (1 - \tau_{l,t})(z_t w_{i,t})^{1-\theta} \\ & a_{t+1} \geq 0, \quad b_{t+1} \geq \bar{b} \end{aligned}$$

where $u(c_t) = \frac{c_t^{1-\sigma}}{1-\sigma}$ and $v(a_t + b_t) = \frac{(a_t + b_t + \zeta)^{1-\Sigma}}{1-\Sigma}$.

The first-order conditions of the problem are

$$\begin{aligned} u'(c_t) &= (1-\xi)\beta \mathbb{E}_s[V_a(a_{t+1}, b_{t+1}, e_{t+1}, z_i)] + \lambda_t \\ u'(c_t)(1 + \chi_1') &= (1-\xi)\beta \mathbb{E}_s[V_b(a_{t+1}, b_{t+1}, e_{t+1}, z_i)] + \lambda_t \end{aligned}$$

The envelope conditions are

$$\begin{aligned} V_a(a_t, b_t, e_t, z_i) &= u'(c_t)(1 + r_t^b) + v'(a_t + b_t) \\ V_b(a_t, b_t, e_t, z_i) &= u'(c_t)(1 + r_t^a - \chi_2) + v'(a_t + b_t) \end{aligned}$$

Note that in Section 4, we defined the idiosyncratic return shock as a shock on r_t^a. For computational purposes, we actually implement a shock on the asset position of the household a_t. In this notation, $\tilde{a}_{t+1}$ denotes the choice of the household while $a_{t+1} = s_{t+1}\tilde{a}_{t+1}$

is the effective asset position after the idiosyncratic shock s_{t+1} is realized. Since s_{t+1} is iid, it does not appear as a state variable in the household's problem: at t, the household cares only about its post-shock asset position a_t, and not about its previous choice $\tilde{a}_t$ or the realization of the shock s_t.

To solve this problem, we discretize the AR(1) process using the Rowerhorst method on a grid of 3 points and use the method of endogenous grid points (Carroll 2005) . See the appendix of Auclert, Bardóczy, et al. (2021) for additional details on how to implement the EGM method for a two assets problem. The only difference in our setting is that we need to account for the taste for wealth when updating V_a and V_b and take into account the shock on s when computing the expectation.

C.2 Computation of the steady-state

To solve for the steady state, we implement the following algorithm:

1. Given a guess on (r^a, r^b), we solve the problem of the firm using the first-order conditions on capital and wages:

$$
\begin{aligned}
K &= \left(\frac{\kappa ra + \delta - \tau_c \delta}{\alpha Z(1-\tau_c)} \frac{\epsilon}{\epsilon - 1} \right)^{\frac{1}{\alpha - 1}} \\
z_i &= \omega_i (1-\alpha) \frac{\epsilon - 1}{\epsilon} \frac{Y}{l_i} \\
d &= (1-\tau_c)(Y - \delta K - z) \\
q &= \frac{(1-\tau_c) d}{r^a}
\end{aligned}
$$

2. We use the budget constraint of the government to solve for τ_l

3. Using our guesses (V_a, V_b) and (r^a, r^b) and the associated (z_i, τ_l), we solve the problem of the household using the method described previously.

4. Once we have obtained the policy functions $c(a,b,e,z), a'(a,b,e,z), b'(a,b,e,z)$, we use Young (2010) lottery method to compute the associated transition matrix and stationary distribution. Note that we also need to account for the probability of death (i.e. to restart with zero wealth) and for the idiosyncratic return shock.

5. We can then use the distribution μ_t to evaluate the market clearing equations

$$
\begin{aligned}
\int a'(a,b,z,i) d\mu_t - q &= error_a \\
\int b'(a,b,z,i) d\mu_t - B_{gov} &= error_a
\end{aligned}
$$

6. If $\max(|error_a, error_b|) > tol$, we update our guesses using Newton's method.

C.3 Transition following a permanent labor income shock

This section describes how to solve the transition between two steady states, after a shock on the permanent labor income parameters $\{z_i\}$.

1. Compute the new terminal steady state associated with the new $\{z_i\}$ and obtain the derivative of the value function V_a, V_b.

2. Guess a path on $\{r_t^a, r_t^b\}_{t=0}^T$ where T is sufficiently large enough (700 in our calibration).

3. Given the guess on the interest rates, solve for the equilibrium wages, equity prices and taxes using the first-order condition of the firm and the fiscal rule of the government. As described in Section 4, note that we need to update the initial return on the risky asset that we denote r_0^h to account for the jump in the equity value.

4. Solve the value function problem of the household backward using the value function at the new steady state as a terminal condition.

5. Use the obtained policy function and the initial distribution μ_0 to solve forward the path of distributions $\{\mu\}_{t=0}^T$

6. Check the market clearing conditions for all t

$$\int a_t'(a,b,z,i)d\mu_t - q = error_{t,a}$$
$$\int b_t'(a,b,z,i)d\mu_t - B_{gov} = error_{t,a}$$

7. Update the guess on the returns using a pseudo-Newton's algorithm where the Jacobians are evaluated around the terminal steady state, using the Sequence Space Jacobian method of Auclert, Bardóczy, et al. (2021).

Because we model the transition as a sequence of unexpected shocks, we need to compute 40 transitions, where the initial conditions are given by the first-period previous transition. That is, for each unexpected inequality shock on $\{\omega\}_s$, we compute the associated terminal steady state and the transition from 0 to T using the previous algorithm. The new transition takes as an initial condition the distribution μ_1, the capital stock K_1, government debt $B_{gov,1}$ and the price of the firm q_1 as its initial condition.

C.4 Decomposition of the general equilibrium effect

We define the general equilibrium effect of a shock on permanent labor income inequality on the wealth distribution as

$$GE_t = \frac{\text{Top wealth share}_t^{\text{general}} - \text{Top wealth share}_t^{\text{partial}}}{\text{Top wealth share}_t^{\text{general}} - \text{Top wealth share}_{ss}^{\text{general}}}$$

To measure this effect, we solve a full transition of our main model, adjusting prices to maintain the market clearing, using the algorithm described in the previous section. We then solve the transition by maintaining prices at their initial level but changing the parameters $\{z_s\}$ to take into account the direct effect of change in permanent labor income inequality.

To compute the partial equilibrium distribution:

1. We compute a new terminal steady state where we fix the prices at their steady state level $(r^a_{ss}, r^b_{ss}, w_{ss})$ and obtain the associated value function of the households $V(a, b, i)$
2. We use those terminal conditions to solve the problem of the household in the transition, keeping the returns constant but allowing for the new path in wages, and using the distribution at the steady state as a the initial distribution. We obtain a path for the policy functions $a'_t(a, b, e, z)$ and $b'_t(a, b, e, z)$
3. We use the policy functions to solve forward the distribution of households $\mu_t(a, b, e, z)$ and compute the associated wealth shares.

C.5 Model without capital gains

In our model without capital gains, we remove the imperfect competition structure and allow households to own and lend capital to the firms directly. The first-order condition of the firm is now

$$r^a_t = \alpha K^{\alpha-1} L^{1-\alpha} - \delta$$

and the market clearing condition for the risky assets is modified to become

$$A^s_t = K_t.$$

In this case, there is no change in the relative value of capital after a permanent labor income shock and we do not need to adjust the period 0 return on risky assets.

We also set $\alpha = \frac{1}{3}$ in this calibration to match the capital and labor share. The following table describes the initial steady state in both models.

Chapter 2

Income Inequality and Monetary Policy

We study the impact of an increase in permanent labor income inequality on the transmission of monetary shocks on the real economy. In a Heterogeneous-Agent New-Keynesian model with standard preferences, we show that the distribution of permanent labor income is neutral with respect to monetary policy shocks. However, this model cannot account for the observed relationship between permanent income and consumption-saving behavior. Including a non-homothetic taste for wealth allows us to match this relationship, and breaks the neutrality result. The direct substitution effect from a monetary policy shock is weakened while indirect effects are stronger. The rise in permanent labor income inequality makes households hold wealth more for a present motive rather than for an intertemporal-substitution motive. As a result, the aggregate elasticity of intertemporal substitution is weakened while the aggregate static MPC is strengthened. In a realistic two-asset HANK model, we quantify the change in the composition of a monetary shock. We observe a rise in the magnitude of a monetary policy shocks as the increase in indirect effects more than outweighs the fall in the direct effect.[1]

1 Introduction

In the US, labor income inequality has increased steadily since the 1980s, with the share of pre-tax total labor income earned by the top 1% doubling from 6% in 1980 to 12% in 2020 (Saez and Zucman 2020). Existing empirical literature suggests that the surge

[1] This chapter was co-written with Eustache Elina, PhD student at the Paris School of Economics.

in labor income inequality is predominantly attributable to an increase in the *permanent* component of labor income inequality (DeBacker et al. 2011; Bloom et al. 2017; Braxton et al. 2021; Fatih Guvenen, Kaplan, et al. 2022) — a term we use to denote the variance in initial outcomes for new cohorts entering the labor market (Straub 2019). In this paper, we explore the implications of rising permanent labor income inequality for monetary policy. We ask two questions. What is its effect on the strength of a monetary policy shock? How does it change the transmission channels of monetary policy?

In a simple textbook IS-LM model, an increase in permanent labor income inequality decreases the output response to monetary policy, if rich households have a lower marginal propensity to consume than poorer ones. Indeed, assume two households – a low income and a high income – with population shares ω and $(1-\omega)$. The low type receives a share $1-z$ of total income and has a high marginal propensity to consume m_l while the high type receives a share z and has a low marginal propensity to consume $m_h < m_l$. The static Keynesian cross writes[2]

$$dY = \frac{1}{1-\omega(1-z)m_l-(1-\omega)zm_h} b_1 dr.$$

An increase in permanent labor income inequality z will thus redistribute income towards low MPCs households, decreasing the multiplier, and hence the output response to a monetary policy shock. This simple model is useful to motivate why the distribution of permanent income might matter for monetary policy, but it misses a few core features of modern macroeconomic models: it lacks dynamics and ignores the endogeneity of the consumption-savings decision to permanent income.

In this paper, we explore this question using a HANK model with rich household-level heterogeneity and featuring an intertemporal Keynesian cross à la Auclert, Rognlie, and Straub (2018). We introduce a decomposition of the impact of rising permanent labor income inequality on monetary policy between three channels. First, an increase in permanent income inequality redistributes income between households with potentially different responses to income and interest rate shocks. We call this channel the composition effect, which is the only channel present in the simple IS-LM model we presented. Secondly, households might further change their response to shocks as they observe an increase or a decrease in their permanent income. We call this the policy function effect. Finally, as the behavior of households changes, their position in the distribution of wealth might change as well, changing the aggregate reaction to interest and income shocks. We call this channel the wealth distribution effect.

Our paper starts with a neutrality result: in a model with preferences only on consumption, those three channels are exactly equal to zero. In this setting, consumption is a linear function of permanent income. As a result, whatever the distribution of permanent income,

[2] b_1 is the sensitivity of aggregate consumption to the interest rate.

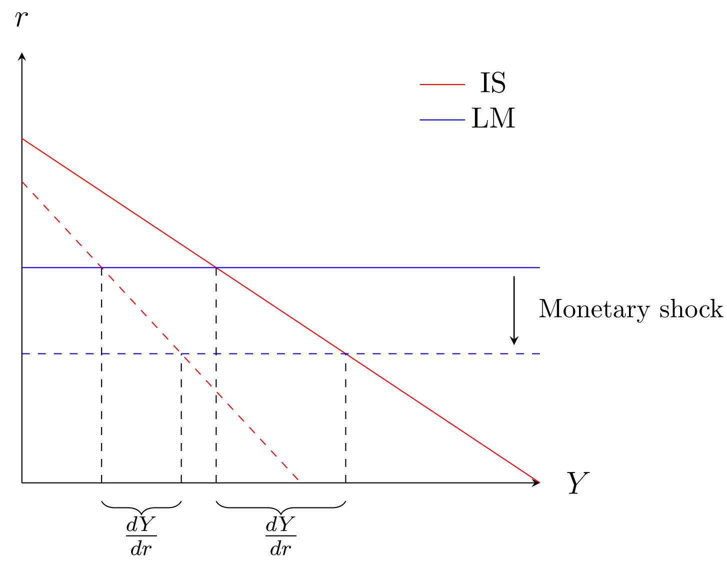

Figure 2.1: Change in equilibrium output in an IS-LM model after a monetary policy shock

Note: The red full line shows the IS curve with low inequality, while the red dashed curve shows the IS curve with high inequality.

the aggregate response of consumption following a monetary shock will remain the same, consistently with Straub (2019). This neutrality result is useful as a benchmark, but largely unrealistic. Indeed, a large empirical literature has shown that households with higher levels of permanent income have a higher propensity to save out of permanent income than the rest of the distribution (Carroll 1998; Dynan, Skinner, and Zeldes 2004; Kumhof, Rancière, and Winant 2015; Straub 2019; Mian, Straub, and Sufi 2020).

A growing literature has been solving that issue by adding wealth to the utility function as a luxury good (Kumhof, Rancière, and Winant 2015; Straub 2019; Mian, Straub, and Sufi 2020). By doing so, they are able to match the relationship between consumption-saving decisions and the level of permanent income. We show that this type of preference breaks down our neutrality result and ex-ante heterogeneity in permanent income matters for the output response to a monetary shock. The rise in permanent labor income inequality observed in the US from 1989 to 2019 changes the transmission channels of monetary policy and raises the output elasticity to an interest shock by 12.5%.

We first study the effect of a rise in permanent labor income inequality in a zero-liquidity HANK model. By doing so, we are able to analytically characterize the contribution of the composition effect and the policy function effect on the transmission channels of monetary policy and its aggregate effect. We show that, at the household level, a rise in permanent labor income raises the sensitivity to an income shock – the marginal propensity to consume – while it dampens the sensitivity to an interest rate shock – the elasticity of intertemporal substitution.

In order to capture the wealth distribution effect, we then relax the zero-liquidity assumption. We show that the rise in permanent labor income inequality decreases the relative share of the direct effect – the effect of a change in the interest rate on consumption, keeping household disposable labor income constant – while raising the share of indirect effects – the effect of the change in household disposable income keeping the path of the interest rate constant. Indeed, the rise in permanent labor income inequality pushes the equilibrium real interest down which increases the income share going to hand-to-mouth households. The increase in the general equilibrium multiplier raises the aggregate effect of a monetary policy shock.

The paper concludes that a simple application of the IS-LM model is misguided: an increase in permanent labor income inequality increases the output response to a monetary policy shock through a rise in the general equilibrium multiplier.

Literature. Our paper belongs to the old and large literature that investigates the transmission channels of monetary policy on aggregate variables. Over the last two decades, this literature has gradually moved away from a representative-agent framework to explore the interactions between distributions of income and wealth, and monetary policy. The wealth distribution matters for monetary policy as it determines the share of direct and indirect effects in the transmission of shocks. Micro survey data on household portfolio reveals that a large portion of households do not hold liquid wealth (Kaplan, G. L. Violante, and Weidner 2014). Those households do not react to interest rate changes but are very sensitive to changes in their disposable income. When including that heterogeneity, Kaplan, Moll, and G. Violante (2018) shows that most of the transmission of monetary policy goes through indirect general equilibrium effects (mainly through the change in labor demand). The composition of a monetary shock matters for policymakers as Martin Blomhoff Holm, Paul, and Tischbirek (2021) shows that indirect effects take time to materialize. As a result, if most of the effect of monetary policy goes through indirect effects, monetary policy is not capable of raising aggregate output in a short time frame.

Monetary policy has also a feedback effect on the wealth and the income distributions (Coibion et al. 2017; Mumtaz and Theophilopoulou 2017). Those papers show that contractionary monetary policy is usually procyclical while expansionary monetary policy tends to dampen income inequality. This feedback effect from the monetary policy on the income distribution not only matters from an equity standpoint but also since it is one of the transmission channels of monetary policy on aggregate variables. Indeed, by redistributing income from low-MPC households to high-MPC households, expansionary monetary policy is amplified compared to the representative-agent benchmark (Auclert 2019).

While the interaction between wealth distribution and monetary policy has been extensively studied, the way the distribution of labor income shapes monetary policy has remained partially under the radar. The main reason is that the drivers behind the increase in labor income inequality were not well understood until recently. The macro implication of a rise in the variance of shocks over the lifetime is vastly different from the rise in the variance of initial outcomes. Both Bloom et al. (2017) and Braxton et al. (2021) show that temporary earning risks have declined. DeBacker et al. (2011) and Fatih Guvenen, Kaplan, et al. (2022) show that most of the increase in labor income inequality has come from an increase in the variance of initial outcomes. Our contribution is to study the implications of that increase on the way monetary policy shocks are transmitted.

Our paper uses recent theoretical and methodological advances made by Auclert, Rognlie, and Straub (2018). They show that modern micro-founded heterogenous-agent New-Keynesian models feature an "intertemporal Keynesian cross", characterized by the sequence-space Jacobian of the consumption function. Our paper extends this methodology to monetary policy, and we recover a similar intertemporal Keynesian cross for monetary policy shocks.

Our paper also belongs to the growing literature that uses a non-homothetic taste for wealth to solve various puzzles. Carroll (1998) proposes wealth as a source of social status to explain why rich households have such high saving rates compared to the rest of the population. Straub (2019) shows that non-homothetic preferences capture the saving behavior along the distribution of permanent income and explain how variations in permanent labor income inequality increase wealth inequality and decrease the equilibrium interest rate. Kumhof, Rancière, and Winant (2015) also uses a non-homothetic taste for wealth to match the saving behavior of richer households, in a model that captures the accumulation of debt in the U.S. in the years preceding the Great Recession. In their literature review, De Nardi, French, and Jones (2016) also mention non-homothetic bequest motive to explain why a large number of households die with significant amounts of wealth. Within the New-Keynesian literature, Michau (2018) and Mian, Straub, and Sufi (2021) also include bonds in the utility to study the over-accumulation of savings in modern economies. Lastly, in Gaillard and Wangner (2021), the non-homothecity in the taste for wealth allows to match the thicker tail of the income distribution compared to the consumption distribution. This finding is consistent with the concavity in the consumption function with respect to permanent income generated by this non-homothecity.

Our emphasis on the interactions between non-homothetic preference in the saving behavior and monetary policy is shared by Michaillat and Saez (2021) and Melcangi and Sterk (2020). Consistent with Michaillat and Saez (2021), the presence of bonds-in-the-utility solves the forward guidance puzzle, even in the absence of idiosyncratic shocks. Melcangi and Sterk (2020) is also concerned by the change in the policy channels and in the aggregate effect of monetary policy. The paper also finds out that, in the US since 1980, the power of monetary policy has strengthened following the rise in the stock market participation channel.

In section 2, we study the impact of an increase in permanent labor income inequality in a one-asset HANK model. We focus on the limit case of zero-liquidity. By doing so, we are able to analytically characterize the effect of the permanent income distribution on the transmission of monetary policy. We then relax that assumption and show that the permanent labor income distribution also changes the transmission of monetary policy through a wealth distribution effect. In section 3, we calibrate a two-asset HANK model and measure quantitatively the effect of the change in the labor income distribution on the transmission of monetary policy and on its aggregate effect.

2 Permanent income inequality and monetary policy in HANK

This section studies the impact of a change in the distribution of permanent income in a heterogenous-agent New-Keynesian model, with and without non-homothetic preferences for wealth. We first focus on the zero-liquidity case to gain tractability. The stylized nature of the model allows us to characterize clearly when the distribution of permanent income is non-neutral with respect to the transmission of monetary policy. In the last section, we then relax that assumption by having positive liquidity.

2.1 Setup

Households. The economy is composed of a continuum of high-productivity households of mass $1-\omega$ denoted by h, and a continuum of low-productivity households of mass ω, denoted l. Households face idiosyncratic productivity shocks. They have access to financial markets and can smooth their consumption over time by holding government bonds. A household of permanent type $i \in \{l, h\}$ solves the following maximization problem:

$$\max_{\{c_{i,t}\}_{t\geq 0}} \mathbb{E}_0 \sum_{t=0}^{\infty} \left(\frac{{c_{i,t}}^{1-\sigma} - 1}{1-\sigma} + \gamma \frac{(a_{i,t+1} + \zeta)^{1-\Sigma}}{1-\Sigma} \right),$$

subject to

$$c_{i,t} + a_{i,t+1} = (1-\tau_t) z_i e_{i,t} N_t + (1+r_t) a_{i,t} \text{ and } a_{i,t+1} \geq 0.$$

$a_{i,t}$ denotes the wealth position of the household at the beginning of period t, $c_{i,t}$ is the consumption choice, N_t is the labor supply, $e_{i,t}$ is the idiosyncratic productivity type, z_i is the level of permanent productivity, and τ_t is the linear tax rate. The labor supply of households is infinitely elastic. In this framework, an increase in labor income inequality means an increase in z_h. We normalize total productivity to 1 which implies that $\omega z_l + (1-\omega) z_h = 1$. Whenever the level of inequality increases, z_l also decreases to keep total productivity constant. The idiosyncratic productivity shock $e_{i,t}$ follows an AR-(1) process that we discretize using the Tauchen method.

We define the measure $\mu_{i,t}(a, e)$ as the mass of household of permanent type i holding wealth a with idiosyncratic type e at time t and $c_{i,t}(a, e)$ as the policy function for consumption for an agent holding wealth a with idiosyncratic type e at time t. Aggregate consumption is given by:

$$C_t = \omega \int c_{l,t}(a, e) d\mu_{l,t}(a, e) + (1 - \omega) \int c_{h,t}(a, e) d\mu_{h,t}(a, e).$$

Firms. A representative firm uses labor to produce a final good according to the following production function $Y_t = (z_l \omega + z_h(1 - \omega))N_t = N_t$. Firms are in perfect competition and subject to complete rigidity on the real wage (normalized to one). The representative firm maximizes its profits $Y_t - N_t$ subject to the technology and the demand constraint $Y_t = C_t$. Due to the wage rigidity, the firm is demand-constrained and any variation in effective demand C_t generates a one-to-one relationship with the labor demand N_t. This wage rigidity thus translates into a complete price rigidity.

Government. The government funds the service of public debt B with a linear tax rate τ_t on labor income so as to keep its budget balanced:

$$\tau_t N_t = r_t B.$$

Central bank. The central bank fixes an exogenous path for the nominal interest rate. As prices are rigid, any variations in the nominal interest rate translate into variations in the real interest rate r_t.

Definition 2.1 (Competitive equilibrium)**.** *A competitive equilibrium is defined as policy functions for consumption* $\{c_{i,t}(a, e)\}_{i,t}$ *and savings* $\{a_{i,t+1}(a, e)\}_{i,t}$*; sequences for labor demand* $\{N_t\}$*, the real interest rate* $\{r_t\}$*, the linear tax rate* $\{\tau_t\}$*, and output* $\{Y_t\}$*; a measure* $\{\mu_{i,t}(a, e)\}_{i,t}$ *such that :*

1. *Households solve their problem given prices and labor demand;*
2. *The representative firm maximizes profits;*
3. *The government maintains a balanced budget;*
4. *Markets clear:*
   (a) *The asset market clears:*
   $\omega \int a_{l,t+1}(a, e) d\mu_{l,t}(a, e) + (1 - \omega) \int a_{h,t+1}(a, e) d\mu_{h,t}(a, e) = B, \quad \forall t$
   (b) *The goods market clears:*
   $Y_t = \omega \int c_{l,t}(a, e) d\mu_{l,t}(a, e) + (1 - \omega) \int c_{h,t}(a, e), \quad \forall t$

2.2 The intertemporal Keynesian cross and permanent labor income inequality

The output response of this model following a monetary policy shock can be described by an intertemporal Keynesian cross as in Auclert and Rognlie (2020). Indeed, note that aggregate consumption at time $t = 0$ can be written as

$$C_0 \equiv \mathcal{C}_0(\{r_t, \tilde{N}_t\}_{t\geq 0})$$

where $\tilde{N}_t = (1-\tau_t)N_t$ is the net labor income and $\mathcal{C}_0(\{r_t, \tilde{N}_t\}_{t\geq 0})$ is the aggregate consumption policy function that depends on all the future paths of real interest rate and net labor income. We assume that the function $\mathcal{C}_t : \ell^\infty \times \ell^\infty \to \ell^\infty$ is Fréchet-differentiable. Totally differentiating the aggregate consumption function, we obtain

$$\begin{aligned} d\mathcal{C}_0(\{r_t, \tilde{N}_t\}_{t\geq 0}) = &\left[\frac{\partial C_0}{\partial r_0} dr_0 + \frac{\partial C_0}{\partial r_1} dr_1 + ...\right] \\ &+ \left[\frac{\partial C_0}{\partial \tilde{N}_0} d\tilde{N}_0 + \frac{\partial C_0}{\partial \tilde{N}_1} d\tilde{N}_1 + ...\right]. \end{aligned}$$

We can rewrite this expression more succinctly by writing it in vector forms

$$d\mathbf{C}(\{r_t, \tilde{N}_t\}_{t\geq 0}) = \mathbf{M}^r d\mathbf{r} + \mathbf{M}^n d\tilde{\mathbf{N}},$$

where $\mathbf{M}^r$ and $\mathbf{M}^{\tilde{n}}$ are aggregate sequence-space Jacobians (infinite-dimensional matrices) which characterize the reaction of aggregate consumption facing shocks on the real interest rate and on net labor demand at different periods, as in Auclert, Rognlie, and Straub (2018) and Auclert, Bardóczy, et al. (2021):

$$\mathbf{M}^r \equiv \begin{pmatrix} \frac{\partial \mathcal{C}_0}{\partial r_0} & \frac{\partial \mathcal{C}_0}{\partial r_1} & \cdots \\ \frac{\partial \mathcal{C}_1}{\partial r_0} & \frac{\partial \mathcal{C}_1}{\partial r_1} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}, \quad \text{and } \mathbf{M}^n \equiv \begin{pmatrix} \frac{\partial \mathcal{C}_0}{\partial N_0} & \frac{\partial \mathcal{C}_0}{\partial N_1} & \cdots \\ \frac{\partial \mathcal{C}_1}{\partial N_0} & \frac{\partial \mathcal{C}_1}{\partial N_1} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}.$$

Note that we can also define the aggregate consumption function as the sum of the consumption functions for each permanent type *by unit of permanent income*:

$$\mathcal{C}_0 \equiv \omega z_l \mathcal{C}_{l,0} + (1-\omega) z_h \mathcal{C}_{h,0}.$$

The change in aggregate consumption is thus given by

$$
\begin{aligned}
d\mathcal{C} &= (1-\omega)z_h d\mathcal{C}_h + \omega z_l d\mathcal{C}_l \\
&= (1-\omega)z_h(\mathbf{M}_h^r d\mathbf{r} + \mathbf{M}_h^n d\tilde{\mathbf{N}}) + \omega z_l(\mathbf{M}_l^r d\mathbf{r} + \mathbf{M}_l^n d\tilde{\mathbf{N}}) \\
&= \underbrace{((1-\omega)z_h\mathbf{M}_h^r + \omega z_l\mathbf{M}_l^r)d\mathbf{r}}_{\text{direct effect}} + \underbrace{((1-\omega)z_h\mathbf{M}_h^n + \omega z_l\mathbf{M}_l^n)d\tilde{\mathbf{N}}}_{\text{indirect effect from net labor demand}}.
\end{aligned}
$$

With $\mathbf{M}_i^x$ the sequence-space jacobian of permanent type i *per unit of permanent income*. The aggregate-level sequence-space Jacobian can thus be written as the following weighted average:

$$\forall x \in \{r, n, T\}, \quad \mathbf{M}^x = \omega z_l \mathbf{M}_l^x + (1-\omega)z_h\mathbf{M}_h^x.$$

Imposing that, in general equilibrium, $d\mathbf{Y} = d\mathbf{N} = d\mathbf{C}$, $d\boldsymbol{\tau} = Bd\mathbf{r} - rBd\mathbf{N}$, and $d\tilde{\mathbf{N}} = (1-\tau)d\mathbf{N} - d\boldsymbol{\tau}$, we can compute the aggregate effect of a monetary shock $d\mathbf{r}$ which is given by Proposition 2.1.

Proposition 2.1. *The aggregate effect of a monetary shock* $d\mathbf{r}$ *is the product of the general equilibrium multiplier and of the direct effect:*

$$d\mathbf{Y} = \mathcal{M}(\mathbf{M}^r - B\mathbf{M}^{\tilde{n}})d\mathbf{r}, \tag{2.1}$$

with $\mathcal{M} = [\mathbf{K}(\mathbf{I} - \mathbf{M}^{\tilde{n}})]^{-1}\mathbf{K}$*,* $\mathbf{K} \equiv -\sum_{t=1}^{\infty}(1+r)^{-t}\mathbf{F}^t$*, and* $\mathbf{F}$ *the forward matrix.*

Proof. Appendix A1 □

Proposition 2.1 shows the output response in our model as a function of the sequence space Jacobians. We can recover from this expression the traditional channels of monetary policy. $\mathbf{M}^r$ captures the direct effect of monetary policy, the change in consumption plans induced by a change in the real interest rate, keeping $\{\tilde{N}_t\}$ constant. A change in the path of the real interest rate has two direct effects: an intertemporal substitution effect and an income effect. By changing relative prices of consuming at different time periods, the new path of the real interest rate induces a change in consumption today. The change in the path of the real interest rate also changes households' financial income, implying a further change in consumption.

A change in the path of $\mathbf{r}$ also affects the budget constraint of the government, which will imply a direct change in the path of taxes τ, further changing the consumption path. This second effect is captured by the $-B\mathbf{M}^{\tilde{n}}$ in the IKC. The total change in the consumption path of households changes aggregate demand, which changes the firm's labor demand and hence the labor income of all households. This second change in consumption, in turn, has a feedback effect on aggregate demand, which is the traditional Keynesian multiplier effect. This general equilibrium amplification is the indirect effect from labor demand, and is captured in the IKC by the matrix $\mathcal{M}$, which is itself a function of the intertemporal marginal propensity to consume matrix $\mathbf{M}^{\tilde{n}}$.

