Weather Shocks and the Optimal Policy Mix in a Climate-Vulnerable Economy

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Abstract

Using data from a selection of Latin American countries affected by El Niño-Southern Oscillation climate phenomena, we observe that extreme weather events can be highly disruptive for an economy, particularly in the agricultural sector, while also giving rise to inflationary pressures. Motivated by these findings, this paper examines the optimal stabilization policies for a climate-vulnerable economy with two segmented sectors: agriculture and manufacturing. In response to climate disasters affecting agriculture, it is found to be optimal to increase fiscal transfers to farmers while maintaining core inflation at its target level. Deviating from the optimal policy mix results in smaller welfare losses as long as core inflation remains stabilized.

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1 Introduction

How should a benevolent government conduct stabilization policy in reaction to weather shocks? What is the optimal policy response to the increased severity of extreme weather events, such as prolonged heat waves, hurricanes, or floods? The answer to these questions is not obvious, as there are several factors to consider. One is that adverse weather events can be particularly disruptive for agriculture (IPCC, 2023), leading to a reduction of production in this sector, and asymmetric inflationary pressures. Moreover, if the structure of the economy is highly segmented, such that labor is sector-specific and some individuals have no access to financial markets, some redistributive policies are necessary to alleviate the adverse effects, hurting the most vulnerable individuals, while the scope of monetary policy can become narrow. For instance, after an adverse weather shock, the fraction of the population that is more vulnerable may not fully benefit from an accommodative monetary policy that tries to revive the economy. As a result, the monetary policy strategy of leaning against the wind and maintaining price stability might not necessarily be optimal for all sectors (one size does not fit all!), while balanced-budget redistributive fiscal policy alone might not be sufficient to stabilize the economy. Therefore, in such circumstances, the design of the optimal policy mix in the face of weather shocks is particularly challenging and requires careful consideration of the economic structure, the severity of weather events, and the potential reallocation effects across sectors.

In this paper, we tackle these climate-related challenges with a focus on emerging economies, where the size of the agriculture sector is relatively large. To motivate our analysis, we start by showing some empirical evidence on the effects of adverse weather events on agriculture, GDP, and prices for a selection of Latin American countries. We then build a theoretical model able to fairly reproduce the dynamics observed in the data and use it to study the optimal fiscal and monetary policy mix in response to weather shocks.

In the last decade, with rising awareness of climate change issues, the economic literature has devoted increasing consideration to the so-called 'physical risk' for the economy. Notably, physical risks refer to the potential for direct or indirect harm to the population, physical assets, infrastructure, and ecosystems caused by climate-related events. In this respect, an important distinction should be made between chronic risks, which are associated with longer-term shifts in climate patterns (e.g., sea level rise and ocean acidification), and acute risks, which are associated with extreme events (e.g., hurricanes, prolonged heatwaves, and droughts).[1]

In this strand of literature on physical risk, particular attention has been devoted to the response of agricultural production to weather fluctuations and climate change. Indeed, due to its direct exposure to weather conditions, agricultural yields are highly sensitive to fluctuations in temperatures and precipitation. The literature documents significant negative impacts of climate change on agricultural production, with negative spillovers to the rest of the economy. The negative effects are found to be stronger for temperate and tropical regions, and for low-income countries. See Schlenker et al. (2007), Challinor et al. (2014), Acevedo et al. (2020) and Gallic and Vermandel (2020). One further complicating factor for the analysis of the economic impact of climate change on agriculture is the non-linearity of the effects. Indeed, while a moderate increase in temperatures may be somewhat beneficial for crop production, extreme temperatures and precipitations may be seriously detrimental to crop yields, as shown by Schlenker and Roberts (2009).

Recently, the literature has also focused on price dynamics, particularly on the response of

[1] On 'physical risk', see, e.g., NFGS (2023b). On the detrimental effect of warmer temperatures on economic activity, see, e.g., Dell et al. (2012), Dell et al. (2014), and Deryugina and Hsiang (2014). For a quantification of the impact of extreme weather conditions and natural disasters, see Yang (2008) and Hsiang (2010), among others.

crop prices to extreme weather events, and on the implications for food prices and inflation dynamics in general. Several studies find strong evidence of significant crop price increases as a result of weather shocks, especially for cultures dedicated to local markets. See, e.g., Fox et al. (2011), Mirzabaev and Tsegai (2012), Brown and Kshirsagar (2015) and Baffes et al. (2019). Looking at a more aggregate level, other papers have found a negative effect of weather variation on consumer price stability. Heinen et al. (2019) investigate the effect of extreme weather shocks on prices and find that rare hurricane and flood events in the Caribbeans induce significant welfare losses due to price increases. Using sub-categories of consumer price indices, Gautier et al. (2023) find that headline inflation is driven by a surge in food prices, while prices in other sectors (e.g., manufacturing sectors) might decline. In the same vein, Parker (2018) finds that natural disasters, such as storms, generate food price inflation in the short run. The paper also finds heterogeneous effects of natural disasters on inflation dynamics depending on the level of development, with stronger responses for developing countries. In their analysis for the euro area countries, Ciccarelli et al. (2024) find that increases in monthly mean temperatures, via their impact on food, energy, and services prices, have inflationary effects in summer and fall, especially in warmer countries. Focusing on emerging and advanced countries, Faccia et al. (2021) confirm that hot summer temperatures increase food prices, especially in emerging market economies. More broadly, Cashin et al. (2017) investigate the role of the El Niño-Southern Oscillation (ENSO), a periodic climatic phenomenon that has worldwide atmospheric implications.[2] The paper identifies short-run inflationary pressures after an ENSO event in many countries, while the impact on economic activity is more heterogeneous.

Given the well-documented evidence of the potential threat that climate change and weather shocks pose to price stability, it is not surprising that climate change considerations are becoming increasingly important also for central banks in the conduct of monetary policy (e.g., Carney 2015, Rudebusch et al. 2019, Lagarde 2021, Hansen 2022, and NFGS 2023a). With the impacts of climate change increasingly materializing around the world, it is crucial to understand the effects of weather shocks on output and inflation, as well as the role that monetary policy can play in response to these events. In this regard, a growing body of economic literature has been focusing on the role of monetary policy in addressing climate-related risks. Most of these studies explore the impact of transition risks on price and/or financial stability and identify potential room for stabilization policies for central banks, while others explore the potential role of conventional or unconventional monetary policies in greening the economy (e.g., Diluiso et al. 2021, Ferrari and Nispi Landi 2023, Giovanardi et al. 2023 and Annicchiarico et al. 2024) or the optimal monetary policy in response to climate policy shocks (e.g., Carli et al. 2025 or to other shocks in the presence of a negative environmental externality (e.g., Annicchiarico and Di Dio 2017 and Giovanardi and Kaldorf 2025).

Less is known, however, about the optimal response of central banks to mitigate weather shocks and physical risks more broadly and about the implications of the asymmetric effects of these shocks on the economy. While several papers highlight the importance of physical risks for price and financial stability (e.g., Batten et al. 2016 and Sanchez 2022), few explicitly address the implementation of monetary policy responses. A recent contribution in this direction is given in Economides and Xepapadeas (2024), who model weather shocks as negative productivity shocks to examine whether monetary policy should account for the adverse impact of climate change on economic productivity when designing policies to stabilize the economy over the business cycle. Another recent contribution to this question is provided by Cantelmo et al. (2024), who compare the performance of various monetary policy rules in disaster-prone countries. They find that focusing on price stability through an inflation-targeting policy appears to be optimal

[2] For an overview of the essential features of the ENSO, see Neelin (2010).

for central banks.[3] On the other hand, the fiscal responses induced by natural disasters have been more extensively studied by the economic literature, mainly for investigating government spending or public deficit implications (see, for example, Noy and Nualsri 2011, Melecky and Raddatz 2011 and Bayar and Yarbrough 2024 or Deryugina 2022 for a comprehensive review).

However, as noted, the asymmetry of climate-related shocks between sectors poses additional challenges to policymakers in the design optimal stabilization policies. Moreover, the segmentation of sectors introduces further complexity that has yet to be explored. To the best of our knowledge, these challenges have not yet been addressed in the literature exploring the effects of climate-related shocks, leaving policymakers without clear policy recommendations. Furthermore, since coordinated actions between different policy areas can better address adverse weather events and ensure more effective stabilization, we argue that it is crucial to study optimal policy responses that consider both fiscal and monetary policies simultaneously.

This paper seeks to fill this gap in the literature by focusing on low-income and emerging countries, where the impact of weather shocks on the agricultural sector is expected to be more severe than in high-income countries, and where a larger proportion of the population is directly exposed to these effects. In particular, this paper investigates the optimal stabilization policies that fiscal and monetary authorities can adopt to mitigate the negative impact of adverse weather shocks that may hit the economic sectors asymmetrically.[4] We focus on policymakers' immediate response to natural disasters, and assess how monetary and fiscal policies can be set optimally to mitigate the short-term impacts of weather shocks, without considering longer-term adaptation measures.

In the first part of the paper, using data on five Latin American economies, Bolivia, Chile, Colombia, Ecuador, and Peru, we show how adverse weather events, particularly under the influence of ENSO phenomena, can be disruptive, giving rise to a sharp contraction in agriculture and asymmetric inflationary pressures. We then rationalize these empirical findings through the lenses of a calibrated model we use as a laboratory for our normative analysis. In particular, we present a variant of the standard New Keynesian sticky-price model, from which we make several departures. First, the economy consists of two sectors with heterogeneity in price stickiness: a conventional manufacturing sector and a rural agricultural sector, where agents have no access to financial markets. Second, production inputs, including labor, are sector-specific. In this respect, the economy presents a certain degree of "dualism". Third, we introduce weather shocks assuming that adverse weather shocks can damage farmland, which can be repaired only by sustaining extra costs in production goods (fertilizers, pesticides, chemicals, seeds, etc.) purchased from the manufacturing sector.

The public sector is represented by a Ramsey planner that controls the short-term nominal interest rate and can levy a lump-sum income tax on households in the modern sector to finance fiscal transfers in favor of households in the rural sector. Via the monetary instrument, the public sector exerts its influence primarily on the manufacturing sector and only to a limited extent on the agriculture sector. Via a tax-transfer scheme, the public sector can affect both sectors, although its ability to stabilize the economy in response to adverse weather shocks is limited by the existence of budgetary constraints.

With this tool in hand, we explore several policy combinations. First, we consider a Ramsey planner jointly selecting monetary and fiscal policies. Second, we analyze the scenario where

[3] Another related paper is that of Levine and Pontines (2024) who, in an environmental New Keynesian model, show that a temporary adverse weather event on the natural interest rate tends to reduce the natural interest rate, so narrowing the space of monetary policy ease.

[4] From this perspective, our paper is also related to the literature that looks at the implications of heterogeneous (and segmented) sectors for the transmission of shocks (see, e.g., Bouakez et al. 2014 and Carvalho et al. 2021) and the conduct of monetary policy (e.g., Aoki 2001, Woodford 2003 and La'O and Tahbaz-Salehi 2022).

a Ramsey planner controls monetary policy under a predetermined fiscal policy. Finally, we investigate a Ramsey planner controlling fiscal policy, assuming monetary policy is governed by an interest-rate rule. These scenarios are motivated by the varying institutional settings where monetary and fiscal authorities may differ in their levels of commitment.

The results of our normative analysis suggest that for a benevolent government, the optimal response to weather shocks is to increase transfers to farmers so as to sustain them in their recovery. This policy should be accompanied by the stabilization of core inflation while allowing headline inflation — driven by rising food prices — to increase freely. In doing so, the monetary policy indirectly favors the recovery of farmers from the shock by improving their terms of trade.

When the policymaker has access only to monetary policy, the optimal policy results in a dynamic response of the economy that qualitatively mimics that observed under full policy optimization, but with a sharper fall in farmers' consumption due to the absence of access to the fiscal instrument. Conversely, when optimal fiscal policy is conducted in isolation, the optimal strategy requires initially reducing the tax burden on households in the manufacturing sector to support production, which is necessary for the recovery of agriculture. The welfare analysis indicates that deviating from this optimal policy mix results in smaller welfare losses as long as core inflation remains stabilized. However, if the shock hits symmetrically both sectors of the economy, then the optimal policy prescribes targeting headline inflation.

Finally, in reaction to increased volatility in weather shocks affecting the agriculture sector, the optimal stabilization policy requires further increases in transfers in favor of farmers to induce investments in adaptive measures that enhance agricultural resilience. Also, in this context, price stability is found to be an optimal policy strategy.

The remainder of the paper is organized as follows. Section 2 presents evidence of the impact of adverse weather events in a selection of Latin American countries. Section 3 introduces the two-sector New Keynesian model we use as a laboratory for our normative analysis. Section 4 describes the calibration and examines the response of the economy to an adverse weather shock affecting agriculture in the absence of optimal policy. Section 5 explores the optimal fiscal and monetary policy mix in response to weather shocks, while Section 6 presents some concluding remarks.

2 Weather Shocks in Emerging Economies

This paper is motivated by the need to study the challenges faced by policymakers in emerging and developing economies, where a sizable share of the gross domestic product is represented by agriculture, a characteristic that heightens their vulnerability to natural disasters driven by climate change. Although many countries face similar climate-related risks, our analysis focuses on five Latin American countries: Bolivia, Chile, Colombia, Ecuador, and Peru. Two features make these countries particularly relevant to our study.

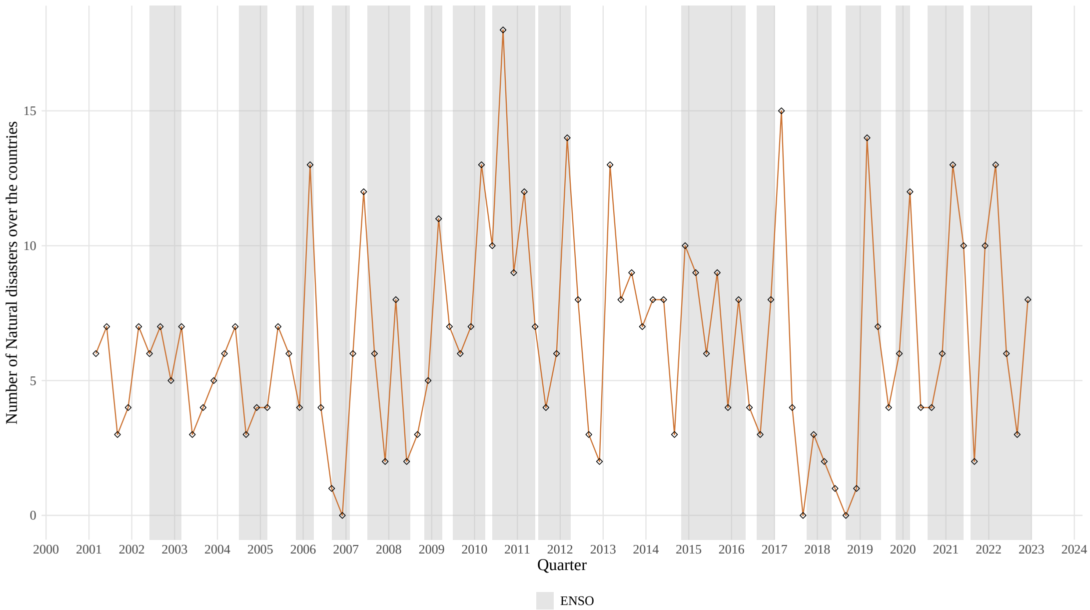
First, the countries listed above follow the Andes Mountain range in South America and have direct access to the Pacific coast (except for Bolivia, a land-locked country). While they cover a large surface (more than 4,500 km^2), are very heterogeneous in terms of climate, and exhibit significant internal climate diversity, they all are exposed to the El Niño-Southern Oscillation (ENSO) phenomenon (see Lin and Qian 2019), which influences the countries' temperatures and intensity of their precipitations, and increases the probability of the occurrence of natural disasters.[5] For illustrative purposes, Figure 1 presents the total number of natural disasters – including floods, droughts, storms, extreme temperatures, wildfires, and wet mass movements – for our five countries of interest from 2001 to 2022, obtained from the Emergency Events

[5]See Cai et al. (2020) for a comprehensive review of the effects of ENSO events on Latin American countries.