Using the IKC as an ordering device, we ask: what happens when permanent labor income inequality goes up? We compare the output response following a monetary shock of two economies, one characterized by a low level of permanent labor income inequality ($\mathbf{z} = (z_l, z_h)$ while the other one is characterized by a higher level of permanent labor income inequality ($\mathbf{z}' = (z_l', z_h')$). A bold z indexes economies with different levels of permanent labor income inequality. Proposition 2.2 shows that we can decompose this change in the output response to a monetary shock between three effects: a composition effect, a Jacobian effect and an amplification effect.

Proposition 2.2. *The difference in the output response following a monetary policy shock in two economies with different levels of permanent income inequality can be decomposed between three terms: (1.) a direct and an indirect composition effect, (2.) a direct and an indirect Jacobian effect, and (3.) an amplification effect:*

$$
\begin{aligned}
d\boldsymbol{Y}(\mathbf{z}') - d\boldsymbol{Y}(\mathbf{z}) = & \underbrace{\overbrace{[(1-\omega)\Delta z_h' \boldsymbol{M}_h^r(\mathbf{z}') + \omega \Delta z_l' \boldsymbol{M}_l^r(\mathbf{z}')]\, d\boldsymbol{r}}^{\textit{direct}} + \overbrace{[(1-\omega)\Delta z_h' \boldsymbol{M}_h^n(\mathbf{z}') + \omega \Delta z_l' \boldsymbol{M}_l^n(\mathbf{z}')]\, d\tilde{\mathbf{N}}(\mathbf{z}')}^{\textit{indirect}}}_{\textit{composition effect}} \\
& + \underbrace{\overbrace{[(1-\omega) z_h \Delta \boldsymbol{M}_h^r(\mathbf{z}') + \omega z_l \Delta \boldsymbol{M}_l^r(\mathbf{z}')]\, d\boldsymbol{r}}^{\textit{direct}} + \overbrace{[(1-\omega) z_h \Delta \boldsymbol{M}_h^n(\mathbf{z}') + \omega z_l \Delta \boldsymbol{M}_l^n(\mathbf{z}')]\, d\tilde{\mathbf{N}}(\mathbf{z}')}^{\textit{indirect}}}_{\textit{Jacobian effect}} \\
& + \underbrace{\boldsymbol{M}^n(\mathbf{z})\Big(d\tilde{\mathbf{N}}(\mathbf{z}') - d\tilde{\mathbf{N}}(\mathbf{z})\Big)}_{\textit{amplification effect}}.
\end{aligned}
$$

With $\Delta \boldsymbol{M}^x(\mathbf{z}') = \boldsymbol{M}^x(\mathbf{z}') - \boldsymbol{M}^x(\mathbf{z})$ *and* $\Delta z_i' = z_i' - z_i$.

Noting that $d\boldsymbol{Y}(\boldsymbol{s}') - d\boldsymbol{Y}(s) = d\boldsymbol{N}(\boldsymbol{s}') - d\boldsymbol{N}(s)$, *we can write*

$$d\mathbf{Y}(\mathbf{z}') - d\mathbf{Y}(\mathbf{z}) = \mathcal{M}(\textit{composition effect} + \textit{Jacobian effect}).$$

Proof. Appendix A2 □

The composition effect captures the fact that even if the response of consumption *per unit of permanent income* for each type does not change, the increase in inequality will put more weight on the response of the high type compared to the low type.

The Jacobian effect captures the change in the coefficients of our sequences-space Jacobians keeping the weights on each matrices constant. The change in coefficients comes from three factors: (1) both types change their consumption-saving decisions as their income increases, (2) in general equilibrium prices adjust, and this change in prices also affects the consumption-saving decisions of households, and (3) the distribution of households also changes across the two economies.

More formally, the change in the type-i Jacobian's now depends on the change in the policy function *and* in the distribution of wealth $\mu_{i,t}$. Indeed, the definition of $M^x_{i,t,j}$, the element in line t, column j of the sequence-space Jacobian M^x_i, can be written as[3]

$$M^x_{i,t,j}(\mathbf{z}) = \int \frac{\partial c_{i,t}(a,e;\mathbf{z})}{\partial x_j} d\mu_{i,t}(a,e;\mathbf{z}).$$

Using this definition of a sequence-space Jacobian we can compute ΔM^x_i, the change in the Jacobian of an agent of type i in period t following a shock on the aggregate variable x in period j as

$$\begin{aligned}\Delta M^x_{i,t,j}(\mathbf{z}') = & \underbrace{\int \Big(\frac{\partial c_{i,t}(a,e;\mathbf{z}')}{\partial x_j} - \frac{\partial c_{i,t}(a,e;\mathbf{z})}{\partial x_j} \Big) d\mu_{i,t}(a,e;\mathbf{z})}_{\text{policy-function effect (1)+(2)}} \\ & + \underbrace{\int \frac{\partial c_{i,t}(a,e;\mathbf{z})}{\partial x_j} \Big(d\mu_{i,t}(a,e;\mathbf{z}') - d\mu_{i,t}(a,e;\mathbf{z}) \Big)}_{\text{wealth-distribution effect (3)}}\end{aligned}$$

Finally, in general equilibrium, the amplification effect magnifies the first two effects. It acts a multiplier of the sum of the composition and the Jacobian effect. Thus, even small Jacobian and composition effect might end up having a large impact on the output response, since they will be amplified by the general equilibrium matrix $\mathcal{M}$. Both the composition and the Jacobian effects can be decomposed into a direct and an indirect effect.

2.3 HANK with Zero-Liquidity

In this section, we focus on the particular case of zero-liquidity $B = 0$ which allows us to compute analytically our sequence-space Jacobians. Using those analytical forms, we compute the aggregate effect of a monetary policy shock. We also perform a decomposition between the direct effect of the real interest rate shock and the indirect effect coming from the change in labor demand. In this framework, we can analytically characterize the effect of the distribution of permanent labor income as well as the effect of the taste for wealth on the transmission of a monetary policy shock.

Analytically solving the Sequence-Space Jacobians

We first derive the analytical expressions for the sequence space Jacobians that compose Equation 2.1 under the zero-liquidity assumption. Note that those expressions do not depend on the particular preferences we assume in the household problem, and thus apply to both

[3] Note that the path of distribution $d\mu_t(a,e;s)$ itself depends on the derivative of the policy functions.

the case with homothetic preferences and non-homothetic preferences. We will distinguish the impact of those different preferences in the Sub-sections 2.3 and 2.3.

In the presence of zero liquidity, all households with an idiosyncratic type lower than the maximum idiosyncratic type $\bar{e}$ will be against the borrowing constraint. Those households behave as hand-to-mouth households and will not react to variations in the real interest rate, while their consumption will react one-to-one to variations in labor income. Defining the saving policy function of permanent type i, $a_i(a, e)$, we have that, at the steady state, $\frac{\partial a_i}{\partial a}(0, e) = 0, \ \forall e < \bar{e}$[4].

At the steady state, households with the highest idiosyncratic type $\bar{e}$ are on their Euler equation, and hence, are indifferent between savings and dissavings. The slope of the steady state saving function of a permanent type i is given by $\lambda_i \equiv \frac{\partial a_i}{\partial a}(0, \bar{e})/\Pi_{\bar{e}\bar{e}}$, with $\Pi_{\bar{e}\bar{e}}$ the probability of staying a high-idiosyncratic type tomorrow conditional on being a high-idiosyncratic type today[5]. For clarity, we define $1 - \mu \equiv \frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}}$ as the effective share of unconstrained households within permanent type i.

Proposition 2.3. *a) The sequence-space Jacobian of the consumption response following a labor demand shock of permanent income type i is*

$$\mathbf{M}_i^{\tilde{n}} = \mu \mathbf{I} + (1-\mu) \begin{pmatrix} 1 - \frac{\lambda_i}{1+r} & \frac{\lambda_i}{1+r}\left(1 - \beta\lambda_i\right) & \cdots \\ \lambda_i\left(1 - \frac{\lambda_i}{1+r}\right) & \left(1 - \frac{\lambda_i}{1+r}\right)\left(1 - \lambda_i\left(1 - \beta\lambda_i\right)\right) & \cdots \\ \lambda_i^2\left(1 - \frac{\lambda_i}{1+r}\right) & \lambda_i\left(1 - \frac{\lambda_i}{1+r}\right)\left(1 - \lambda_i\left(1 - \beta\lambda_i\right)\right) & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

where $\boldsymbol{I}$ is the matrix of intertemporal marginal propensities to consume (iMPCs) of constrained households and the second matrix is the iMPCs of unconstrained households of permanent type i.

b) The sequence-space Jacobian of the consumption response following an interest rate shock of permanent income type i is

$$\boldsymbol{M}_i^r = (1-\mu)\beta\rho(\bar{e})\frac{1}{\sigma}\lambda_i \begin{pmatrix} 0 & -\frac{1}{1+r} & -\frac{\beta\lambda_i}{1+r} & \cdots \\ 0 & 1 - \frac{\lambda_i}{1+r} & \beta\lambda_i(1 - \frac{\lambda_i}{1+r}) - \frac{1}{1+r} & \cdots \\ 0 & \lambda_i(1 - \frac{\lambda_i}{1+r}) & (1 + \beta\lambda_i^2)(1 - \frac{\lambda_i}{1+r}) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}.$$

where $\rho(\bar{e}) = \sum_{e'} \Pi_{\bar{e}e'} \left(\frac{e'}{\bar{e}}\right)^{-\sigma}$

Proof. For $\mathbf{M}_i^r$, see Appendix A.5 and for $\mathbf{M}_i^n$, see Appendix A.8 □

[4] See appendix A.2 for formal derivation.

[5] See appendix A.3 for formal derivation.

The interpretation of those two sequence-space Jacobian is intuitive.

Jacobian with respect to the labor demand. Starting with the sequence jacobian of the consumption response following a labor demand shock, the first column of $\mathbf{M}_i^{\tilde{n}}$ gives us the intertemporal marginal propensity to consume (iMPC) out of a one-time income shock of households of permanent type i. It is a weighted average of the iMPCs of the constrained and unconstrained households *among* a permanent type i. Note that the MPC of constrained households is 1, and that the MPC of unconstrained households is $1 - \lambda_i/(1+r)$. In the absence of a taste for wealth and idiosyncratic shocks, $\lambda_i = 1$ and we recover the standard MPC in a representative agent model, $r/(1+r)$.

Aggregating over both permanent types, we obtain the aggregate sequence-space Jacobian $\mathbf{M}^{\tilde{n}} = \omega_l z_l \mathbf{M}_l^{\tilde{n}} + \omega_h z_h \mathbf{M}_h^{\tilde{n}}$, a weighted sum of the Jacobian per permanent-type. The contemporaneous aggregate iMPC[6] is given by the first element of the first column of this infinite matrix:

$$\begin{aligned} iMPC_0 &= 1 - (1-\mu)\frac{1}{1+r}\sum_i \omega_i z_i \lambda_i \\ &= \underbrace{\mu \sum_i \omega_i z_i}_{\text{income share of constrained}} + \underbrace{(1-\mu)\sum_i \omega_i z_i}_{\text{income share of unconstrained}} \left(1 - \frac{\lambda_i}{1+r}\right). \end{aligned}$$

The rest of the first column gives the path of *intertemporal* marginal propensity to consume out of an income shock:

$$iMPC_t = (1-\mu)\sum_i \omega_i z_i \lambda_i^t \left(1 - \frac{\lambda_i}{1+r}\right).$$

The income shock is spent down at a rate λ_i.

Jacobian with respect to the interest rate. The sequence space Jacobian $\mathbf{M}_i^r$ describes the consumption response to a shock on r_t. It is characterized by two different elasticities: the elasticity of intertemporal substitution and the intertemporal marginal propensity to consume. The elasticity of intertemporal substitution determines to which extent households want to exploit differences in relative prices while the intertemporal marginal propensity to consume determines the speed at which additional incomes are consumed. The strength of that intertemporal substitution is determined by the EIS[7] of the unconstrained household:

$$\text{EIS} = \frac{\rho(\bar{e})\beta}{\sigma}\lambda_i \left[\left(1 - \frac{\lambda_i}{1+r}\right)\bar{e} + \frac{\mathbb{E}[e'|\bar{e}]}{1+r}\right] \frac{1+r}{\bar{e}\mathbb{E}[e'|\bar{e}]\Pi_{\bar{e}\bar{e}}},$$

which is an increasing function of λ_i[8]. When r increases in the future, consuming today is

[6] The classic MPC in the literature.

[7] Notice that, in the absence of taste for wealth and idiosyncratic shocks, the formula simplifies to $1/\sigma$.

[8] Indeed, recall that λ_i is between 0 and 1. The negative second-order term of this polynomial will thus

relatively more expensive. Today's consumption falls while future consumption increases. Households postpone part of their consumption to later periods by increasing their savings and then consume a fraction $\lambda_i^t[1 - \lambda_i/(1+r)]$ at period t of this additional income[9].

Interpretation of λ_i. The variable λ_i determines the contemporaneous MPC, the persistence of the iMPC, and the EIS of unconstrained households. The MPC is a decreasing function of λ_i while the EIS is an increasing function of λ_i. It is thus key in understanding the behavior of households as in it pins down the degree to which households are forward-looking.

When $\lambda_i = 1$, unconstrained households behave as forward-looking, permanent-income households in a riskless world. Their consumption response to an income shock is perfectly smoothed and they consume at every period a fraction $r/(1+r)$ of that income shock. In that case, the indirect effect is low as the consumption response of unconstrained households does not move much with transitory income shocks. Conversely, the consumption of unconstrained households is very sensitive to changes in the real interest rate as it controls the relative prices of consumption at different time periods. As households put a large weight on future consumption, their consumption response is very sensitive to a change in relative prices of future consumption. As a result, the direct effect of a monetary shock is high.

When $\lambda_i < 1$, households are less forward-looking. There is now an extra discounting of future consumption flows. Their contemporaneous MPC is higher than future iMPC. In that case, the indirect effect is high as the consumption response of unconstrained households largely moves with a contemporaneous income shock. Conversely, the consumption of the unconstrained household is less sensitive to changes in the real interest rate as the EIS decreases.

The aggregate effect of a monetary policy shock

Combining Proposition 2.1 and the analytical solutions for our two sequence-space Jacobians, we compute the aggregate effect of a monetary policy shock $r_0 < r^{ss}$ with persistence ρ. We also compute the direct and the indirect effects.

Proposition 2.4. *The aggregate effect of a monetary policy shock r_0 is given by:*

$$dY_0 = -\beta\rho(\bar{e})\frac{1}{\sigma}\frac{\rho}{1-\rho}dr_0. \tag{2.2}$$

The direct effect of a monetary policy shock is given by:

$$\textit{Direct effect}_0 = -(1-\mu)\rho(\bar{e})\frac{1}{1+r}\frac{1}{\sigma}\sum_i \omega_i z_i \frac{\rho\lambda_i\beta}{1-\rho\lambda_i\beta}dr_0.$$

be negligible and dominated by the positive linear term.

[9] Since there is no wealth in our model, interest rate shocks have no initial income effects and an unexpected change in r_0 has no impact on consumption. The first column of $\mathbf{M}_i^r$ is thus zero.

The indirect effect of a monetary policy shock is given by:

$$\textit{Indirect effect}_0 = dN_0 - (1-\mu)\frac{1}{1+r}(1-\rho)\sum_i \omega_i z_i \frac{\lambda_i}{1-\beta\lambda_i\rho} dN_0.$$

The direct effect is an increasing function of λ_i while the indirect effect is a decreasing function of λ_i.

Proof. Appendix A4 □

The structure of preferences and the level of ex-ante heterogeneity matter for monetary policy as they jointly determine the value of λ_i and the equilibrium r. At the aggregate level, λ_i determines the relative weight of the direct and indirect effects of a monetary shock on output. The larger λ_i, the higher the direct effect and the lower the indirect effect. This is consistent with the fact that the static MPC is a decreasing function of λ_i while the EIS is an increasing function of λ_i. In the next section, we are going to study what happens when ex-ante heterogeneity rises (1) in the absence of a non-homothetic taste for wealth ($\gamma = 0$) and (2) in the presence of a non-homothetic taste for wealth ($\gamma > 0$).

Benchmark: monetary policy without a taste for wealth

We first study this model in the benchmark case without a taste for wealth by setting γ to 0.

Proposition 2.5. *In the HANK model with zero-liquidity, when $\gamma = 0$ (no preference for wealth), the Jacobians $\boldsymbol{M}_i^r$ and $\boldsymbol{M}_i^n$ do not depend on z:*

$$\forall i \in \{l,h\}, x \in \{r,n\}, \quad \Delta\mathbf{M}_i^x(z') = 0 \textit{ and } \mathbf{M}_l^x = \mathbf{M}_h^x.$$

1. *There is neither a composition effect nor a behavior effect.*

2. *A change in permanent labor income inequality does not affect the magnitude of a monetary policy shock.*

Proof. Appendix C □

Without a taste for wealth, the slope of the steady-state savings function λ_i does not depend on the level of permanent income. $\forall i$, $\lambda_i \equiv \lambda$. Thus, the share of constrained households across types is the same, and the sequence-space Jacobians per unit of permanent income are equal across types. The distribution of permanent income is neutral on the transmission of monetary policy.

Indeed, without a non-homothetic taste for wealth, differences in permanent productivity scale linearly consumption and savings functions across permanent types (Straub 2019). As the slope of the saving function of the highest idiosyncratic type evaluated at the steady state is constant across permanent types, the sequence-space Jacobians per unit of permanent income are equal across types. As a result, the total, direct, and indirect effects do not depend on the distribution of permanent productivity. A change in the distribution of permanent income thus does not affect the output response to a monetary policy shock, nor the transmission channel of monetary policy.

Accounting for the non-homotheticity in saving behavior

We now study the impact of an increase in permanent income inequality in the zero-liquidity model under non-homothetic preferences. In the presence of a taste for wealth, all low permanent income types are constrained, $\lambda_l = 0$ and $\lambda \equiv \lambda_h$[10]. A rise in permanent labor income inequality changes the transmission channels of monetary policy, leaving the aggregate effect constant.

Permanent income and behavior effect. Under non-homothetic preferences, λ decreases with permanent income because r is itself a decreasing function of permanent income. Thus, an increase in permanent labor income inequality increases the MPC, decreases the persistence of the iMPC, and decreases the EIS. In Proposition 2.2, this change in λ and r determines the behavior effects $\Delta \mathbf{M}_h$ which is the change in the coefficients of our sequence-space Jacobians *per unit of permanent income.*

When permanent labor income increases under non-homothetic preferences, the Euler equation is more "discounted" in terms of McKay, Nakamura, and Steinsson (2017) and Michaillat and Saez (2021). Indeed, as the high-productivity households become richer, their consumption increases, decreasing their marginal utility from consumption. For their Euler equation to hold at a steady state, the real interest rate has to fall, since

$$1 + r = \frac{1}{\beta\rho(\bar{e})}\left[1 - \frac{\gamma\zeta^{-\Sigma}}{(z_h\bar{e})^{-\sigma}}\right], \quad \frac{dr}{dz_h} < 0.$$

Outside of the steady state, unconstrained households now put a lower weight $\beta(1+r_{t+1}) < 1$ on future consumption since the Euler equation writes

$$c_t^{-\sigma} = (1 + r_{t+1})\beta\mathbb{E}[c_{t+1}^{-\sigma}] + \gamma(a_{t+1} + \zeta)^{-\Sigma}.$$

As a result, a change in the path of real interest rates, i.e. a change in relative prices of consuming at different time periods has a lower effect on consumption today (as future

[10]The Euler equation now depends on z_i and the real interest rate will adjust so that the Euler equation will hold with equality only for the high permanent income type with the highest idiosyncratic type. See Appendix A.2 for details.

consumptions are more discounted). Unconstrained households would like to hold wealth relatively more for a *present motive* due to the non-homothetic nature of the taste for wealth rather than for an intertemporal substitution motive. At the micro level, unconstrained households become less sensitive to variations in the real interest rate, and their EIS falls. At the same time, they frontload their consumption reaction to an income shock, and their MPC rises. At the macro level, the direct effect is weakened while the indirect effect is strengthened[11].

Composition effect. A change in permanent income also redistributes a higher share of income towards households with a lower MPC and a higher EIS, since all the constrained households have a MPC of 1 and an EIS of 0. Formally, it changes the weights on each sequence-space Jacobian $\Delta\mathbf{M}_i$, which increases the direct effect and decreases the indirect effect.

To sum up, an increase in permanent labor income inequality entails both a composition and a behavior effect, and both those effects impact the transmission channels of monetary policy:

$$\frac{d\text{Indirect effect}_0}{dz_h} = \underbrace{\text{composition effect}_0}_{<0} + \underbrace{\text{behavior effect}_0}_{>0},$$
$$\frac{d|\text{Direct effect}_0|}{dz_h} = \underbrace{\text{composition effect}_0}_{>0} + \underbrace{\text{behavior effect}_0}_{<0}.$$

Furthermore, with zero liquidity, the change in the permanent labor income distribution has no effect on the incidence of monetary policy on output[12]. The "as-if" result of Werning (2015) holds in this framework. The change in the income share of constrained and unconstrained households generates no aggregate amplification since, in the absence of government bonds, the elasticity of the net income of hand-to-mouth households to aggregate income is one (Bilbiie 2008). In a simulation exercise done in Section 2.4, the composition effect dominates the behavior effect. The rise in permanent labor income inequality hence leads to a rise in the indirect effect and a fall in the direct effect. The results are displayed in Table 2.2.

2.4 HANK with positive liquidity

We now relax the zero-liquidity assumption and allow for a realistic level of liquid wealth. The distribution of wealth is no longer degenerate, with a mass of agents bunched at zero wealth. An increase in permanent income inequality changes the distribution of wealth, which in turn impacts the aggregate consumption response to a monetary policy shock.

[11] We prove this formally in Appendix A.

[12] Note that Equation 2.2 depends neither on r nor on λ.

Calibration

For the distribution of permanent labor income, we set ω to 0.1 and chose z_h so as to match the labor income share held by the top 10% in 1989 and in 2019. We follow Straub (2019) to calibrate the CRRA parameter on wealth in order to match an elasticity of consumption to permanent income of 0.7. The last two remaining parameters γ, the strength of the taste for wealth, and ζ, the Stone-Geary parameter, are calibrated with 2019 level of permanent labor income inequality so as to match a static aggregate MPC of 0.51 and a one-year intertemporal MPC of 0.18 as in Auclert, Rognlie, and Straub (2018). When we decrease the level of permanent labor income inequality to its 1989 level, we keep the rest of the calibration constant. Table 2.1 summarizes our calibration.

Table 2.1: Calibration of the one-asset HANK model

Parameter	**Description**	**Value**	**Source**
Household			
β	Discount factor		To match $r = 5\%$
σ	CRRA on consumption	1	Auclert and Rognlie (2020)
γ	Strength of the taste for wealth	0.03	Internally calibrated
ζ	Stone-Geary shifter	0.4	Internally calibrated
Σ	CRRA on wealth	0.7	Straub (2019)
Labor income			
ρ_e	Autocorrelation productivity shocks	0.92	Straub (2019)
σ_e	s.d. productivity shocks	0.2	Straub (2019)
ω	High permanent labor income type	0.1	Internally calibrated
z_h	High productivity type	$\{2.8, 3.4\}$	Piketty, Saez, and Zucman (2018)
Government			
r_{ss}	Steady state interest rate	5%	
ρ_r	Autocorrelation of monetary shock	0.15	Kaplan, Moll, Violante (2018)
σ_r	s.d. of monetary policy shock	0.01	Kaplan, Moll, Violante (2018)
B	Government debt	0.23	Auclert and Rognlie (2020)

Results

The introduction of positive liquidity results in a non-degenerate distribution of wealth that can endogenously vary with the distribution of permanent labor income. This shift in the distribution of wealth alters the results obtained in the zero-liquidity case. The rise in permanent labor income inequality increases the size of the indirect effect and decreases the size of the direct effect (see table 2.2). The increase in the indirect effect outweighs the reduction in the direct effect, leading to a larger overall impact of a monetary shock on output following the rise in permanent labor income inequality.

Table 2.2: Change in total output elasticity and partial effect

	Partial effect			Total effect
	r	N	Tax	Y
Zero liquidity	0.28	-0.27	-0.01	0
Positive liquidity	-1.91	2.74	-0.83	7.75

Note: The three first columns of this table describe the change in the percentage of total output explained by the partial effect in an economy with a high and a low level of permanent labor income inequality in the first period. For example, the first number means that in the zero liquidity model, the share of output change explained by the direct effect 'r' decreased by 0.27%. The last column shows the percentage change in the elasticity of total output to a monetary policy shock.

Indirect effect. The rise in the indirect channel comes from an increase in the aggregate MPC (see table 2.3) which ultimately stems from three effects: the change in policy functions, the change in the wealth distribution, and the composition effect.

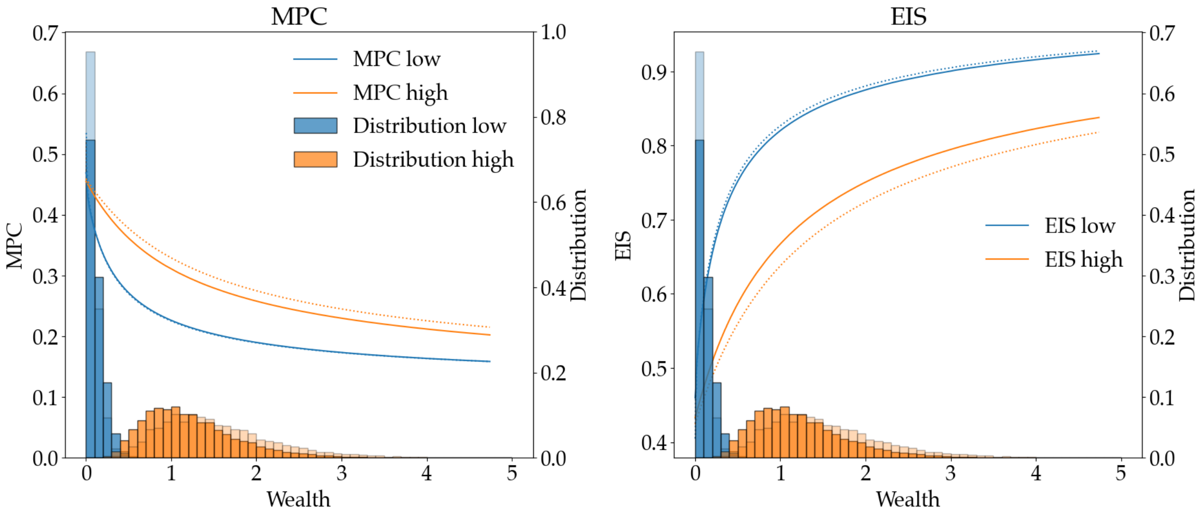

Figure 2.2: MPC and EIS along the wealth distribution

Note: This figure plots the marginal propensity to consume out of a one-time income shock (on the left) and the elasticity of intertemporal substitution (on the right) for different levels of wealth (x-axis) and for different levels of permanent income (in orange, the permanent labor income of the top 10% in 1989, in dotted orange the permanent labor income of the top 10% in 2019; in blue, the permanent labor income of the bottom 90% in 1989, in dotted blue the permanent labor income of the bottom 90% in 2019. We also plot the wealth distributions of the two permanent income types normalized (in blue, the low-income type, and in orange, the high-income type) before and after the rise in permanent labor income inequality (in dark color before and transparent after the rise).

First, the rise in permanent labor income inequality leads to a change in policy functions. For a given level of wealth, high-permanent income households have higher MPC after the rise in their permanent income (see Section 2.3) which tends to increase the aggregate MPC. This is shown in the left panel of Figure 2.2.

Second, the rise in permanent labor income inequality leads to a change in the wealth distribution. In particular, we observe a significant rise in the share of hand-to-mouth households. Indeed, when permanent labor income inequality rises, high-permanent income households put a relatively higher weight on the taste for wealth, as wealth is a luxury good.

They want to increase savings everything else equal. For the asset market to clear, the real interest rate has to fall. However, at the bottom of the income distribution, households put a relatively lower weight on the taste for wealth. Their savings decision is hence driven mostly by the precautionary and intertemporal substitution motives so that the decrease in the real interest rate pushes them to dissave. As a result, the share of hand-to-mouth households increases, as shown in the left panel of 2.2. This wealth distribution effect tends to increase the aggregate MPC.

Table 2.3: Change in the MPC

	Low type	High type	Aggregate
Low inequality	0.38	0.3	0.37
High inequality	0.41	0.3	0.4

Lastly, the composition effect tends to dampen the rise in the aggregate MPC. Indeed, as the average MPC is higher among low permanent-income households than among high permanent-income households, the rise in permanent labor income inequality decreases the aggregate MPC. Quantitatively, the sum of the first two effects largely dominates the last one leaving the aggregate MPC higher after the rise in permanent labor income inequality.

Direct effect. The change in the direct effect occurs in the opposite direction of the change in the indirect effect. First, the change in the policy function reduces the EIS, as it decreases with rising permanent income (see Section 2.3), leading to a lower aggregate EIS. Second, the change in the wealth distribution further diminishes the direct effect, as a larger proportion of households are now hand-to-mouth and thus unresponsive to interest rate changes. Finally, the composition effect reallocates income towards households with a higher EIS (see the first two columns of Table 2.4), increasing the aggregate EIS. However, quantitatively, the combined impact of the first two effects outweighs the third, resulting in a lower aggregate EIS following the rise in permanent labor income inequality (see the last column of Table 2.4).

Amplification. The aggregate neutrality of the permanent labor income distribution no longer holds with a realistic level of wealth. The rise in the share of hand-to-mouth households amplifies the output response to a monetary shock. Indeed, the elasticity of hand-to-mouth net income to aggregate income is greater than one. In the case of a fall in the real interest rate, the net income of hand-to-mouth households increases both from the rise in labor demand and from the fall in the labor tax rate (Bilbiie 2008). Moreover, even if the change in policy functions and distributions might be small quantitatively, the overall impact on the output response to a monetary shock remains economically significant since those composition, behavior, and wealth effects are amplified by the change in labor income (see Proposition 2.2).

Table 2.4: Change in the EIS

	Low type	High type	Aggregate
Low inequality	0.59	0.68	0.6
High inequality	0.55	0.68	0.57

Impact of an increase in the variance of idiosyncratic shocks

Does the nature of the rise in labor income inequality matter for monetary policy? In other words, what would have happened if the rise in labor income inequality were to be driven by an increase in the variance of shocks happening over the lifetime. The results are displayed in Figure 2.5 in the appendix.

In the zero-liquidity case, an increase in the variance of shocks decreases λ and raises $\rho(\bar{e})$. The fall in λ, through a rise in the aggregate MPC, increases the indirect response. At the same time, the rise in $\rho(\bar{e})$ magnifies the intertemporal substitution effect. As high idiosyncratic type households earn more, a change in the relative price of consumption has a higher effect on their aggregate consumption. Combining the rise in indirect and direct effects, an increase in the variance of shocks unambiguosly increase the effect of monetary policy in the zero-liquidity case.

This property no longer holds when households have access to a sufficiently-large stock of government bonds. Indeed, there is now an additional effect. When the variance of shocks increases, more households end up at or close to the borrowing constraint. The EIS of those households is low and so the direct effect is weakened. On top of that, there is an aggregate dampening of a monetary shock as the equilibrium r decreases when labor income inequality increases[13]. The lower interest rate means that the equilibrium tax rate is lower and the elasticity of the disposable income of hand-to-mouth households to aggregate income decreases (but remains above 1). There is less amplification and a monetary shock has a lower aggregate effect after the rise in the variance of idiosyncratic shocks.

We see that the predictions of the effect of a rise in the variance in initial outcomes compared to the effect of a rise in the variance in idiosyncratic shocks are largely reversed. The nature of the rise in labor income inequality does matter to understand the change in its aggregate effect and its composition.

3 A quantitative two-asset HANK model

Our previous model featured only one endogenous variable, N_t. It also abstracted from a realistic supply side, investment and inflation, in order to represent the entire path of the

[13]As households now want a higher buffer stock of savings, everything else equal.

economy through an intertemporal-Keynesian cross. In this section, we extend our previous analysis to a quantitative environment that features a two-asset choice on the household side and includes the previously omitted elements.

3.1 Environment

Households. The problem of a household of type i in labor union k[14] is given by:

$$V_{i,t}(\ell_t, a_t, e_t) = \max_{c_t} \left\{ \frac{c_t^{1-\sigma} - 1}{1-\sigma} - \varphi \frac{n_{kt}^{1+\nu}}{1+\nu} + \gamma \frac{(a_t + \ell_t + \zeta)^{1-\Sigma} - 1}{1-\Sigma} + \beta \mathbb{E}_t[V_{i,t+1}(a_{t+1}, \ell_{t+1}, e_{t+1}) | e_t] \right\},$$

subject to the law of motion,

$$\begin{aligned} c_t + \ell_{t+1} &= \lambda_t (z_i e_t w_{kt} n_{kt})^{1-\tau} + (1 + r_t^\ell)\ell_t + d_t, \\ a_{t+1} &= (1 + r_t^a) a_t - d_t(a_t). \end{aligned}$$

We follow Auclert, Rognlie, and Straub (2020) and assume that flows from and towards the illiquid are determined exogenously by the following rule

$$d_t(a_t) = \frac{r_{ss}^a}{1 + r_{ss}^a} (1 + r_t^a) a_t + \Omega \left((1 + r_t^a) a_t - (1 + r_{ss}^a) \bar{a}_i \right)$$

where $\bar{a}_i$ is a target level of illiquid wealth determined exogenously, and Ω is a number close to zero. This rule implies that, at the steady state, households receive a fixed income $r_{ss}^a \bar{a}_i$ from their illiquid account and that the total supply of illiquid assets is $\sum_i \omega_i \bar{a}_i$. In the transition, they will transfer the excess or missing returns toward the liquid account. The evolution of the idiosyncratic productivity shocks follows a log AR(1) process given by

$$\log(e_t) = \rho \log(e_{t-1}) + \varepsilon_t^e,$$

with $\varepsilon_t^e \sim \mathcal{N}(0, \sigma_e^2)$. Finally, notice that the number of hours supplied is not a control variable as it is chosen by the labor union. This household block gives rise to the aggregate consumption and the aggregate asset supply functions

$$\begin{aligned} L_t &= \mathcal{L}_t(\{r_s, N_s, \lambda_s\}_{s \geq t}, \mu_t), \\ A_t &= \mathcal{A}_t(\{r_s, N_s, \lambda_s\}_{s \geq t}, \mu_t), \\ C_t &= \mathcal{C}_t(\{r_s, N_s, \lambda_s\}_{s \geq t}, \mu_t), \end{aligned}$$

where μ_t is the distribution of households over idiosyncratic states, asset positions, and permanent types.

Unions. Every worker belongs to a union k. Each union k aggregates efficient units of

[14] See next section.

work into a union-specific task N_{kt} and sells those union-specific tasks at price W_{kt} to a competitive labor packer with an elasticity of substitution of ε between union-specific tasks. The problem of the union is specified in the Appendix. Solving the union problem yields the following non-linear New-Keynesian Phillips curve on wage inflation:

$$\pi_t^w = \kappa \left(\varphi \left(N_t\right)^\nu - \frac{1}{\mu} \left(1 - \lambda_t\right) w_t \left(C_t\right)^{-\sigma} \right) + \beta \pi_{t+1}^w$$

Central bank. The central bank follows a Taylor rule

$$i_t = r + \phi_\pi \pi_t + \varepsilon_t^r,$$

where r is the steady-state interest rate. The innovations to the nominal interest rate set by the central bank follow an AR(1) process with persistence ρ_r. The *ex-ante* real interest rate is given by the Fisher equation

$$1 + r_t = \frac{1 + i_t}{1 + \pi_{t+1}}.$$

Firms. The firm block of our model follows Auclert and Rognlie (2020). The supply side is composed of two sectors. A final goods producer that uses a basket of intermediate inputs $x_{i,t}$ with an elasticity of substitution $\mu_p/(\mu_p - 1)$, and a continuum of intermediate firms in imperfect competition, which produces the intermediate goods using capital and labor with a Cobb-Douglas technology production function. Intermediate goods are produced by a mass one of identical monopolistically competitive firms, whose shares v_t are traded, with price p_t and dividends d_t at time t, and owned by households. Intermediate firms own the stock of physical capital, make investment decisions subject to convex adjustment, and make pricing decisions subject to Rotemberg adjustment costs. The intermediate's firm problem can be found in Appendix E.1 This setup yields a standard non-linear New-Keynesian Phillips curve on final-goods price inflation[15]:

$$\pi_t \left(1 + \pi_t\right) = \kappa^p \left(\mu^p \cdot mc_t - 1\right) + \frac{1}{1 + r_t} \pi_{t+1} \left(1 + \pi_{t+1}\right) \frac{Y_{t+1}}{Y_t}.$$

where the marginal cost is given by, $mc_t = \frac{1}{1-\alpha} w_t \frac{N_t}{Y_t}$, with w_t the real wage, κ^p the parameter governing the Rotemberg cost, and μ^p the markup of intermediate firms. The investment decision is governed by the usual marginal Tobin's Q equations

$$Q_t = 1 + \frac{1}{\delta \epsilon_I} \left(\frac{K_t}{K_{t-1}} - 1 \right),$$

$$\left(1 + r_{t-1}\right) Q_{t-1} = mc_t \cdot F_K \left(K_t, N_t\right) - \left(\frac{K_{t+1}}{K_t} - (1 - \delta) \right) - \varphi \left(\frac{K_{t+1}}{K_t} \right) + \frac{K_t}{K_t} Q_t.$$

[15] Appendix G.1 in Auclert, Rognlie, and Straub (2018)

Finally, the price of the firm p_t is given by the non-arbitrage condition between owning equity in the firm and government bonds:

$$p_t = \frac{d_{t+1} + p_{t+1}}{r_{t+1}}.$$

Financial intermediary. There is a financial intermediary that receives liquid and illiquid deposits from households and invests them in equity and government bonds. It performs this liquidity transformation at a fixed cost ξ so that $r_t = r_t^a = r_t^b - \xi$. We assume that the financial intermediary is in perfect competition so that it makes no profit in equilibrium.

The flow-of-fund constraint at the beginning of period t states that the value of liabilities must be equal to the liquidation value of the intermediaries portfolio:

$$(1 + r_t^a) A_t + \left(1 + r_t^l\right) L_t = (1 + r_t) B_t + (p_t + d_t) v_t - \xi L_t.$$

At the end of period t, new investments in bonds and shares should be equal to intermediary liabilities (or aggregate savings):

$$p_t v_{t+1} + B_{t+1} = A_{t+1} + L_{t+1}$$

Finally, returns on the illiquid assets are subject to capital gains following a one-time unexpected shock. The return on illiquid assets in period 0 following an unexpected shock is given by

$$r_0^a = \frac{p_{ss}}{B + p_{ss}} \frac{d_1 + p_1}{p_0} + \frac{B_{ss}}{B + p_{ss}} r_0.$$

The firm term of this expression captures the fact that following an unexpected shock, the price of the firm might jump (or fall) unexpectedly, increasing (or decreasing) the real return on equity compared to what households expected to receive the period before the shock, at the steady state. Due to perfect foresight, the usual non-arbitrage condition holds for all the remaining transition periods.

Government. The government imposes a progressive tax on labor income, determined by the HSV coefficient τ and the rate λ_t. The budget constraint is

$$N_t w_t = \lambda_t \sum_i \omega_i \int (w_t e_t s_i N_t)^{1-\tau} d\mu_{i,t} + r_t B.$$

Market clearing. Market clearing implies that

1. Asset market: $A_t = p_t + B$;
2. Labor market: $N_t^s = N_t^d$;
3. Goods market: $Y_t = C_t + I_t + G + \xi L_t + \varphi\left(\frac{K_{t+1}}{K_t}\right) + \kappa_p\left(\frac{P_{t+1}}{P_t} Y_t\right)$.

3.2 Calibration

Calibration of permanent types

Our quantitative model has four types of households, each belonging to a group of the distribution of permanent income: the **b**ottom **50%**, the **n**ext **40%**, the **n**ext **9%** and the **t**op **1%** of the distribution of permanent income. We calibrate the corresponding z_i to match the distribution of labor income described in Piketty, Saez, and Zucman (2018). We then associate each of those groups to a target of illiquid asset $\bar{a}_i$, as in Auclert, Rognlie, and Straub (2020). We set those targets to match the unconditional distribution of illiquid assets in the Survey of Consumer Finance, and to match a share of liquid assets to output of 0.23, as in Kaplan, Moll, and G. Violante (2018) and Auclert and Rognlie (2020). In our main computational exercise, we compute the impact of a monetary policy shock in an economy where the $(s_{b5}, s_{n40}, s_{n9}, s_{t1})$ and $(a_{b5}, a_{n40}, a_{n9}, a_{t1})$ are calibrated to match the distribution of income in 2019 (high inequality) and 1989 (low inequality).

Calibration of the taste for wealth

We calibrate internally only two parameters: the strength of the taste for wealth γ and the Stone-Geary shifter ζ. We set those parameters to match the distribution of wealth in our model in 2019, given a distribution of permanent labor income $(s_{b5}, s_{n40}, s_{n9}, s_{t1})$ and a distribution of illiquid wealth $(a_{b5}, a_{n40}, a_{n9}, a_{t1})$. Table 1.1 describes the total distribution of wealth in our economy[16]. Our model also does a fairly good job at reproducing the distribution of wealth in 1989, which we do not target in the calibration of the taste for wealth (overestimating the wealth share of the middle 40% and underestimating the top 10% wealth share).

Notice that, when calibrating, we do not target the path of iMPC, only the wealth distribution. However, we do get quite close on the aggregate MPC from Fagereng, Martin B Holm, and Natvik (2021), but we undershoot the iMPC one year after the income shock estimated in Auclert, Rognlie, and Straub (2018) (from 0.16 to 0.18 depending on the data source).

Due to the two-asset structure, the share of hand-to-mouth aggregates both poor hand-to-mouth households that have no liquid and illiquid wealth and wealthy hand-to-mouth households that have no liquid wealth but have positive illiquid wealth. The later are reluctant to dissave their illiquid wealth. As a result, they feature high MPC out of any labor income shock even if they have positive weealth.

[16] We use the extended series available on `https://gabriel-zucman.eu/`.

Table 2.5: Calibration of the quantitative model

Parameters	**Description**	**Value**	**Source**
Preferences			
β	Discount factor	0.85	Internally calibrated
σ	CRRA coefficient on consumption	1	Auclert et al. (2024)
γ	Strength of the taste for wealth	0.7	Internally calibrated
Σ	CRRA coefficient on wealth	0.7	Straub (2019)
ζ	Stone-Geary parameter	0.25	Internally calibrated
Productivity			
σ_z	Variance of idiosyncratic productivity shocks	0.2	Straub (2019)
ρ_z	Autocorrelation of shocks	0.91	Straub (2019)
Union			
κ_w	Slope of NKPC	0.03	Auclert et al. (2024)
μ_w	Markup of the union	1.01	Auclert et al. (2024)
Firm			
α	Cobb-Douglas coefficient for capital	1/3	
δ	Depreciation rate	8%	Auclert et al. (2024)
μ_p	Markup of the firms	1.01	Auclert et al. (2024)
ε_I	Investment cost parameter	4	Auclert et al. (2024)
κ^p	Rotemberg cost parameter	0.23	Auclert et al. (2024)
Portfolio choice			
Ω	Flows from illiquid account	0.005	Auclert et al. (2020)
ζ	Illiquidity premium	2%	Auclert et al. (2024)
r_{ss}	Steady-state interest rate	5%	
Government			
G	Government spendings	0.2	
τ	Progressiveness of labor tax	0.181	Auclert et al. (2024)
B	Public debt	0.7	Auclert et al. (2024)
Monetary policy			
r_{ss}	Steady state interest rate	5%	Auclert et al. (2024)
ϕ_π	1.5		
ρ_r	0.15		

Table 2.6: Distribution of wealth in the model and the data

	Bottom 50%	Middle 40%	Top 10%	Top 1%
Data PSZ 2019	0	28	71	34
Model 2019	1	28	69	38
Data PSE 1989	1	33	64	28
Model 1989	3	37	59	29

3.3 Results

We now investigate the impact of rising permanent labor income inequality in this quantitative framework. In our main experiment, we study the impact of an expansionary monetary policy shock in two different economies: one where the distribution of permanent labor income and illiquid wealth is calibrated on the U.S. economy in 1989, and one where those distributions are calibrated on 2019[17].

Table 2.7: Decomposition of the effect of a monetary policy shock

	Low inequality	High inequality	Change
Elasticity of Y	-2.13	-2.4	12.4 %
Elasticity of C	-1.46	-1.92	31.4%
Elasticity of I	-3.36	-3.19	-4.86%
Elasticity of C, part. eq.	-0.5	-0.37	-25.7 %
Component of % change of C due to			
Direct effect of r^b	36	20	-16 p.p.
Indirect effect of N	28	42	14 p.p.
Indirect effect of taxes	33	36	3p.p.
Indirect effect of p	3	2	-1p.p.

Note: Average response over the first year. The first column reports the number in the economy with low permanent labor income inequality, calibrated on 1989. The second column reports the number in the economy with high permanent labor income inequality, calibrated on 2019. The last column reports the % change of the elasticities, and the p.p. for the partial effects.

Table 2.7 reports the main results of this quantitative exercise. We find that the increase in permanent labor income inequality increases the output elasticity to a monetary policy shock by 12.4%, a result in line with our findings in the previous section. This increase is mostly driven by a higher sensitivity of consumption to changes in labor income, as reported by the second part of Table 2.7, and attenuated by a lower sensitivity of consumption to changes in the interest rate. Indeed, the partial elasticity of consumption decreases by 25%

[17]We run the same exercise as in Section 3.3, but keep the distribution of illiquid wealth constant. Looking at Table 2.9 and 2.10, we get similar results as before.

in our model, while the share of total change in consumption, explained by the indirect effects, increases significantly.

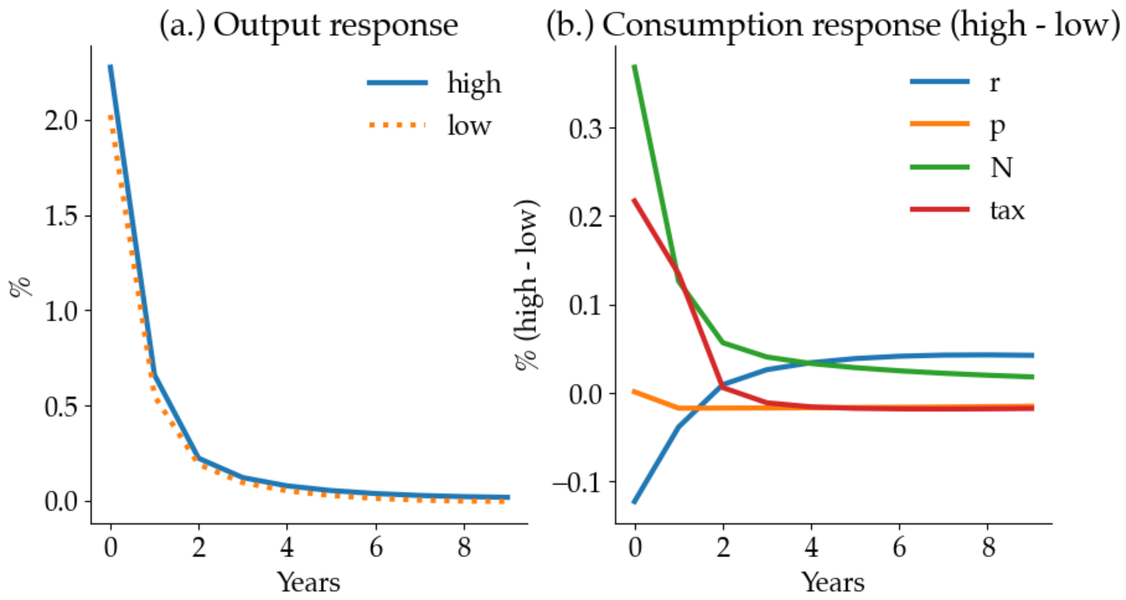

Figure 2.3: Effect on output of a monetary shock

Note: The left figure plots the output response following a monetary shock. The right figure plots the difference in the decomposition between the high-inequality economy minus the low-inequality economy.

What are the implications of an increase in permanent labor income inequality on the transmission of monetary policy with a realistic wealth distribution?

Our results remain consistent with the findings from Section 2.4. An increase in labor permanent income inequality increases the effect of a monetary shock. Looking at the decomposition in Figure 2.3 (b.), the contribution of indirect effects (from taxes and the labor demand) increases while the contribution of the direct effect is slightly lower. Consistently with Section 2.4, the rise in indirect effects comes from the increase in the income share going to hand-to-mouth households as the wealth-distribution effect dominates the composition effect. The endogeneous rise in the mass of hand-to-mouth among low-permanent income types dominates the fall in the income share going to low-permanent income households. The wealth distribution effect is reinforced by the policy function effect. Indeed, the rise in permanent income increases the marginal propensity to consume of high-permanent income households. Not surprisingly, in Figure 2.4 (a.), we see that the aggregate MPC goes up while the subsequent iMPCs decrease.

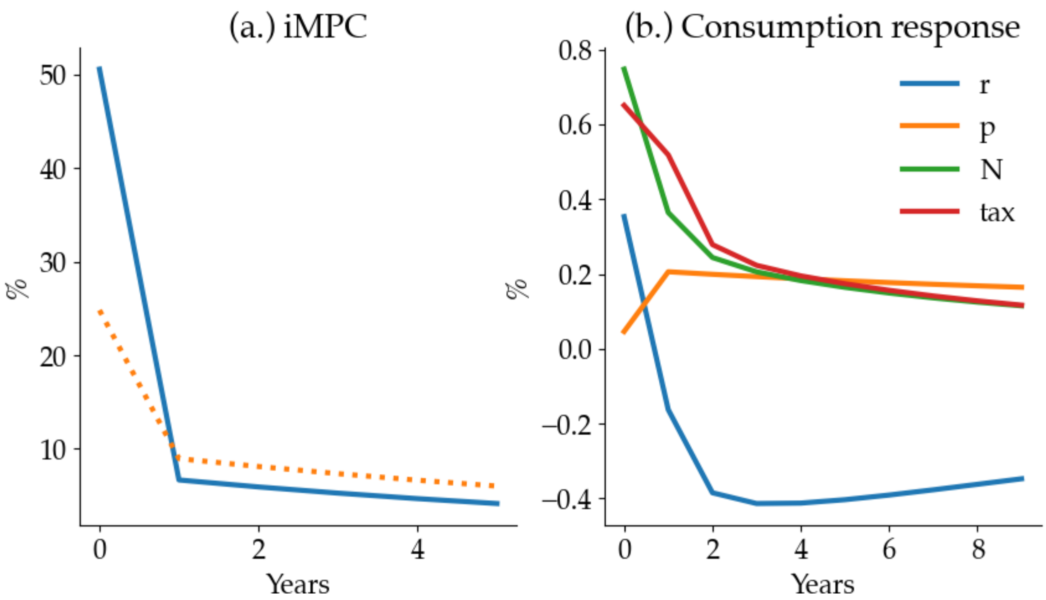

Figure 2.4: iMPC and decomposition of a monetary shock

Note: The left figure plots the iMPC. The right figure plots the decomposition of a monetary policy shock in the high-inequality economy.

At the same time, the rise in permanent labor income inequality tends to dampen the aggregate elasticity of intertemporal substitution. Similarly as in Section 2.4, the composition effect tends to raise the aggregate EIS by giving a higher income share to households that have *on average* a higher EIS. However, the composition effect is largely dominated by the sum of the policy function effect and the wealth distribution effect.

4 Conclusion

In this paper, we have shown that the rise in permanent labor income inequality changes the composition of a monetary shock by decreasing the share of direct and increasing the share of indirect effects. Decomposing the effect of the rise in permanent labor income inequality on monetary policy, we show that our main result is attributable to the combination of the policy function effect and the wealth distribution effect which outweigh the composition effect. The change in the permanent labor income distribution also generates amplification of monetary policy through the change in the income share going to hand-to-mouth households.

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Deriving the Intertemporal Keynesian Cross

In the goods space:

$$\mathbf{Y} = (1-\omega)\mathbf{C}_h(\{r_s, \tilde{N}_s\}) + \omega\mathbf{C}_l(\{r_s, \tilde{N}_s\})$$

Differentiating:

$$d\mathbf{Y} = (1-\omega)z_h\mathbf{M}_h^{\tilde{n}}d\tilde{\mathbf{N}} + (1-\omega)z_h\mathbf{M}_h^r d\mathbf{r} + z_l\omega\mathbf{M}_l^{\tilde{n}}d\tilde{\mathbf{N}} + \omega z_l\mathbf{M}_l^r d\mathbf{r}$$

In general equilibrium, $d\mathbf{Y} = d\mathbf{N} = d\mathbf{C}$, $d\boldsymbol{\tau} = Bd\mathbf{r} - rBd\mathbf{N}$, $\tau = rB$ and $d\tilde{\mathbf{N}} = (1-\tau)d\mathbf{N} - d\boldsymbol{\tau}$.

Hence, $d\tilde{\mathbf{N}} = (1-rB)d\mathbf{Y} - Bd\mathbf{r} + rBd\mathbf{Y} = d\mathbf{Y} - Bd\mathbf{r}$

We have that

$$d\mathbf{Y} = (1-\omega)z_h\mathbf{M}_h^{\tilde{n}}(d\mathbf{Y} - Bd\mathbf{r}) + (1-\omega)z_h\mathbf{M}_h^r d\mathbf{r} + z_l\omega\mathbf{M}_l^{\tilde{n}}(d\mathbf{Y} - Bd\mathbf{r}) + \omega z_l\mathbf{M}_l^r d\mathbf{r}$$

Solving for $d\mathbf{Y}$:

$$\left(\mathbf{I} - (1-\omega)z_h\mathbf{M}_h^{\tilde{n}} - z_l\omega\mathbf{M}_l^{\tilde{n}}\right)d\mathbf{Y} = \left((1-\omega)z_h\mathbf{M}_h^r + \omega z_l\mathbf{M}_l^r d\mathbf{r} - B(1-\omega)z_h\mathbf{M}_h^{\tilde{n}} - Bz_l\omega\mathbf{M}_l^{\tilde{n}}\right)d\mathbf{r}$$

Using that $\forall x \in \{r, \tilde{n}\}, \quad \mathbf{M}^x = \omega z_l\mathbf{M}_l^x + (1-\omega)z_h\mathbf{M}_h^x$,

$$\left(\mathbf{I} - \mathbf{M}^{\tilde{n}}\right)d\mathbf{Y} = \left(\mathbf{M}^r - B\mathbf{M}^{\tilde{n}}\right)d\mathbf{r}$$

Mutiplying by $\mathbf{K} \equiv -\sum_{t=1}^{\infty}(1+r)^{-t}\mathbf{F}^t$ on both sides with $\mathbf{F}$ the forward matrix. Then inverting, we have that:

$$d\mathbf{Y} = \left(\mathbf{K}\left(\mathbf{I} - \mathbf{M}^{\tilde{n}}\right)\right)^{-1}\mathbf{K}\left(\mathbf{M}^r - B\mathbf{M}^{\tilde{n}}\right)d\mathbf{r}$$

A Appendix to HANK zero-liquidity

Solving the zero-liquidity model

This section shows how to derive analytically the main sequence space Jacobian of the zero-liquidity model. This proof follows closely the appendix D.4 of Auclert and Rognlie (2020), but extends it to the case of monetary policy shocks, with different permanent types and a non-homothetic taste for wealth.

A.1 Notation

Let $c_{i,t}(a,e)$ and $a_{i,t+1}(a,e)$ be the policy functions for consumption and savings at time t of a permanent income type i. $c(a,e)$ and $a(a,e)$ are the steady-state policy functions. Similarly, $V_{i,t}(a,e)$ is the value function at time t of a permanent income type i during a transition following an aggregate shock, while$V_i(a,e)$ is the steady state value function.

We denote:

- $c_i'(a,e)$ and $a_i'(a,e)$ the derivative of the steady state policy functions *with respect to* a
- $dc_{i,t}(a,e) = \frac{\partial c_{i,t}(a,e)}{\partial x_s}dx_s$, $da_{i,t}(a,e) = \frac{\partial a_{i,t+1}(a,e)}{\partial x_s}dx_s$ the change in the policy function at time t when there is a shock to a variable at time s
- $V_i'(a,e)$ is the derivative of the steady state value function with respect to a
- $dV_{i,t}(a,e)$ is the change in the value function at t when there is a shock to x at s: $dV_t = \frac{\partial V_{i,t}(a,e)}{\partial x_s}dx_s$

A.2 Solving for the steady-state interest rate

The main idea of the proof is that, in the zero-liquidity limit, all households except the highest productivity type of the high-permanent type will be constrained. Thus, the equilibrium interest rate at the steady state will be such that only this high idiosyncratic type, high permanent productivity type household will be on its Euler equations.

First, recall that the Euler equation in the zero-liquidity model of an agent i with idiosyncratic productivity e_t can be written as

$$(z_i e_t N_t)^{-\sigma} \geq \beta(1+r_t)\sum_{e'} \Pi_{ee'} \left(z_i e_{t+1} N_{t+1}\right)^{-\sigma} + \gamma\zeta^{-\Sigma}$$

Focusing on the steady state, we can write

$$1 \geq \beta(1+r)\rho(e) + \gamma\zeta^{-\Sigma}(z_i e)^{\sigma} \tag{2.3}$$

where $\rho(e) \equiv \sum_{e'} \Pi_{ee'} \left(\frac{e'}{e}\right)^{-\sigma}$. We assume that $\Pi_{ee'}$ is such that $\rho(e)$ is a strictly increasing function of e, and that $\bar{e} = \arg\max \rho(e)$ is the highest idiosyncratic productivity type[18]. Let us first focus on the case with homothetic preferences, when $\gamma = 0$. In this case, we have

$$1 \geq \beta(1+r)\rho(e).$$

[18] This is the case if $\Pi_{e'e}$ approximates an AR(1) process.

Assume that there exists an $\tilde{e} < \bar{e}$ such that

$$1 = \beta(1+r)\rho(\tilde{e}).$$

Since $\rho(\tilde{e}) < \rho(\bar{e})$, this implies that

$$1 < \beta(1+r)\rho(\bar{e}),$$

which violates 2.3. Since this holds for all $\tilde{e} < \bar{e}$, if there exists an r such that Equation 2.3 holds with equality, it must be that

$$1 = (1+r^*)\beta\rho(\bar{e}).$$

However, since there is no liquidity in the economy and we assume that $a_t \geq 0$ for all households, there exists an infinity of interest rate $r < r^*$ such all households are constrained and the asset market clears. However, as shown by Werning (2015), all those equilibria disappear if we introduce an ε amount of liquidity in the economy. We thus discard them and focus on a steady-state equilibrium where $r = r^*$.

When $\gamma > 0$, note that Equation 2.3 is an increasing function of both e and z_i. By the same argument, if there exists an r^* such that Equation 2.3 holds, it must be that it holds for $e = \bar{e}$ and $i = h$. Thus, the equilibrium interest rate is given by

$$1 + r = \frac{1 - \gamma\zeta^{-\Sigma}(z_h\bar{e})^{\sigma}}{\beta\rho(\bar{e})}.$$

Note that this is a strictly decreasing function of z_h, and the steady-state interest rate will thus decrease when permanent income inequality increases.

A.3 Computing the sequence-space Jacobians $\mathbf{M}^r$ and $\mathbf{A}^r$

We now move on to solving for the main object of interest of this paper, the sequence-space Jacobians for consumption and savings following an interest rate shock $\mathbf{M}^r$, $\mathbf{A}^r$, and an income shock $\mathbf{M}^n$, and $\mathbf{A}^n$.