Database (EM-DAT) developed by the Centre for Research on the Epidemiology of Disasters. We observe that natural disasters tend to occur with a higher probability during or right after an ENSO event. Figure A-1 in Appendix A decomposes this analysis by country, revealing that no particular country drives this feature. The IPCC has documented the growing vulnerability of these countries to climate change, particularly due to the increasing frequency and intensity of extreme events. In particular, Chapter 12 of the IPCC Assessment Report 6 (Working group 2, see Castellanos et al. 2022) points out the increase in rainfall variability during ENSO events, with more severe heatwaves for some regions (in Chile or Colombia, for example), while in others, more heavy rains and floods are expected.

Additionally, the data indicate that ENSO events tend to amplify the variability in natural disaster occurrences. Table A-2 compares the standard deviations of the occurrence of these shocks during or immediately after an ENSO event. We find that standard deviations increase for most of the countries, a pattern that holds even when the data are pooled for a combined analysis.

Figure 1: Number of Natural Disasters Occurring in a Selection of Latin American Countries



Notes: The points correspond to the quarterly total number of natural disasters (including floods, droughts, storms, extreme temperatures, wildfires, and wet mass movements) of the five countries of the sample (Bolivia, Chile, Colombia, Ecuador, and Peru). The grey areas correspond to ENSO phases (both warm and cold phases).
Source: EM-DAT and NOAA. Authors' computation.

Another reason pushing us to select these countries is due to the non-negligible role the agricultural sector plays in their economies. Although the contribution of this sector to the GDP has decreased over time, becoming less significant as a country's income rises, agriculture still employs an important share of the population. The share of employment in the agricultural sector over total employment varies from 10.42% in Chile to 32% in Bolivia, on average, from 2001 to 2022.[6] Interestingly, the decrease in employment appears to be stable over time and not necessarily correlated to ENSO events, as shown in Figure A-2. As a result, a significant portion of the population is directly affected by a weather shock, leading to an immediate contraction

[6]By way of comparison, agriculture accounted for 1.73% of total employment in the United States and 5.72% in the European Union over the same period.

in their income. This sector is also characterized by low use of financial tools, due to limited access to credit, particularly for smallholder farmers. As a result, most of the literature has found, following a weather shock, a sharp decrease in agricultural production and productivity (Dell et al. 2012, Schlenker and Roberts 2009) and in farmers' incomes (Deryugina and Hsiang 2014, Aragón et al. 2021) and, an increase in households' vulnerability and income inequalities (Sietz et al. 2012, Aggarwal 2021, Cappelli et al. 2021, Zapata 2023).

Table A-1 in Appendix A summarizes the different sources of data we use for the empirical analysis we perform in the next section. In addition, Table A-3 presents some descriptive statistics of a selection of macroeconomic variables for the five countries in our sample.

2.1 Empirical Analysis

In this subsection, we carry out an empirical analysis using local projections *à la* Jordà (2005) to understand how key macroeconomic variables react to natural disasters. A similar exercise has been carried out in Parker (2018), over a large set of countries to examine the price response to extreme weather shocks. We differ from that work in the sense that we investigate the effect of the occurrence of a natural disaster rather than the intensity, over a smaller set of countries but for multiple key economic variables used in our model: the growth rate of the agricultural sector value added, the growth rate of the GDP, the relative price of agricultural goods compared to the general price level and the consumer price index inflation.

Thus, for each of the aforementioned variables, we project the evolution of their growth rate relying on the model of local projections in a panel dimension such as Acevedo et al. (2020):

$$y_{c,t+h} = \alpha_{t\in q,h} + \alpha_{c,h} + \pi_h w_{c,t} + \psi_h(L)X_t + \epsilon^c_{c,t+h} \tag{1}$$

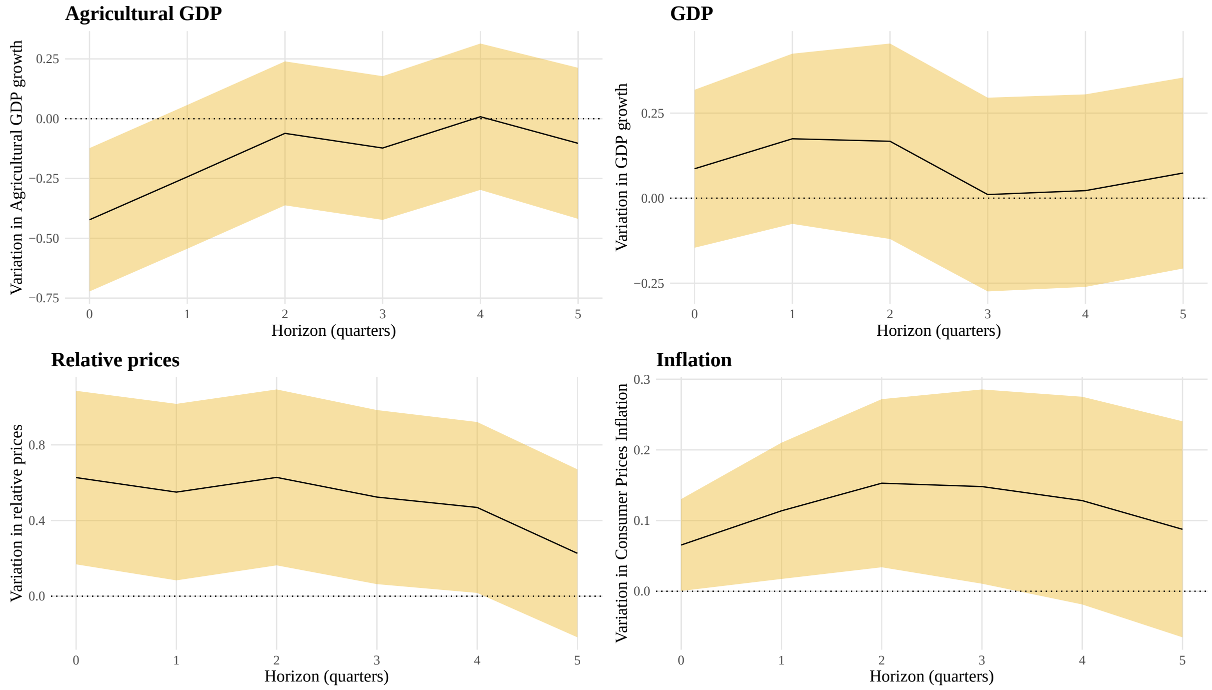
where $y_{c,t+h}$ is the variation in the variable of interest (alternatively, the growth rates of agricultural value added, of the GDP, the relative agricultural prices, and the CPI inflation) in the country c at predicted time $t+h$; $\alpha_{t\in q,h}$ and $\alpha_{c,h}$ are, respectively, quarter (q) and country fixed effects;[7] π_h is the vector of estimated parameter vectors assessing the effect of the natural disasters $w_{c,t}$, occurring at time t; X_t represents the set of the control variables we introduce in the model, here the country-specific CPI inflation, US inflation, and the oil inflation rates, all taken with a one-quarter lag; ψ_h is the vector of corresponding estimated parameters. Finally, $\epsilon_{c,t+h}$ is the error term for the estimation at the horizon h.

Figure 2 below presents the response for the four economic variables of interest after the occurrence of a natural disaster, using the coefficients obtained by estimating (1). We observe an overall detrimental effect of natural disasters on economic outcomes. The occurrence of an extreme weather shock leads to an immediate contraction in the agricultural sector's production by 0.5%. The GDP growth tends to increase, but the variation is not statistically significant. This result may be driven by the rise in the demand for material inputs employed for reconstruction and land restoration purposes.

Regarding prices, the agricultural price index rises more than the general price index. The relative price increases by 0.6 percent on impact and remains persistently higher for over four quarters. Additionally, the shock leads to inflationary pressures with a lagged effect, with inflation going up to 0.15 percentage points two quarters after the shock. These findings align with the estimates of Gallic and Vermandel (2020) for New Zealand, Crofils et al. (2025) for Peru, and Parker (2018) for headline inflation, both in terms of magnitude and direction.

[7] We also add two annual fixed effects for 2009 and 2020, controlling implicitly for the Global Financial Crisis and the Covid-19 crisis, respectively.

Figure 2: Response of Key Economic Variables to a Natural Disaster



Notes: The figure presents the impulse response function of the selected macroeconomic variables following the occurrence of a weather shock. The time horizon is in quarters, and the shadow areas represent the 90% confidence intervals.
Source: Authors' estimates.

In addition to these results, we want to see whether the responses may differ depending on the state of the ENSO phases. Given that the number and variability in natural disasters occurrence appears to increase in general with ENSO events (see Table A-2), we investigate here whether farmers may anticipate this increase in risk and if thus the effects are lower or higher than in our baseline estimation. We use the local projections as in our baseline but augmented with a state variable that allows for non-linear responses, as in Auerbach and Gorodnichenko (2012). Instead of using a smooth transition variable, we define the ENSO phases using a dummy variable I_{t-1} that takes value 1 if an ENSO event occurs (without distinguishing between El Niño and La Niña), and 0 otherwise.[8] Equation 2 below details the model:

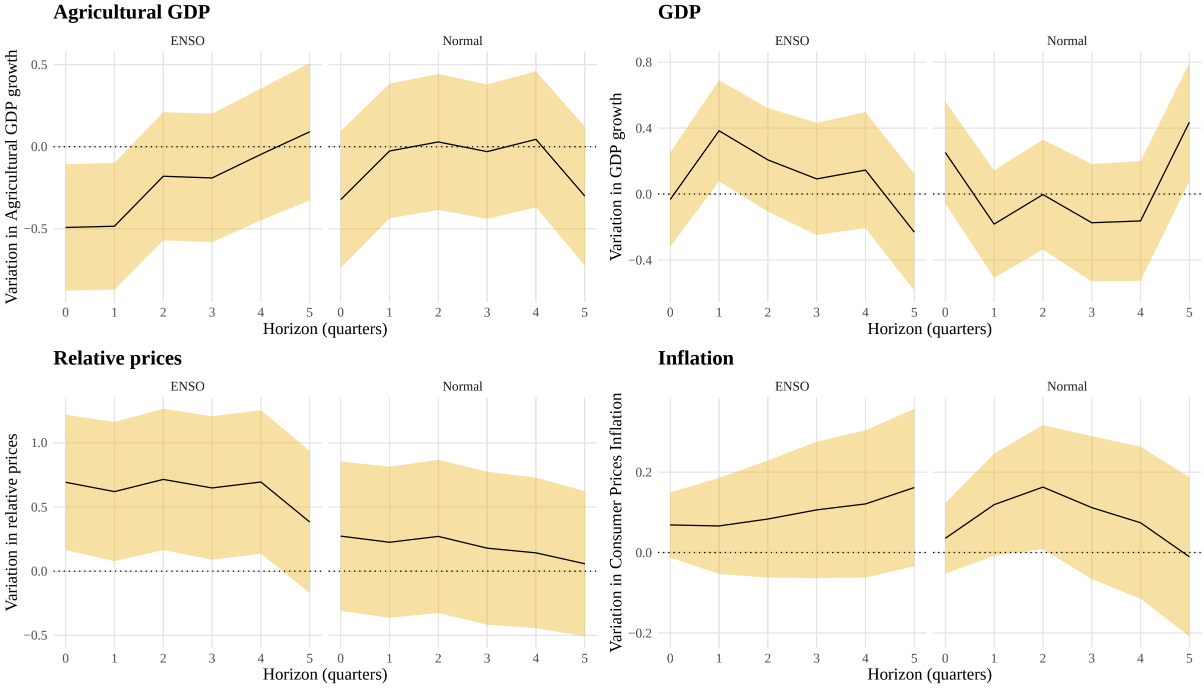
$$
\begin{aligned}
y_{c,t+h} = & I_{t-1}\Big(\alpha_{t\in q,h}^{\text{ENSO}} + \alpha_{c,h}^{\text{ENSO}} + \pi_h^{\text{ENSO}} w_{c,t} + \psi_h^{\text{ENSO}}(L)X_t\Big) + \\
& + (1 - I_{t-1})\Big(\alpha_{t\in q,h}^{\text{Normal}} + \alpha_{c,h}^{\text{Normal}} + \pi_h^{\text{Normal}} w_{c,t} + \psi_h^{\text{Normal}}(L)X_t\Big) + \\
& + \epsilon_{c,t+h},
\end{aligned} \tag{2}
$$

where the superscript $ENSO$ refers to the estimated parameters corresponding to an ENSO phase, while $Normal$ stands for parameters estimated for periods outside ENSO phases. The variables remain unchanged with respect to Equation 1.

This distinction in ENSO phases highlights the fact that a weather shock has a more detrimental effect when it happens during or right after an El Niño event. In such cases, agricultural

[8] An El Niño (or La Niña) event is defined by a five consecutive three-months periods with an Oceanic Niño Index (ONI) above 0.5 (or below -0.5 for a La Niña event).

Figure 3: Response of Key Economic Variables to a Natural Disaster
ENSO v. Normal Conditions



Notes: The figure presents the impulse response function of the selected macroeconomic variables following the occurrence of a weather shock. The time horizon is in quarters, and the yellow areas represent the 90% confidence intervals.
Source: Authors' estimates.

production tends to decline more sharply, while GDP growth increases for one quarter. More interestingly, agricultural prices appear to be significantly affected only during an ENSO phase, driving the results we obtained in the linear exercise above. On the contrary, inflationary effects on the CPI are significant only when the shock happens outside of an ENSO phase. This result suggests that unanticipated weather shocks happening outside ENSO phases may have more inflationary effects on CPI prices, while agricultural prices may not increase as much. This finding contrasts with Natoli (2023), who found that unexpected temperature shocks in the US tend to decrease inflationary pressures.

Given these results, a natural question arises: what is the optimal policy mix in response to weather shocks? To address this question, in the next section, we introduce a theoretical model designed to fairly reproduce the observed dynamics and the characteristics of the economies considered in this section, and explore the optimal monetary and fiscal policy mix that can effectively mitigate the adverse effects of weather shocks on the agricultural sector while ensuring macroeconomic stability under different weather conditions.

3 The Model Economy

The model economy consists of a variant of the New Keynesian model with two sectors: the agriculture and the non-agricultural sector. Each sector produces a specific good that is exchanged with the other. In the agricultural sector, consumers subsist by working as farmers and exchanging their produce for non-agricultural goods, which they use for consumption and to buy what is needed to improve land quality. In this sector, prices are flexible, and farmers are price takers. The non-agricultural sector consists of households that derive utility from consumption and leisure. On the production side of this sector, monopolistic competitive firms produce differentiated goods and face price adjustment costs *à la* Rotemberg (1983). On top of these producers, there are final-good producers who simply combine the differentiated goods into a bundle that is then sold in a perfectly competitive market. The total population is constant and normalized to one. Labor is sector-specific and, therefore, not mobile between sectors, implying that households remain in the same sector. In the spirit of Lewis (1954), the structure of the economy is then meant to capture a certain degree of dualism, where a traditional agricultural sector coexists with a modern non-agricultural sector, primarily identified with manufacturing.[9] The public sector that controls the short-term interest rate and the tax-transfer scheme is assumed to be benevolent in the Ramsey sense; that is, the public sector aims to achieve the decentralized equilibrium that maximizes social welfare and has the ability to commit to its promises, preventing it from reneging on its commitments. See, e.g., Schmitt-Grohé and Uribe (2004).

3.1 Agricultural Sector

The agricultural sector is populated by a mass $s_F \in (0,1)$ of identical households that derive their subsistence from the land they own and, in part, from fiscal transfers, consuming a portion of their production while selling the surplus to the rest of the households. The proceeds from selling excess produce are used to purchase material from the manufacturing sector and cover the land costs necessary to restore land and rebuild livestock. These agents do not have access to financial markets, and the only way they can smooth out consumption over time is through their spending on the quality of land.[10] We refer to these agents as farmers and use the superscript F to indicate the economic variables that refer to them.

Farmers earn their living from agricultural production according to the following Cobb-Douglas technology:

$$Y_t^A = B_A \left(\Omega(\varepsilon_t^w) L_{t-1}^F\right)^{\alpha_A} (H_t^F)^{1-\alpha_A}, \tag{3}$$

where Y_t^A is the quantity produced, $\alpha_A \in (0,1)$, $B_A > 0$ is a measure of the total factor productivity, L_{t-1}^F is the amount of land used by a farmer to produce and H_t^F denotes the time spent farming, while the term $\Omega(\varepsilon_t^w)$ is a function representing the fraction of land that can be lost following an adverse weather shock ε_t^w. As in Gallic and Vermandel (2017), it is assumed that the land evolves according to the following law of motion:

$$L_t^F = (1-\delta_L)\Omega(\varepsilon_t^w) L_{t-1}^F + V_t^F, \tag{4}$$

where $\delta_L \in (0,1)$ is the natural decay rate of land and V_t^F is a variable representing the quantity of non-agricultural goods needed to restore land and keep its level of productivity. In this sense, the stock variable land can be interpreted as a 'catch-all' production factor embodying all accumulable factors necessary for agricultural production, such as hectares of arable land and machinery, while V_t^F includes both investment goods and input materials such as pesticides, herbicides, fertilizers, etc. To capture the fact that agricultural production depends on weather conditions and account for the potential damage caused by weather shocks, following Gallic and Vermandel (2020) and in the spirit of the Integrated Assessment Models pioneered by Nordhaus

[9] The variant of the New Keynesian model we propose is similar to the two-sector model presented in Aoki (2001), which features both a flexible-price sector and a sticky-price sector. However, our model differs in that markets are incomplete, resulting in households from different sectors having distinct consumption paths and, therefore, in consumption misallocation. See Section 3.5. Additionally, in this model, the two sectors are interconnected, as restoring productive land requires materials produced in the manufacturing sector.

[10] This assumption will be removed in Appendix E.

(1991), we introduce the damage function that determines land productivity in the following way:

$$\Omega(\varepsilon_t^w) = (\varepsilon_t^W)^{-\theta_W}, \tag{5}$$

where $\theta_W > 0$ represents the elasticity of land productivity with respect to the weather shocks, ε_t^W, in turn evolving exogenously according to the process

$$\log \varepsilon_t^W = \rho_W \log \varepsilon_{t-1}^W + \eta_t^W, \tag{6}$$

where $\rho_W \in [0, 1)$ is the persistence of the weather shock, while η_t^W is assumed to be identically and independently distributed with mean zero and standard deviation equal σ_W. Depending on the size of the persistence, a positive realization of η_t^W can potentially give rise to a prolonged episode of extreme weather conditions that damage crops and livestock.

Each household derives utility from consumption and disutility from labor, so that the lifetime utility function is of the form

$$\mathcal{U}_0^F = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t^F) - \chi_H \frac{(H_t^F)^{1+\eta_H}}{1+\eta_H} \right), \tag{7}$$

where $\mathbb{E}_0$ denotes the rational expectation operator, $\beta \in (0, 1)$ is the subjective discount factor, C_t^F is a consumption basket composed by agricultural goods $C_{A,t}^F$, and manufacturing goods, $C_{M,t}^F$, while $\eta_H > 0$ is the inverse of the Frisch elasticity of labor supply, and χ_H is a scale parameter measuring the relative disutility of labor and pinning down the steady state of hours worked. We assume that the representative farmer allocates their consumption between the two goods according to a CES function:

$$C_t^F = \left[\varphi^{\frac{1}{\mu}} C_{A,t}^F{}^{\frac{\mu-1}{\mu}} + (1-\varphi)^{\frac{1}{\mu}} C_{M,t}^F{}^{\frac{\mu-1}{\mu}} \right]^{\frac{\mu}{\mu-1}}, \tag{8}$$

where $\mu > 0$ is the elasticity of substitution, while $\varphi \in (0, 1)$ denotes the share of agricultural goods in the total consumption basket. The cost minimization conditions imply that, at the optimum, the quantity demanded for each good is $C_{A,t}^F = \varphi \left(P_t^A / P_t \right)^{-\mu} C_t^F$ and $C_{M,t}^F = (1 - \varphi) \left(P_t^M / P_t \right)^{-\mu} C_t^F$, where P_t^A and P_t^M denote the nominal price of the agricultural and manufacturing goods, while P_t is the 'ideal' consumption price index: $P_t = \left[\varphi (P_t^A)^{1-\mu} + (1-\varphi)(P_t^M)^{1-\mu} \right]^{\frac{1}{1-\mu}}$.

Since in this sector, households earn their living only from agricultural production, the flow budget constraint faced by the typical farmer is

$$P_t^A (Y_t^A - C_{A,t}^F) + P_t Tr_t^F = P_t^M C_{M,t}^F + P_t^M \tau_V \frac{\left(V_t^F\right)^{\phi_V}}{\phi_V}, \tag{9}$$

where $\phi_V > 1$ and $\tau_V > 0$ are parameters that determine land restoration costs, while Tr_t^F measures the amount of fiscal transfers, defined in real terms, that farmers may receive from the public sector.

The representative farmer chooses the set of variables $\{C_t^F, H_t^F, V_t^F, L_t^F\}$ so to maximize the expected lifetime utility (7), given prices, fiscal transfers, the initial stock of land L_{t-1}^F, the available technology (3), the land time evolution process (4), the damage function (5), the flow budget constraint (9), and the realization of the weather shocks (8). See Appendix B for further details. Note that these agents do not have access to financial markets, therefore, the only way they have to smooth out their consumption over time is through decisions regarding the amount of resources to be spent on land.

3.2 Manufacturing Sector

In the manufacturing sector, there are three agents: (i) a continuum of monopolistically competitive firms, each of which produces a single horizontally differentiated intermediate good, (ii) perfectly competitive firms that combine intermediate goods to produce the final manufacturing firm, and (iii) a mass of identical households that consume, offer labor services, and rent out capital to firms in the manufacturing sector.

3.2.1 Final Good Producers

We assume the existence of a mass $1 - s_F$ of identical and perfectly competitive final-good producers whose individual production is denoted as Y_t^M. These producers combine differentiated intermediate manufacturing goods according to a CES technology:

$$Y_t^M = \left(\frac{1}{1 - s_F} \int_0^{1-s_F} Y_{j,t}^{M\,(\theta-1)/\theta} dj \right)^{\frac{\theta}{\theta-1}}, \tag{10}$$

where $Y_{j,t}^M$ denotes the quantity of the generic intermediate good j, while $\theta > 1$ is the elasticity of substitution between differentiated intermediate goods. In the optimum, the typical producer minimizes total costs so that the demand function for the generic intermediate good j is $Y_{j,t}^M = \left(P_{j,t}^M / P_t^M \right)^{-\theta} Y_t^M$, where P_t^M is the 'ideal' price index $P_t^M = \left[\frac{1}{1-s_F} \int_0^{1-s_F} \left(P_{j,t}^M \right)^{1-\theta} dj \right]^{\frac{1}{1-\theta}}$ that, given the assumption of perfect competition determines the price at which manufacturing production is sold.

3.2.2 Intermediate Goods Producers

The manufacturing sector consists of a continuum of monopolistically competitive producers indexed by $j \in (0, 1 - s_F)$. Each producer hires sector-specific labor inputs, $H_{j,t}^{\bar{F}}$, and physical capital $K_{j,t-1}^{\bar{F}}$ in perfectly competitive factor markets to produce the manufacturing good $Y_{j,t}^M$ using the following Cobb-Douglas technology:

$$Y_{j,t}^M = B_M (K_{j,t-1}^{\bar{F}})^{\alpha_M} (H_{j,t}^{\bar{F}})^{1-\alpha_M} \tag{11}$$

where $\alpha_M \in (0, 1)$ and $B_M > 0$ measures the level of total factor productivity. Each producer has monopolistic power in the production of its own specific good and, when setting its price, faces quadratic adjustment costs as in Rotemberg (1983), measured in terms of the final good, equal to $(\chi_P/2) \left(P_{j,t}^M / P_{j,t-1}^M - 1 \right)^2 P_t^M Y_t^M$, where $\chi_P > 0$ captures the degree of price rigidity. Note that for the factor inputs, we are using the superscript $\bar{F}$ to denote the variables referring to non-farmers who own these factors.

Given the available technology (11) and the demand function $Y_{j,t}^M = \left(P_{j,t}^M / P_t^M \right)^{-\theta} Y_t^M$, the problem of a typical j firm is then to choose the set of variables $\{H_{j,t}^{\bar{F}},\, K_{j,t}^{\bar{F}},\, P_{j,t}^M\}$ to maximize the expected discounted sum of profits

$$\mathbb{E}_0 \sum_{t=0}^{\infty} Q_{t,0}^{\bar{F}} \left[P_{j,t}^M Y_{j,t}^M - W_t H_{j,t}^{\bar{F}} - R_t^k K_{j,t-1}^{\bar{F}} - \frac{\chi^P}{2} \left(\frac{P_{j,t}^M}{P_{j,t-1}^M} - 1 \right)^2 P_t^M Y_t^M \right], \tag{12}$$

where $Q_{t,0}^{\bar{F}}$ is the nominal discount factor that agents use in period t to value nominal profits and is equal to the stochastic discount factor of non-farmers households, while W_t and R_t^k denote the nominal wage and the rental rate of capital. See Appendix B for details.

3.2.3 Households

There is a mass $1-s_F$ of households that work only in the manufacturing sector. As for farmers, the typical non-farmer derives utility from consuming a consumption basket, $C_t^{\bar{F}}$, and disutility from labor, $H_t^{\bar{F}}$, and faces a lifetime utility function of the form:

$$\mathcal{U}_0^{\bar{F}} = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t^{\bar{F}}) - \chi_H \frac{(H_t^{\bar{F}})^{1+\eta_H}}{1+\eta_H} \right). \tag{13}$$

Likewise farmers, the non-farmers' consumption basket $C_t^{\bar{F}}$, is a composite good made of quantities $C_{A,t}^{\bar{F}}$ of agricultural goods and $C_{M,t}^{\bar{F}}$ of manufacturing goods according to a CES function:

$$C_t^{\bar{F}} = \left[\varphi^{\frac{1}{\mu}} C_{A,t}^{\bar{F}}{}^{\frac{\mu-1}{\mu}} + (1-\varphi)^{\frac{1}{\mu}} C_{M,t}^{\bar{F}}{}^{\frac{\mu-1}{\mu}} \right]^{\frac{\mu}{\mu-1}}. \tag{14}$$

therefore, the cost minimization conditions determine the quantity demanded for each good is $C_{A,t}^{\bar{F}} = \varphi C_t^{\bar{F}} \left(P_t^A/P_t\right)^{\mu}$ and $C_{M,t}^{\bar{F}} = (1-\varphi) C_t^{\bar{F}} \left(P_t^M/P_t\right)^{\mu}$.

Non-farmers are the sole owners and workers of the firms in the manufacturing sector and own physical capital that they rent out to producers. The flow budget constraint of the typical non-farmer household then reads as

$$P_t C_t^{\bar{F}} + P_t^M I_t^{\bar{F}} + B_t^{\bar{F}} = W_t H_t^{\bar{F}} + R_t^k K_{t-1}^{\bar{F}} + R_{t-1} B_{t-1}^{\bar{F}} + D_t^{\bar{F}} - P_t T_t^{\bar{F}}, \tag{15}$$

where $I_t^{\bar{F}}$ is investment spending, $B_t^{\bar{F}}$ denotes the quantity of one-period risk-free nominal bonds, $B_{t-1}^{\bar{F}}$ denotes the amount of bond carried from period $t-1$, R_{t-1} is the nominal (gross) interest rate, W_t is the nominal wage, R_t^k is the nominal rate of return on physical asset $K_{t-1}^{\bar{F}}$ and $D_t^{\bar{F}}$ are dividends from ownership of firms. Finally, $T_t^{\bar{F}}$ denotes lump-sum taxation. During each period, a fraction δ_K of capital depreciates, requiring households to invest to compensate for this decline. This gives rise to the standard law of motion for physical capital:

$$K_t^{\bar{F}} = (1-\delta_K) K_{t-1}^{\bar{F}} + I_t^{\bar{F}}. \tag{16}$$

The representative non-farmer household chooses $\{C_t^{\bar{F}}, H_t^{\bar{F}}, I_t^{\bar{F}}, K_t^{\bar{F}}, B_t^{\bar{F}}\}$ so to maximize the lifetime utility (13), given prices, taxes, the risk-free nominal interest rate, the initial stock of capital $K_{t-1}^{\bar{F}}$, the budget constraint (15) and the accumulation equation of capital (16). See Appendix B.

3.3 The Public Sector

The public sector controls the risk-free nominal interest rate R_t and by jointly setting Tr_t^F, $T_t^{\bar{F}}$ decides over the tax-transfer redistributive scheme between the two sectors. However, in doing so, the public sector is assumed to be constrained by a balanced budget rule so that at any time it must be that the fiscal transfers directed to the farmers must be financed by the revenues from taxes levied on non-farmers, that is

$$s_F Tr_t^F = (1-s_F) T_t^{\bar{F}}. \tag{17}$$

In the following sections, we explore several different ways in which the public sector sets monetary and fiscal policies. First, we consider a Ramsey planner that simultaneously selects the optimal monetary-fiscal policy mix. Then, we analyze the scenarios where a Ramsey planner controls either monetary or fiscal policy, while the other policy is determined according to a predetermined rule. As a benchmark case, we will also consider the case in which the policymaker adopts non-optimal monetary and fiscal rules.

3.4 Aggregation and Equilibrium Conditions

After aggregating all variables of the economy and imposing market clearing conditions on factor and goods markets, the standard equilibrium conditions of the model economy can be derived. See Appendix B, where a formal definition of decentralized competitive equilibrium is provided.

Since the economy is populated by a mass s_F of farmers and $1-s_F$ of non-farmers, the market clearing condition for agricultural goods requires aggregate supply to be equal to aggregate consumption, that is

$$s_F Y_t^A = s_F C_{A,t}^F + (1-s_F)\, C_{A,t}^{\bar{F}}. \tag{18}$$

For the manufacturing good, the market clearing condition is instead equal to

$$(1-s_F)\, Y_t^M \left[1 - \frac{\chi_P}{2}\left(\frac{P_{j,t}^M}{P_{j,t-1}^M} - 1\right)^2\right] = s_F \left(C_{M,t}^F + \tau_V \frac{\left(V_t^F\right)^{\phi_V}}{\phi_V}\right) + (1-s_F)\,(C_{M,t}^{\bar{F}} + I_t^{\bar{F}}), \tag{19}$$

where we account for the price adjustment costs sustained to re-set prices and the fact that this good is also used for investment purposes and to increase the quality of land. By combining (18) with (9) the market clearing condition can be expressed in terms of exchange between the two sectors:

$$(1-s_F)\, P_t^A C_{A,t}^{\bar{F}} = s_F P_t^M \left(C_{M,t}^F + \tau_V \frac{\left(V_t^F\right)^{\phi_V}}{\phi_V,}\right) \tag{20}$$

which simply implies that the total expenditure on agricultural goods by non-farmers must equal the total expenditure on manufactured goods by farmers. The price ratio P^A/P^M represents the terms of trade for the agricultural sector.

For future reference, we also define aggregate total real production in the economy, say Y_t, as:

$$P_t Y_t = s_F P_t^A Y_t^A + (1-s_F) P_t^M Y_t^M. \tag{21}$$

Finally, we define core inflation as the (gross) inflation rate in the manufacturing sector, measured as $\Pi^M = P_t^M / P_{t-1}^M$. Headline inflation is, instead, defined as the inflation rate based on the variation in the 'ideal' price index of a consumption basket that includes both manufacturing goods and agricultural goods (identified as food). This is measured as $\Pi = P_t/P_{t-1}$. This distinction will come in handy when discussing inflation dynamics under different policy scenarios.

Before turning to the study of the optimal policy response to weather shocks, in the next section, we discuss some characteristics of the model economy that make the choice over the optimal monetary-fiscal policy mix particularly challenging.

3.5 Sources of Inefficiencies, Dualism, and First Best Allocation

The model economy we use as a laboratory for our analysis of optimal policy presents some sources of inefficiency that are common to New Keynesian models, along with some specific characteristics to be ascribed to the 'dual' structure of the economy.

The first source of inefficiency arises from the assumption of costly price adjustments. Notably, this pricing assumption leads to a wedge between aggregate demand and aggregate output, as resources are needed to adjust prices. See the market clearing condition 19. This wedge vanishes in the absence of inflation. For this reason, it would be optimal to stabilize prices in the manufacturing sector and have a zero-core inflation policy.

Another source of inefficiency stems from the presence of monopolistically competitive firms in the manufacturing sector. These firms set prices above marginal costs, leading to positive price markups and an inefficiently low level of economic activity. This is a static distortion from standard monopoly analysis. As a result of costly price adjustments, markups are time-varying. In response to shocks, price markups induce inefficient output fluctuations in manufacturing, which call for monetary policy interventions.

In addition to the above distortions that derive from the New Keynesian structure of the manufacturing sector, the economy is, in some respects, 'dual' in the sense that it is divided into a rural, agricultural sector in which households work their own land and have no access to financial markets and a modern manufacturing sector in which households earn labor income, own firms, and have unconstrained access to financial markets and risk-free bonds. Moreover, agents cannot move from one sector to another; that is, there is no labor mobility between sectors.