First, recall that the budget constraint of the household can be written in terms of policy functions as

$$c_{i,t}(a,e) + a_{i,t+1}(a,e) = N_t z_i e + (1+r_t)a_t. \tag{2.4}$$

Note that, at the steady state, the market clearing equation implies that we have $a = 0$ for all households. Taking the derivative of Equation 2.4 with respect to a and evaluating it at the steady state yields

$$\frac{\partial c_i}{\partial a}(0,e) + \lambda_{i,e} = 1 + r.$$

We define as $\lambda_{i,e}$ the slope of the savings policy function of an agent with permanent type i and idiosyncratic productivity e:

$$\lambda_{i,e} \equiv \frac{\partial a_i}{\partial a}(0, e).$$

Note that, for any sequence of shock on r_t, we can take the derivative of 2.4 with respect to time and evaluate it at zero wealth to obtain

$$dc_{i,t}(0, e) + da_{i,t+1}(0, e) = 0$$

This means that any change in the policy function for consumption at time t following a shock on the interest rate must be perfectly compensated by a change in the policy function for savings. This is intuitive: since there is no wealth in the economy, an interest rate shock has no income effect. If households want to save more, they will have to consume less.

To characterize the consumption response following a sequence of shock, we will study the response of the policy function to each shock separately, and aggregate them at the end.

1. First, let us start with a shock that happens at $t = s$. Since the shock happens only at $t = s$, the value function tomorrow will be equal to the steady state value function. Since an interest rate shock has no income effect, and future wealth is valued at the same rate ($dV_{i,t}(a, e) = 0$), we must have

$$dc_{i,s}(0, e) = 0.$$

This implies that the first column of the Jacobians $\mathbf{M}^r$ and $\mathbf{A}^r$ will be only zeros.

2. When shock happens in the future, that is, when $t < s$, the envelope condition is

$$V'_{i,t}(0, e) = (1 + r_t)u'(c_{i,t}(0, e))$$

Totally differentiating this expression and evaluating it at the steady state yields

$$dV'_{i,t}(0, e) = (1 + r)u''(z_i e)dc_{i,t}(0, e) + u'(z_i e)dr_t. \tag{2.5}$$

Evaluating this expression at the period of the shock $t = s$, and since $dc_{i,s}(0, e) = 0$, this simplies to

$$dV'_{i,s}(0, e) = u'(z_i e)dr_s.$$

Using the fact that (see derivation in appendix D1 in Auclert, Rognlie, and Straub (2018))

$$dV'_{i,t}(0, e) = \beta\lambda_{i,e} \sum_{e'} \Pi_{ee'} dV'_{i,t+1}(0, e')$$

We thus have

$$dc_{i,t}(0,e) = \beta\lambda_{i,e}\sum_{e'}\Pi_{ee'}\left[dc_{i,t+1}(0,e) + \frac{u'(z_i e')}{u''(z_i e)(1+r)}dr_{t+1}\right]$$

Note that

$$\frac{u'(z_i e')}{u''(z_i e)} = z_i\frac{(e')^{-\sigma}}{-\sigma(e)^{-\sigma-1}}.$$

But since $\lambda_{i,e} = 0$ (constrained households consume all marginal additional unit of wealth) for all $e \neq \bar{e}$, we have

$$dc_{i,t}(0,\bar{e}) = \beta\lambda_{i,\bar{e}}dc_{i,t+1}(0,\bar{e}) + z_i\sum_{e'}\Pi_{\bar{e}e'}\frac{u'(e')}{u''(\bar{e})(1+r)}dr_{t+1}.$$

Let us define

$$K^r \equiv \sum_{e'}\Pi_{\bar{e}e'}\frac{(e')^{-\sigma}}{\bar{e}^{-\sigma-1}}\frac{1}{\Pi_{\bar{e}\bar{e}}}$$

Note that, when the variance of shocks tends to 0 and the auto-correlation of shock tends to 1, $K^r \to 1$.

We can then write

$$dc_{i,t}(0,\bar{e}) = \beta\lambda_{i,\bar{e}}dc_{i,t+1}(0,\bar{e}) - z_i\frac{K^r}{\sigma(1+r)}dr_{t+1}.$$

Solving this equation forward, we obtain that for any shock at $s > t$ (using the fact that $dr_{t+1} = 0$ except when $t+1 = s$):

$$dc_{i,t}(0,\bar{e}) = -(\beta\lambda_{i,\bar{e}}\Pi_{\bar{e}\bar{e}})^{s-t}\left(z_i\frac{K^r}{\sigma(1+r)}\right)dr_s \quad \text{for } s > t.$$

Summing for all potential shocks, we get

$$dc_{i,t}(0,\bar{e}) = -\sum_{s>t}(\beta\lambda_{i,\bar{e}}\Pi_{\bar{e}\bar{e}})^{s-t}\left(z_i\frac{K^r}{\sigma(1+r)}\right)dr_s \quad \text{for } s > t$$

And using the fact that $da_{t+1}(0,\bar{e}) = -dc_t(0,\bar{e})$, we obtain

$$da_{i,t+1}(0,\bar{e}) = \sum_{s>t}(\beta\lambda_{i,\bar{e}}\Pi_{\bar{e}\bar{e}})^{s-t}\left(z_i\frac{K^r}{\sigma(1+r)}\right)dr_s \quad \text{for } s > t$$

which we can rewrite as

$$da_{i,t+1}(0,\bar{e}) = \sum_{s>t}(\beta\lambda_i)^{s-t}\left(z_i\frac{K^r}{\sigma(1+r)}\right)dr_s \quad \text{for } s > t$$

where $\lambda_i \equiv \lambda_{i,\bar{e}}\Pi_{\bar{e}\bar{e}}$.

Aggregation.

We compute the aggregate supply of savings of permanent type i at time t. The savings at time t for an unconstrained household of permanent type i that has been unconstrained for the last $\tau - 1$ periods is:

$$a_{i,\tau,t+1} = a_{i,t+1}(a_{i,\tau-1,t}, \bar{e})$$

Where we define $a_{i,-1,0} = 0$ the wealth holdings of all constrained households whatever their permanent types.

Totally differentiating the expression yields

$$da_{i,\tau,t+1} = \underbrace{da_{i,t+1}(0, \bar{e})}_{\text{change in policy function}} + \lambda_{i,\bar{e}} \underbrace{da_{i,\tau-1,t}}_{\text{change in wealth holdings}}$$

Aggregating with weights $\pi_{\bar{e}}(1 - \Pi_{\bar{e}\bar{e}})\Pi^{\tau}_{\bar{e}\bar{e}}$ and

$$\sum_{\tau=0}^{\infty} \pi_{\bar{e}} \left(1 - \Pi_{\bar{e}\bar{e}}\right) \Pi^{\tau}_{\bar{e}\bar{e}} da_{i,\tau,t+1} = \sum_{\tau=0}^{\infty} \pi_{\bar{e}} \left(1 - \Pi_{\bar{e}\bar{e}}\right) \Pi^{\tau}_{\bar{e}\bar{e}} (da_{i,t+1}(\bar{e}, 0) + \lambda_{i,\bar{e}} da_{i,\tau-1,t})$$

using that $A_{i,t+1} = \sum_{\tau=0}^{\infty} \pi_{\bar{e}} \left(1 - \Pi_{\bar{e}\bar{e}}\right) \Pi^{\tau}_{\bar{e}\bar{e}} a_{i,\tau,t+1}$, we get

$$dA_{i,t+1} = \sum_{\tau=0}^{\infty} \pi_{\bar{e}} \left(1 - \Pi_{\bar{e}\bar{e}}\right) \Pi^{\tau}_{\bar{e}\bar{e}} (da_{i,t+1}(0, \bar{e}) + \lambda_{i,\bar{e}} da_{i,\tau-1,t})$$

$$dA_{i,t+1} = da_{i,t+1}(0, \bar{e}) \sum_{\tau=0}^{\infty} \pi_{\bar{e}} \left(1 - \Pi_{\bar{e}\bar{e}}\right) \Pi^{\tau}_{\bar{e}e} + \sum_{\tau=0}^{\infty} \pi_{\bar{e}} \left(1 - \Pi_{\bar{e}\bar{e}}\right) \Pi^{\tau}_{\bar{e}\bar{e}} \lambda_{i,\bar{e}} da_{i,\tau-1,t}$$

$$dA_{i,t+1} = \pi_{\bar{e}} da_{i,t+1}(0, \bar{e}) + \sum_{\tau=0}^{\infty} \pi_{\bar{e}} \left(1 - \Pi_{\bar{e}\bar{e}}\right) \Pi^{\tau}_{\bar{e}e} \lambda_{i,\bar{e}} da_{i,\tau-1,t}$$

Noting that $da_{i,-1,t} = 0$, we get

$$dA_{i,t+1} = \pi_{\bar{e}} da_{i,t+1}(0, \bar{e}) + \sum_{\tau=0}^{\infty} \pi_{\bar{e}} \left(1 - \Pi_{\bar{e}\bar{e}}\right) \Pi^{\tau}_{\bar{e}e} \lambda_{i,\bar{e}} da_{i,\tau,t}$$

Note that that second term can be written as

$$\sum_{\tau=0}^{\infty} \pi_{\bar{e}} \left(1 - \Pi_{\bar{e}e}\right) \Pi^{\tau}_{\bar{e}e} \lambda_{i,\bar{e}} da_{i,\tau} = \Pi_{\bar{e}e} \lambda_{i,\bar{e}} dA_{i,t}$$

so that we have

$$\begin{aligned} dA_{i,t+1} &= da_{i,t+1}(0, \bar{e}) \pi_{\bar{e}} + \lambda_{i,\bar{e}} \Pi_{\bar{e}\bar{e}} dA_{i,t} \\ &= da_{i,t+1}(0, \bar{e}) \pi_{\bar{e}} + \lambda_i dA_{i,t} \end{aligned}$$

From the previous subsection, we have

$$da_{i,t+1}(0,\bar{e}) = \sum_{s>t} (\beta\lambda_i)^{s-t} \left(z_i \frac{K^r}{\sigma(1+r)} \right) dr_s \quad \text{for } s > t$$

Combining with the law of motion, we get

$$dA_{i,t+1} = \pi_{\bar{e}} \sum_{s>t} (\beta\lambda_i)^{s-t} \left(z_i \frac{K^r}{\sigma(1+r)} \right) dr_s + \lambda_i dA_{i,t}$$

For an unexpected shock at $s = 0$, we have

$$dA_{i,t+1} = 0$$

the first column is only zero.

For a shock at $s = 1$, we have in $t = 0$,

$$dA_{i,1} = \pi_{\bar{e}} \beta\lambda_i \left(\frac{K^r}{\sigma(1+r)} z_i \right) dr_1$$

And,

$$dA_1 = \sum_i \omega_i dA_{i,1} = \pi_{\bar{e}} \beta \sum_i \omega_i \lambda_i \left(\frac{K^r}{\sigma(1+r)} z_i \right) dr_1$$

$$\mathbf{A}^r = \pi_{\bar{e}} \sum_i \omega_i z_i \mathbf{T}_i^r(a_+) \mathbf{T}_i^r(a_-)$$

$$\mathbf{T}_i^r(a_+) = \begin{pmatrix} 1 & 0 & 0 & \cdots \\ \lambda_i & 1 & 0 & \cdots \\ \lambda_i^2 & \lambda_i & 1 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \text{ and } \mathbf{T}_i^r(a_-) = \begin{pmatrix} 0 & \frac{\beta\lambda_i}{1+r}\frac{K^r}{\sigma} & \frac{(\beta\lambda_i)^2}{1+r}\frac{K^r}{\sigma} & \cdots \\ 0 & 0 & \frac{\beta\lambda_i}{1+r}\frac{K^r}{\sigma} & \cdots \\ 0 & 0 & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

A.4 Solving for λ_i

The key parameter that determines the behavior of households is λ_i. To solve for it, we use the Euler equation of the highest permanent type h with the highest idiosyncratic type $\bar{e}$ at the steady state

$$c_h(a_-, \bar{e})^{-\sigma} = \beta(1+r) \sum_{e'} \Pi_{\bar{e}e'} \left(c_h \left(a_h(a_-, \bar{e}), e' \right) \right)^{-\sigma} + \gamma (a_h(a_-, \bar{e}) + \zeta)^{-\Sigma}$$

Differentiating with respect to a_- and evaluating at $a_- = 0$:

$$u''(z_h\bar{e})\frac{\partial c_h}{\partial a_-}(0,\bar{e}) = \beta(1+r)\sum_{e'}\Pi_{\bar{e}e'}u''\left(z_h e'\right)\frac{\partial c_h}{\partial a_h}\left(0,e'\right)\frac{\partial a_h}{\partial a_-}(0,\bar{e}) - \gamma\Sigma(a_h\left(0,\bar{e}\right)+\zeta)^{-\Sigma-1}\frac{\partial a_h}{\partial a_-}(0,\bar{e})$$

Using that $\frac{\partial c_h}{\partial a_-}(0,\bar{e}) = (1+r)m_{h,\bar{e}}$ and $\frac{\partial a_h}{\partial a_-}(0,\bar{e}) = (1+r)(1-m_{h,\bar{e}})$, at the steady state $a_h\left(0,\bar{e}\right) = 0$ and,

$$u''(z_h\bar{e})m_{h,\bar{e}} = \beta(1+r)^2\sum_{e'}\Pi_{\bar{e}e'}u''\left(z_h e'\right)m_{h,e'}\cdot(1-m_{h,\bar{e}}) - \gamma\Sigma(1-m_{h,\bar{e}})\zeta^{-\Sigma-1}$$

$$-\sigma(z_h\bar{e})^{-\sigma-1}m_{h,\bar{e}} = -\sigma\beta(1+r)^2\sum_{e'}\Pi_{\bar{e}e'}(z_h e')^{-\sigma-1}m_{h,e'}\cdot(1-m_{h,\bar{e}}) - \gamma\Sigma(1-m_{h,\bar{e}})\zeta^{-\Sigma-1}$$

$$m_{h,\bar{e}} = \beta(1+r)^2\sum_{e'}\Pi_{\bar{e}e'}\left(\frac{e'}{\bar{e}}\right)^{-\sigma-1}m_{h,e'}\cdot(1-m_{h,\bar{e}}) + \gamma\frac{\Sigma}{\sigma}(1-m_{h,\bar{e}})\zeta^{-\Sigma-1}(z_h\bar{e})^{\sigma+1}$$

Using that $\forall e' \neq \bar{e}, \quad m_{h,e'} = 1$,

$$m_{h,\bar{e}} = \beta(1+r)^2\left(\sum_{e'\neq\bar{e}}\Pi_{\bar{e}e'}\left(\frac{e'}{\bar{e}}\right)^{-\sigma-1} + \Pi_{\bar{e}\bar{e}}m_{h,\bar{e}}\right)\cdot(1-m_{h,\bar{e}}) + \gamma\frac{\Sigma}{\sigma}(1-m_{h,\bar{e}})\zeta^{-\Sigma-1}(z_h\bar{e})^{\sigma+1}$$

$$\frac{m_{h,\bar{e}}}{1-m_{h,\bar{e}}} = \beta(1+r)^2\left(\sum_{e'\neq\bar{e}}\Pi_{\bar{e}e'}\left(\frac{e'}{\bar{e}}\right)^{-\sigma-1} + \Pi_{\bar{e}\bar{e}}m_{h,\bar{e}}\right) + \gamma\frac{\Sigma}{\sigma}\zeta^{-\Sigma-1}(z_h\bar{e})^{\sigma+1}$$

This is a quadratic equation that pins down the MPC $m_{h,\bar{e}}$ of the highest permanent type with idiosyncratic type $\bar{e}$. Notice that, when there is no taste for wealth, $\gamma = 0$, the equation no longer depends on z_h and $\forall i, \quad m_{i,\bar{e}} = m_{\bar{e}}$. From $m_{h,\bar{e}}$, we recover λ_h since:

$$\lambda_h = \Pi_{\bar{e}\bar{e}}(1+r)(1-m_{h,\bar{e}})$$

Since there is always one unique λ whatever the preference, we can drop the type subscript and have $\lambda \equiv \lambda_h$.

A.5 Rewritting the sequence-space Jacobians

Writing the sequence-space Jacobian of the savings reponse following an interest rate shock:

$$\mathbf{A}^r = \pi_{\bar{e}}\frac{\beta\lambda_i}{1+r}\frac{K^r}{\sigma}\sum_i \omega_i z_i \mathbf{T}_i^r(a_+)\mathbf{T}_i^r(a_-)$$

$$\mathbf{T}_i^r(a_+) = \begin{pmatrix} 1 & 0 & 0 & \cdots \\ \lambda_i & 1 & 0 & \cdots \\ \lambda_i^2 & \lambda_i & 1 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \text{ and } \mathbf{T}_i^r(a_-) = \begin{pmatrix} 0 & 1 & \beta\lambda_i & \cdots \\ 0 & 0 & 1 & \cdots \\ 0 & 0 & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

When there is no taste for wealth, there is always a unique λ common across permanent types, we can get rid of the i subscript in the $\mathbf{T}$ matrices and: A

$$\mathbf{A}^r = \pi_{\bar{e}} \sum_i \omega_i z_i \mathbf{T}^r(a_+)\mathbf{T}^r(a_-) = \pi_{\bar{e}} \mathbf{T}^r(a_+)\mathbf{T}^r(a_-)$$

When there is a taste for wealth, there is still one λ for the highest permanent type, all other λs are 0, and:

$$\mathbf{A}^r = \pi_{\bar{e}} z_h \omega_h \mathbf{T}^r(a_+)\mathbf{T}^r(a_-)$$

$$\mathbf{A}^r = \pi_{\bar{e}} z_h \omega_h \frac{\beta\lambda}{1+r}\frac{K^r}{\sigma}\begin{pmatrix} 0 & 1 & \beta\lambda & \cdots \\ 0 & \lambda & 1+\beta\lambda^2 & \cdots \\ 0 & \lambda^2 & \lambda^2\beta\lambda+\lambda & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$da_1 = \beta\lambda dr_2, dc_0 = -\beta\lambda dr_2$$

$$da_2 = (1+\beta\lambda)dr_2$$

$$c_2 + a_2 = (1+r)a_1 + N \iff dc_2 = (1+r)da_1 - da_2 = (1+r)\beta\lambda dr_2 - (1+\beta\lambda)dr_2$$

$$\iff dc_2 = [(1+r)\beta\lambda - (1+\beta\lambda)]dr_2$$

From $\mathbf{A}^r$, we recover $\mathbf{M}^r$ using the vectorized budget constraint:

$$\mathbf{M}^r + \mathbf{A}^r = (1+r)\mathbf{L}\mathbf{A}^r \iff \mathbf{M}^r = ((1+r)\mathbf{L} - \mathbf{I})\mathbf{A}^r$$

Starting from the non-homothetic case:

$$\mathbf{M}^r = \pi_{\bar{e}} z_h \omega_h \frac{\beta\lambda}{1+r}\frac{K^r}{\sigma}\begin{pmatrix} -1 & 0 & 0 & \cdots \\ 1+r & -1 & 0 & \cdots \\ 0 & 1+r & -1 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}\begin{pmatrix} 0 & 1 & \beta\lambda & \cdots \\ 0 & \lambda & 1+\beta\lambda^2 & \cdots \\ 0 & \lambda^2 & \lambda^2\beta\lambda+\lambda & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$\mathbf{M}^r = \pi_{\bar{e}} z_h \omega_h \frac{\beta\lambda}{1+r}\frac{K^r}{\sigma}\begin{pmatrix} 0 & -1 & -\beta\lambda & \cdots \\ 0 & 1+r-\lambda & (1+r)\beta\lambda - 1 - \beta\lambda & \cdots \\ 0 & (1+r)\lambda - \lambda^2 & (1+r)(1+\beta\lambda^2) - \lambda^2\beta\lambda - \lambda & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Finishing with the homothetic case:

$$\mathbf{M}^r = \pi_{\bar{e}} \frac{\beta\lambda}{1+r}\frac{K^r}{\sigma}\begin{pmatrix} 0 & -1 & -\beta\lambda & \cdots \\ 0 & 1+r-\lambda & (1+r)\beta\lambda - 1 - \beta\lambda & \cdots \\ 0 & (1+r)\lambda - \lambda^2 & (1+r)(1+\beta\lambda) - \lambda^2\beta\lambda - \lambda & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

A.6 Computing the sequence-space Jacobians $\mathbf{M}^n$ and $\mathbf{A}^n$

We follow closely Auclert, Rognlie, and Straub (2018), appendix D4, with the introduction of permanent types. Differentiating the budget constraint, we have that:

$$dc_{i,t}(0,e) = m_e z_i dN_t$$

We have that

$$dV'_{i,t}(0,e) = \beta\lambda_e \sum_{e'} \Pi_{ee'} dV'_{i,t+1}(0,e')$$

Computing the Envelope condition

$$V'_{i,t}(a_-,e) = (1+r)u'(c_{i,t}(a_-,e))$$

Differentiating and evaluating it at the steady state,

$$dV'_{i,t}(0,e) = (1+r)u''(ez_iN)dc_{i,t}(0,e)$$

Plugging it in the equation above:

$$(1+r)u''(ez_iN)dc_{i,t}(0,e) = \beta\lambda_e \sum_{e'} \Pi_{ee'}(1+r)u''(e'z_iN)dc_{i,t+1}(0,e')$$

$$dc_{i,t}(0,e) = \beta\lambda_e \sum_{e'} \Pi_{ee'} \left(\frac{e'z_iN}{ez_iN}\right)^{-\sigma-1} dc_{i,t+1}(0,e')$$

$$dc_{i,t}(0,e) = \beta\lambda_e \sum_{e'} \Pi_{ee'} \left(\frac{e'}{e}\right)^{-\sigma-1} dc_{i,t+1}(0,e')$$

The change in the policy function for consumption of permanent type i at time t due to shock on N_s

$$dc_{i,t}(0,e) = \begin{cases} (\beta\lambda_{\bar{e}}\Pi_{\bar{e}\bar{e}})^{s-t}\left(\sum_{e'\neq\bar{e}} \frac{\Pi_{\bar{e}e'}}{\Pi_{\bar{e}\bar{e}}}\left(\frac{e'}{\bar{e}}\right)^{-(\sigma+1)} \cdot e' + m_{i,\bar{e}}\bar{e}\right) z_i dN_s & s>t, e=\bar{e} \\ m_{i,\bar{e}}\bar{e}z_i dN_t & s=t, e=\bar{e} \\ 0 & s<t \end{cases}$$

Adding up across all shocks $\{N_s\}$,

$$dc_{i,t}(0,\bar{e}) = m_{i,\bar{e}}\bar{e}z_i dN_t + \left(\sum_{e'\neq\bar{e}} \frac{\Pi_{\bar{e}e'}}{\Pi_{\bar{e}\bar{e}}}\left(\frac{e'}{\bar{e}}\right)^{-(\sigma+1)} \cdot e' + m_{i,\bar{e}}\bar{e}\right)\sum_{s>t}^{\infty}\left(\beta\lambda_{\bar{e}}\Pi_{\bar{e}\bar{e}}\right)^{s-t} z_i dN_s$$

$$da_{i,t+1}(0,\bar{e}) = (1-m_{i,\bar{e}})\bar{e}z_i dN_t - \bar{e}\left(\sum_{e'\neq\bar{e}} \frac{\Pi_{\bar{e}e'}}{\Pi_{\bar{e}\bar{e}}}\left(\frac{e'}{\bar{e}}\right)^{-\sigma} + m_{i,\bar{e}}\right)\sum_{s>t}^{\infty}\left(\beta\lambda_{\bar{e}}\Pi_{\bar{e}\bar{e}}\right)^{s-t} z_i dN_s$$

A.7 Aggregation

As before, we have that,

$$dA_{i,t+1} = da_{i,t+1}(0,\bar{e})\pi_{\bar{e}} + \lambda_i dA_{i,t}$$

Combining the last two equations and defining $K \equiv \sum_{e'\neq\bar{e}} \frac{\Pi_{\bar{e}e'}}{\Pi_{\bar{e}\bar{e}}}\left(\frac{e'}{\bar{e}}\right)^{-\sigma}$, we get:

$$dA_{i,t+1} = \pi_{\bar{e}}(1-m_{i,\bar{e}})\bar{e}z_i dN_t - \pi_{\bar{e}}\bar{e}\left(K + m_{i,\bar{e}}\right)\sum_{s>t}^{\infty}\left(\beta\lambda_{\bar{e}}\Pi_{\bar{e}\bar{e}}\right)^{s-t} z_i dN_s + \lambda_i dA_{i,t}$$

Summing across permanent types given that $dA_{t+1} = \sum_i \omega_i dA_{i,t+1}$, we get the following aggregate sequence-space Jacobian:

$$\mathbf{A}^n = \frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}}\sum_i \omega_i z_i \mathbf{T}_i^n(a_+)\mathbf{T}_i^n(a_-)$$

$$\text{With } \mathbf{T}_i^n(a_+) = \begin{pmatrix} 1 & 0 & 0 & \cdots \\ \lambda_i & 1 & 0 & \cdots \\ \lambda_i^2 & \lambda_i & 1 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$\text{and } \mathbf{T}_i^n(a_-) = \begin{pmatrix} \frac{\lambda_i}{1+r} & -\left(\frac{1}{\beta(1+r)} - \frac{\lambda_i}{1+r}\right)(\beta\lambda) & -\left(\frac{1}{\beta(1+r)} - \frac{\lambda_i}{1+r}\right)(\beta\lambda_i)^2 & \cdots \\ 0 & \frac{\lambda_i}{1+r} & -\left(\frac{1}{\beta(1+r)} - \frac{\lambda_i}{1+r}\right)(\beta\lambda_i) & \cdots \\ 0 & 0 & \frac{\lambda_i}{1+r} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

A.8 Rewritting the sequence-space Jacobian for income shocks

As before, when there is no preference for wealth, the sequence-space Jacobian is given by:

$$\mathbf{A}^n = \frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}}\frac{1}{1+r}\mathbf{T}^n(a_+)\mathbf{T}^n(a_-).$$

When we have preference for wealth,

$$\mathbf{A}^n = \frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}}\frac{\omega_h z_h}{1+r}\mathbf{T}^n(a_+)\mathbf{T}^n(a_-).$$

$$\text{With } \mathbf{T}^n(a_+) = \begin{pmatrix} 1 & 0 & 0 & \cdots \\ \lambda & 1 & 0 & \cdots \\ \lambda^2 & \lambda & 1 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$\text{and } \mathbf{T}^n(a_-) = \begin{pmatrix} \lambda & -\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda) & -\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda)^2 & \cdots \\ 0 & \lambda & -\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda) & \cdots \\ 0 & 0 & \lambda & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$\mathbf{A}^n = \frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}}\frac{\omega_h z_h}{1+r}\begin{pmatrix} \lambda & -\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda) & -\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda)^2 & \cdots \\ \lambda^2 & -\lambda\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda)+\lambda & -\lambda\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda)^2-\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda) & \cdots \\ \lambda^3 & -\lambda^2\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda)+\lambda^2 & -\lambda^2\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda)^2-\lambda\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda)+\lambda & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}.$$

From $\mathbf{A}_h^n = \mathbf{A}^n/(\omega_h z_h)$, we recover $\mathbf{M}_h^n$ using the vectorized budget constraint:

$$\mathbf{M}_h^n + \mathbf{A}_h^n = (1+r)\mathbf{L}\mathbf{A}_h^n + \mathbf{I} \iff \mathbf{M}_h^n = ((1+r)\mathbf{L}-\mathbf{I})\mathbf{A}_h^n + \mathbf{I}$$

Defining

$$\tilde{\mathbf{M}}_h^n = \begin{pmatrix} -\lambda & \left(\frac{1}{\beta}-\lambda\right)(\beta\lambda) & \left(\frac{1}{\beta}-\lambda\right)(\beta\lambda)^2 & \cdots \\ (1+r)\lambda-\lambda^2 & (\lambda-(1+r))\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda)-\lambda & (\beta\lambda^2-(1+r)\beta\lambda+1)\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda) & \cdots \\ (1+r)\lambda^2-\lambda^3 & \cdots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$\mathbf{M}_h^n = \frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}}\frac{1}{1+r}\tilde{\mathbf{M}}_h^n + \mathbf{I}$$

And:

$$\mathbf{M}^n = \omega_h z_h \mathbf{M}_h^n + \omega_l z_l \mathbf{I} = \frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}}\frac{\omega_h z_h}{1+r}\tilde{\mathbf{M}}^n + \mathbf{I}$$

The first line, first column of $\mathbf{M}_h^n$ is the static MPC :

$$1-\frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}}\frac{\lambda}{1+r} = \underbrace{(1-\frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}})}_{\text{share of constrained within high type}}\underbrace{1}_{\text{MPC HtM}} + \underbrace{\frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}}}_{\text{share of Ricardian within high type}}\underbrace{(1-\frac{\lambda}{1+r})}_{\text{MPC Ricardian}}$$

While the following elements on the first column give us the iMPC:

$$\underbrace{\frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}}}_{\text{share of Ricardian}} \quad \underbrace{\lambda^t}_{\text{rate of decay}} \underbrace{(1 - \frac{\lambda}{1+r})}_{\text{static MPC}}$$

A.9 Aggregate Intertemporal Keynesian Cross

Differentiating the goods market clearing condition, we have that:

$$d\mathbf{Y} = (1-\omega)z_h\mathbf{M}_h^n d\mathbf{N} + (1-\omega)z_h\mathbf{M}_h^r d\mathbf{r} + \omega z_l \mathbf{M}_l^r d\mathbf{r} + z_l\omega\mathbf{M}_l^n d\mathbf{N}$$

In the non-homothetic case, we have that:

$$d\mathbf{Y} = (1-\omega)z_h\mathbf{M}_h^n d\mathbf{N} + (1-\omega)z_h\mathbf{M}_h^r d\mathbf{r} + z_l\omega\mathbf{I}d\mathbf{N}$$

And the IKC is:

$$(\mathbf{I} - (1-\omega)z_h\mathbf{M}_h^n - z_l\omega\mathbf{I})d\mathbf{Y} = (1-\omega)z_h\mathbf{M}_h^r d\mathbf{r}$$

$$\iff d\mathbf{Y} = [\mathbf{K}(\mathbf{I} - (1-\omega)z_h\mathbf{M}_h^n - z_l\omega\mathbf{I})]^{-1}\mathbf{K}(1-\omega)z_h\mathbf{M}_h^r d\mathbf{r}$$

$$\iff d\mathbf{Y} = \underbrace{[(1-\omega)z_h\mathbf{K}(\mathbf{I} - \mathbf{M}_h^n)]^{-1}\mathbf{K}}_{\text{GE amplification}}\underbrace{(1-\omega)z_h\mathbf{M}_h^r d\mathbf{r}}_{\text{Direct effect}}$$

Notice that, with non-homothetic preferences, an increase in permanent income inequality increases the direct effect and decreases the indirect effect. However, at the aggregate level, those two effects cancel out.

$$\iff d\mathbf{Y} = [\mathbf{K}(\mathbf{I} - \mathbf{M}_h^n)]^{-1}\mathbf{K}\mathbf{M}_h^r d\mathbf{r}$$

In the homothetic case, sequence-space Jacobians do not depend on permanent types and we can drop the subscript for types:

$$d\mathbf{Y} = \mathbf{M}^n d\mathbf{N} + \mathbf{M}^r d\mathbf{r}$$

$$d\mathbf{Y} = [\mathbf{K}(\mathbf{I} - \mathbf{M}^n)]^{-1}\mathbf{K}\mathbf{M}^r d\mathbf{r}$$

With homothetic preferences, an increase in permanent income inequality has no effect on the weight of the direct and indirect effect and so no effect at the aggregate level.