To understand the implications of this segmentation of the economy, we can consider the first-best allocation arising as a solution to the problem of a social planner problem maximizing a utilitarian social welfare function given preferences, technologies, and the resource constraints of the economy. See Appendix C. In the steady state, the efficient condition of land accumulation reads as follows:

$$\beta \frac{\alpha_A (H_t^F)^{1+\eta_H}}{(1-\alpha_A)\, L^F} = [1-\beta(1-\delta_L)] \frac{(H_t^{\bar{F}})^{1+\eta_H}}{(1-\alpha_M)\, Y_t^M} \tau_V \left(V^F\right)^{\phi_V - 1}, \tag{22}$$

where the term on the left is the present discounted value of the marginal benefit derived from having an additional unit of productive land in the following period, while the term on the right represents the marginal cost of restoring an extra unit of cultivable land, net of the next-period marginal costs saved on land carried out from the current period.

In the decentralized equilibrium, the corresponding equilibrium condition is instead of the following form:

$$\beta \frac{\alpha_A (H_t^F)^{1+\eta_H}}{(1-\alpha_A)\, L^F} = [1-\beta(1-\delta_L)] \frac{(H_t^{\bar{F}})^{1+\eta_H}}{(1-\alpha_M)\, Y_t^M} \tau_V \left(V^F\right)^{\phi_V - 1} \mathcal{M}^p \mathcal{H}, \tag{23}$$

Condition (23) is different from condition (22) due to the term $\mathcal{M}^p$, which represents the level of the (gross) price markup in a steady state with zero inflation, and $\mathcal{H} \equiv C^{\bar{F}}/C^F$, an index of heterogeneity between the consumption levels of farmer and non-farmer households. Clearly, there is consumption heterogeneity in favor of non-farmers if $\mathcal{H} > 1$ and consumption heterogeneity in favor of farmers if $\mathcal{H} < 1$. Since $\mathcal{M}^p > 1$, imperfectly competitive markets distort the decentralized steady-state equilibrium by making the marginal benefit of land exceed its efficient level. This results in inefficiently low investment in land. Under perfect competition, this term would vanish, but conditions (23) and (22) would still differ due to the term $\mathcal{H}$.

In the first-best allocation, in fact, the entire production is confiscated by the social planner and then redistributed equally across all households, eliminating consumption misallocation and ensuring $\mathcal{H} = 1$. In a decentralized equilibrium (even under perfect competition), since households are stuck in one sector, their consumption levels can differ.[11] This implies that starting from an initial stock of land and capital in the decentralized competitive equilibrium, consumption misallocation can occur.[12] If $\mathcal{H} > 1$, as it will be assumed in our initial calibration

[11] Contrary to the two-sector New Keynesian model of Aoki (2001), in this model, markets are incomplete, so households cannot insure one another against the difference of revenues that they could receive in future states.

[12] In principle, this misallocation could be corrected by a system of non-distortionary tax/transfer schemes, which is in line with the second welfare theorem.

without any fiscal policy scheme, the decentralized equilibrium results in an even lower stock of land. Therefore, two factors contribute to the inefficient level of land accumulation in this economy: positive markups and dualism mainly resulting from market segmentation. The latter, in turn, leads to consumption misallocation between rural and urban households.

In what follows, we will show that adverse weather shocks are likely to worsen the consumption misallocation between farmers and non-farmer households while increasing inflation. In Section 5, we will show that all these features introduce further trade-offs for the Ramsey planner.

Finally, a further remark is needed here on the scope of monetary policy in this economy. It should be noted that monetary policy has a direct influence only on consumption and investment decisions among individuals in the manufacturing sector, where agents have access to financial markets. Meanwhile, the consumption patterns of farmers are influenced by the value of agricultural production, the available cultivable land (and therefore by weather events), and the terms of trade, which determine farmers' purchasing power. The influence of monetary policy on this sector is, therefore, indirect. This limits the stabilizing role of monetary policy and its ability to stabilize headline inflation in the face of an adverse weather event that primarily damages agriculture.

4 Weather Shocks and Model Dynamics under a Non-Optimal Policy Mix

In this section, we describe the dynamic behavior of the economy in the decentralized competitive equilibrium for the non-optimal policy case.[13] This case provides a useful benchmark for the analysis of the optimal fiscal and monetary mix to which we turn in the next section. In particular, we analyze the dynamic response of the economy to an adverse weather shock in the decentralized competitive equilibrium in the absence of any redistributive policy, setting $Tr_t^F = T_t^{\bar{F}} = 0$ and then assuming that monetary policy is conducted according to a standard Taylor rule of the type:

$$\frac{R_t}{R} = \left(\frac{\Pi_t}{\Pi}\right)^{\iota_\pi} \left(\frac{Y_t}{Y}\right)^{\iota_y}, \tag{24}$$

where non-indexed variables refer to steady-state levels, and $\iota_\pi > 0$ and $\iota_y > 0$ measure the responsiveness of the nominal interest rate to changes in inflation and aggregate output. In what follows, we first describe the calibration strategy and then present the dynamic behavior of the economy in response to a weather shock in the simplest case in which monetary and fiscal policies are not optimally set.

4.1 Calibration

The model is calibrated to reproduce an initial steady-state equilibrium of a fictive economy reflecting some specific features of the five Latin American economies we have considered in Section 2. Time is in quarters.[14] Table 1 summarizes the values of the parameters. We partition the model parameters into two groups: calibrated and fitted parameters.

[13] In Appendix C, we describe the dynamic response of the economy under the social planner's solution.

[14] The model is solved using the Dynare package, using a third-order approximation perturbation method. See Adjemian et al. (2022).

4.1.1 Calibrated Parameters

We calibrate the first group of parameters using steady-state relationships and results from related studies. Specifically, to match the empirical evidence, we rely on the statistics observed for the five countries of our dataset, from 2001 to 2022, presented in Table A-3 in Appendix A.

Using data on our set of countries, we obtain an average quarterly nominal risk-free interest rate of $R - 1 = 1.49\%$. The data also exhibit a trend in inflation, which we include in the steady state of the model. Accordingly, we set the headline inflation rate, $\Pi - 1 = \pi$ to 1.04%, leading to a quarterly real interest rate of 0.45%.[15] We use this value to pin down the discount factor of the economy β to 0.9956, a value close to the standards of the literature. In the steady state, core and headline inflation rates are equal, so $\Pi^M - 1 = \pi^M = 1.04\%$. We set the mass of farmers in the economy $s_F = 0.2402$ to match the average share of employment in the agricultural sector in our set of countries, according to the World Bank. We set the steady-state relative price of the manufacturing good P^M/P to match the share of the agricultural sector in the economy $s_F P^A Y^A / PY$ to 0.0746, close to the average we have observed in Section 2.

On the agricultural sector side, we first normalize the initial total endowment of productive land, $s_F L^F$, to 1. To calibrate the other parameters of the agricultural sector, we rely on the estimates and calibration of Gallic and Vermandel (2020). We fix the natural decay of land to $\delta_L = 0.05$ based on their corresponding estimate. Likewise, we set the elasticity of land productivity to weather shock to θ_W to 20.59. We also set the share of agricultural goods in the consumption basket to $\varphi = 0.15$ and the elasticity of productive land to agricultural production to $\alpha_A = 0.12$ following their calibration. Concerning the land cost function, the curvature of the function is fixed to $\phi_V = 1.76$ to match the estimates of Gallic and Vermandel (2017) for this parameter, while τ_V is a scale parameter implied by the restrictions set on the relative size of the agriculture sector and all the other parameters. The authors also estimated the degree of substitutability between agricultural and manufacturing goods. Here, we diverge from the value they obtain because we focus on a fictive emerging economy, where one can expect that agricultural and non-agricultural goods are imperfect complements rather than imperfect substitutes. In that sense, we rely on the estimations of Ginn and Pourroy (2022), who also integrate a CES function for food and non-food consumption dynamics in their model for India. While their estimate leads to a value of 0.71, we opt for a slightly higher degree of substitutability by calibrating μ to 0.8.

Concerning the manufacturing sector, we normalize aggregate production $(1 - s_F)Y^M$ to one, and set the elasticity of capital intensity to output to $\alpha_M = 0.33$, a common value in the literature. The elasticity of substitution between manufacturing goods is fixed to $\theta = 6$, a standard value and also consistent with the one of Cantelmo et al. (2024), while the degree of price rigidity is set to $\chi_P = 38.4928$, so to be approximately equivalent to a probability to keep the price unchanged between quarters of 0.7 in a Calvo's pricing scheme. Finally, we set the capital depreciation rate to $\delta_K = 0.025$, a conventional value as in Gallic and Vermandel (2020). For both types of households, the inverse of the Frisch elasticity of labor supply η^H is set to 1, a standard value in the literature. We normalize the steady-state values of the hours worked for non-farmers to $H^{\bar{F}} = 1/3$, implying that non-farmers spend one-third of their time working. Since we are assuming that households have the same preferences, the scale parameter measuring the disutility of labor χ_H is also the same. As a result of this further restriction, H^F is implied and is equal to 0.3773.

Finally, given the restrictions on the total endowment of land, aggregate production in manufacturing, and hours worked in that sector, the remaining scale parameters are implied.

[15] The average inflation rate reflects the influence of varying monetary policy frameworks across these economies. See Table A-4.

This is the case for the weights of labor disutility in the welfare function of households, χ_H, and for total factor productivity, B_A and B_M in the two sectors.

4.1.2 Fitted Parameters

The second group of parameters include the standard deviation of the weather shock σ_W, its persistence ρ_W, and the two policy parameters ι_π and ι_y of the interest rate rule (24) that determines monetary policy in the non-optimal policy scenarios. These parameters are fitted to minimize the distance between the impulse responses implied by our theoretical model and the empirical responses of Figure 3 in the ENSO scenario. Formally, the fitted parameters represent the solution to the following problem:

$$\Theta \equiv \underset{\zeta}{min}[\hat{\mathcal{I}} - \mathcal{I}(\zeta)]'\Sigma^{-1}[\hat{\mathcal{I}} - \mathcal{I}(\zeta)] \tag{25}$$

where $\hat{\mathcal{I}}$ represents the empirical impulse responses in Figure 3, ζ denotes the vector of the fitted parameters, $\mathcal{I}(\zeta)$ is the model-implied impulse responses to an adverse weather event and Σ^{-1} is a diagonal matrix reporting the empirical variances of the empirical impulse responses.[16]. The fitted parameters are reported at the bottom of Table 1. As we can see, the persistence of the shock is close to zero, as expected, so the duration of the effects of the shock is carried solely by the natural decay of land productivity δ_L.

4.2 The Dynamic Response of the Economy to an Adverse Weather Event

In this section, we illustrate the dynamic behavior of our prototype economy in response to an adverse weather shock. Note that according to equation (24), monetary policy targets headline inflation. Figure 4 illustrates the response of key macroeconomic variables to an adverse weather shock. The response of the economy is as expected and consistent with the results discussed in Section 2. The shock negatively impacts cultivable land, leading to a sharp decline in agricultural production and, consequently, in the consumption levels of farmers. To restore land productivity, farmers are forced to reduce their consumption further to purchase production goods from the manufacturing sector.

In the manufacturing sector, the shock propagates through different channels. First, the increase in the relative price of agricultural goods negatively affects the consumption of non-farmers. Since the two goods are imperfect complements, there is also a fall in demand for manufacturing goods, which is not compensated by the higher demand for production goods of farmers. Monetary policy, which responds more intensively to the rise in headline inflation than to the output contraction, is restrictive. This results in a further decrease in consumption among individuals in the manufacturing sector, worsening the recessionary effects of the weather shock for this sector. As a result, we observe that the negative weather shock immediately triggers an increase in the price markup that further exacerbates the inefficiency inherent to the decentralized market equilibrium.[17]

Inflation dynamics in the manufacturing sector result from two opposing effects. On one hand, marginal costs initially decrease due to the contraction in production caused by the initial drop in demand. On the other hand, the rise in the relative price of the flexible-price

[16] The variables we consider are the output growth in agriculture, $\log({Y_t}^A) - \log(Y_{t-1}^A)$, total output growth $\log(Y_t) - \log(Y_{t-1})$, the relative price of agriculture production P^A/P, and headline inflation Π. The parameters are fitted so to be restricted to belong to the following intervals: $\sigma_w \in (0.001, 0.005)$, $\rho_W \in (0, 0.4)$, $\iota_\pi \in (1.1, 1.8)$ and $\iota_y \in (0, 0.2)$

[17] Nominal marginal costs decline because of the lower production while, since changing prices is costly in this sector, the price markup temporarily increases.

Table 1: Calibrated Parameters of the Model

Parameter	Name	Value
Households		
β	Discount factor	0.9956
s_F	Mass of farmers households	0.2402
μ	Elasticity of substitution between goods	0.8
φ	Share of agricultural goods in the consumption basket	0.15
η_H	Inverse Frisch elasticity of labor supply	1
χ_H	Weight of labor disutility	6.5958
Agricultural Sector		
α_A	Elasticity of agricultural output to land	0.12
δ_L	Natural decay of land	0.05
ϕ_V	Curvature of the land cost function	1.76
θ_W	Elasticity of land productivity to weather shocks	20.59
B_A	Productivity factor of the agricultural sector	8.3327
τ_V	Land restoration costs parameter	0.5912
Manufacturing Sector		
α_M	Elasticity of manufacturing output to capital	0.33
δ_K	Capital depreciation rate	0.025
θ	Elasticity of substitution between manufacturing goods	6
χ_P	Degree of price rigidity	38.4928
B_M	Productivity factor of the manufacturing sector	1.2002
Non-Optimal Monetary and Fiscal Policies		
$\pi = \pi^M$	Core and headlines inflation rates	0.0104
Tr^F	Transfers to farmers	0
ι_π	Reaction to inflation	1.4503
ι_y	Reaction to output	0.1499
Weather Shock		
ρ_W	Persistence of the weather shock	0.0500
σ_W	Standard deviation of the weather shock	0.0030

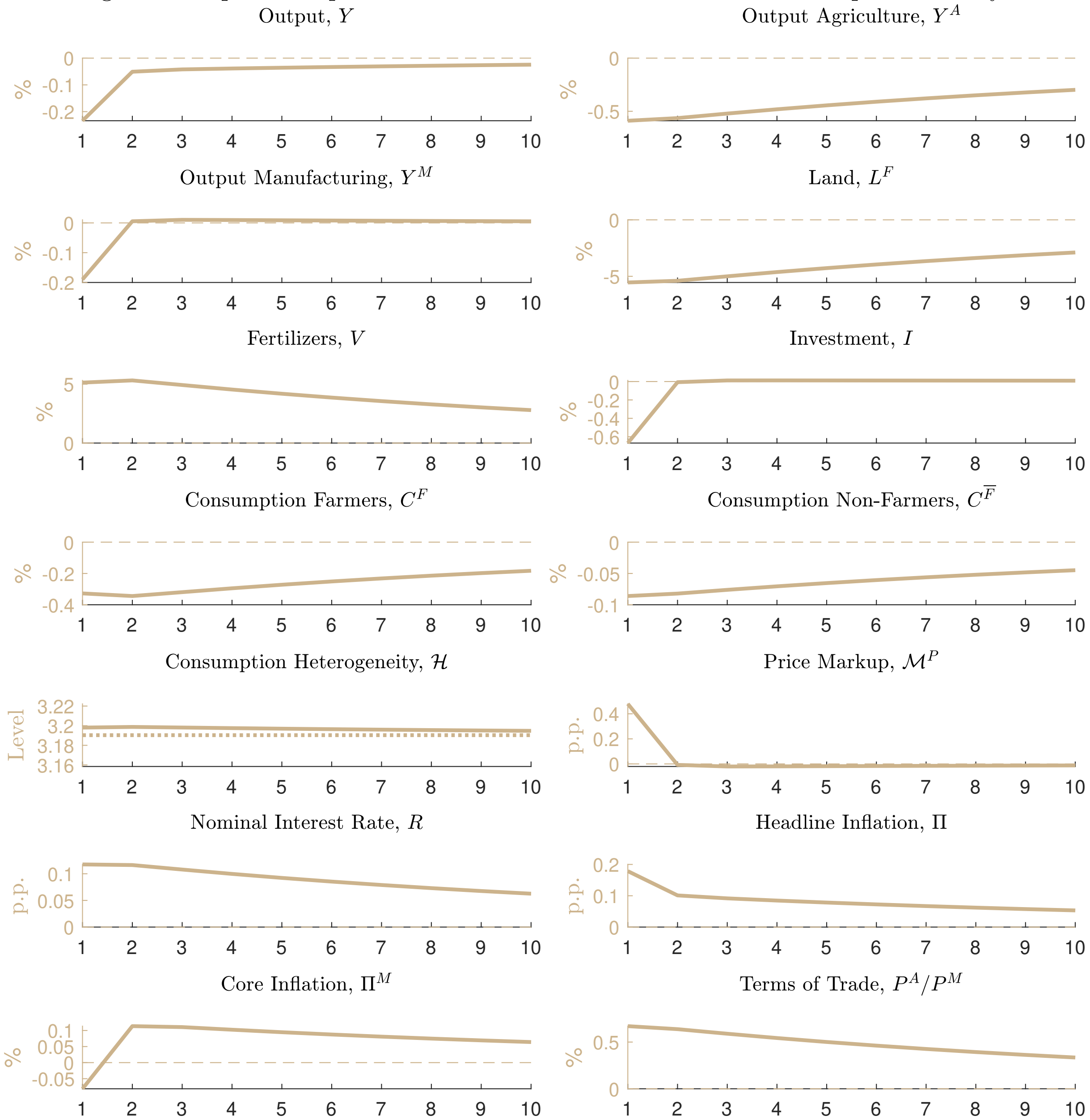
good creates inflationary pressure in the sticky-price sector via a reallocation of demand toward manufacturing goods, magnified by the need of farmers to restore land. The initial decline in core inflation is driven by the first effect, while the second effect subsequently prevails, leading to an eventual rise in core inflation.[18]

The opposite dynamics of relative prices in the two sectors translate into an improvement in terms of trade in favor of farmers. This implies that farmers can sell their produce at a relatively higher price, requiring them to exchange a smaller quantity of agricultural output Y^A for each unit of fertilizer V. The terms-of-trade improvement tends to mitigate the detrimental consequences of the weather shock for farmers. However, despite this effect, consumption disparities increase as a result of the shock.