A.10 Aggregate effect of monetary policy shock (proof 4)

To compute the aggregate effect of a monetary policy shock on output, we need to start from the vectorized asset market clearing condition:

$$\mathbf{A}(\{r_t, N_t\}) = \mathbf{0}.$$

Totally differentiating the equation, we get that:

$$\mathbf{A}^r d\mathbf{r} + \mathbf{A}^n d\mathbf{N} = 0$$

In equilibrium, $d\mathbf{N} = d\mathbf{Y}$ and the aggregate effect of a monetary policy shock is given by

$$d\mathbf{Y} = -(\mathbf{A}^n)^{-1}\mathbf{A}^r d\mathbf{r}. \tag{2.6}$$

Remember that those two aggregate sequence-space Jacobians can be written as the product of two Toeplitz matrices (all diagonal elements are equal):

$$\mathbf{A}^n = \frac{\pi_{\bar{e}}\bar{e}}{\Pi_{\bar{e}\bar{e}}}\frac{\omega_h z_h}{1+r}\mathbf{T}^n(a_+)\mathbf{T}^n(a_-),$$

With $\mathbf{T}^n(a_+) = \begin{pmatrix} 1 & 0 & 0 & \cdots \\ \lambda & 1 & 0 & \cdots \\ \lambda^2 & \lambda & 1 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$ and $\mathbf{T}^n(a_-) = \begin{pmatrix} \lambda & -\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda) & -\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda)^2 & \cdots \\ 0 & \lambda & -\left(\frac{1}{\beta}-\lambda\right)(\beta\lambda) & \cdots \\ 0 & 0 & \lambda & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$.

And:

$$\mathbf{A}^r = \pi_{\bar{e}}\frac{\beta\lambda}{1+r}\frac{K^r}{\sigma}\omega_h z_h \mathbf{T}^r(a_+)\mathbf{T}^r(a_-),$$

With:

$$\mathbf{T}^r(a_+) = \begin{pmatrix} 1 & 0 & 0 & \cdots \\ \lambda & 1 & 0 & \cdots \\ \lambda^2 & \lambda & 1 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \text{ and } \mathbf{T}^r(a_-) = \begin{pmatrix} 0 & 1 & \beta\lambda & \cdots \\ 0 & 0 & 1 & \cdots \\ 0 & 0 & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}.$$

Using that Toeplitz structure to solve the aggregate effect of a monetary policy shock in equation 2.6,

$$d\mathbf{Y} = -\beta\lambda\frac{K^r}{\sigma}\frac{\Pi_{\bar{e}\bar{e}}}{\bar{e}}\mathbf{T}^n(a_-)^{-1}\mathbf{T}^n(a_+)^{-1}\mathbf{T}^r(a_+)\mathbf{T}^r(a_-)d\mathbf{r}.$$

Noticing that $\mathbf{T}^n(a_+) = \mathbf{T}^r(a_+)$, we get that,

$$d\mathbf{Y} = -\beta\lambda\frac{K^r}{\sigma}\frac{\Pi_{\bar{e}\bar{e}}}{\bar{e}}\mathbf{T}^n(a_-)^{-1}\mathbf{T}^r(a_-)d\mathbf{r}.$$

Notice that any Toeplitz matrix can be summarised by its symbol. For $\mathbf{T}^n(a_-)$, its symbol is given by:

$$g_n(z) = \lambda - \sum_{k=1}^{\infty}(\frac{1}{\beta} - \lambda)(\beta\lambda z^{-1})^k \iff g_n(z) = \lambda - (\frac{1}{\beta} - \lambda)\frac{\beta\lambda z^{-1}}{1-\beta\lambda z^{-1}}.$$

The symbol associated to $\mathbf{T}^r(a_-)$ is given by:

$$g_r(z) = \sum_{k=1}^{\infty}(\beta\lambda z^{-1})^k = \frac{\beta\lambda z^{-1}}{1-\beta\lambda z^{-1}}.$$

Computing the product of the symbols of the two Toeplitz matrices gives us the symbol associated to the product of those two matrices:

$$g_n(z)^{-1}g_r(z) = \left(\lambda - (\frac{1}{\beta} - \lambda)\frac{\beta\lambda z^{-1}}{1-\beta\lambda z^{-1}}\right)^{-1}\frac{\beta\lambda z^{-1}}{1-\beta\lambda z^{-1}} = \frac{\beta z^{-1}}{1-z^{-1}} = \beta\sum_{k=1}(z^{-1})^k.$$

Using that symbol, we compute the first element of the $d\mathbf{Y}$ vector

$$dY_0 = -\beta\frac{K^r}{\sigma}\frac{\Pi_{\bar{e}\bar{e}}}{\bar{e}}\frac{\rho}{1-\rho}dr_0 \text{ with } K^r = \sum_{e'}\Pi_{\bar{e}e'}\frac{(e')^{-\sigma}}{\bar{e}^{-\sigma-1}}\frac{1}{\Pi_{\bar{e}\bar{e}}}.$$

B Direct and Indirect Effects

B.1 Direct effect

The direct effect of a monetary policy shock is given by:

$$\text{Direct effect} = -\mathbf{M}^r d\mathbf{r} = \pi_{\bar{e}}\omega_h z_h\sum_{t=1}^{\infty}\frac{(\beta\lambda)^t}{1+r}\frac{K^r}{\sigma}\rho^t dr_0 = -\pi_{\bar{e}}\omega_h z_h\frac{1}{1+r}\frac{K^r}{\sigma}\frac{\rho\lambda\beta}{1-\rho\lambda\beta}dr_0.$$

Computing the derivative of the direct effect with respect to the level of inequality,

$$\frac{d|\text{Direct effect}|}{dz_h} = \underbrace{\frac{\text{Direct effect}}{z_h}}_{\text{composition effect}>0} \underbrace{+\pi_{\bar{e}}\omega_h z_h\frac{K^r}{\sigma}\rho\beta dr_0\left[\frac{d\lambda}{dz_h}\frac{1+\rho\beta(1-\lambda)}{(1-\rho\lambda\beta)^2} - \frac{\frac{dr}{dz_h}}{(1+r)^2}\right]}_{\text{behavior effect}<0}.$$

Controlling for the composition effect, the direct effect is negative.

B.2 EIS high permanent/idiosyncratic type

To compute the EIS, we need to compute the expected ratio of the consumption of the high p/i (permanent/idiosyncratic) type in $t = 1$ over the consumption of the high p/i type in

$t = 0$ conditional on the household being a high p/i type in $t = 0$ when there is an expected shock on the real interest rate in $t = 1$.

Starting with the change in the policy function of the high p/i type in $t = 0$ given that there is a real interest rate shock in $t = 1$:

$$dc_{h,0}(0, \bar{e}) = -\left(\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}}\right)\left(z_h \frac{K^r}{\sigma(1+r)}\right) dr_1$$

$$dc_{h,0}(0, \bar{e}) = -\left(\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}}\right)\left(z_h \frac{K^r}{\sigma(1+r)}\right) dr_1$$

And, given that the shock has just been announced, the consumption at $t = 0$ is just given by the change in the policy function in $t = 0$:

$$c_{h,0} = \bar{e}z_h - \left(\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}}\right)\left(z_h \frac{K^r}{\sigma(1+r)}\right) dr_1$$

Computing the savings of the high p/i (permanent/idiosyncratic) type:

$$a_{h,1} + c_{h,0} = (1+r)a_h^{ss} + z_h\bar{e}N_0$$

Which simplifies to:

$$a_{h,1} = -c_{h,0} + z_h\bar{e} = -dc_{h,0}(0, \bar{e})$$

There is no change in policy function at $t = 1$ since the shock is contemporaneous, and we thus have

$$dc_{h,1}(0, \bar{e}) = 0$$

However, conditional on staying unconstrained, the actual consumption level of the household will change since it has accumulated some wealth at the previous period. The increase in consumption $dc_{h,1}$ will be

$$dc_{h,1} = m_{\bar{e}}da_{h,1}(0, \bar{e}) = -m_{\bar{e}}dc_{h,0}(0, \bar{e}).$$

$$dc_{h,1} = m_{\bar{e}}da_{h,1}(0, \bar{e}) = -(1 + r + dr_1)m_{\bar{e}}dc_{h,0}(0, \bar{e}).$$

Taking into account the expectation with respect to idiosyncratic shock, we obtain

$$\mathbb{E}[c_{h,1}|e = \bar{e}] = \mathbb{E}[e'z_h - (1 + r + dr_1)m_{e'}dc_{h,0}(0, \bar{e})]$$

Noting that $m_{e'} = 1$ if $e' \neq \bar{e}$, we can rewrite this as

$$\mathbb{E}[c_{h,1}|e = \bar{e}] = \mathbb{E}[e'|\bar{e}]z_h - (1 + r + dr_1)\Big(\Pi_{\bar{e}\bar{e}}m_{e'} + (1 - \Pi_{\bar{e}\bar{e}})\Big)dc_{h,0}(0, \bar{e})$$

We can then compute the ratio of the two consumption levels as

$$\frac{\mathbb{E}[c_{h,1}]}{c_{h,0}} = \frac{\mathbb{E}[e'|\bar{e}]z_h + (1+r+dr_1)\Big(\Pi_{\bar{e}\bar{e}}m_{e'} + (1-\Pi_{\bar{e}\bar{e}})\Big)(\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}})\left(z_h\frac{K^r}{\sigma(1+r)}\right)dr_1}{\bar{e}z_h - (\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}})\left(z_h\frac{K^r}{\sigma(1+r)}\right)dr_1}$$

Getting rid of the second-order term, we obtain:

$$\frac{\mathbb{E}[c_{h,1}]}{c_{h,0}} = \frac{\mathbb{E}[e'|\bar{e}]z_h + \Big(\Pi_{\bar{e}\bar{e}}m_{e'} + (1-\Pi_{\bar{e}\bar{e}})\Big)(\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}})\left(z_h\frac{K^r}{\sigma}\right)dr_1}{\bar{e}z_h - (\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}})\left(z_h\frac{K^r}{\sigma(1+r)}\right)dr_1}$$

Taking the derivative with respect to dr_1, we obtain

$$\frac{d\frac{\mathbb{E}[c_{h,1}]}{c_{h,0}}}{dr_1} = \frac{\Big(\Pi_{\bar{e}\bar{e}}m_{\bar{e}} + (1-\Pi_{\bar{e}\bar{e}})\Big)(\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}})\left(z_h\frac{K^r}{\sigma}\right)c_{h,0} + \mathbb{E}[c_{h,1}](\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}})\left(z_h\frac{K^r}{\sigma(1+r)}\right)}{(\bar{e}z_h - (\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}})\left(z_h\frac{K^r}{\sigma(1+r)}\right)dr_1)^2}.$$

Which simplifies to

$$\frac{d\frac{\mathbb{E}[c_{h,1}]}{c_{h,0}}}{dr_1} = (\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}})\left(z_h\frac{K^r}{\sigma}\right)\frac{\Big(\Pi_{\bar{e}\bar{e}}m_{\bar{e}} + (1-\Pi_{\bar{e}\bar{e}})\Big)c_{h,0} + \mathbb{E}[c_{h,1}]/(1+r)}{(\bar{e}z_h - (\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}})\left(z_h\frac{K^r}{\sigma(1+r)}\right)dr_1)^2}$$

Now, taking the limit as $dr_1 \to 0$, we get

$$\frac{d\frac{\mathbb{E}[c_{h,1}]}{c_{h,0}}}{dr_1} = (\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}})\left(z_h\frac{K^r}{\sigma}\right)\frac{\Big(\Pi_{\bar{e}\bar{e}}m_{\bar{e}} + (1-\Pi_{\bar{e}\bar{e}})\Big)c_{h,0} + \mathbb{E}[c_{h,1}]/(1+r)}{(\bar{e}z_h)^2}$$

Which simplifies to

$$\frac{d\frac{\mathbb{E}[c_{h,1}]}{c_{h,0}}}{dr_1} = (\beta\lambda_{h,\bar{e}}\Pi_{\bar{e}\bar{e}})\left(\frac{K^r}{\sigma}\right)\frac{\Big(\Pi_{\bar{e}\bar{e}}m_{\bar{e}} + (1-\Pi_{\bar{e}\bar{e}})\Big)c_{h,0} + \mathbb{E}[c_{h,1}]/(1+r)}{\bar{e}^2 z_h}$$

Note that $K^r = \frac{\bar{e}}{\Pi_{\bar{e}\bar{e}}}\rho(\bar{e})$, so that

$$\frac{d\frac{\mathbb{E}[c_{h,1}]}{c_{h,0}}}{dr_1} = (\beta\lambda_{h,\bar{e}})\left(\frac{\rho(\bar{e})}{\sigma}\right)\frac{\Big(\Pi_{\bar{e}\bar{e}}m_{\bar{e}} + (1-\Pi_{\bar{e}\bar{e}})\Big)c_{h,0} + \mathbb{E}[c_{h,1}]/(1+r)}{\bar{e}z_h}.$$

Computing the EIS:

$$\text{EIS} = \frac{1+r}{\frac{\mathbb{E}[c_{h,1}]}{c_{h,0}}}\frac{d\frac{\mathbb{E}[c_{h,1}]}{c_{h,0}}}{dr_1} = (1+r)\beta\lambda_{h,\bar{e}}\left(\frac{\rho(\bar{e})}{\sigma}\right)\frac{\Big(\Pi_{\bar{e}\bar{e}}m_{\bar{e}} + (1-\Pi_{\bar{e}\bar{e}})\Big)c_{h,0} + \mathbb{E}[c_{h,1}]/(1+r)}{\bar{e}z_h\mathbb{E}[e'|\bar{e}]}.$$

Plugging the values for consumptions and given that $m_{\bar{e}} = 1 - \frac{\lambda}{\Pi_{\bar{e}\bar{e}}(1+r)}$,

$$\text{EIS} = \frac{\rho(\bar{e})(1+r)\beta}{\bar{e}\mathbb{E}[e'|\bar{e}]\Pi_{\bar{e}\bar{e}}}\lambda\left[\left(1 - \frac{\lambda}{1+r}\right)\bar{e} + \frac{\mathbb{E}[e'|\bar{e}]}{1+r}\right]\frac{1}{\sigma}.$$

Notice that, in the absence of taste for wealth and idiosyncratic shocks, the EIS collapses to $1/\sigma$.

The sign of the derivative is given by:

$$\frac{d\lambda}{dz_h}\left\{\left[\left(1 - \frac{\lambda}{1+r}\right)\bar{e} + \mathbb{E}[e'|\bar{e}]/(1+r)\right] - \frac{\lambda}{1+r}\bar{e}\right\} = \underbrace{\frac{d\lambda}{dz_h}}_{<0}\underbrace{\left[\left(1 - \frac{\lambda}{1+r}\right)\bar{e} + \frac{\mathbb{E}[e'|\bar{e}] - \lambda}{1+r}\right]}_{>0} < 0.$$

The elasticity of intertemporal substitution is a decreasing function of permanent labor income.

B.3 Indirect effect

The indirect effect of a labor demand shock is given by :

$$\text{Indirect effect} = \mathbf{M}^n d\mathbf{N}.$$

Taking the first element of the vector:

$$\text{Indirect effect}_0 = dN_0 - (1-\mu)\frac{\omega_h z_h}{1+r}\frac{\lambda(1-\rho)}{1-\beta\lambda\rho}dN_0.$$

Taking the derivative of the indirect effect with respect to z_h:

$$\begin{aligned}\frac{d\text{Indirect effect}_0}{dz_h} =& \underbrace{-(1-\mu)\frac{\omega_h}{1+r}\frac{dN_0}{1-\beta\lambda\rho}\lambda(1-\rho)}_{\text{composition effect}<0} \\ & - (1-\mu)\frac{\omega_h z_h}{1+r}(1-\rho)dN_0\left(\frac{\frac{d\lambda}{dz_h}(1-\beta\lambda\rho) + \beta\rho\frac{d\lambda}{dz_h}\lambda}{(1-\beta\lambda\rho)^2} - \frac{dr}{dz_h}\frac{1}{1+r}\frac{1}{1-\beta\lambda\rho}\lambda\right)\end{aligned}$$

$$\begin{aligned}\frac{d\text{Indirect effect}_0}{dz_h} =& \underbrace{-(1-\mu)\frac{\omega_h}{1+r}\frac{dN_0}{1-\beta\lambda\rho}\lambda(1-\rho)}_{\text{composition effect }<0} \\ & \underbrace{-(1-\mu)\frac{\omega_h z_h}{1+r}\frac{1-\rho}{1-\beta\lambda\rho}dN_0\left(\frac{d\lambda}{dz_h}\frac{1}{1-\beta\lambda\rho} - \frac{dr}{dz_h}\frac{\lambda}{1+r}\right)}_{\text{behavior effect }>0}\end{aligned}$$

C Matrices Summary

C.1 Sequence-space Jacobians with zero liquidity

With homothetic preferences

$$\mathbf{A}^n = s^u\beta \begin{pmatrix} 1 & -(1-\beta) & -(1-\beta)\beta & -(1-\beta)\beta^2 & \cdots \\ 1 & \beta & -\left(1-\beta^2\right) & -\left(1-\beta^2\right)\beta & \cdots \\ 1 & \beta & \beta^2 & -\left(1-\beta^3\right) & \ddots \\ \vdots & \vdots & \vdots & \beta^3 & \ddots \end{pmatrix}$$

$$\mathbf{A}^r = s^u \begin{pmatrix} 0 & \frac{\beta}{1+r}\left(\frac{c}{\sigma}\right) & \frac{\beta^2}{1+r}\left(\frac{c}{\sigma}\right) & \cdots \\ 0 & \frac{\beta}{1+r}\left(\frac{c}{\sigma}\right) & \frac{\beta^2}{1+r}\left(\frac{c}{\sigma}\right)+\frac{\beta}{1+r}\left(\frac{c}{\sigma}\right) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

With element t, s of $\mathbf{A}^n$ being $\frac{\text{‘}\partial a_{t+1}}{\partial w_s}$ and element t, s of $\mathbf{A}^r$ being $\frac{\text{‘}\partial a_{t+1}}{\partial r_s}$

With non-homothetic preferences

$$\mathbf{A}^n = s^u \begin{pmatrix} \frac{\lambda}{1+r} & -\left(1-\frac{\lambda}{1+r}\right)\cdot\beta\lambda & -\left(1-\frac{\lambda}{1+r}\right)\cdot(\beta\lambda)^2 & \cdots \\ \frac{\lambda^2}{1+r} & -\left(1-\frac{\lambda}{1+r}\right)\cdot\beta\lambda^2+\frac{\lambda}{1+r} & -\left(1-\frac{\lambda}{1+r}\right)\beta\lambda(\beta\lambda^2+1) & \cdots \\ \frac{\lambda^3}{1+r} & -\left(1-\frac{\lambda}{1+r}\right)\cdot\beta\lambda^3+\frac{\lambda^2}{1+r} & -\left(1-\frac{\lambda}{1+r}\right)\beta\lambda^2(\beta\lambda^2+1)+\frac{\lambda}{1+r} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$\mathbf{A}^r = \begin{pmatrix} 0 & \frac{\beta\lambda}{1+r}\left(\frac{c}{\sigma}\right) & \frac{(\beta\lambda)^2}{1+r}\left(\frac{c}{\sigma}\right) & \cdots \\ 0 & \frac{\beta\lambda^2}{1+r}\left(\frac{c}{\sigma}\right) & \lambda\frac{(\beta\lambda)^2}{1+r}\left(\frac{c}{\sigma}\right)+\frac{\beta\lambda}{1+r}\left(\frac{c}{\sigma}\right) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

With element t, s of $\mathbf{A}^n$ being $\frac{\text{‘}\partial a_{t+1}}{\partial w_s}$ and element t, s of $\mathbf{A}^r$ being $\frac{\text{‘}\partial a_{t+1}}{\partial r_s}$

C.2 Jacobians with positive liquidity

With non-homothetic preferences

$$\mathbf{A}^n = s^u \begin{pmatrix} \frac{\lambda}{1+r} & -\left(1-\frac{\lambda}{1+r}\right)\cdot\beta\lambda & -\left(1-\frac{\lambda}{1+r}\right)\cdot(\beta\lambda)^2 & \cdots \\ \frac{\lambda^2}{1+r} & -\left(1-\frac{\lambda}{1+r}\right)\cdot\beta\lambda^2+\frac{\lambda}{1+r} & -\left(1-\frac{\lambda}{1+r}\right)\beta\lambda(\beta\lambda^2+1) & \cdots \\ \frac{\lambda^3}{1+r} & -\left(1-\frac{\lambda}{1+r}\right)\cdot\beta\lambda^3+\frac{\lambda^2}{1+r} & -\left(1-\frac{\lambda}{1+r}\right)\beta\lambda^2(\beta\lambda^2+1)+\frac{\lambda}{1+r} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$\mathbf{A^r} = \begin{pmatrix} \frac{\lambda a}{1+r} & \frac{\beta\lambda}{1+r}\left(\frac{c}{\sigma} - (1+r-\lambda)a\right) & \frac{(\beta\lambda)^2}{1+r}\left(\frac{c}{\sigma} - (1+r-\lambda)a\right) & \cdots \\ \frac{\lambda^2 a}{1+r} & \frac{\beta\lambda^2}{1+r}\left(\frac{c}{\sigma} - (1+r-\lambda)a\right) + \frac{\lambda a}{1+r} & \lambda\frac{(\beta\lambda)^2}{1+r}\left(\frac{c}{\sigma} - (1+r-\lambda)a\right) + \frac{\beta\lambda}{1+r}\left(\frac{c}{\sigma} - (1+r-\lambda)a\right) & \cdots \\ \frac{\lambda^3 a}{1+r} & \frac{\beta\lambda^3}{1+r}\left(\frac{c}{\sigma} - (1+r-\lambda)a\right) + \frac{\lambda^2 a}{1+r} & \lambda\frac{(\beta\lambda)^3}{1+r}\left(\frac{c}{\sigma} - (1+r-\lambda)a\right) + \frac{\beta\lambda^2}{1+r}\left(\frac{c}{\sigma} - (1+r-\lambda)a\right) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

C.3 Some useful matrices

$$\mathbf{F} = \begin{pmatrix} 0 & 1 & 0 & \cdots \\ 0 & 0 & 1 & \cdots \\ 0 & 0 & 0 & \cdots \\ \vdots & & & \ddots \end{pmatrix} \text{ and } \mathbf{L} = \begin{pmatrix} 0 & 0 & 0 & \cdots \\ 1 & 0 & 0 & \cdots \\ 0 & 1 & 0 & \cdots \\ \vdots & & & \ddots \end{pmatrix}$$

$$\mathbf{K} = -\sum_{t=1}^{\infty} \frac{\mathbf{F}^t}{(1+r)^t} = -\begin{pmatrix} 0 & 1/(1+r) & 0 & \cdots \\ 0 & 0 & 1/(1+r) & \cdots \\ 0 & 0 & 0 & \cdots \\ \vdots & & & \ddots \end{pmatrix} - \begin{pmatrix} 0 & 0 & 1/(1+r)^2 & \cdots \\ 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & \cdots \\ \vdots & & & \ddots \end{pmatrix} - ...$$

D Additional Material for One-asset Model

D.1 Decomposition of a monetary policy shock

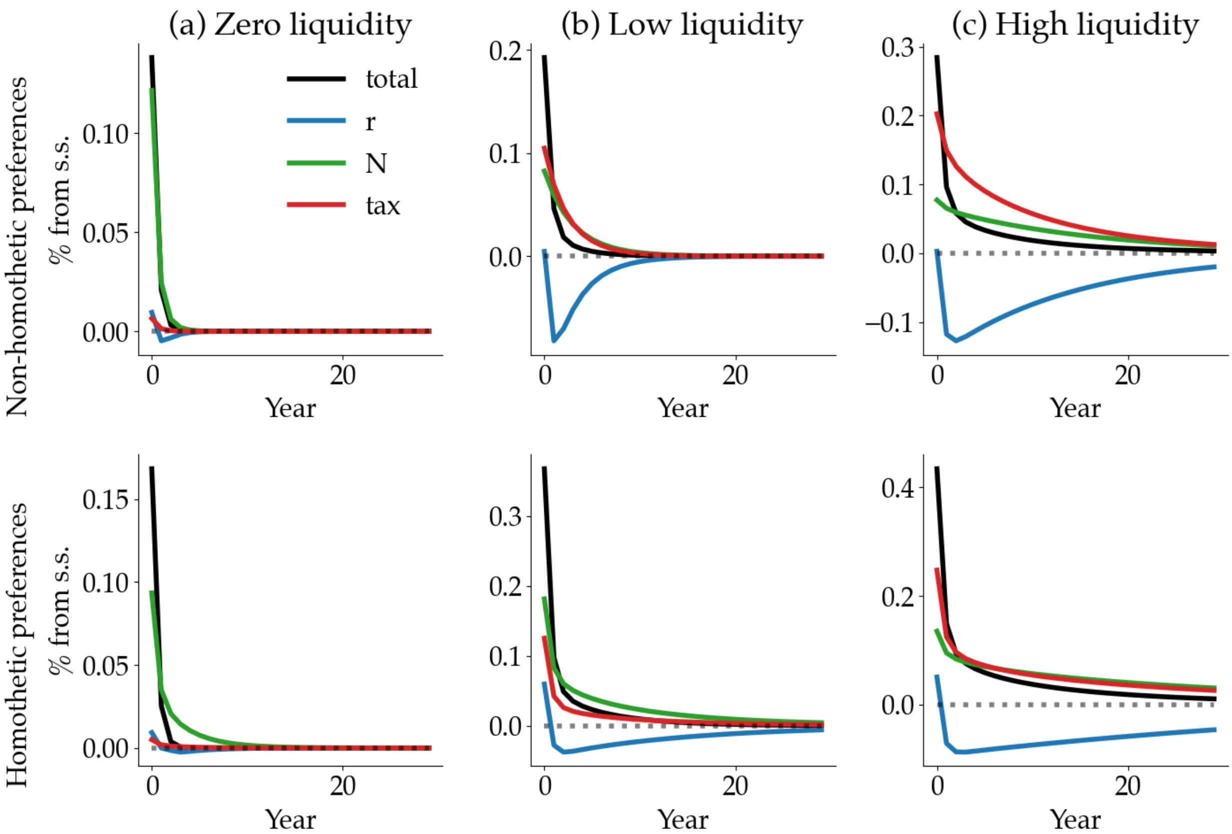

Figure 2.5: Decomposition of the effect of a monetary shock on output

Note: This figure plots the aggregate effect and the transmission channels of a monetary policy shock for different levels of government bonds (from zero on the left, to a low level in the middle, and to high a level on the right). On top, the aggregate effect and the transmission channels are computed with non-homothetic preferences for wealth while at the bottom they are computed without non-homothetic preferences for wealth.

D.2 Rise in permanent labor income inequality with homothetic preferences

We set $\gamma = 0$ and study the effect of permanent labor income inequality on the transmission of a monetary policy shock. We find that an increase in permanent labor income has almost no effect on the output response to a monetary policy shock, even in the presence of a positive supply of liquidity. Indeed, as shown by Straub (2019) in Lemma 1, steady-state policy functions in a model with homothetic preferences are linear in permanent income.

Figure 2.6 gives us a visual representation of this neutrality result. In the presence of homothetic preferences, the MPC and the EIS are still functions of permanent income. But they are now *linear* functions of permanent income. The EIS and the MPC normalized by

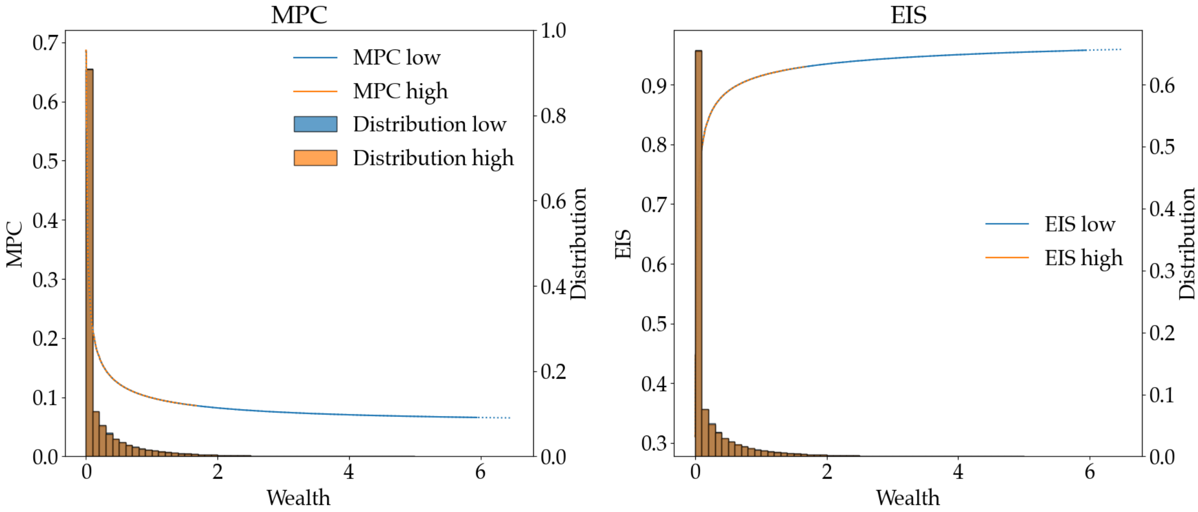

Figure 2.6: MPC and EIS along the wealth distribution

Note: This figure plots the marginal propensity to consume out of a one-time income shock (on the left) and the elasticity of intertemporal substitution (on the right) normalized by the level of permanent income for different levels of wealth (x-axis) and for different levels of permanent income (in orange, the permanent labor income of the top 10% in 1989, in dotted orange the permanent labor income of the top 10% in 2019; in blue, the permanent labor income of the bottom 90% in 1989, in dotted blue the permanent labor income of the bottom 90% in 2019. We also plot the wealth distributions of the two permanent income types normalized (in blue, the low-income type, and in orange, the high-income type) before and after the rise in permanent labor income inequality (in dark color before and transparent after the rise). B is fixed at the low-liquidity value (0.23). Notice that the two normalized distributions are perfectly equal to each other.

permanent income are hence equal across permanent income types. Redistributing permanent income across households leaves the aggregate MPC and the aggregate EIS constant. Similarly, wealth distributions normalized by the level of permanent income are equal across types.

This neutrality result on both the aggregate effect and the transmission channels of the permanent labor income distribution is confirmed in Figure 2.7.

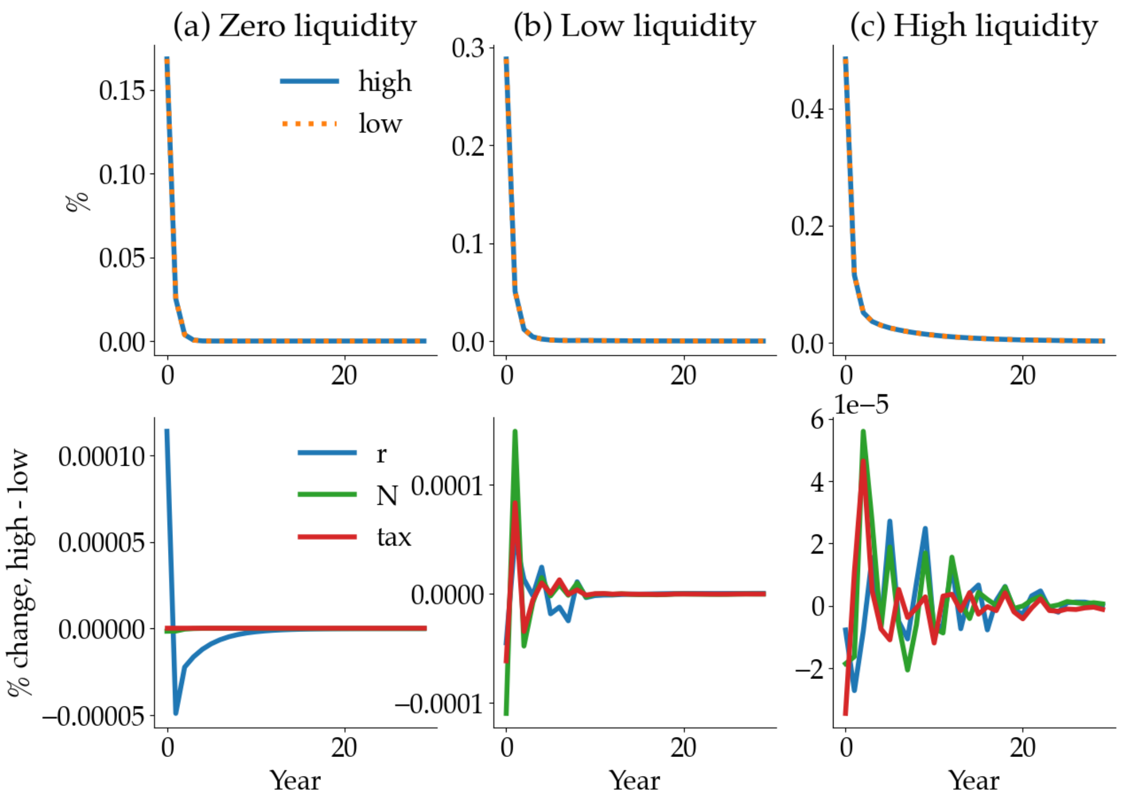

Figure 2.7: Decomposition of the effect of a monetary shock on output

D.3 Rise in the variance of idiosyncratic shocks

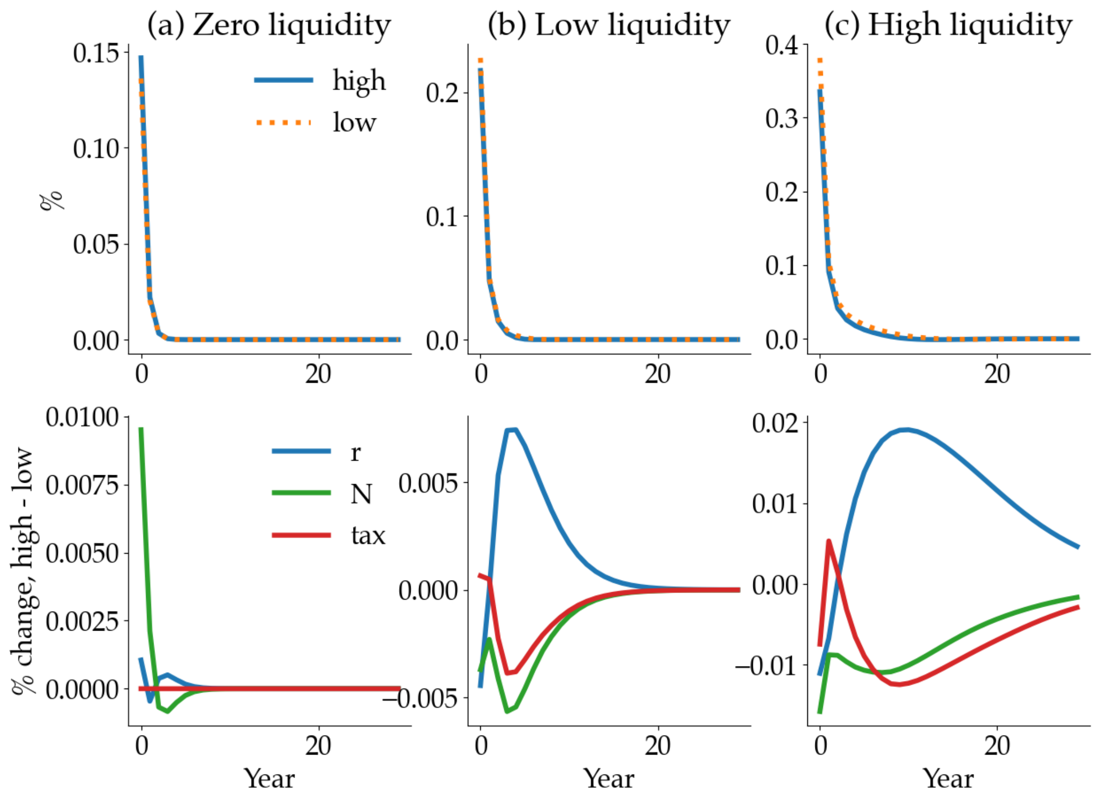

Figure 2.8: Decomposition of the effect of a monetary shock on output

E Additional Material for Two-asset Model

E.1 Intermediate firm's problem in two-asset HANK

Intermediate firms choose prices, labor, and capital next period so as to maximize their

$$J_t\left(k_t\right)=\max_{\mathcal{P}_t,k_{t+1},n_t}\left\{\frac{\mathcal{P}_t}{P_t}F\left(k_t,n_t\right)-\frac{W_t}{P_t}n_t-i_t-\varphi\left(\frac{k_{t+1}}{k_t}\right)k_t-\xi\left(\mathcal{P}_t,\mathcal{P}_{t-1}\right)Y_t+\frac{1}{1+r_{t+1}}J_{t+1}\left(k_{t+1}\right)\right\},$$

with investment $i_t = k_{t+1} - (1-\delta)k_t$,

subject to the final-goods firm's demand: $F\left(k_t,n_t\right)=\left(\frac{\mathcal{P}_t}{P_t}\right)^{-\mu^p/(\mu^p-1)}Y_t.$

Given the Rotemberg adjustment costs: $\xi\left(\mathcal{P}_t,\mathcal{P}_{t-1}\right)\equiv\frac{1}{2\kappa^p\left(\mu^p-1\right)}\left(\frac{\mathcal{P}_t-\mathcal{P}_{t-1}}{\mathcal{P}_{t-1}}\right)^2,$

Year	bottom50	next40	top10	top100
1989	20%	51%	28%	8%
2019	18%	48%	34%	11%

Table 2.8: Distribution of permanent income used to calibrate the model

Year	Bottom 50%	Next 40%	Next 9%	Top 1%
1989	3%	28%	37%	33%
2019	2%	20%	38%	40%

Table 2.9: Distribution of illiquid wealth in the Survey of Consumer Finance used to calibrate the model

And the quadratic capital adjustment costs: $\varphi\left(\frac{k_{t+1}}{k_t}\right) k_t$ with $\varphi(x) \equiv \frac{1}{2\delta\varepsilon_I}(x-1)^2$.

With ε_I, the sensitivity of gross investment to the Tobin's Q.

E.2 Distribution of permanent income and illiquid wealth

Tables 2.8 and 2.9 describe respectively the distribution of labor income from Piketty, Saez, and Zucman (2018) and the distribution of illiquid wealth in the Survey of Consumer finance that we use to calibrate our parameters $(s_{b50}, s_{n40}, s_{n9}, s_{top1})$ and $(a_{b50}, a_{n40}, a_{n9}, a_{top1})$. To move from the labor shares to the parameters s, we divide them by the weight of each household type. For the illiquid wealth, we divide them by the share of illiquid wealth and multiply them by the total amount of illiquid wealth in the economy.

E.3 Two-asset with constant portfolio

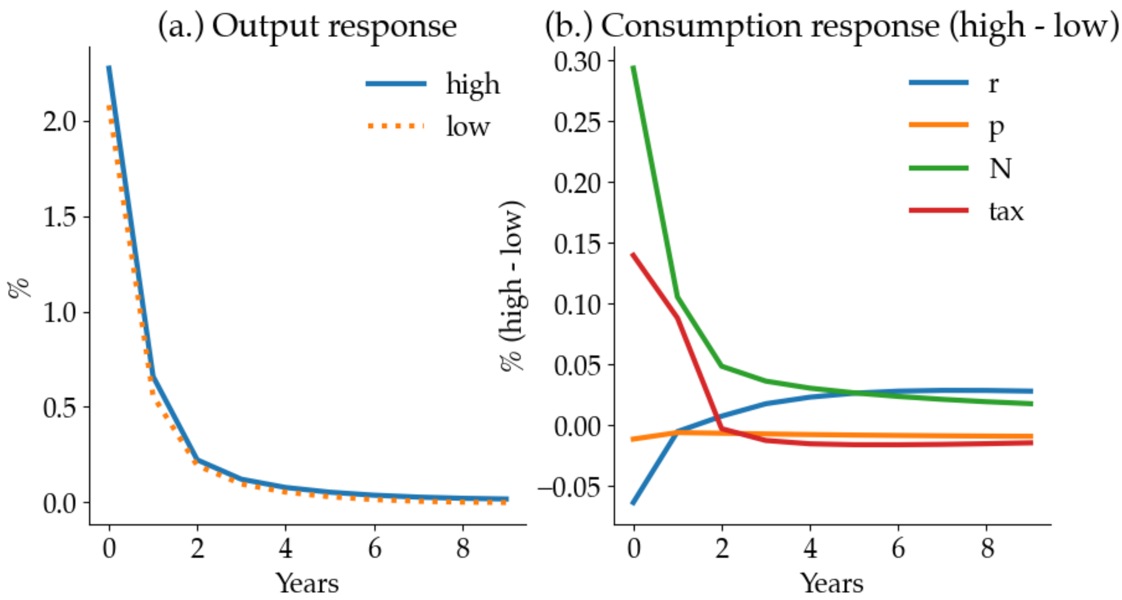

Figure 2.9: Output reponse and Decomposition

Note: The left figure plots the output response following a monetary shock. The right figure plots the difference in the decomposition between the high-inequality economy minus the low-inequality economy.

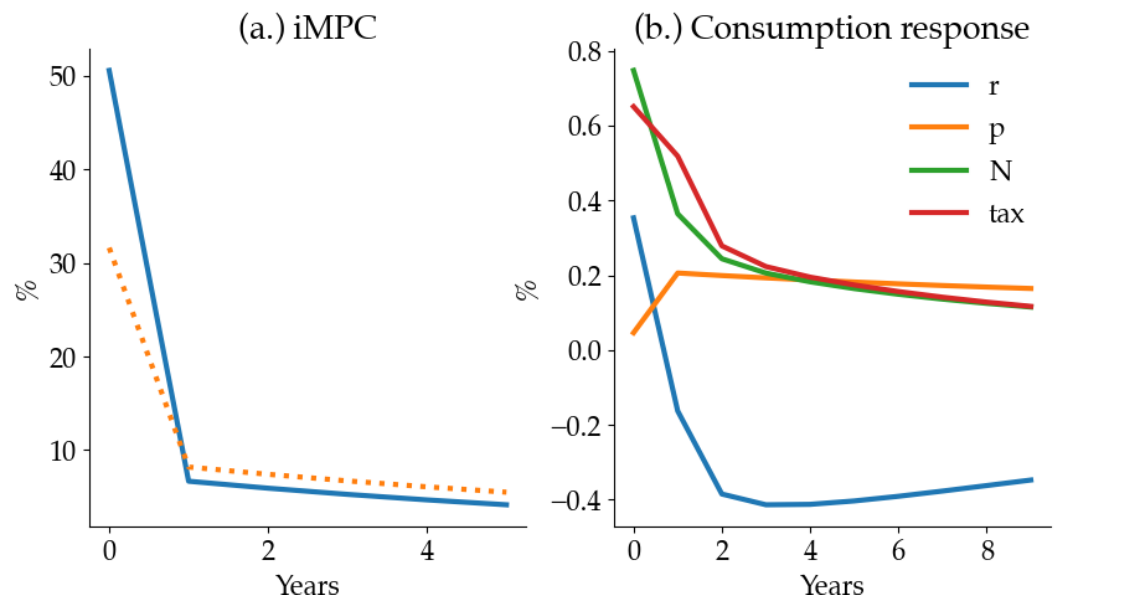

Figure 2.10: iMPC and decomposition

Note: The left figure plots the iMPC. The right figure plots the decomposition of a monetary policy shock in the high-inequality economy.

E.4 Computational details

We solve the HANK model of Section 2 and the quantitative model of Section 3 using the Sequence-Space Jacobian method of Auclert, Bardóczy, et al. (2021), and their package available online.

To solve for the steady-state, we fix the interest rate at $r = 5\%$ and find a β to clear the asset with a bisection method, using the endogenous-grid method to solve the problem of the household.

In the one-asset HANK model, we solve the problem of the household on a grid of 500 assets points and discretize the AR(1) process for idiosyncratic shock using the Rouwenhorst method with 11 points.

In the two-assets HANK model, we solve the problem of the household on a grid of 50 points for the illiquid assets and 50 points for the illiquid assets. The productivity process is discretized on a grid of 5 points.

Chapter 3

Why is there still investment in polluting capital?

Despite governments' commitments to limit global warming to 1.5 degrees Celcius, there is still investment in carbon-intensive capital. This paper uses a growth model featuring irreversible investment, capacity utilization, and clean and polluting capital to study this apparent paradox. It shows that current investment in polluting capital and CO_2 emissions are coherent with expectations of a future carbon tax if investors also expect a bailout of polluting capital. This result implies that governments' credibility can play an important role in reducing the cost of implementing an optimal carbon tax by committing not to bail out. However, there exists a temptation for a short-sighted government to boost output and consumption in the short run by announcing a future bailout.

1 Introduction

The climate literature has shown that the CO_2 emissions implied by the existing stock of polluting capital already exceed the remaining carbon budget to limit global warming to 2°C or less (Davis and Socolow 2014; Pfeiffer, Millar, et al. 2016; Pfeiffer, Hepburn, et al. 2018). Figure 3.2 shows the shrinking world carbon budget. The total carbon budget to keep global warming below 1.5°C with 80% probability is only equal to 2.5 years of annual emissions. Some of the existing polluting capital stock must become 'stranded' to meet our climate objectives. However, despite this overaccumulation of polluting capital and the government's commitment to respect this carbon budget, firms and households keep investing in polluting capital.

This paper studies this apparent paradox in the allocation of resources towards polluting capital, focusing on the role of climate policy uncertainty. Indeed, although there is evidence

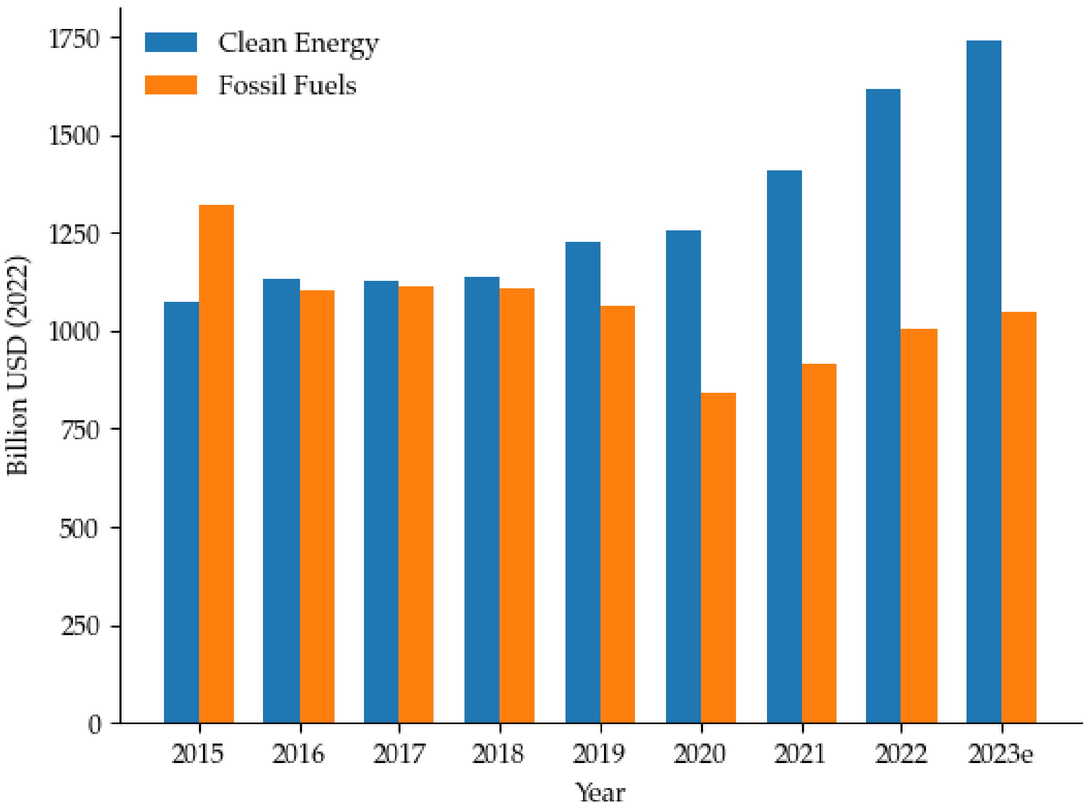

Figure 3.1: Global energy investment in clean energy and in fossil fuels, 2015-2023e

Note: Data from the IEA. Measured in billions of dollars.

that firms and households expect climate policy to become more stringent in the future, there is still uncertainty surrounding when a carbon tax will be imposed and precisely what type of policy will be implemented. More precisely, there appears to be a lot of uncertainty about whether owners of stranded assets will be bailed out or compensated by governments. For example, Sen and von Schickfus (2019) shows that, in Germany, investors expected that the tax on the lignite coal power plants would be accompanied by a form of bailout to compensate stockholders for their financial losses. Only when a court decided this policy was against national and European legislation did the value of the firms owning those lignite coal power plants decrease.

Thus, one potential explanation for the persistent investment in polluting capital is that households and firms expect compensation for future losses due to a more stringent climate policy. Indeed, if polluting capital is more productive than clean capital, it can be optimal for investors to keep investing and using polluting capital if they expect a bailout compensating them for the potentially stranded assets.

In this work, I study the impact of climate policy uncertainty on investment in pollut-

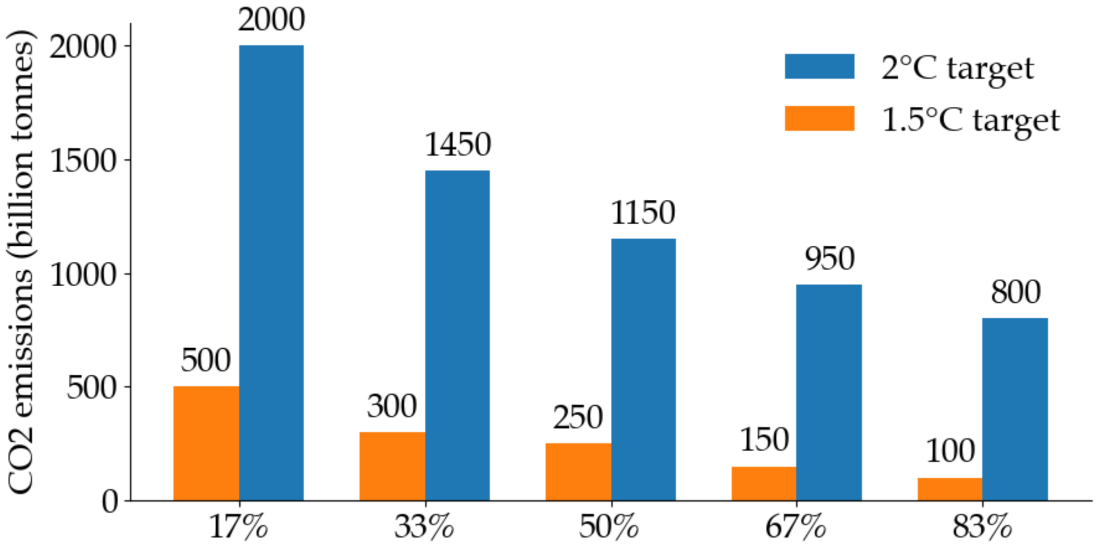

Figure 3.2: Remaining carbon budget for the 2°C and 1.5°C target.

Note: This figure shows the remaining carbon budget in 2022 depending on the likelihood of keeping global warming below 1.5°C or 2°C. Sources are from Our World in Data.

ing capital and the existence of stranded assets. We use a two-asset neo-classical model along the lines of Rozenberg, Vogt-Schilb, and Hallegatte (2018) with three key features: (1.) irreversibility in polluting capital, (2.) capacity utilization of polluting capital, (3.) uncertainty about future climate policy. A key feature of our model is in line with Sen and von Schickfus (2019), firms are unsure about both the timing of climate policy and whether the government will bail out stranded assets or not.

We first show that non-punitive climate policies such as subsidies on clean capital are probably not feasible under the current level of polluting capital, which makes it more likely that investors expect a future carbon tax. Secondly, in a stochastic equilibrium where investors expect a future bailout, the steady-state level of polluting capital can be above the laissez-faire equilibrium if the bailout is sufficiently large. Thus, expectations of a future climate policy can be coherent with an increase in current emissions when we include the possibility of a bailout. Finally, we show that a short-term government might want to commit to a future bailout of polluting capital to temporarily increase output and consumption at the cost of a longer transition and more stranded assets. Conversely, committing never to bail out polluting capital reduces output today but decreases the cost of transition and the amount of stranded assets in the future. Finally, we show that, despite the absence of any financial frictions in our model, the price of clean and polluting firms will overreact to climate policy commitments in the future, confirming that expectations about future climate policies might have a large impact on financial markets.

Literature review. There are two types of stranded assets. The first ones are the known fossil fuel reserves that need to remain under the ground to respect the objective of 2°C set by the 2015 Paris Agreement. Indeed, as shown by McGlade and Ekins (2015), known reserves in 2015 vastly exceeded the carbon budget of 1,100 gigatonnes of carbon dioxide, and around a third of oil reserves, half of gas reserves, and 80% of coal reserves need to remain unused. This overabundance of fossil fuels has thus shifted attention from the risk of "peak oil" to the risk of stranded assets (van der Ploeg and Rezai 2019).

A second type of stranded asset is the infrastructure and capital that directly or indirectly requires carbon fuels to operate. Such assets can be directly related to the energy sector, such as a coal plant, an oil refinery, or an oil tanker, but they are not limited to it: airports, highways, and central heating systems can also be affected. Davis and Socolow (2014) estimated that the committed emissions – that is, the cumulative emissions that would be emitted if an asset is used for its total lifetime at its expected use rate – implied by those carbon-intensive infrastructures were increasing at 4% a year in the energy sector. Subsequent studies found that the committed emissions from total carbon-intensive infrastructures already exceeded the current carbon budget, making the appearance of stranded assets inevitable (Pfeiffer, Millar, et al. 2016; Pfeiffer, Hepburn, et al. 2018). The main conclusion from the empirical literature on stranded assets is that there is too much carbon fuel at our disposal and too much carbon-intensive infrastructure to use compared to our remaining carbon budget. This over-abundance makes it more likely that a climate transition will imply stranded assets.

In theory, stranded assets can be the most efficient solution and are a desirable consequence of a carbon tax. If investors made mistakes in the past and didn't properly internalize the climate constraint and the social cost of carbon, it can be more efficient today not to use those assets once the climate constraint is revealed (Rozenberg, Vogt-Schilb, and Hallegatte 2018). In that sense, stranded assets are a typical example of avoiding a sunk-cost fallacy. If the marginal cost of using those assets is superior to the implied marginal benefit, it is best not to use them, whatever the previous cost of investing in them. However, in practice, stranded assets might create risks for financial stability and incentivize politicians not to implement efficient climate policies. Many central bankers, especially in Europe, (Carney 2016; ECB 2019; Andersson and Baccianti 2020; Batten 2018) have thus focused on the risk that those assets could pose to financial stability. Banks that have carbon assets on their balance sheets could become insolvent due to the decrease in the value of those assets following a more stringent climate policy (Lucia, Ossola, and Panzica 2019). Secondly, investors who own potentially stranded assets might be able to lobby against climate policies and block efficient and needed action against climate change. In addition, investors might demand financial compensation, increasing the cost of climate policies and pushing the government to delay climate policies.

Given the overabundance of polluting capital of fossil fuel reserves and the potentially harmful effects of stranded assets, a natural question arises: why do investors keep financing carbon-intensive capital when most governments have already committed to limiting climate change to 1.5-2C° with the 2015 Paris Agreement? Indeed, as shown by Pfeiffer, Hepburn, et al. (2018), investment in carbon-intensive capital is still positive even though the climate constraint has long been discovered. Batten, Sowerbutts, and Tanaka (2016) found that although the Paris Agreement positively impacted the valuation of renewable companies, it had no significant effect on carbon-emitting companies. A good example of this paradox is coal: although it is the most polluting carbon fuel, the installed capacity of coal-fueled electricity plants has constantly risen in previous years. Three potential factors can explain such a paradox.

The first would be that investors have not internalized governments' commitment to limit global warming or believe this commitment is not credible. However, this would be at odds with numerous studies that find that investors expect some kind of climate policy and have already priced in the risks associated with climate policies and global warming (Batten, Sowerbutts, and Tanaka 2016; Byrd and Cooperman 2018). Bolton and Kacperczyk (2019) finds that investors consider a carbon risk in the sense that they demand higher returns for higher CO_2 intensive firms, which indicates that they expect a climate policy in the future. Fried, Novan, and Peterman (2019) also provides evidence that some large US firms use an internal carbon price to guide their investment decisions, indicating that they expect a more stringent climate policy in the future. Thus, even though firms doubt the timing of climate policies (or, equivalently, the actual size of the carbon budget), they expect some action against climate change will be taken in the future.

A second explanation could be that investors expect that technological innovations, such as carbon capture, will allow the retrofitting of carbon-intensive capital. In that sense, they expect that the irreversibility of polluting capital will not be binding and that it will be transformed into cleaner capital in the future (Byrd and Cooperman 2018; van der Ploeg and Rezai 2019). There is indeed evidence that the potential of carbon capture could limit the carbon intensity of some coal plants and other polluting capital (Fisch-Romito et al. 2020).

A last reason could be that investors expect to be compensated for their losses by governments. If investors expect governments to bail out stranded assets, investing in carbon-intensive infrastructures can be rational and profitable even though the climate constraint is already known. In this sense, the uncertainty about climate policy is deeply related to the political economy issues previously mentioned (van der Ploeg and Rezai 2019). Sen and von Schickfus (2019) provides some evidence of investors expecting a bailout in Germany, where the federal government announced a future ban on lignite coal plants. Their study found that the prices of coal-related firms weren't affected by the announcement of the ban but dropped only after a court ruled that any kind of compensation would be illegal.

This work is related to recent theoretical works that have shown the impact of a carbon tax on the level of stranded assets. Rozenberg, Vogt-Schilb, and Hallegatte (2018) found that, in a Ramsey growth model with polluting and clean capital, a tradeoff exists for the social planner between intertemporal efficiency and the level of stranded assets. However, their study didn't take into account the anticipation of climate policy by investors and the potential commitment issues from the government: they assumed that once the climate constraint is discovered, there is an immediate and optimal carbon tax imposed. This is a potential issue as there has been a lot of debate about the impact of expectations of climate policy on current emissions. For example, Sinn (2012) showed that expectations about a future carbon tax could push carbon-intensive sectors to increase their use of carbon fuel in the short term to limit the amount of future carbon reserves under the ground. On the contrary, Fried, Novan, and Peterman (2019) showed that if investors expect an efficient carbon tax to be imposed in the future, they will reduce their current investment in polluting infrastructures, and the cost of actually implementing the carbon tax will be smaller.