In the next section, we will see how a benevolent Ramsey planner, by controlling monetary and fiscal policy, finds it optimal to stabilize core inflation while supporting farmers via a generous increase in fiscal transfers.

[18] In Appendix B, we show how changes in the relative price of agricultural goods affect core inflation.

Figure 4: Impulse Responses to an Adverse Weather Shock - Non-Optimal Policy



Notes: The figure presents the impulse responses to a one standard deviation weather shock for the calibrated economy under the non-optimal policy with headline inflation targeting. All variables are reported as percentage deviations from their stochastic steady-state level, with the exception of the nominal interest rate and the inflation rates, which are reported as annualized percentage point deviations, the markup in percentage points deviations, and consumption heterogeneity expressed in level.

5 Ramsey Monetary and Fiscal Policies

We are now ready to derive the optimal policy mix in response to weather shocks hurting the agriculture sector. Specifically, we consider the problem of a policymaker, referred to as the 'Ramsey planner', who controls the nominal interest rate R_t and the tax-transfer redistributive scheme between the two sectors. The Ramsey planner's objective is to maximize the expected utility of all households, given the constraints imposed by the general equilibrium conditions of the decentralized economy outlined in Appendix B. In particular, we focus on the following objective function:

$$\mathcal{U}_t = s_F \mathcal{U}_t^F + (1 - s_F)\mathcal{U}_t^{\bar{F}}, \tag{26}$$

where $\mathcal{U}_t^F$ and $\mathcal{U}_t^{\bar{F}}$ are the lifetime utility functions of farmers and non-farmer households defined in (7) and (13). Equation (26) is then the (utilitarian) social welfare function of the economy.

Following standard practice in the literature, we assume that the Ramsey planner is able to bind itself to contingent policy rules it announces in period t (i.e., there is an ex-ante commitment to a feedback policy enabling dynamic adaptation of the policy in response to evolving economic conditions).[19] We further assume that the government runs a balanced budget at all times, consistently with (17), this implies that transfers to farmers are fully financed by taxes levied on non-farmers. Given this assumption, the monetary/fiscal regime consists of the announcement of state-contingent plans for the nominal interest rate and the transfer in favor of farmers, $\{R_t, Tr_t^F\}$. See Appendix B for further details.

In what follows, we first characterize the steady-state properties of the model economy under the optimal policy mix, we then turn to the dynamic and welfare analysis.

5.1 Steady State

We start our analysis of optimal monetary and fiscal policy by considering the long-run state of the Ramsey equilibrium in an economy without uncertainty, which we refer to as the Ramsey steady state. As a first result, the steady-state nominal interest rate is equal to the inverse of the discount factor, $R = 1/\beta$, implying that the inflation rate associated with the Ramsey optimal policy is zero.[20] In doing so, the planner selects the inflation rate that eliminates the price adjustment costs in the manufacturing sector. Furthermore, at the calibration presented in the previous section, the optimal transfer is positive at steady state and is such that the index of heterogeneity, $\mathcal{H}$, is less than one. This result can be easily explained by considering condition (23). By redistributing resources from non-farmers to farmers, the Ramsey planner reduces the consumption misallocation observed in the non-optimal policy economy. However, pushing $\mathcal{H}$ closer to one is insufficient to achieve an efficient level of land use, as the steady state is further distorted by the presence of a positive markup. To mitigate the static inefficiency derived from an imperfectly competitive manufacturing market, the Ramsey planner finds it optimal to redistribute resources via a tax-transfer scheme in such a way that $\mathcal{H}$ is pushed below one, resulting in $C^F > C^{\bar{F}}$. These findings can be summarized as follows:

Result 1 *The Ramsey steady state is characterized by zero inflation and positive transfers in favor of farmers.*

Based on the calibration illustrated in the previous section, Table 2 presents the steady-state values of key macroeconomic variables under the Ramsey policy. The table also includes the deterministic steady state of the model under the first-best solution and the non-optimal policy model on which the calibration is based.

[19]This is known as the 'timeless perspective' approach to optimal policy so that the initial period problem becomes irrelevant once the initial period has long since passed. See, e.g., Woodford (2003) and Schmitt-Grohé and Uribe (2004).

[20]This result is consistent with those obtained in a streamlined New Keynesian model with Rotemberg pricing, as in Schmitt-Grohé and Uribe (2008). The inflation rate computed is the so-called *modified golden rule steady-state* inflation, differing from the *golden rule steady-state* inflation, which is instead the inflation rate that maximizes welfare at the deterministic steady state.

In the non-optimal steady state, the stock of usable land and capital is inefficiently low. Additionally, output in manufacturing is low due to imperfect competition, while there is an excess of production in agriculture due to an overuse of labor. Consumption misallocation is high to the detriment of farmers.

The first-best solution prescribes a lower level of agricultural output but a higher level of output in manufacturing. Usable land and accumulated capital stock are higher, as discussed in Section 3.5. Moreover, it is optimal to allocate more labor to the the manufacturing sector (the production of which is used for productive land accumulation), while consumption levels are equalized, as previously discussed.

In the second-best case, the Ramsey planner uses the available policy instruments to reduce distortions and reallocate resources to approach the first-best equilibrium. However, due to the balanced-budget constraint and the absence of subsidies to monopolistic competitive producers to offset the effects of markups, it is not possible to achieve the first-best equilibrium. By taxing non-farmers, the Ramsey planner can boost the consumption of farmers via transfers, thereby reducing consumption misallocation. At the optimal Ramsey steady state, our heterogeneity measure $\mathcal{H}$ is closer to one compared to the non-optimal policy regime, yet remains slightly below one, indicating a consumption heterogeneity favoring farmers. As explained, this bias in favor of farmers partially compensates for the distortions caused by imperfect competition in the manufacturing sector, thereby reducing the under-accumulation of land.

Table 2: Steady State Under Different Policy Scenarios

	Ramsey	First-Best	Non-Optimal
Output in agriculture Y^A	2.7972	2.9622	4.1935
Output in manufacturing Y^M	1.4487	1.7631	1.3161
Land L^F	4.7366	5.1648	4.1632
Physical capital $K^{\bar{F}}$	13.5374	19.7699	12.3028
Labor of farmers H^F	0.2340	0.2468	0.3773
Labor of non-farmers $H^{\bar{F}}$	0.3670	0.4083	0.3333
Consumption of farmers C^F	1.3079	1.3549	0.4275
Consumption of non-farmers $C^{\bar{F}}$	1.1601	1.3549	1.3629
Inflation Π, Π^M	1	-	1.0104
Transfers to farmers Tr^F	0.8048	-	0
Consumption heterogeneity $\mathcal{H}$	0.8870	1	3.1880
Gross markup $\mathcal{M}^P$	1.2000	-	1.1996
Social welfare $\mathcal{U}^F$	-17.3636	-1.5581	-52.0654
Welfare of farmers $\mathcal{U}^F$	33.5656	38.5034	-263.6330
Welfare of non-farmers $\mathcal{U}^{\bar{F}}$	-33.4641	-14.2230	14.8187

Notes: The table reports the deterministic steady-state equilibrium of the calibrated model under three scenarios: the optimal monetary and fiscal policy mix (Ramsey), the social planner's solution (first best), and the decentralized competitive equilibrium under the non-optimal policy (non-optimal).

5.2 The Optimal Policy Mix in Response to an Adverse Weather Event

In this section, we examine the dynamic response of the economy to an adverse weather shock when the Ramsey planner can utilize both fiscal and monetary instruments. Figure 5 presents the results for a selection of variables. The gold lines represent the dynamics under the Ramsey planner solution, while the grey lines represent the dynamics under the decentralized competitive equilibrium under the non-optimal policy. For the sake of comparability, and differently from Figure 4, we now assume that the (deterministic) steady state of the non-optimal policy scenario is the same as in the Ramsey solution, with trend inflation set to zero and positive transfers to farmers. See the first column of Table 2. However, the monetary policy is conducted according to a standard Taylor rule with headline inflation targeting (HIT), under the parametrization of Section 4, while fiscal transfers are kept constant.

As we can see, the Ramsey planner reacts to the shock by immediately increasing fiscal transfers in favor of farmers who are directly affected by the adverse weather event. On the other hand, the monetary policy is less aggressive than that prescribed by a standard Taylor rule, with the nominal interest rate rising much less than under the non-optimal policy scenario. Consequently, headline inflation increases more in the Ramsey equilibrium. Farmers then benefit from the larger transfers and the increase in agricultural prices, which, in turn, improve their terms of trade. Clearly, the Ramsey optimal policy mix is designed to support farmers' consumption and allocate more resources to restore the quality of land.

Turning to the manufacturing sector, we observe that under the Ramsey policy, core inflation is stabilized, while price markups increase much less than in the non-optimal policy scenario.[21] By stabilizing core inflation, the Ramsey planner neutralizes the distortions derived from costly price adjustments and further fosters the terms of trade improvement in favor of farmers. As a result of the combined effects of higher demand from farmers and of the mitigated effects on the markup, manufacturing production increases, contrary to what is observed on impact in the decentralized equilibrium, but consistent with the dynamics seen in the first-best equilibrium, as shown in Appendix C.

Finally, it should be noted that, due to the fiscal policy transferring resources from the manufacturing to the agriculture sector, the consumption ratio $\mathcal{H}$ — used as a measure of consumption heterogeneity — exhibits opposite dynamics in the two scenarios. While it increases in favor of non-farmers in the non-optimal case, it decreases under the optimal policy mix. This is because, the Ramsey planner finds it optimal to increase consumption heterogeneity further, which favors farmers in better addressing the asymmetric shock.

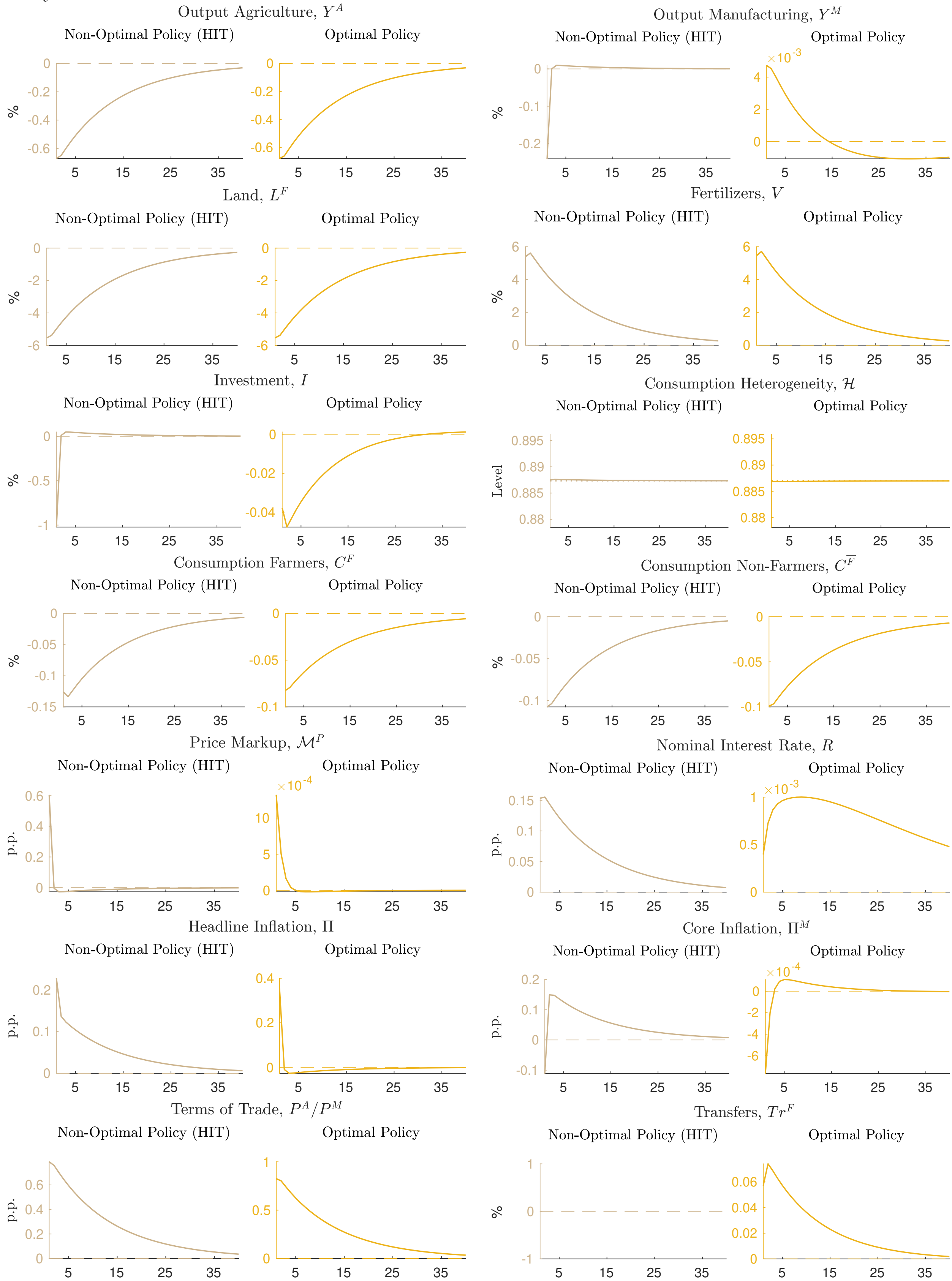
We can summarize the main results discussed above as follows.

Result 2 *In response to an adverse weather shock affecting the agriculture sector, the Ramsey monetary and fiscal policy mix prescribes increasing transfers to farmers while stabilizing core inflation.*

In Appendix E, we show that when the adverse shock impacts both sectors, it becomes optimal to temporarily reduce transfers to farmers in order to alleviate the tax burden on non-farmers and support the manufacturing sector, whose production is essential for restoring both quality of land and the physical capital, also negatively impacted by the weather shock. See Figure E-2.

[21] The optimality of core inflation stabilization is consistent with the optimal policy prescription that can be found in a New Keynesian model with a flexible-price sector and a sticky-price sector as in the Aoki (2001).

Figure 5: Impulse Responses to an Adverse Weather Shock - Ramsey Policy v. Non-Optimal Policy



Notes: The figure presents the impulse responses to a one standard deviation weather shock under the Ramsey equilibrium (right-hand figures, gold lines) and the non-optimal policy equilibrium with headline inflation targeting - HIT (left-hand figures, grey lines). All variables are reported as percentage deviations from their stochastic steady-state level, with the exception of the nominal interest rate and the inflation rates, which are reported as annualized percentage point deviations, the markup in percentage points deviations, and consumption heterogeneity expressed in level.