This model contributes to the debate by showing that this "Green paradox" versus "reversed Green paradox" depends on the ability of the government to commit to a clean climate policy. Suppose the government credibly announces that it will not bail out future stranded assets. In that case, our model suggests that emissions should decrease before the implementation of the policy, compared to the laissez-faire equilibrium, and the cost of imposing a carbon tax will be lower. Previous works also investigate the impact of investors' expectations on stranded assets but didn't account for some of the general equilibrium effects or the impact on the cost of climate policy that we investigate. van der Ploeg and Rezai (2018) and van der Ploeg and Rezai (2020) study the impact of policy uncertainty on investment in polluting capital in a model of the energy sector and found that polluting firms' profits were higher when the carbon tax was delayed or when a subsidy on clean capital was imposed instead. However, their model didn't account for general equilibrium effects and the impact of climate policy on output. Finally, in a larger sense, this work belongs to an older but large literature on investment under uncertainty and irreversible investment (Arrow and Kurz 1970; Abel 1983; Abel and Eberly 1993; A. K. Dixit, R. K. Dixit, and Pindyck 1994; A. Dixit 1995).

This paper is structured in three parts. In the first part, we present and solve the model for the laissez-faire equilibrium and the planner's solution. In the second part, we study a decentralized equilibrium under an optimal carbon tax, a second-best subsidy on clean capital, and an optimal carbon tax associated with a bailout. In the third part, we study the stochastic equilibrium before a climate policy is imposed and when investors expect either an optimal carbon tax or a tax jointly with a bailout. We calibrate the model and present some numerical simulations.

2 A growth model with clean and polluting capital

In this section, we present the main model without policy uncertainty. It is a neoclassical model with two assets in discrete time, similar to Rozenberg, Vogt-Schilb, and Hallegatte (2018). We first solve for the decentralized equilibrium under "laissez-faire", that is, without the climate constraint. We then solve the central planner's problem under the climate constraint.

2.1 Laissez-faire equilibrium

The economy comprises three sectors: a final goods producer, an intermediate clean producer, and an intermediate polluting sector. The representative household owns shares in the two clean and polluting firms.

Firms

Final goods producer. A final goods producer produces total output y_t using an intermediate good x_t and labor l, with the following aggregate production function

$$y_t = x_t^{\alpha} l^{1-\alpha}.$$

The intermediate good x_t is a composite of the clean and polluting intermediate goods x_t^c and x_t^p

$$x_t = \left((x_t^c)^{\frac{\varepsilon-1}{\varepsilon}} + (x_t^p)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}.$$

The first-order conditions of the final good producer determines the price of the intermediary goods

$$p_t^c = \alpha \left((x_t^c)^{\frac{\varepsilon-1}{\varepsilon}} + (x_t^p)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}\alpha-1} (x_t^c)^{\frac{-1}{\varepsilon}},$$
$$p_t^p = \alpha \left((x_t^c)^{\frac{\varepsilon-1}{\varepsilon}} + (x_t^p)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}\alpha-1} (x_t^p)^{\frac{-1}{\varepsilon}}.$$

Clean intermediate good. A clean intermediary firm owns the stock of clean capital and makes investment decisions to maximize its stock market value, subject to a linear production function

$$V(k_t^c) = \max_{k_{t+1}^c} \left\{ d_t^c + \frac{V(k_{t+1}^c)}{1+r_{t+1}^c} \right\} \quad \text{s.t.} \quad x_t^c = z^c k_t^c$$
$$d_t^c = p_t^c x_t^c - k_{t+1}^c + (1-\delta)k_t^c.$$

The first-order condition yields the usual equation for the productivity of capital

$$r_t^c = p_t^c z^c - \delta. \tag{3.1}$$

Polluting intermediate good. The polluting firm owns the stock of polluting capital and makes investment decisions but is also subject to an irreversibility constraint on investment to represent the difficulty of transforming polluting capital into clean capital, as in Arrow and Kurz (1970). We also allow the firm to use only part of its installed stock of capital $q_t^p \leq k_t^p$ to produce the intermediary good. We say that the economy has stranded assets if $q_t^p < k_t^p$.

$$
\begin{aligned}
V(k_t^p) = \max_{q_t^p, k_{t+1}^p} \left\{ d_t^p + \frac{V(k_{t+1}^p)}{1 + r_{t+1}^p} \right\} \quad \text{s.t.} \quad & x_t^p = z^p q_t^p \\
& d_t^p = p_t^p x_t^p - k_{t+1}^p + (1-\delta) k_t^p \\
& k_{t+1}^p \geq (1-\delta) k_t^p \\
& k_t^p \geq q_t^p
\end{aligned}
$$

The corresponding Lagrangian is

$$
L = d_t^p + \frac{V(k_{t+1}^p)}{1 + r_{t+1}^p} + \psi_t (k_{t+1}^p - (1-\delta) k_t^p) + \nu_t (k_t^p - q_t^p).
$$

This yields the following first-order conditions

$$
\begin{aligned}
1 - \psi_t &= \frac{V'(k_{t+1}^p)}{1 + r_{t+1}^p}, \\
p_t^p z^p &= \nu_t. \qquad (3.2)
\end{aligned}
$$

Along with the associated Karush-Kuhn-Tucker conditions

$$
\nu_t (q_t^p - k_t^p) = 0, \quad \nu_t \geq 0, \qquad (3.3)
$$

$$
\psi_t (k_{t+1}^p - (1-\delta) k_t^p) = 0, \quad \psi_t \geq 0. \qquad (3.4)
$$

The associated envelope condition is

$$
V'(k_t^p) = -\psi_t (1-\delta) + \nu_t,
$$

so that the investment decision of the polluting firm is determined by the following equation

$$
(1 - \psi_t)(1 + r_{t+1}^p) = p_{t+1}^p z^p + (1 - \psi_{t+1})(1-\delta). \qquad (3.5)
$$

Proposition 3.1. *In the laissez-faire equilibrium, assets are never stranded.*

Proof. Since the aggregate production function respects the Inada conditions, the marginal productivity of capital goes to infinity as x_t^p goes to 0 and thus, p_t^p will always be strictly positive. Equation 3.2 thus implies that the multiplier on the capacity constraint ν_t will be strictly positive. Equation 3.3 then implies that $q_t^p = k_t^p$, and the economy will not display stranded assets. $\square$

The intuition behind this result is straightforward: there is no cost associated with using polluting capital, so it is always efficient to use all of the installed capacity. The investment decision is only based on the tradeoff between consuming today and consuming tomorrow, without taking into account emissions or the social cost of carbon.

Households

The economy is composed of a representative household that maximizes its expected discounted sum of utilities over an infinite horizon

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t u(c_t).$$

The household owns shares in the clean firm s_t^c, whose price is v_t^c, and the polluting firm s_t^p, with price v_t^p. The budget constraint is thus

$$c_t + v_t^c s_{t+1}^c + v_t^p s_{t+1}^p = s_t^c(v_t^c + d_t^c) + s_t^p(v_t^p + d_t^p).$$

The instantaneous utility function is a CRRA function of the form

$$u(c_t) = \frac{c_t^{\chi-1}}{\chi - 1}.$$

The following two Euler equations characterize the optimal consumption-saving decision of the household

$$v_t^c c_t^{-\chi} = \beta c_{t+1}^{-\chi}(d_{t+1}^c + v_{t+1}^c) \tag{3.6}$$
$$v_t^p c_t^{-\chi} = \beta c_{t+1}^{-\chi}(d_{t+1}^p + v_{t+1}^p) \tag{3.7}$$

Proposition 3.2. *In the laissez-faire equilibrium, assuming the absence of irreversibility costs, the marginal productivity of installed polluting capital is equal to the marginal productivity of clean capital.*

Proof. Let us first define the (stochastic) discount factor of the households as

$$1 + r_{t+1}^c = \frac{d_{t+1}^c + v_{t+1}^c}{v_t^c}, \quad 1 + r_{t+1}^p = \frac{d_{t+1}^p + v_{t+1}^p}{v_t^p}.$$

Equation 3.6 and 3.7 imply that

$$r_{t+1}^c = r_{t+1}^p.$$

If we substitute Equations 3.1 and 3.5 and assume that $\psi_{t+1} = \psi_t = 0$, we obtain

$$p_t^c z^c = p_t^p z^p.$$

$\square$

The main conclusion of the laissez-faire equilibrium is that, in the absence of a carbon tax on the use of polluting capital, there are never stranded assets and the marginal productivity of polluting and clean capital will be equal. Assuming a higher marginal productivity of using fossil fuel, we will thus have a higher share of polluting capital in this economy.

2.2 Central planner's solution under a climate constraint

We now focus on the social planner's problem, taking into account the carbon constraint.

The climate constraint is represented by a carbon budget $m_t \leq \bar{m}$ where $\bar{m}$ represents the maximum level of cumulative emissions to limit global warming to 2°C. This is coherent with the literature on climate change that has shown that global warming is closely related to cumulative past emissions (Allen et al. 2009; Matthews 2016).

This allows us to model the complex carbon cycle through a simple law of motion of cumulative CO_2 emissions, represented by $m_{t+1} = e_t + (1-\varepsilon)m_t$ with e_t being the emissions of CO_2 at each period and ε a coefficient measuring the dissipation rate of CO_2. In practice, ε is so small compared to the depreciation of capital δ that it is negligible in the short and medium term, but we take it into account to simplify some calculations. Finally, the use of q_t^p causes emissions at a rate G, which represents the carbon-intensity of polluting capital, so that $e_t = q_t^p G$.

The social planner maximizes the representative household's utility subject to the resource constraint of the economy, the law of motion of carbon emissions and of clean and polluting capital, the physical constraint on the use of polluting capital, the irreversibility constraint, and the carbon budget constraint. The problem of the social planner is thus

$$\max_{c_t; i_{t,p}, i_{t,c}} \sum_{t=0}^{\infty} \beta^t u(c_t) \quad \text{s.t.} \quad \begin{aligned}[t] & c_t + k_{t+1}^c + k_{t+1}^p = y_t + (1-\delta)(k_t^c + k_t^p) \\ & y_t = \left(\left((x_t^c)^{\frac{\varepsilon-1}{\varepsilon}} + (x_t^p)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}} \right)^{\alpha} \\ & x_t^c = z^c k_t^c, \quad x_t^p = z_p q_t^p \\ & m_{t+1} = q_t^p G + (1-\varepsilon) m_t \\ & k_t^p \geq q_t^p \\ & k_{t+1}^p \geq (1-\delta) k_t^p \\ & \bar{m} \geq m_t \end{aligned}$$

The associated Bellman equation of the problem is

$$
\begin{aligned}
V_t(k_t^c, k_t^p, m_t) = \max_{k_{t+1}^c, k_{t+1}^p, q_t^p} & \left\{ u(c_t) + \beta V_{t+1}(k_{t+1}^c, k_{t+1}^p, m_{t+1}) \right\} \\
& + \psi_t(k_{t+1}^p - (1-\delta)k_t^p) \\
& + \nu_t(k_t^p - q_t^p) \\
& + \mu_t(m_{t+1} - G q_t^p - (1-\varepsilon)m_t) \\
& + \phi_t(\bar{m} - m_t)
\end{aligned}
$$

The first-order conditions are

$$
\begin{aligned}
u'(c_t) &= \beta \frac{\partial V_{t+1}(k_t^c, k_t^p)}{\partial k_{t+1}^c} \\
u'(c_t) &= \beta \frac{\partial V_{t+1}(k_t^c, k_t^p)}{\partial k_{t+1}^p} + \psi_t \\
\nu_t &= u'(c_t) \frac{\partial y(k_t^c, q_t^p)}{\partial q_t^p} - G\mu_t && (3.8) \\
-\mu_t &= \beta \frac{\partial V_{t+1}(k_t^c, k_t^p)}{\partial m_{t+1}}. && (3.9)
\end{aligned}
$$

and the Karush-Kuhn-Tucker conditions are

$$
\begin{aligned}
&\psi_t(k_{t+1}^p - (1-\delta)k_t^p) &&= 0, \quad \psi_t \geq 0 \\
&\nu_t(k_t^p - q_t^p) &&= 0, \quad \nu_t \geq 0 \\
&\phi_t(\bar{m} - m_t) &&= 0, \quad \phi_t \geq 0
\end{aligned}
$$

The envelope conditions are

$$
\begin{aligned}
\frac{\partial V_t(k_t^c, k_t^p, m_t)}{\partial k_t^c} &= u'(c_t) \left(\frac{\partial y(k_t^c, q_t^p)}{\partial k_t^c} + 1 - \delta \right) \\
\frac{\partial V_t(k_t^c, k_t^p, m_t)}{\partial k_t^p} &= u'(c_t)(1-\delta) - (1-\delta)\psi_t + \nu_t \\
\frac{\partial V_t(k_t^c, k_t^p, m_t)}{\partial m_t} &= -(1-\varepsilon)\mu_t - \phi_t
\end{aligned}
$$

Substituting the envelope conditions inside the first-order conditions, we find

$$
\begin{aligned}
u'(c_t) &= \beta u'(c_{t+1}) \left(\frac{\partial y(k_{t+1}^c, q_{t+1}^p)}{\partial k_{t+1}^c} + 1 - \delta \right) && (3.10) \\
u'(c_t) &= \beta u'(c_{t+1}) \left(\frac{\partial y(k_{t+1}^c, q_{t+1}^p)}{\partial q_{t+1}^p} + 1 - \delta - G \frac{\mu_{t+1}}{u'(c_{t+1})} - \ell_{t+1} \right) && (3.11) \\
\mu_{t+1} &= \frac{1}{1-\varepsilon} \left(\frac{\mu_t}{\beta} - \phi_{t+1} \right) && (3.12)
\end{aligned}
$$

with $\ell_{t+1} = \frac{\beta(1-\delta)\psi_{t+1}-\psi_t}{\beta u'(c_{t+1})}$ being the legacy costs associated with the excess of polluting capital that cannot be disinvested.

Proposition 3.3. *The economy features stranded assets if*

$$\frac{\partial y(k_t^c, k_t^p)}{\partial q_t^p} < G\mu_t.$$

Proof. The optimal choice of q_t^p is determined by Equation 3.8. Let us assume that $q_t^p = k_t^p$. If the marginal productivity of polluting capital when using all of the installed capital $\frac{\partial y(k_t^c, k_t^p)}{\partial q_t^p}$ is below the marginal value of an extra unit of CO_2 $G\mu_t$. Then since $\nu_t \geq 0$ by construction, $q_t^p < k_t^p$ for equation 3.8 to hold. □

Equations 3.10 and 3.11 also state no-arbitrage conditions between the clean and polluting capital, but taking into account the social cost of carbon. The planner will thus invest in types of both capitals until their discounted marginal value is equal to the marginal value of consuming today. If the level of polluting capital is too high, the planner cannot adjust it instantaneously, and it will bear the cost ψ_t.

Proposition 3.4. *The social cost of carbon μ_t will increase at the rate $1/(\beta(1-\varepsilon))$ as long as $m_t < \bar{m}$.*

Proof. The first-order condition, jointly with the envelope condition, imply that $\mu_{t+1} = \frac{1}{1-\varepsilon}\left(\frac{\mu_t}{\beta} - \phi_{t+1}\right)$, and the Karush-Kuhn-Tucker condition implies that $\phi_t = 0$ when $m_t < \bar{m}$. □

This result comes from the fact that, in this model, carbon emissions do not provoke any direct damage but can be considered as an almost finite resource. Thus, we can interpret this result as a modified Hotelling rule, which states that the scarcity rent of a non-renewable resource will grow at the rate of the discount rate. Here, carbon emissions are a (almost non) renewable resource, and this rate is modified to take into account the dispersion rate ε. Note that when we have $\varepsilon = 0$, we get the usual Hotelling rule in discrete time.

Proposition 3.5. *When the economy features stranded assets at t, the irreversibility constraint was binding at $t-1$, and there was no investment in polluting capital.*

Proof. From Proposition 3, we know that if the economy features stranded assets, we have

$$\frac{\partial y(k_{t+1}^c, q_{t+1}^p)}{\partial q_{t+1}^p} = G\frac{\mu_{t+1}}{u'(c_{t+1})}.$$

Thus, the relative level of used polluting capital and clean capital is

$$\begin{aligned}\frac{\partial y(k_{t+1}^c, q_t^p)}{\partial k_{t+1}^p} &= \frac{\partial y(k_{t+1}^c, q_t^p)}{\partial q_{t+1}^p} - G\frac{\mu_{t+1}}{u'(c_{t+1})} - \ell_{t+1}\\ &= -\ell_{t+1}\end{aligned}$$

Because of the Inada conditions, we know that $\frac{\partial y(k^c_{t+1}, q^p_t)}{\partial k^p_{t+1}} > 0$ when the level of capital is finite. Thus, we have $\psi_t - \beta(1-\delta)\psi_{t+1} > 0 \rightarrow \psi_t > 0$ which implies that $i_{t,p} = 0$ by the Karush-Kuhn-Tucker conditions. □

The intuition behind this result is straightforward: if the planner uses an amount of polluting capital inferior to the installed capacity $q^p_{t+1} < k^p_{t+1}$, it means that there is too much polluting and the planner was constrained when it made the investment decision.

Proposition 3.6. *The steady-state equilibrium of the constrained economy is defined as*

$$\begin{aligned}
m_{ss} &= \bar{m} \\
q_{ss,p} &= k_{ss,p} = \frac{\bar{m}\varepsilon}{G} \\
i_{ss,c} &= \delta k_{ss,c} \\
i_{ss,p} &= \delta k_{ss,p} > 0 \\
\psi_{ss} &= 0 \\
\frac{\partial y(k^c_{t+1}, q^p_{t+1})}{\partial k^c_{t+1}} &= \frac{\partial y(k^c_{t+1}, q^p_{t+1})}{\partial k^p_{t+1}} - G\frac{\mu_{t+1}}{u'(c_{t+1})}
\end{aligned}$$

Proof. See appendix. □

Note that, in practice, ε is very small, and the amount of polluting capital will be close to zero. This steady state is thus equivalent to a fully decarbonized economy.

To sum up what we have learned so far, the main result from this section is an insight already shown by Rozenberg, Vogt-Schilb, and Hallegatte (2018): in the presence of an excessive amount of polluting capital and irreversible investment, it can be the most efficient solution to have stranded assets. This result comes from the fact that, contrary to the investment decision which is by essence intertemporal, the level of polluting capital used is an intra-temporal decision. Using the entire stock of installed polluting capital would be falling prey to a sunk-cost fallacy: the central planner might wish it had invested less in polluting capital in the past, but it is optimal, today, to "strand" some of those assets. However, this decision is costly from the point of view of production: lowering q^p_t reduces production and, hence, consumption in the short run. Moreover, when the economy transitions from the laissez-faire equilibrium to the constrained equilibrium, if the level of polluting capital is too high, it will feature a phase with stranded assets and zero investment in polluting capital.

3 Three types of decentralized equilibriums

In this section, we compare three ways to meet the climate constraint in a decentralized equilibrium. We focus on an optimal carbon tax, a subsidy on clean capital, and an optimal carbon tax with compensation for owners of stranded assets.

3.1 Decentralized equilibrium with a tax

We now show that we can decentralize the previous allocation through a carbon tax τ_t. The problems of the household, the final representative firm, and the clean intermediary firm remain similar as in the 'laissez-faire' equilibrium. The dividends of the polluting firm, however, become

$$d_t^p = p_t^p z^p q_t^p - k_{t+1}^p + (1-\delta)k_t^p - q_t^p G\tau_t$$

where τ_t is the carbon tax per ton of CO_2. We assume that the proceeds from the tax are redistributed through a lump-sum transfer to the households. The problem of the polluting firm is now

$$\begin{aligned} V(k_t^p) = \max_{q_t^p, k_{t+1}^p} \left\{ d_t^p + \frac{V(k_{t+1}^p)}{1+r_{t+1}^p} \right\} \quad \text{s.t.} \quad & x_t^p = z^p q_t^p \\ & d_t^p = p_t^p x_t^p - k_{t+1}^p + (1-\delta)k_t^p - q_t^p \tau_t \\ & k_{t+1}^p \geq (1-\delta)k_t^p \\ & k_t^p \geq q_t^p \end{aligned}$$

which yields the following first-order conditions

$$\begin{aligned} 1 - \psi_t &= \frac{V'(k_{t+1}^p)}{1+r_{t+1}^p}, \\ p_t^p z^p - G\tau_t &= \nu_t. \end{aligned} \tag{3.13}$$

The envelope condition is

$$V'(k_t^p) = \nu_t - (1-\delta)(1-\psi_t).$$

Substituting, we get

$$(1+r_{t+1}^p)(1-\psi_t) = p_t^p z^p - G\tau_t - (1-\psi_{t+1})(1-\delta)$$

Proposition 3.7. *The decentralized equilibrium with a carbon tax is equivalent to the social planner's allocation if $\tau_t = \frac{\mu_t}{u'(c_t)}$ until $m_t = \bar{m}$.*

Proof. Note that $p_t^p z^p = \frac{\partial y(k_t^p, q_t^p)}{\partial q_t^p}$. When $\tau_t = \frac{\mu_t}{u'(c_t)}$, we thus have

$$p_t^p z^p - G\tau_t = \frac{\partial y(k_t^p, q_t^p)}{\partial q_t^p} - G\frac{\mu_t}{u'(c_t)} = \nu_t$$

which is the same condition as 3.11. $\square$

Thus, just as in the central planner problem, we will have stranded assets when

$$\frac{\partial y(k_t^p, k_t^p)}{\partial q_t^p} < G\tau_t.$$

3.2 Decentralized equilibrium with a subsidy on clean capital

We now show that we can obtain the same relative allocation of clean and polluting capital using a subsidy σ_t^c on clean capital.

The problem of the clean firm now becomes

$$V(k_t^c) = \max_{k_{t+1}^c} \left\{ d_t^c + \frac{V(k_{t+1}^c)}{1+r_{t+1}^c} \right\} \quad \text{s.t.} \quad x_t^c = z^c k_t^c$$
$$d_t^c = p_t^c x_t^c - k_{t+1}^c + (1-\delta)k_t^c + \sigma_t^c k_t^c.$$

The first-order condition of the clean firm now becomes

$$1 + r_{t+1}^c = p_{t+1}^c z^c + \sigma_{t+1}^c + 1 - \delta.$$

Using the Euler equations from the household, we thus have

$$\frac{\partial y(k_{t+1}^c, q_{t+1,p})}{\partial y_{t+1}^c} + \sigma_{t+1}^c = \frac{\partial f(k_{t+1}^c, q_{t+1,p})}{\partial q_{t+1,p}} - \ell_{t+1}$$

which is the same relative allocation of clean and polluting capital if the clean capital subsidy is set to the level of the social cost of carbon adjusted for the carbon intensity of the polluting capital $\sigma_{t+1} = \frac{\mu_{t+1} G}{u'(c_t)}$.

However, the main difference between the decentralized economy with a subsidy and the decentralized economy with a carbon tax is that, in the first case, there can be no stranded assets as the government has no 'punitive' tool to limit the use of polluting capital in the short run. The economy will thus use all of the installed capacity at each period. This, in turn, implies that this allocation is feasible only if the level of installed capital is small enough so that the total level of emissions when using the whole capital stock until its total depreciation will be inferior to the remaining carbon budget.

This result is important because, according to recent studies on committed emissions, the level of polluting capital today already exceeds the remaining carbon budget (Pfeiffer, Millar, et al. 2016; Pfeiffer, Hepburn, et al. 2018). A carbon tax will thus be necessary to limit global warming to 2°C or less.

We summarize and prove those facts in the two following propositions.

Proposition 3.8. *In the decentralized equilibrium with a clean capital subsidy, the economy will never feature stranded assets.*

Proposition 3.9. *The climate constraint can be met with a subsidy on clean capital only if*

$$\bar{m} \geq \frac{k_0 G}{\delta} + m_0.$$

Proof. See appendix. □

3.3 Constrained equilibrium with compensation

We now want to account for the main controversial point behind stranded assets: the compensation of owners of polluting capital. Thus, we assume that the government implements an optimal carbon tax τ_t similar to the first decentralized economy, but also want to compensate owners of polluting capital for their losses through a subsidy σ_t^p.

The problem of the polluting firm now becomes

$$V(k_t^p) = \max_{q_t^p, k_{t+1}^p} \left\{ d_t^p + \frac{V(k_{t+1}^p)}{1 + r_{t+1}^p} \right\} \quad \text{s.t.} \quad \begin{aligned} x_t^p &= z^p q_t^p \\ d_t^p &= p_t^p x_t^p - k_{t+1}^p + (1-\delta) k_t^p - q_t^p \tau_t + \sigma_t^p k_t^p \\ k_{t+1}^p &\geq (1-\delta) k_t^p \\ k_t^p &\geq q_t^p \end{aligned}$$

It is important to note that the firm pays a tax on the amount of polluting capital that it uses but gets a subsidy on the level of capital that it owns. This setup corresponds to the incentive structure set up by the German government regarding its lignite coal industry and described by Sen and von Schickfus (2019). The German government planned to pay the lignite industry to keep some power plants off the electricity grid while implementing a higher carbon tax on electricity producers.

The first-order conditions are

$$p_t^c z_p - \tau_t = \nu_t,$$
$$(1 + r_{t+1}^p)(1 - \psi_t) = \nu_{t+1} + \sigma_{t+1}^p + (1 - \psi_{t+1})(1 - \delta).$$

Proposition 3.10. *The emission path in the constrained equilibrium with compensation will follow the same path as in the benchmark case if* $\tau_t = \frac{\mu_t}{u'(c_t)}$.

Proposition 3.11. *In the constrained equilibrium with compensation, the optimal level of polluting capital* k_t^p *can be above the actual use level of polluting capital* q_t^p.

Proof. Assume we have stranded assets so that $\nu_t = 0$. We can rewrite the Euler equation of the polluting firm as

$$\frac{\partial f(k_t^c, q_t^p)}{\partial q_t^p} = \sigma_t - \ell_t > 0$$

using equation 3.3. We see that if $\sigma_t > 0$, then ℓ_t can take any value such that $\ell_t < \sigma_t$, including $\ell_t = 0$, and the Inada conditions will still be met. Thus, this economy can feature stranded assets while the irreversibility condition is not binding if σ_t is large enough. $\square$

In this economy, we can thus have no legacy costs $\ell_{t+1} = 0$ and still stranded assets, which means that the existence of stranded assets doesn't necessarily imply that the stock of polluting capital will decrease and converge to $q_t^p = k_t^p$. The government can thus adjust σ_t so that the irreversibility constraint is never binding and that the representative entrepreneur will never have to bear the legacy cost due to its excessive investment in polluting capital.

4 Stochastic transition with tax and compensation

We now introduce uncertainty in the model. We assume the economy is in the laissez-faire equilibrium without tax or subsidy. At each period, there is a probability ρ to transit to a new state, called 2, where the government imposes an optimal carbon tax τ that might create stranded assets, as in the benchmark case. With probability η, the economy moves to another state, called 3, where the government imposes a carbon tax but compensates the owner of polluting capital at a rate σ. With probability $1 - \rho - \eta$, the economy remains in the stochastic state in state 1. We assume the government is credible because there is no probability of moving to another state once a policy is imposed. We can summarize the probability space as such

State	1	2	3
1	$1 - \rho - \eta$	ρ	η
2	0	1	0
3	0	0	1

Table 3.1: State-dependent probabilities

This model thus features two kinds of uncertainty: one related to the timing of the policy (i.e. when the uncertainty will be resolved), and one related to the political preferences of the government regarding the potential bailout of owners of polluting capital (i.e. whether the economy transit to state 2 or state 3. The variable o denote the policy state of the world.

Households

The problem of the households now write

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \mathbb{E}_o[u(c_t)]$$

subject to

$$c_t + v_t^c s_{t+1}^c + v_t^p s_{t+1}^p = s_t^c(v_t^c + d_t^c) + s_t^p(v_t^p + d_t^p).$$

The associated Euler equations are

$$v_t^c c_t^{-\chi} = \beta \mathbb{E}_o[c_{t+1}^{-\chi}(d_{t+1}^c + v_{t+1}^c)], \tag{3.14}$$

$$v_t^p c_t^{-\chi} = \beta \mathbb{E}_o[c_{t+1}^{-\chi}(d_{t+1}^p + v_{t+1}^p)]. \tag{3.15}$$

Firms

The problem of the firms now takes into account the policy uncertainty. For simplicity, we mention only the first-order conditions of the optimal decisions of the polluting firm

$$(1-\psi_t)(1+r_{t+1}^p) = \mathbb{E}\left[\frac{\partial V(k_{t+1}^p|o)}{\partial k_{t+1}}\right].$$

where we have

$$\begin{aligned}
\frac{\partial V(k_{t+1}^p|o=1)}{\partial k_{t+1}} &= p_{t+1}^p z^p + (1-\delta)(1-\psi_t), \\
\frac{\partial V(k_{t+1}^p|o=2)}{\partial k_{t+1}} &= p_{t+1}^p z^p + (1-\delta)(1-\psi_t) - G\tau_{t+1}, \\
\frac{\partial V(k_{t+1}^p|o=3)}{\partial k_{t+1}} &= p_{t+1}^p z^p + (1-\delta)(1-\psi_t) - G\tau_{t+1} + \sigma_{t+1}^p.
\end{aligned}$$

Proposition 3.12. *During the transition period, the economy never features stranded assets.*

Proof. Same as the proof for the laissez-faire equilibrium, using derivative of the value function of the polluting firm when $o = 1$. □

In this stochastic equilibrium, the level of polluting capital and of CO_2 emissions will thus depend on the relative size of τ_t, σ_t, η and ρ. If investors expect a large bailout in the future, emissions can increase compared to the laissez-faire equilibrium and the discovery of the climate constraint can thus be coherent with a temporary increase in emissions. We further discuss the implications of this model in the next part.

4.1 Computational algorithm

Although our model is stylized, it's important to note that it is still challenging to solve. It is a highly non-linear two-asset model with four state variables (polluting and clean capital, carbon stock in the atmosphere, and the policy state), three occasionally binding constraints, and permanent shocks. We first simplify the model by assuming that taxes and subsidies are constant, and not implied by an optimal policy function derived from the carbon budget. This strong assumption allows us to get rid of a state variable and might be relaxed in further work.