5.3 Ramsey Policy with a Single Policy Instrument

In this section, we study how the optimal policy changes when the Ramsey planner can optimally set either fiscal or monetary policy. We solve the model under two different scenarios. In the first scenario, fiscal policy is set optimally, while monetary policy follows a Taylor rule of the form (24), with headline inflation Π replaced by core inflation Π^M. This choice is motivated by our previous findings, which indicate that stabilizing core inflation is optimal when the economy faces adverse weather shocks hitting the economy asymmetrically. In the second scenario, monetary policy is set optimally by the Ramsey planner, while fiscal policy consists of keeping transfers to farmers at their deterministic steady-state level.

Figure 6 shows the impulse response for a selection of variables following an adverse weather shock when the Ramsey planner is restricted to optimally setting either fiscal policy (bronze lines) or monetary policy (silver lines), compared to the scenario where both policies can be optimally set (gold lines).

When the Ramsey planner controls monetary policy, the dynamics of manufacturing output, price markup, and inflation rates are qualitatively similar to those under the full policy optimization. However, without access to the fiscal instrument, the consumption of farmers cannot be sustained, leading to a slight increase in heterogeneity in favor of non-farmers. Conversely, when fiscal policy is optimally set, initial transfers to farmers are reduced. By sustaining demand for agents operating in the relatively more productive sector, production in manufacturing increases, inflation rises, and price markups decrease. As shown in Figure E-1 in Appendix E, investments also increase, while the percentage decline in farmers' consumption is twice as large as that observed under the optimal policy mix. Later, fiscal transfers to farmers increase and remain persistently above their initial level during the adjustment process. Without control over monetary policy to stabilize the manufacturing sector, the Ramsey planner finds it optimal to prioritize manufacturing before addressing the needs of the agricultural sector. These results can be summarized as follows.

Result 3 *In reaction to an adverse weather shock affecting the agriculture sector, when the government has access to only one policy instrument, optimal monetary policy results in macroeconomic variables that qualitatively mirror those under full policy optimization, but with a greater decline in farmers' consumption due to the lack of access to the fiscal instrument. Conversely, optimal fiscal policy requires an initial reduction in transfers to farmers, leading to a sharper decline in their consumption while stimulating a greater expansion in the manufacturing sector.*

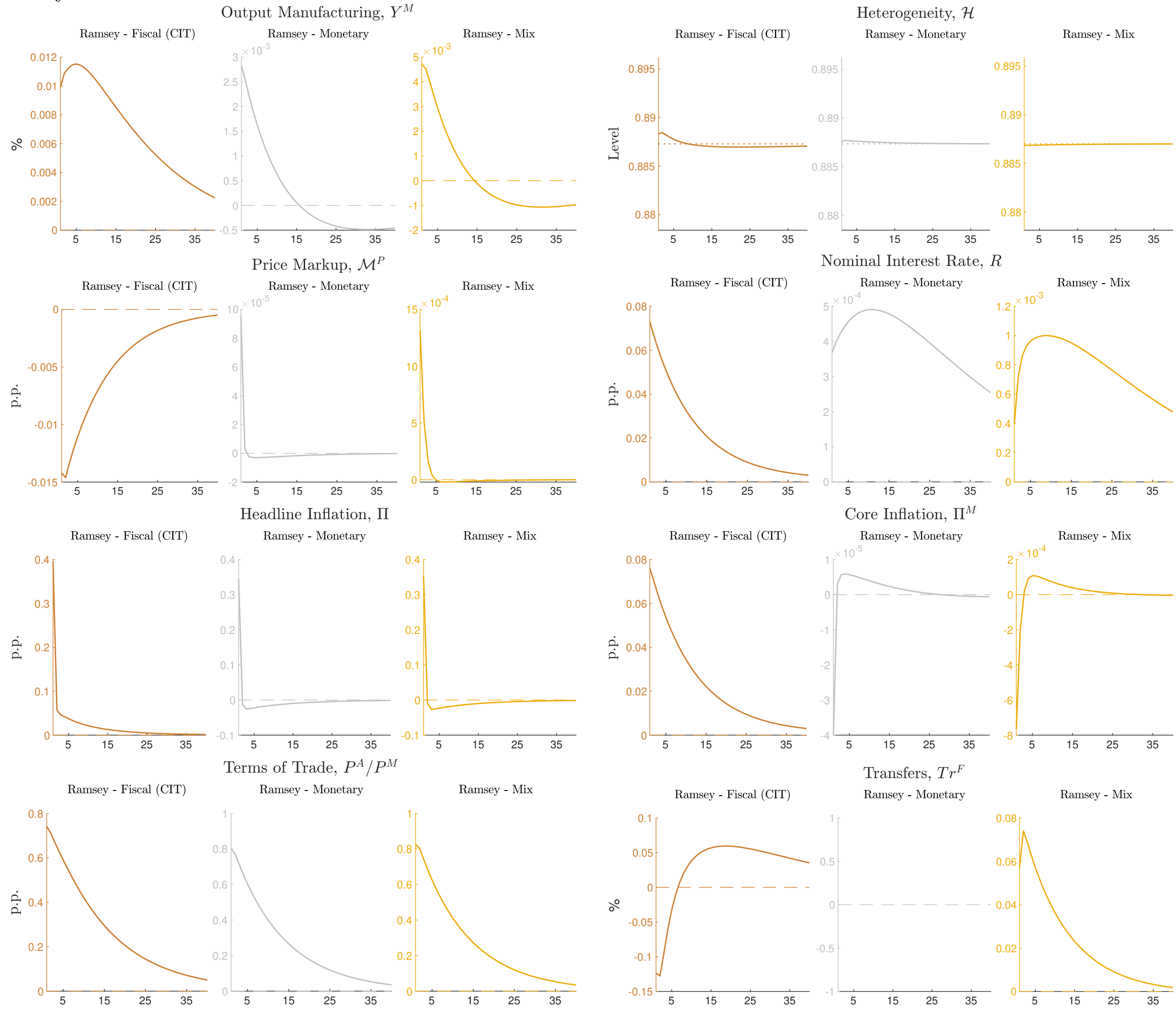
5.4 Welfare Analysis

In this section, we compare the performance of different monetary-fiscal policy combinations in terms of welfare. Table 3 presents the social welfare levels, including the welfare of farmers and non-farmers, under six policy scenarios. These scenarios are distinguished by whether the Ramsey planner has control over both, one, or neither policy instrument. In the scenarios where monetary policy is not optimally set and follows a Taylor rule, we examine two cases: one targeting headline inflation and the other targeting core inflation.

The metric we use is conditional welfare, that is the expected welfare conditional on the initial state of the economy being the deterministic Ramsey steady state.[22] To facilitate comparison

[22]This metric is commonly used along with unconditional welfare when comparing different policy regimes. See, e.g., Schmitt-Grohé and Uribe (2007). In Appendix E, Table E-4 reports the results using unconditional welfare measures.

Figure 6: Impulse Responses to an Adverse Weather Shock - Ramsey Policy with Different Policy Instruments



Notes: The figure presents the impulse responses to a one standard deviation weather shock when the Ramsey planner has only access to fiscal policy with core inflation targeting - CIT (left-hand figures, bronze lines), to monetary policy (figures in the middle, silver lines) and to both instruments (right-hand figures, gold lines). All variables are reported as percentage deviations from their stochastic steady-state level, with the exception of the nominal interest rate and of the inflation rates, which are reported as annualized percentage point deviations, the markup in percentage points deviations, and consumption heterogeneity expressed in level.

across different policy scenarios, we also measure the welfare cost of each monetary-fiscal policy combination relative to the Ramsey policy mix. This is defined as the increase in consumption required to make a representative consumer in either sector indifferent between living in an economy with the specific policy mix and an economy where the policymaker follows the Ramsey monetary and fiscal policy scheme.

Table 3: Welfare - Conditional Measures

	Social		Farmers		Non-Farmers	
	level	cost	level	cost	level	cost
Ramsey Mix	-17.3000	0	33.6451	0	-33.4056	0
Ramsey Fiscal with HIT	-17.3086	0.0038	33.5627	0.0364	-33.3909	-0.0065
Ramsey Fiscal with CIT	-17.3042	0.0019	33.5638	0.0358	-33.3854	-0.0089
Ramsey Monetary	-17.3017	0.0008	33.5482	0.0427	-33.3772	-0.0125
Non-Optimal with HIT	-17.3122	0.0054	33.5457	0.0438	-33.3902	-0.0068
Non-Optimal with CIT	-17.3041	0.0018	33.5477	0.0430	-33.3801	-0.0112

Notes: Welfare costs are measured with respect to the Ramsey policy mix and are expressed in percentage. A positive (negative) figure indicates that welfare is higher (lower) under the Ramsey policy than under the alternative policy scenarios.

Consider the results on social welfare. We observe that the cost of not implementing the Ramsey mix is particularly high when the Ramsey planner has no access to monetary policy and the Taylor rule targets headline inflation. For farmers, the welfare costs are lower when the Ramsey planner controls fiscal policy. This is consistent with our previous findings, as the Ramsey planner optimally increases fiscal transfers to support households affected by adverse weather shocks. Conversely, for non-farmers, the welfare cost becomes negative, indicating they benefit from deviating from the Ramsey policy. The greatest benefits for non-farmers arise from adopting a Ramsey monetary policy while keeping fiscal transfers at their steady-state level or adopting a core inflation-targeting Taylor rule, which closely mimics the Ramsey monetary policy. An aggressive monetary policy targeting headline inflation, in fact, would reduce aggregate demand by a large amount, depressing the level of economic activity in the manufacturing sector. The main findings can be summarized as follows.

Result 4 *When adverse weather shocks affect the agriculture sector, deviating from the optimal policy mix is less costly when the Taylor rule targets core inflation or when at least monetary policy is optimally set. The Ramsey policy mix benefits farmers but is detrimental to non-farmers.*

The above result, however, holds only when the adverse weather shock hurts exclusively agriculture. In Appendix E, we show that when shocks symmetrically affect both sectors, deviating from the optimal policy mix remains less costly when monetary policy is optimally set, but in other cases, targeting headline inflation under a Taylor rule becomes less detrimental than targeting core inflation. By stabilizing headline inflation, the Ramsey planner can mitigate the terms of trade deterioration in the manufacturing sector, where price rigidity hinders immediate price adjustment. Furthermore, the Ramsey policy mix tends to benefit both farmers and non-farmers, while in the case of Ramsey monetary policy, it becomes slightly costly for non-farmers.

5.5 Alternative Parametrizations

In this section, we check whether our results on welfare are robust to different parametrizations by undertaking a sensitivity analysis. We solve the model for different values of the parameters μ, ϕ_v and δ_L. We vary each parameter at a time along with the the implied scale parameters χ_H, B_A and B_M and the relative price of the manufacturing good, so as to keep the normalization we made in Section 4 for the steady values of land, manufacturing production, and employment, and target the relative size of the agriculture sector consistently with data. We also consider the effects of varying the policy parameters of the interest rate rule (24) in scenarios where the monetary policy is not optimally set. Tables 4 and 5 show the social welfare cost of deviating from the Ramsey policy mix under different scenarios and parametrizations. Overall, we observe that the optimality of core inflation targeting is confirmed under different parametrizations.

Elasticity of Substitution in the Consumption Basket

We start by varying the elasticity of substitution μ in the CES consumption basket of households, the baseline value of which was set to 0.8. By increasing the degree of complementarity between manufacturing and agricultural goods, deviation from the optimal policy in response to asymmetric weather shocks becomes more costly. Intuitively, in the case of a negative weather shock hurting agriculture, a lower elasticity of substitution would imply a stronger disruption in the manufacturing sector.

Curvature of the Land Cost Function

When changing the parameter governing the curvature of the land restoration cost function, ϕ_v, results do not change significantly from the baseline case (i.e., $\phi_v = 1.76$) as long as fiscal policy is optimally set and consumption of farmers is stabilized. In the non-optimal policy case, targeting headline inflation becomes relatively less costly than targeting core inflation, the less convex the land restoration cost function is. Clearly, the lower the increase in cost sustained by farmers, the diminished the need to enhance their purchase power via the terms of trade.

Natural Decay of Land

The lower (higher) the decay rate of land, the higher (lower) the welfare cost deviating from the optimal policy mix. A lower decay rate, in fact, makes past land investment choices more 'irreversible', therefore, in the case of weather shocks reducing the quality of the existing stock of land, the damage would be relatively higher.

Taylor Rule Parameters

We conclude our sensitivity exercises by varying the parameters of the interest-rate rule parameter in the scenarios where monetary policy is not optimally set. Consider the effects of varying the reactivity of the risk-free rate to output. Setting to zero the reactivity to output improves the performance of non-optimal policies. This is because weather shocks hitting agriculture, the flexible price sector, by means of their effects on relative prices, mainly materialize in the manufacturing sector as a cost-push shock, giving rise to a trade-off between inflation and output stabilization.[23] On the other hand, consistent with the results found so far, a sharper reaction

[23] See Appendix Appendix B, where from a log-linearized version of New Keynesian Phillips curve we show how the relative price of the agricultural good enters as a cost push-shock.

to inflation reduces the welfare cost of deviating from the optimal policy but makes it relatively more costly to target headline inflation than to target core inflation.

Table 4: Social Welfare Cost of Deviating from the Ramsey Policy Mix

	Baseline	Elasticity of Substitution		Curvature of the land cost function		Natural decay of land productivity	
		$\mu = 0.5$	$\mu = 1.2$	$\phi_v = 1.2$	$\phi_v = 2.5$	$\delta_L = 0.025$	$\delta_L = 0.075$
Ramsey Fiscal HIT	0.0038	0.0051	0.0027	0.0039	0.0038	0.0054	0.0031
Ramsey Fiscal CIT	0.0019	0.0020	0.0016	0.0018	0.0019	0.0034	0.0012
Ramsey Monetary	0.0008	0.0020	0.0001	0.0013	0.0008	0.0014	0.0005
Non-Optimal with HIT	0.0054	0.0124	0.0024	0.0040	0.0061	0.0073	0.0046
Non-Optimal with CIT	0.0018	0.0035	0.0008	0.0018	0.0021	0.0036	0.0011

Notes: Welfare costs are measured with respect to the Ramsey policy mix and are expressed in percentage. A positive (negative) figure indicates that welfare is higher (lower) under the Ramsey policy than under the alternative policy scenarios.

Table 5: Social Welfare Cost of Deviating from the Ramsey Policy Mix under Different Parametrizations of the Taylor Rule

	Baseline	Reaction to output		Reaction to inflation	
		$\iota_y = 0$	$\iota_y = 0.5$	$\iota_\pi = 1.1$	$\iota_\pi = 3$
Ramsey Fiscal HIT	0.0038	0.0033	0.0124	0.0085	0.0024
Ramsey Fiscal CIT	0.0019	0.0000	0.0125	0.0072	0.0005
Ramsey Monetary	0.0008	-	-	-	-
Non-Optimal with HIT	0.0054	0.0050	0.0385	0.0191	0.0038
Non-Optimal with CIT	0.0018	0.0008	0.0351	0.0071	0.0010

Notes: Welfare costs are measured with respect to the Ramsey policy mix and are expressed in percentage. A positive (negative) figure indicates that welfare is higher (lower) under the Ramsey policy than under the alternative policy scenarios.

5.6 The Optimal Policy Mix in Response to an Increase in Weather Volatility

We conclude our analysis by examining the consequences of increased weather shock volatility rather than focusing solely on the effects of a one-time weather shock. This approach aligns with the evidence presented in Section 2, which demonstrates that the of natural disasters tends to rise during ENSO events. Furthermore, recent climate research highlights how anthropogenic greenhouse warming may lead to more frequent extreme El Niño events (see, e.g., Cai et al. 2014 and Thirumalai et al. 2024).

To capture this dynamic, we model the standard deviation we now assume that the standard deviation σ^W is time-varying and follows the process:

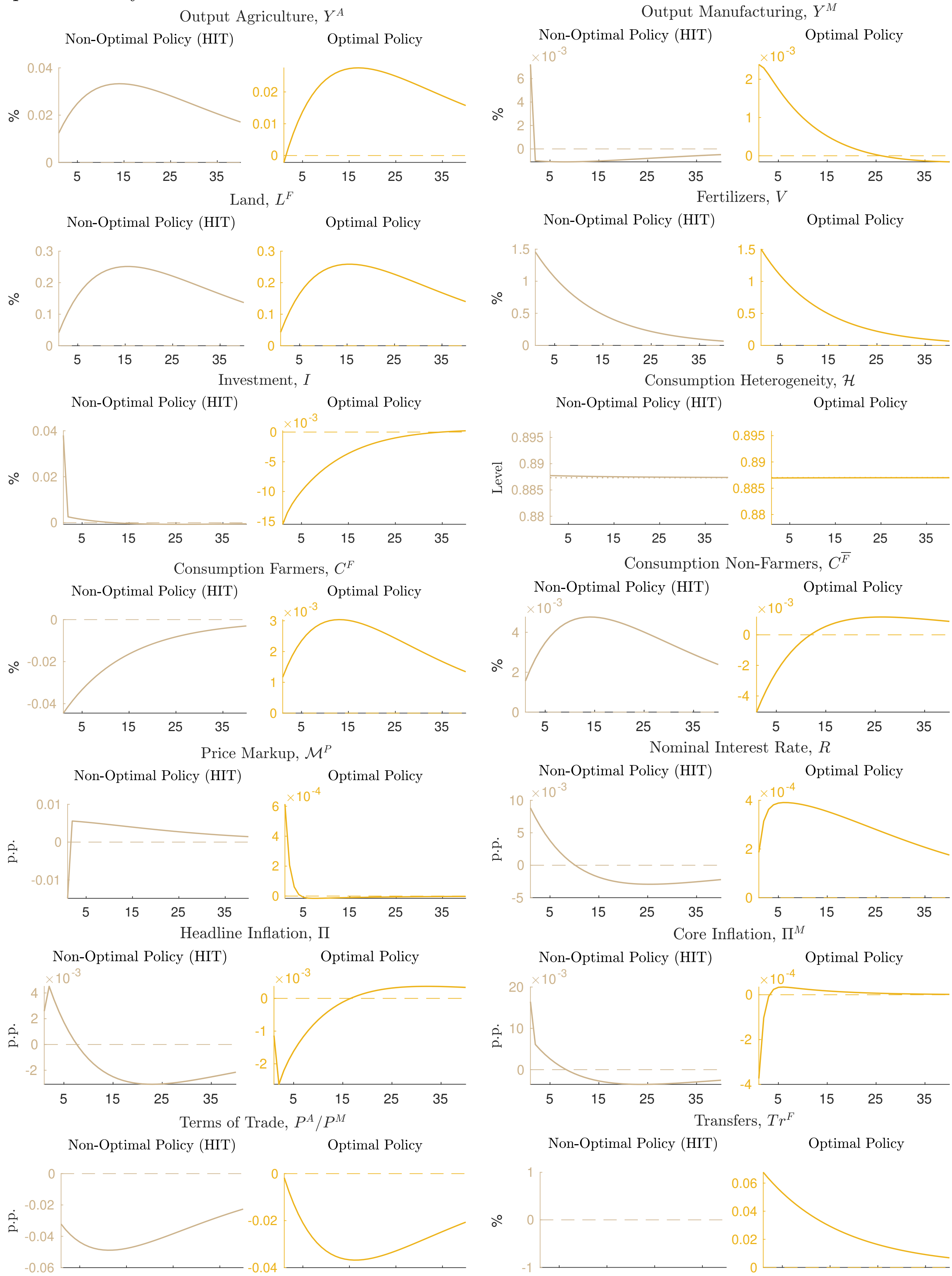
$$\sigma_{W,t} = (1 - \rho_\sigma)\sigma_W + \rho_\sigma \sigma_{W,t-1} + \eta_t^\sigma, \tag{27}$$

where where $\rho_\sigma \in [0, 1)$, while η_t^σ is the idiosyncratic shock to weather volatility.

A higher standard deviation of weather shocks implies that agents expect a greater severity of weather events. In the face of such heightened climate risk, farmers are likely to invest more in land accumulation and other adaptive measures to safeguard agricultural productivity. For illustrative purposes, we assume that the volatility of the weather shock temporarily increases from 0.0030 to 0.0060, with the persistence ρ_σ set at 0.95.

Figure 7 presents the results, comparing the economic response under a non-optimal policy and headline inflation targeting to that of an economy where the Ramsey planner has access to

Figure 7: Impulse Responses to an Adverse Volatility Weather Shock - Ramsey Policy v. Non-Optimal Policy



Notes: The figure presents the impulse responses to a one standard deviation weather volatility shock under the Ramsey equilibrium (right-hand figures, gold lines) and the non-optimal policy equilibrium with headline inflation targeting (left-hand figures, grey lines). All variables are reported as percentage deviations from their stochastic steady-state level, with the exception of the nominal interest rate and the inflation rates, which are reported as annualized percentage point deviations, the markup in percentage points deviations, and consumption heterogeneity expressed in level.

both policy instruments. As expected, in both policy scenarios, investments in land productivity increase. In the face of increased variability in the magnitude of weather shocks, adaptation requires preventive measures to enhance resilience to potentially devastating natural disasters. Consequently, agricultural production increases. However, under the non-optimal policy, this comes at the cost of reduced consumption for farmers. Moreover, investments increase, at least on impact, while both core and headline inflation rates go up. Conversely, the Ramsey planner responds to the heightened climate risk by sustaining the consumption of farmers through increased transfers, while mitigating inflationary pressure. In particular, inflation stabilization remains an optimal strategy even in this context. Non-farmers partially sustain the burden of this policy experiencing a slight and short-lived drop in their consumption. These results are summarized here.

Result 5 *In response to an increase in the volatility of weather shocks that affect the agriculture sector, it is optimal to increase transfers in favor of farmers and promote expenditure in adaptive measures to improve agricultural resilience, while ensuring stable inflation and farmers consumption.*

6 Conclusions

The design of the correct policy response to weather shocks can be particularly challenging. This difficulty arises mainly from the fact that these shocks asymmetrically impact different sectors of the economy, with agriculture being particularly vulnerable. Moreover, when the economic sectors are segmented, reflecting a certain degree of dualism, designing an optimal mix of fiscal and monetary policies that can stabilize the economy and support recovery becomes even more complicated. The challenge can be particularly pronounced in low-income and emerging countries, where the agricultural sector is often more fragile, and a larger share of the population is directly exposed to the consequences of adverse weather events. For example, several Latin American countries, where agriculture represents an important share of their economy, are exposed to El Niño-Southern Oscillation phenomena, which influence their temperatures and the intensity of their precipitations, and increase the probability of the occurrence of natural disasters. This paper seeks to address these issues by examining the optimal fiscal and monetary policy mix in response to adverse weather shocks within a two-sector New Keynesian model calibrated to represent a climate-prone economy, where a rural agricultural sector producing food coexists with a modern manufacturing sector.

In response to an adverse weather shock that reduces agricultural production and triggers inflationary pressure on food prices, the optimal mix of monetary and fiscal policies consists of increasing transfers to farmers while stabilizing core inflation. Intuitively, given the disproportionate burden of weather shocks on the agricultural sector and their negative impact on farmers' consumption, it is optimal to implement fiscal policies aiming at sustaining farmers to speed up their recovery. However, by stabilizing core inflation, rather than headline inflation, the monetary policy indirectly benefits farmers by letting their terms of trade improve, thus providing them with more resources to restore their land productivity. Both policies, when jointly optimally set, then work in the direction of supporting the sector directly hit by the shock. Our results indicate that even when the policymaker has access to only one policy instrument—either monetary or fiscal—or neither, deviating from the optimal policy mix results in relatively small welfare losses, provided that core inflation remains stabilized. By allowing food prices to rise while stabilizing prices in the manufacturing sector, the terms of trade for farmers are kept favorable during the recovery phase, ensuring that they have the resources needed to recover effectively. However, if the adverse weather event is more pervasive and hits both sectors of the economy, then deviating from the optimal policy mix results in smaller welfare losses only if headline inflation is stabilized.

The design of the optimal policy mix becomes even more critical when considering the increased risks of natural disasters, such as those associated with El Niño or La Niña events, which are further exacerbated by climate change. In this context, it remains optimal to increase fiscal transfers to farmers while maintaining price stability, thus ensuring a stable environment and supporting measures that enhance agricultural resilience.

The results of this paper have two main policy implications. First, as natural disasters become more frequent and intense, it is challenging for policymakers to respond effectively, particularly in fragile and segmented economies where access to all policy tools may be limited. This limitation could be due to factors such as high levels of public debt (which limits the available fiscal space), narrow tax bases, excessive external debt, adherence to common currency areas, or fixed exchange regimes. These further complicating factors should be explored in future research. The second policy implication regards the role that central banks can have in the face of adverse weather events that can asymmetrically impact the economy. The findings emphasize the importance of monetary policy, even when the central bank cannot directly target the sector affected by the shock or when fiscal policy is not optimally set. For emerging economies, where financial inclusion is still a challenge, we show that the central bank can still improve the welfare of households lacking access to financial markets while conducting its primary mandate of price stability.

Declarations of interest

None.

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Appendix A

This appendix presents the data used in Section 2 to analyze the effects of weather shocks on Latin American economic outcomes.

Data

We rely on multiple sets of data. Table A-1 below presents the different sources we used.

Production data for all countries are extracted on a quarterly basis. Prices are obtained on a monthly basis and aggregated quarterly using a simple average. Quarterly growth rates and inflation rates are then computed with respect to the value of the past year, to reduce seasonal variation. Construction of the data set has led to recomputing data for Colombia and Ecuadorian GDP and for Bolivian IPC in order to express the time series with the same reference year before calculating the variation rates.

To characterize better the economic sectors of these economies, we include information about the share of employment in the agricultural sector (as a percentage of total employment) and the quarterly interest rates in effect in the countries we study. The former is obtained from the World Bank Data, while the latter corresponds to the Central Bank Policy Rates from the International Monetary Fund Data (International Financial Statistics).

Natural Disasters are collected from the EM-Data database developed by the Centre for Research on the Epidemiology of Disasters at the University of Louvain (UCLouvain). From this dataset, we extract the number of weather-related natural disasters registered, composed of floods, droughts, storms, extreme temperatures, wildfires, and wet mass movements between 2001 and 2022. We then use the number of events happening every quarter for each of the countries included in the sample. Note that for drought events, no end date is reported in the data for five instances. In that case, we input the end month to be the same of the start month. Figure A-1 presents the distribution of these events by country.

Variations in the El Niño-Southern Oscillation (ENSO) are obtained from the U.S. National Oceanic and Atmospheric Administration (NOAA, tables available here). Following the definition given by the source, an El Niño event occurs when the Oceanic Niño Index (ONI) exceeds a 0.5 threshold for 5 consecutive periods. Symmetrically, a La Niña event happens when the ONI is lower than the -0.5 threshold for 5 consecutive periods. In the paper, we do not distinguish between warm (El Niño) and cold (La Niña) phases and define an ENSO event when either El Niño or La Niña occurs. "Normal" periods are by opposition quarters when none of the events happen.

Finally, to control for the international economic cycle, we include data on Consumer Price Inflation of the United States and an index of oil prices, both obtained from the IMF.

With these data, we obtain a quarterly unbalanced[24] dataset of five countries from 2001 to 2022. Table A-3 presents the averaged values of the socio-economic variables for the five countries in our sample and the simple average at the bottom line that we use later to calibrate the model.

[24]Data on Food CPI for Ecuador start in 2005.

Table A-1: Sources of the Data

	Bolivia	Chile	Colombia	Ecuador	Peru
	Economic Variables				
Production	Instituto Nacional de Estadística	Banco Central Chile	Banco de la República - Colombia	Banco Central de Ecuador, 2022	Banco Central de Reserva del Perú
GDP	GDP at Market Prices	Producto interno bruto	PIB reportado	PIB (miles de USD 2007)	PIB Global
GDPa	Agriculture, Forestry, Hunting and Fishing	Agropecuario-silvícola y pesca	Agricultura, ganadería, caza, silvicultura	Agricultura y pesca	Agropecuario
Prices	Instituto Nacional de Estadística	Banco Central de Chile	Banco de la República - Colombia	Instituto Nacional de Estadística y Censos	Banco Central de Peru
IPC	General Index	IPC general	IPC Total	Indice General	IPC
IPCa	General Index, Food	IPC Alimentos volátiles	IPC Alimentos	Alimentos y bebidas no alcohólicas	IPC Alimentos y bebidas
Interest rates	IMF Data, International Financial Statistics, `IMF.IFS.FID_PA`				
Employment	World Bank, World Development Indicators, `sl.agr.empl.zs`				
US ICP	IMF Data				
Oil prices	IMF Commodity prices Data				
	Weather Variables				
Natural Disasters	EM-DAT, CRED / UCLouvain, Brussels, Belgium				
Oceanic Niño Index	National Oceanic and Atmospheric Administration				

Additional Tables

Table A-2: Mean and Standard Deviations of Natural Disasters Occurrences

Country	Total		State of the ENSO at the previous quarter: ENSO Event		State of the ENSO at the previous quarter: Normal state	
	Mean	Std Deviation	Mean	Std Deviation	Mean	Std Deviation
Bolivia	1.59	1.63	1.66	1.82	1.53	1.46
Chile	0.64	0.91	0.53	0.70	0.73	1.06
Colombia	2.01	1.74	1.69	1.65	2.29	1.79
Ecuador	0.80	1.37	0.54	1.36	1.02	1.36
Peru	1.46	1.55	1.14	1.28	1.73	1.72
Total	1.30	1.55	1.11	1.49	1.46	1.58

Notes: The second and third columns of the table present respectively to the average number of natural disaster occurrence (column 2) and the corresponding standard deviation (column 3) over the whole sample by country. Columns 4 and 5 display the statistics for natural disasters happening when an ENSO event was occurring one quarter before for each country, while columns 5 and 6 depict the statistics outside of ENSO events. Row "Total" refers to the computation of average occurrence and standard deviations of natural disasters when pooling the data regardless of the country.
Source: EM-DAT and NOAA. Authors' computation.

Table A-3: Average Values of Selected Variables - 2001-2022

Country	Share of Employ. in Agriculture	Share of Agri. VA (% of GDP)	Total number of Disasters	Mean CPI inflation	Mean FPI inflation	Mean GDP Growth	Mean Agri. VA Growth	Mean Interest Rate
Bolivia	32.94	11.50	140	4.21	5.51	3.77	3.62	5.29
Chile	10.42	3.78	59	3.72	5.83	8.74	7.47	3.95
Colombia	17.91	6.94	181	5.04	7.14	3.81	2.46	8.37
Ecuador	28.81	8.03	70	5.16	3.90	3.00	3.26	8.46
Peru	30.03	7.05	134	3.05	3.75	4.33	3.51	4.33
Total	24.02	7.46	584	4.24	5.23	4.73	4.07	6.08

Notes: Each column of the table corresponds to simple averages of the economic variables presented before, except for "Total number of disasters" where the sum is applied.
Source: Authors' computation using the sources presented in Table A-1.

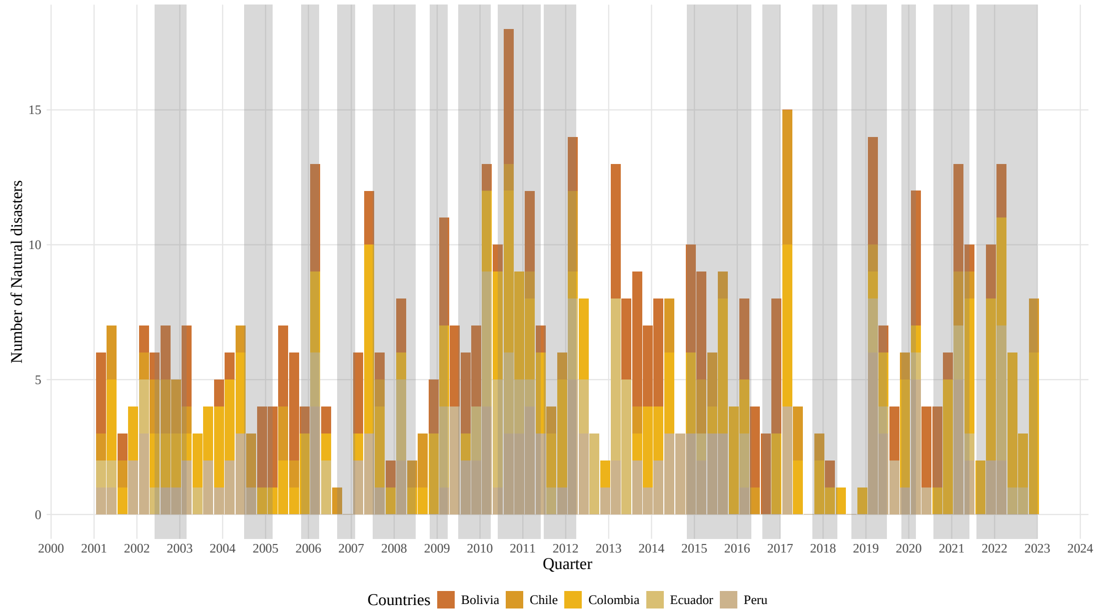
Table A-4: Monetary Policy Framework of the Selected Countries

Country	Exchange rate regime
Bolivia	Stabilized arrangement (Monetary aggregate target)
Chile	Free Floating exchange rate regime (Inflation Targeting framework)
Colombia	Floating exchange rate regime (Inflation Targeting framework)
Ecuador	No separate legal tender (with the US dollar)
Peru	Floating exchange rate regime (Inflation Targeting framework)

Source: IMF report, "Annual Report on Exchange Arrangements and Exchange Restrictions 2021", available here.