We then use a modified version of Rendahl (2015) time iteration algorithm with an occasionally binding constraint. This global approximation method allows us to take into account all the non-linearities of the model and the risk implied by the policy shocks. We then compute policy announcements as MIT shocks on the probabilities to go to different climate policies. This means that households are rational with respect to a future climate policy, but they are unaware that the *probabilities themselves* of going to a different policy state might change over time.

4.2 Calibration

Our calibration follows the work of Fried, Novan, and Peterman (2019) on US data.

To determine the share of clean and polluting capital z^p and z^c, we follow the computations of Fried, Novan, and Peterman (2019) and set $z^p = 3$ and $z^c = 1$. This calibration reflects two main factors: it follows the capital share of the oil and coal sector in the US, to which we add the more carbon-intensive capital from other less polluting sectors, such as cars, heating systems, etc. However, it should be noted that this distinction between clean and polluting capital is mostly theoretical as, in practice, no infrastructure exists without associated carbon emissions in a life-cycle analysis.

ρ is set to 0.15 as in Fried, Novan, and Peterman (2019), who estimate this parameter using data from internal carbon prices in large US firms. Due to a lack of data about investors' expectations of a global bailout, η is set to 0.05.

4.3 Simulations

In this section, we study how the economy reacts to (1.) a climate policy shock, depending on the prior expectations of households and firms, and (2.) a shock on the expectations of households and firms regarding the future climate policy.

Climate policy shocks

Figures 3.3 and 3.5 show the impact of imposing a carbon tax, without a bailout, when coming from a state where investors expected only a carbon tax (Figure 3.3), or also a bailout (Figure 3.5). Formally, we compute a transition from a shochastic steady state, before the policy uncertainty is resolved, to a steady state where the policy is $o = 1$. We do so in two cases: in a stochastic steady state where investors only expected a carbon tax

Parameters	Calibration
Household	
Discount rate: β	0.95
CRRA coefficient: χ	2
Production function	
Capital share: α	1/3
Polluting capital efficiency: z^p	3
Polluting capital share: z^c	1
Depreciation rate: δ	0.05
Policy	
Probability of carbon tax: ρ	0.10
Probability of compensation: η	0.05
Size of carbon tax: τ	0.2
Size of compensation: σ_0	0.1

Table 3.2: Calibration of the parameters of the model

($\rho > 0, \eta = 0$) and in a world where investors expected only a carbon tax with a bailout ($\rho = 0, \eta > 0$). In the second case, the transition towards a carbon tax only world is an event with probability 0 from the point of views of investors. This transition thus reflects the impact of a mistake in policy expectations from the point of view of investors in polluting capital.

Given our calibration, we see that if investors expect a carbon tax in the future, the transition can avoid stranded assets and the irreversibility of capital is binding for only a few periods, and the output cost is 18%. If investors expected instead a bailout of stranded assets, the stock of polluting capital needs to adjust by 80%, and output diminishes by 20% compared to the initial steady state. Expectations about the type of future climate policy can thus have a large impact on the cost of implementing a carbon tax.

The transition in a world where firms expected a bailout of polluting capital also features stranded assets and a longer investment period in which the irreversibility constraint on polluting capital is binding. Expectations of a bailout thus make not only the transition costlier but also longer to achieve. This, in turn, has a large impact on the financial valuations of firms. The dashed-line line Figure 3.4 display the % change in the average Tobin's Q of the polluting firm in the transition, after a carbon tax is imposed, when firms expected a bailout. The model predicts that the valuations of polluting firms will overreact to the implementation of the carbon tax, with the average Tobin's Q collapsing by almost 80%. This is due to the fact that, for the first initial periods of the transition where assets are stranded, a large part of the stock of physical capital is useless, decreasing the profitability and hence the valuation of the firm. This over-reaction of the price of firms is corrected

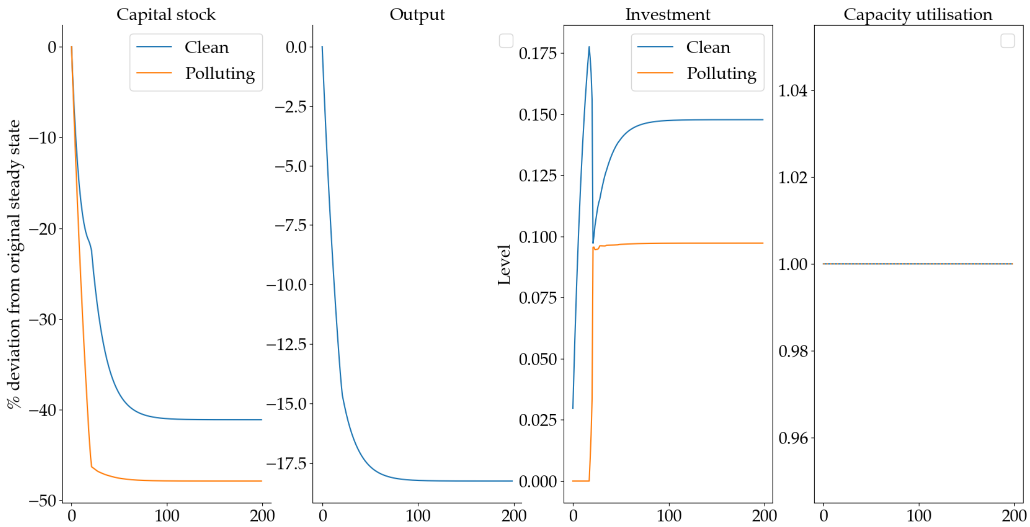

Figure 3.3: Impact of imposing a carbon tax without subsidy when investors expect only a carbon tax

over the long term, as the stock of physical capital adjusts and the capacity utilization rate increases again.

In our model, this over-reaction of the valuations of firms does not have a feedback effect on output, investment, or consumption, since there is no financial friction that could connect the financial sphere to the real sphere. However, we can conjecture that, in a model with a financial accelerator à la Bernanke, Gertler, and Gilchrist (1996), this would trigger a large decrease in loans, decreasing aggregate demand, and hence output.

Shocks to the expectations about future climate policy

We now turn to the impact of a government committing to a future climate policy. Figures 3.6 and 3.7 show the impact of a government committing to a carbon tax in the future (Figure 3.6) or a bailout (Figure 3.7), without actually implementing it. Numerically, this implies computing a MIT shock where the economy moves from a state where there is a positive probability of a future bailout ($\rho > 0$ and $\eta = 0$) to one where there is no probability of a future bailout ($\rho = 0$ and $\eta > 0$).

We see that committing to a carbon tax (i.e., excluding a bailout) increases the stock of clean capital and decreases the stock of polluting capital. Output is reduced by 17%, but assets are never stranded, which is coherent with our previous propositions. Thus, some of the cost of transitioning to a clean economy is paid today, but the cost of a transition will be lower in the future, as shown by the previous figures.

At the opposite, committing to a bailout of polluting capital creates an investment boom

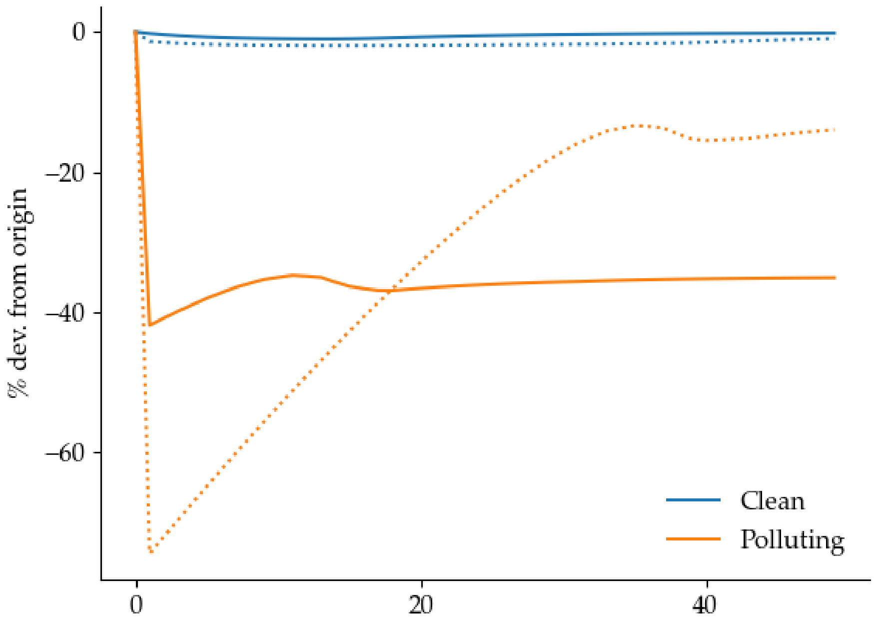

Figure 3.4: Tobin's Q following a carbon tax without a bailout

Note: The thick lines show the average Tobin's Q, measured as the price of the firm divided by its quantity of physical capital, after a carbon tax is imposed by the government, when investors expected only a carbon tax. The dashed-line shows the evolution of the average Tobin's Q if investors expected a bailout instead.

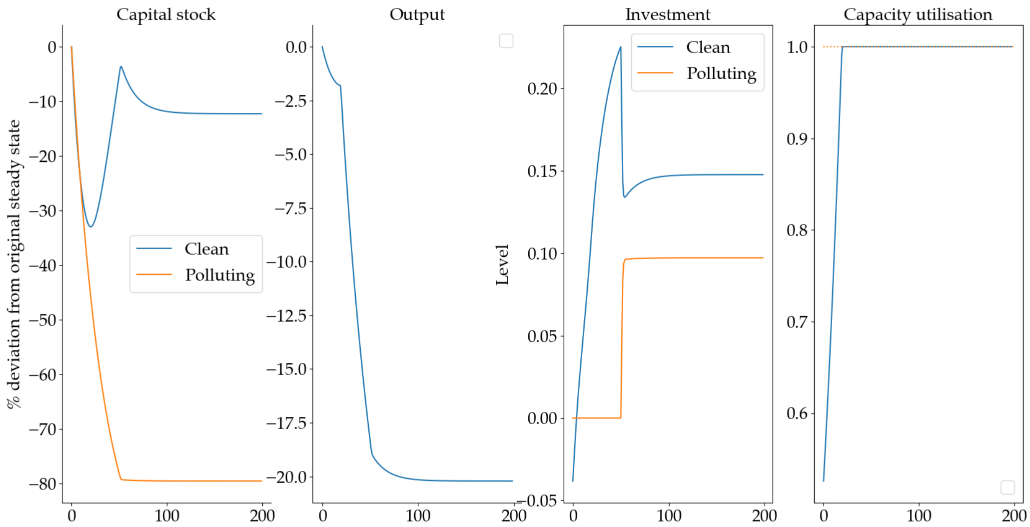

Figure 3.5: Impact of imposing a carbon tax without subsidy when investors expect a bailout of polluting capital

in polluting capital that increases output by almost 20% compared to a state where firms expected no bailout, at the cost of a longer transition once a carbon tax is imposed (Figure 3.7).

Those policy commitments are enough to create large changes in the valuations of both the clean and the polluting firms, as shown in Figure 3.8. This is coherent with the empirical findings from Sen and von Schickfus (2019), which we mentioned earlier, that the price of polluting firms might react a lot to changes in expected climate policies, such as committing to never bailing them out.

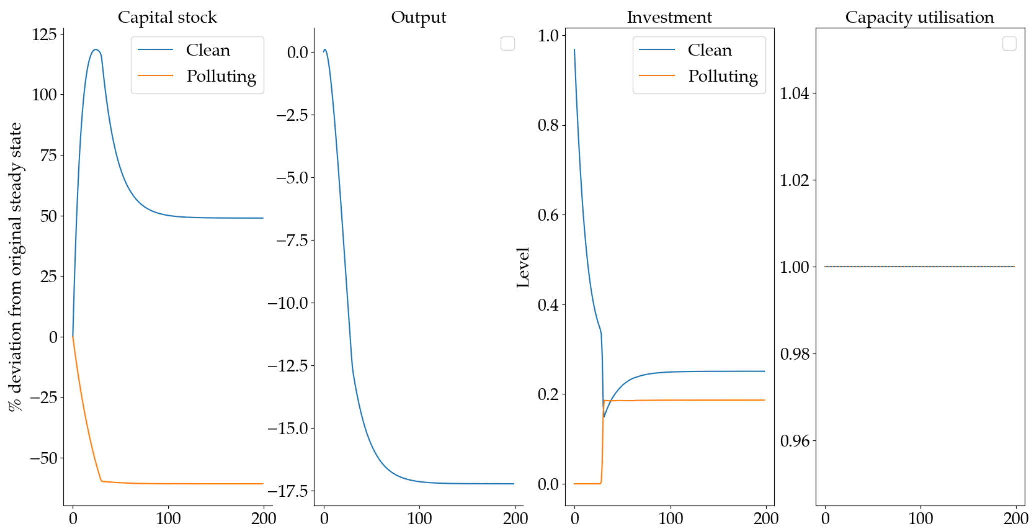

Figure 3.6: Impact of a government committing to a carbon tax in the future

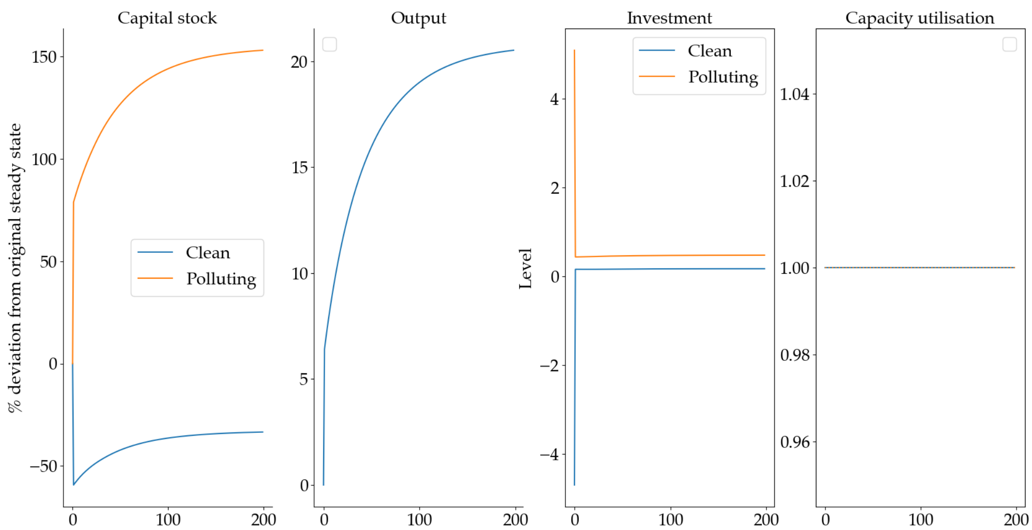

Figure 3.7: Impact of a government committing to a bailout in the future

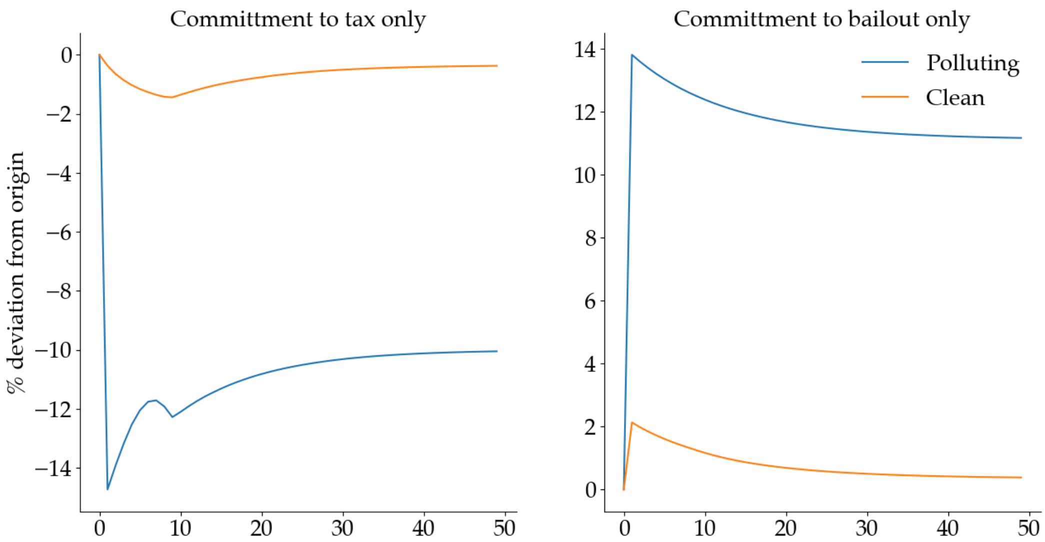

Figure 3.8: Average Tobin's Q of the clean and polluting firms after committing to a carbon tax or a bailout

5 Conclusion

Our model shows that investment in polluting capital and CO_2 emissions can increase even after the climate constraint has been discovered, if investors expect that a carbon tax will be accompanied by a bailout. This behavior can have an important impact on the cost of implementing a carbon tax or the length of the energetic transition. This reveals the essential role of announcing a credible climate policy for the government: committing not to bail out future stranded assets will reduce the current level of polluting capital and make the transition toward a green economy less painful. However, there is also an incentive for a shortsighted government to increase current production and consumption by announcing a future bailout of stranded assets, which would significantly increase the cost of the transition and decrease the remaining carbon budget. This difficult choice of committing to a "hard" transition is necessary: another conclusion of our model is that it is too late for a strictly "non-punitive" climate policy. Given that the committed emissions implied by the current size of polluting capital already exceeds the remaining carbon budget, a subsidy on clean capital will not be enough to meet a 2°C global warming target.

Our analysis could be further developed in several ways. First, the transition between the stochastic state and the state with a carbon tax could be analyzed further, showing how wrong expectations by investors could increase the level of stranded assets in the future period. Secondly, we could include the financial aspect of stranded assets and some game-theoretical components. In our model, there is no benefit for society of a bailout. In practice, bailing out polluting capital could be a way to limit the financial risks associated with a stringent climate policy. There could thus be a space for strategic interactions between the government and "too-big-to-fail" owners of polluting capital, that could force a bailout by continuing to invest in polluting capital and putting their solvency at risk in case of a high carbon tax. Finally, our model could be enriched by including uncertainty about the future productivity of clean capital and some “learning by doing” effects.

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A Proof of the feasibility constraint for the subsidy on clean capital

Take $\varepsilon \to 0$, we get

$$m_{t+1} = k_0(1-\delta)^t + m_t$$

The solution to this difference equation is

$$m_t = \sum_{t=1}^{t}(1-\delta)^{t-1}k_0 G + m_0$$

This sequence will converge to

$$\lim_{t\to\infty} m_t = \frac{k_0 G}{\delta} + m_0$$

The condition for the equilibrium with a subsidy on clean capital to be feasible is thus that $\bar{m} \geq \frac{k_0 G}{\delta} + m_0$

B Computation of the steady state

B.1 For the Laissez faire

For the clean capital

We have

$$\alpha A k_{t,c}^{\alpha-1}(k_t^p)^{\gamma} = \frac{1}{\beta} + \delta - 1 \to k_{t,c} = \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}(k_t^p)^{-\gamma}\right)^{\frac{1}{\alpha-1}} = \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}(k_t^p)^{\frac{-\gamma}{\alpha-1}}$$

$$\gamma A k_{t,c}^{\alpha}(k_t^p)^{\gamma-1} = \frac{1}{\beta} + \delta - 1 \to k_t^p = \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\gamma A}k_{t,c}^{-\alpha}\right)^{\frac{1}{\gamma-1}} = \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\gamma A}\right)^{\frac{1}{\gamma-1}} k_{t,c}^{\frac{-\alpha}{\gamma-1}}$$

Substituting the first equation in the second, we get

$$
\begin{aligned}
k_{t,c} &= \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}\left(\left(\left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\gamma A}\right)^{\frac{1}{\gamma-1}} k_{t,c}^{\frac{-\alpha}{\gamma-1}}\right)\right)^{\frac{-\gamma}{\alpha-1}} \\
&= \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}\left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\gamma A}\right)^{\frac{-\gamma}{\gamma\alpha-\gamma-\alpha+1}} k_{t,c}^{\frac{\gamma\alpha}{\gamma\alpha-\gamma-\alpha+1}} \\
k_{t,c}^{\frac{1-\alpha-\gamma}{\gamma\alpha-\gamma-\alpha+1}} &= \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}\left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\gamma A}\right)^{\frac{-\gamma}{\gamma\alpha-\gamma-\alpha+1}} \\
k_{t,c} &= \left(\left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}\left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\gamma A}\right)^{\frac{-\gamma}{\gamma\alpha-\gamma-\alpha+1}}\right)^{\frac{\gamma\alpha-\gamma-\alpha+1}{1-\alpha-\gamma}} \\
&= \left(\left(\frac{1}{\beta}+\delta-1\right)^{\frac{-1}{\gamma\alpha-\gamma-\alpha+1}}\frac{1}{\alpha A}^{\frac{1}{\alpha-1}}\frac{1}{\gamma A}^{\frac{-\gamma}{\gamma\alpha-\gamma-\alpha+1}}\right)^{\frac{\gamma\alpha-\gamma-\alpha+1}{1-\alpha-\gamma}} \\
&= \left(\frac{1}{\beta}+\delta-1\right)^{\frac{-1}{1-\alpha-\gamma}}\frac{1}{\alpha A}^{\frac{1}{\alpha-1}\frac{\gamma\alpha-\gamma-\alpha+1}{1-\alpha-\gamma}}\frac{1}{\gamma A}^{\frac{-\gamma}{1-\alpha-\gamma}}
\end{aligned}
$$

For the polluting capital

Substituting the second equation in the first, we get

$$
\begin{aligned}
k_t^p &= \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\gamma A}\right)^{\frac{1}{\gamma-1}}\left(\left(\left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}(k_t^p)^{\frac{-\gamma}{\alpha-1}}\right)\right)^{\frac{-\alpha}{\gamma-1}} \\
&= \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\gamma A}\right)^{\frac{1}{\gamma-1}}\left(\frac{1}{\beta}+\delta-1\right)^{\frac{-\alpha}{\gamma\alpha-\gamma-\alpha+1}}\frac{1}{\alpha A}^{\frac{-\alpha}{\gamma\alpha-\gamma-\alpha+1}}(k_t^p)^{\frac{\alpha\gamma}{\gamma\alpha-\gamma-\alpha+1}} \\
(k_t^p)^{\frac{1-\gamma-\alpha}{\gamma\alpha-\gamma-\alpha+1}} &= \left(\frac{1}{\beta}+\delta-1\right)^{\frac{-1}{\gamma\alpha-\gamma-\alpha+1}}\frac{1}{\gamma A}^{\frac{1}{\gamma-1}}\frac{1}{\alpha A}^{\frac{-\alpha}{\gamma\alpha-\gamma-\alpha+1}} \\
k_t^p &= \left(\left(\frac{1}{\beta}+\delta-1\right)^{\frac{-1}{\gamma\alpha-\gamma-\alpha+1}}\frac{1}{\gamma A}^{\frac{1}{\gamma-1}}\frac{1}{\alpha A}^{\frac{-\alpha}{\gamma\alpha-\gamma-\alpha+1}}\right)^{\frac{\gamma\alpha-\gamma-\alpha+1}{1-\gamma-\alpha}} \\
&= \left(\frac{1}{\beta}+\delta-1\right)^{\frac{-1}{1-\gamma-\alpha}}\frac{1}{\gamma A}^{\frac{1}{\gamma-1}\frac{\gamma\alpha-\gamma-\alpha+1}{1-\gamma-\alpha}}\frac{1}{\alpha A}^{\frac{-\alpha}{1-\gamma-\alpha}}
\end{aligned}
$$

B.2 For the benchmark case

For the polluting capital

At the steady state, we have $m_t = \bar{m}$ and $m_{t+1} = m_t$ so that

$$\begin{aligned} \bar{m} &= Gq_{t,p} + (1-\varepsilon)\bar{m} \\ q_{t,p} &= \frac{\varepsilon \bar{m}}{G} \end{aligned}$$

Because $i_{t,p} = \delta k_t^p$, we have that $\psi_t = 0$ so that the marginal value of polluting and clean capital is equal, which implies that $q_{t,p} = k_t^p$. Thus, we have

$$k_t^p = \frac{\varepsilon \bar{m}}{G}$$

For the clean capital

We now have

$$\begin{aligned} k_{t,c} &= \left(\left(\frac{1}{\beta} + \delta - 1\right)\frac{1}{\alpha A}(k_t^p)^{-\gamma}\right)^{\frac{1}{\alpha-1}} = \left(\left(\frac{1}{\beta} + \delta - 1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}(k_t^p)^{\frac{-\gamma}{\alpha-1}} \\ k_t^p &= \frac{\varepsilon \bar{m}}{G} \end{aligned}$$

Substituting the second equation into the first, we get

$$k_{t,c} = \left(\left(\frac{1}{\beta} + \delta - 1\right)\frac{1}{\alpha A}(k_t^p)^{-\gamma}\right)^{\frac{1}{\alpha-1}} = \left(\left(\frac{1}{\beta} + \delta - 1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}\left(\frac{\varepsilon \bar{m}}{G}\right)^{\frac{-\gamma}{\alpha-1}}$$

B.3 For the decentralized equilibrium

For the clean capital

We now have

$$\begin{aligned} k_{t,c} &= \left(\left(\frac{1}{\beta} + \delta - 1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}(k_t^p)^{\frac{-\gamma}{\alpha-1}} \\ k_t^p &= \left(\left(\frac{1}{\beta} + \delta - 1 + \tau\right)\frac{1}{\gamma A}\right)^{\frac{1}{\gamma-1}} k_{t,c}^{\frac{-\alpha}{\gamma-1}} \end{aligned}$$

Plugging the second equation into the first, we get

$$\begin{aligned}
k_{t,c} &= \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}\left(\left(\left(\frac{1}{\beta}+\delta-1+\tau\right)\frac{1}{\gamma A}\right)^{\frac{1}{\gamma-1}} k_{t,c}^{\frac{-\alpha}{\gamma-1}}\right)^{\frac{-\gamma}{\alpha-1}} \\
&= \left(\left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}\left(\left(\left(\frac{1}{\beta}+\delta-1+\tau\right)\frac{1}{\gamma A}\right)^{\frac{1}{\gamma-1}}\right)^{\frac{-\gamma}{\alpha-1}}\right)^{\frac{\gamma\alpha-\alpha-\gamma+1}{1-\alpha-\gamma}} \\
&= \left(\left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}\left(\left(\frac{1}{\beta}+\delta-1+\tau\right)\frac{1}{\gamma A}\right)^{\frac{-\gamma}{\gamma\alpha-\gamma-\alpha+1}}\right)^{\frac{\gamma\alpha-\alpha-\gamma+1}{1-\alpha-\gamma}} \\
&= \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}\frac{\gamma\alpha-\gamma-\alpha+1}{1-\alpha-\gamma}}\left(\left(\frac{1}{\beta}+\delta-1+\tau\right)\frac{1}{\gamma A}\right)^{\frac{-\gamma}{1-\alpha-\gamma}}
\end{aligned}$$

For the polluting capital

We now have

$$\begin{aligned}
k_t^p &= \left(\left(\frac{1}{\beta}+\delta-1+\tau\right)\frac{1}{\gamma A}\right)^{\frac{1}{\gamma-1}} k_{t,c}^{\frac{-\alpha}{\gamma-1}} \\
&= \left(\left(\frac{1}{\beta}+\delta-1+\tau\right)\frac{1}{\gamma A}\right)^{\frac{1}{\gamma-1}}\left(\left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}\frac{\gamma\alpha-\gamma-\alpha+1}{1-\alpha-\gamma}}\left(\left(\frac{1}{\beta}+\delta-1+\tau\right)\frac{1}{\gamma A}\right)^{\frac{-\gamma}{1-\alpha-\gamma}}\right)^{\frac{-\alpha}{\gamma-1}} \\
&= \left(\left(\frac{1}{\beta}+\delta-1+\tau\right)\frac{1}{\gamma A}\right)^{\frac{\gamma\alpha-\gamma-\alpha+1}{1-\alpha-\gamma}\frac{1}{\gamma-1}}\left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{-\alpha}{1-\alpha-\gamma}}
\end{aligned}$$

B.4 For the stochastic transition period

We now have

$$\begin{aligned}
k_{t,c} &= \left(\left(\frac{1}{\beta}+\delta-1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}}(k_t^p)^{\frac{-\gamma}{\alpha-1}} \\
k_t^p &= \left(\left(\frac{1}{\beta}+\delta-1+(\eta+\rho)\tau-\eta\sigma\right)\frac{1}{\gamma A}\right)^{\frac{1}{\gamma-1}} k_{t,c}^{\frac{-\alpha}{\gamma-1}}
\end{aligned}$$

For the clean capital

Substituting the second equation into the first, we get

$$k_{t,c} = \left(\left(\frac{1}{\beta} + \delta - 1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}} \left(\left(\left(\left(\frac{1}{\beta} + \delta - 1 + (\eta+\rho)\tau - \eta\sigma\right)\frac{1}{\gamma A}\right)^{\frac{1}{\gamma-1}} k_{t,c}^{\frac{-\alpha}{\gamma-1}}\right)\right)^{\frac{-\gamma}{\alpha-1}}$$

$$= \left(\left(\frac{1}{\beta} + \delta - 1\right)\frac{1}{\alpha A}\right)^{\frac{1}{\alpha-1}\frac{\gamma\alpha-\gamma-\alpha+1}{1-\alpha-\gamma}} \left(\left(\frac{1}{\beta} + \delta - 1 + (\eta+\rho)\tau - \eta\sigma\right)\frac{1}{\gamma A}\right)^{\frac{-\gamma}{1-\alpha-\gamma}}$$

For the polluting capital

Substituting the first equation into the second, we get

$$k_t^p = \left(\left(\frac{1}{\beta} + \delta - 1 + (\eta+\rho)\tau - \eta\sigma\right)\frac{1}{\gamma A}\right)^{\frac{\gamma\alpha-\gamma-\alpha+1}{1-\alpha-\gamma}\frac{1}{\gamma-1}} \left(\left(\frac{1}{\beta} + \delta - 1\right)\frac{1}{\alpha A}\right)^{\frac{-\alpha}{1-\alpha-\gamma}}$$

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