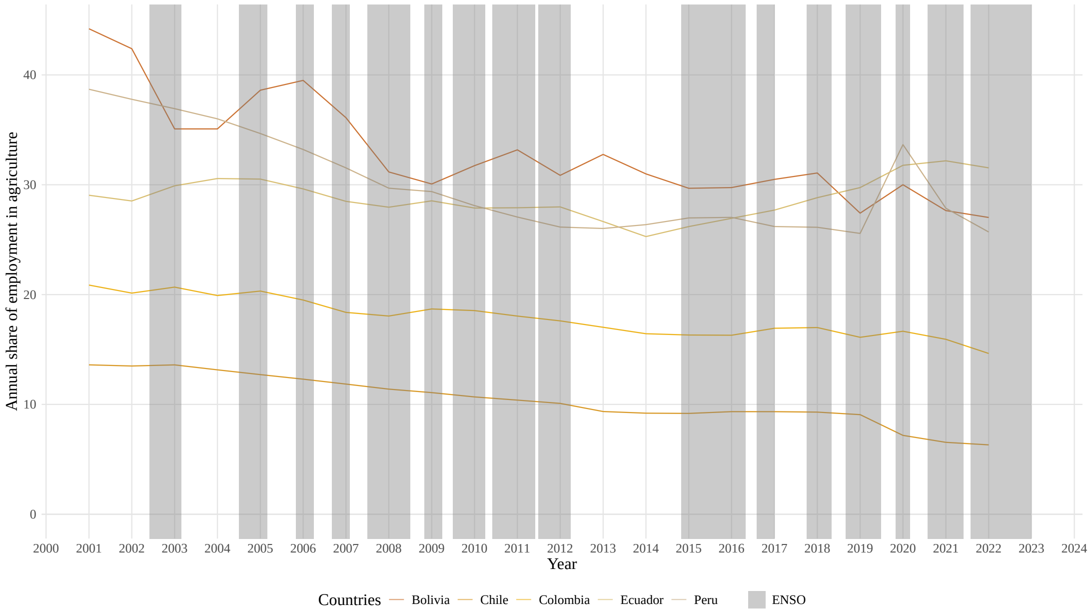
Additional Figures

Figure A-1: Number of Natural Disasters Occurring by Quarter and Country



Notes: The bars correspond to the quarterly total number of natural disasters (including floods, droughts, storms, extreme temperatures, wildfires, and wet mass movements) for each country in the sample between 2001 and 2022. The grey areas correspond to ENSO phases (both warm and cold phases).
Source: EM-DAT and NOAA. Authors' computation.

Figure A-2: Variation in Annual Employment in Agriculture by Country



<u>Notes:</u> The lines correspond to the quarterly evolution of employment in the agricultural sector (in % of total employment) for each country in the sample between 2001 and 2022. The grey areas correspond to ENSO phases (both warm and cold phases).
<u>Source:</u> World Bank and NOAA. Authors' computation.

Appendix B

This appendix reports the first-order conditions describing the optimal solution to the agents' problem operating in both sectors and provides a formal definition for the decentralized competitive equilibrium of the economy.

Agricultural Sector

The typical farmer chooses $\{C_t^F,\ H_t^F,\ V_t^F,\ L_t^F\}$ so to maximize the expected lifetime utility (7), given prices, fiscal transfers, the initial stock of land L_{t-1}^F, the flow budget constraint (9), the available technology (3), the land time evolution process (4), the damage function (5), and the realization of the weather shocks (8). At the optimum, for $t > 0$, the following first-order conditions must hold:

$$\frac{1}{C_t^F} = P_t \lambda_t^F, \tag{B-1}$$

$$\chi_H (H_t^F)^{\eta_H} = \lambda_t^F P_t^A (1-\alpha_A)\, Y_t^A \frac{1}{H_t^F}, \tag{B-2}$$

$$\lambda_t^L = \lambda_t^F P_t^M \tau_V \left(V_t^F\right)^{\phi_V - 1}, \tag{B-3}$$

$$\alpha_A \beta \mathbb{E}_t \lambda_{t+1}^F P_{t+1}^A Y_{t+1}^A \frac{1}{L_t^F} - \lambda_t^L + \beta \mathbb{E}_t \lambda_{t+1}^L (1-\delta_L) \Omega(\varepsilon_{t+1}^w) = 0, \tag{B-4}$$

where λ_t^F and λ_t^L represent the Lagrange multipliers associated with the flow budget constraint (9) and to the land accumulation equation (4), respectively. By combining the above conditions, one can easily obtain the two conditions determining the optimal labor supply and optimal decision regarding land accumulation:

$$\chi_H (H_t^F)^{\eta_H} = \frac{1}{C_t^F} p_t^A (1-\alpha_A)\, Y_t^A \frac{1}{H_t^F}, \tag{B-5}$$

$$p_t^M \tau_V \left(V_t^F\right)^{\phi_V - 1} = \beta \mathbb{E}_t \frac{C_t^F}{C_{t+1}^F} \left[\alpha_A p_{t+1}^A Y_{t+1}^A \frac{1}{L_t^F} + (1-\delta_L) p_{t+1}^M \tau_V \left(V_{t+1}^F\right)^{\phi_V - 1} \Omega(\varepsilon_{t+1}^w) \right], \tag{B-6}$$

where $p_t^A = P_t^A / P_t$ and $p_t^M = P_t^M / P_t$.

Manufacturing Sector

Intermediate Goods Producers Given the available technology (11) and the demand function $Y_{j,t}^M = \left(P_{j,t}^M / P_t^M\right)^{-\theta} Y_t^M$, the problem of a typical j firm is then to choose $\{H_{j,t}^{\bar{F}},\ K_{j,t}^{\bar{F}},\ P_{j,t}^M\}$ to maximize the expected discounted sum of profits.

At the optimum, the first-order conditions with respect to the two-factor inputs are,

$$\Phi_{j,t}(1-\alpha_M) B_M (K_{j,t-1}^{\bar{F}})^{\alpha_M} (H_{j,t}^{\bar{F}})^{-\alpha_M} = W_t, \tag{B-7}$$

$$\Phi_{j,t} \alpha_M B_M (K_{j,t-1}^{\bar{F}})^{\alpha_M - 1} (H_{j,t}^{\bar{F}})^{1-\alpha_M} = R_t^k, \tag{B-8}$$

where $\Phi_{j,t}$ denotes the nominal marginal cost of production. Since all firms have access to the same technology and face the same demand functional form, profit maximization implies that all firms choose the same price, that is $P_{j,t}^{\bar{F}} = P_t^{\bar{F}}$ for all $j \in (0, 1 - s_F)$, produce the same output $Y_t^{\bar{F}}$, with the same factor inputs. The optimal price setting delivers the following New Keynesian Phillips Curve:

$$(1-\theta)\, Y_t^M - \chi_P \left(\Pi_t^M - 1\right) \Pi_t^M Y_t^M + \chi_P \mathbb{E}_t Q_{t,t+1} \left(\Pi_{t+1}^M - 1\right) Y_{t+1}^M \left(\Pi_{t+1}^M\right)^2 + \theta \frac{\Phi_t^R}{p_t^M} Y_t^M = 0, \quad \text{(B-9)}$$

where $\Pi_t^M = P_t^M / P_{t-1}^M$ and $\Phi_t^R = \Phi_t / P_t$.

Households The typical household in this sector chooses $\{C_t^{\bar{F}}, H_t^{\bar{F}}, I_t^{\bar{F}}, K_t^{\bar{F}}, B_t^{\bar{F}}\}$ so to maximize the lifetime utility (13), given prices, taxes, the risk-free nominal interest rate, the initial stock of capital $K_{-1}^{\bar{F}}$, the budget constraint (15) and the accumulation equation of capital (16). At the optimum, the following first-order conditions must hold:

$$\frac{1}{C_t^{\bar{F}}} = P_t \lambda_t^{\bar{F}}, \quad \text{(B-10)}$$

$$\chi_H (H_t^{\bar{F}})^{\eta_H} = \lambda_t^{\bar{F}} W_t, \quad \text{(B-11)}$$

$$\lambda_t^q = \lambda_t^{\bar{F}} P_t^M, \quad \text{(B-12)}$$

$$\lambda_t^{\bar{F}} P_t^M + \beta(1-\delta_K) \mathbb{E}_t \lambda_{t+1}^{\bar{F}} P_{t+1}^M + \mathbb{E}_t \beta \lambda_{t+1}^{\bar{F}} R_{t+1}^k = 0, \quad \text{(B-13)}$$

$$\frac{1}{R_t} = \beta \mathbb{E}_t \left(\frac{\lambda_{t+1}^{\bar{F}}}{\lambda_t^{\bar{F}}} \right), \quad \text{(B-14)}$$

where λ_t^F and λ_t^q represent the Lagrange multipliers associated to the flow budget constraint (15) and to the land accumulation equation (16), respectively. Given the definition of $\lambda_t^{\bar{F}}$, the nominal discount factor in (B-9) is then $Q_{t,t+1} = \beta \left(\frac{\lambda_{t+1}^{\bar{F}}}{\lambda_t^{\bar{F}}} \right)$.

By combining the above conditions, one can easily obtain the optimal condition determining the optimal labor supply and the Euler equations on physical capital and risk-free bonds:

$$\chi_H (H_t^{\bar{F}})^{\eta_H} = \frac{1}{C_t^{\bar{F}}} w_t, \quad \text{(B-15)}$$

$$\frac{1}{R_t} = \beta \mathbb{E}_t \left(\frac{C_t^{\bar{F}}}{\Pi_{t+1} C_{t+1}^{\bar{F}}} \right), \quad \text{(B-16)}$$

$$p_t^M = \beta(1-\delta_K) \mathbb{E}_t \frac{C_t^{\bar{F}}}{C_{t+1}^{\bar{F}}} p_{t+1}^M + \beta \mathbb{E}_t \frac{C_t^{\bar{F}}}{C_{t+1}^{\bar{F}}} r_{t+1}^k, \quad \text{(B-17)}$$

where $\Pi_t = P_t / P_{t-1}$.

Decentralized Competitive Equilibrium

We are now ready to provide a formal definition for the decentralized competitive equilibrium of the economy. To this end, we define factor inputs in real terms as $w_t = W_t/P_t$ $r_t^k = R_t^k/P_t$, and as usual, we set aggregate nominal risk-free bonds to zero, $(1-s_F)B^{\bar{F}} = 0$.

Definition 1 *For a given monetary and fiscal policy mix determining $\{R_t, Tr_t^F, T_t^{\bar{F}}\}_{t=0}^{\infty}$ subject to the balanced-budget rule $s_F Tr_t^F = (1-s_F)T_t^{\bar{F}}$, and for a given set of the exogenous process on the weather $\{\varepsilon_t^w\}_{t=0}^{\infty}$, a competitive equilibrium for the distorted competitive economy is described by a sequence of allocations and prices $\{C_{A,t}^F, C_{M,t}^F, C_t^F, Y_t^A, C_{A,t}^{\bar{F}}, C_{M,t}^{\bar{F}}, C_t^{\bar{F}}, Y_t^M, \Pi_t, \Pi_t^M, \Phi_t^R, I_t^{\bar{F}}, K_t^{\bar{F}}, H_t^{\bar{F}}, H_t^F, V_t^F, L_t^F, w_t, r_t^k, p_t^A, p_t^M\}_{t=0}^{\infty}$, that for a given initial level of land and capital $\{L_{-1}, K_{-1}\}$ satisfy the following equilibrium conditions:*

1. $\left[\varphi(p_t^A)^{1-\mu} + (1-\varphi)(p_t^M)^{1-\mu}\right]^{\frac{1}{1-\mu}} = 1$

2. $C_{A,t}^F = \varphi C_t^F \left(p_t^A\right)^{-\mu}$

3. $C_{M,t}^F = (1-\varphi)\, C_t^F \left(p_t^M\right)^{-\mu}$

4. $p_t^A Y_t^A + Tr_t^F = C_t^F + p_t^M \tau_V \frac{(V_t^F)^{\phi_V}}{\phi_V}$

5. $Y_t^A = B_A(\Omega(\varepsilon_t^w) L_{t-1}^F)^{\alpha_A} (H_t^F)^{1-\alpha_A}$

6. $\chi_H (H_t^F)^{\eta_H} = \frac{1}{C_t^F} p_t^A \,(1-\alpha_A)\, Y_t^A \frac{1}{H_t^F}$

7. $p_t^M \tau_V \left(V_t^F\right)^{\phi_V - 1} = \beta \mathbb{E}_t \frac{C_t^F}{C_{t+1}^F} \left[\alpha_A p_{t+1}^A Y_{t+1}^A \frac{1}{L_t^F} + (1-\delta_L) p_{t+1}^M \tau_V \left(V_{t+1}^F\right)^{\phi_V - 1} \Omega(\varepsilon_{t+1}^w)\right]$

8. $L_t^F = (1-\delta_L)\Omega(\varepsilon_t^w) L_{t-1}^F + V_t^F$

9. $C_{A,t}^{\bar{F}} = \varphi C_t^{\bar{F}} \left(p_t^A\right)^{-\mu}$

10. $C_{M,t}^{\bar{F}} = (1-\varphi)\, C_t^{\bar{F}} \left(p_t^M\right)^{-\mu}$

11. $p_t^M Y_t^M - T_t^{\bar{F}} = C_t^{\bar{F}} + p_t^M I_t^{\bar{F}} + \frac{\chi_P}{2} \left(\Pi_t^M - 1\right)^2 p_t^M Y_t^M$

12. $p_t^M = \beta(1-\delta_K)\mathbb{E}_t \frac{C_t^{\bar{F}}}{C_{t+1}^{\bar{F}}} p_{t+1}^M + \beta \mathbb{E}_t \frac{C_t^{\bar{F}}}{C_{t+1}^{\bar{F}}} r_{t+1}^k$

13. $\frac{1}{R_t} = \beta \mathbb{E}_t \left(\frac{C_t^{\bar{F}}}{\Pi_{t+1} C_{t+1}^{\bar{F}}}\right)$

14. $\chi_H (H_t^{\bar{F}})^{\eta_H} = \frac{1}{C_t^{\bar{F}}} w_t$

15. $K_t^{\bar{F}} = (1-\delta_K) K_{t-1}^{\bar{F}} + I_t^{\bar{F}}$

16. $Y_t^M = B_M (K_{t-1}^{\bar{F}})^{\alpha_M} (H_t^{\bar{F}})^{1-\alpha_M}$

17. $\Phi_t^R (1-\alpha_M) \frac{Y_t^M}{H_t^{\bar{F}}} = w_t$

18. $\Phi_t^R \alpha_M \frac{Y_t^M}{K_{t-1}^{\bar{F}}} = r_t^k$

19. $\Pi_t = \Pi_t^M \frac{p_{t-1}^M}{p_t^M}$

20. $(1-\theta)Y_t^M - \chi_P \left(\Pi_t^M - 1\right) Y_t^M \Pi_t^M + \frac{\Phi_t^R}{p_t^M}\theta Y_t^M + \chi^P \beta \mathbb{E}_t \left(\frac{C_t^{\bar{F}}}{\Pi_{t+1} C_{t+1}^{\bar{F}}}\right) \left(\Pi_{t+1}^M - 1\right) Y_{t+1}^M \left(\Pi_{t+1}^M\right)^2 = 0$

21. $(1 - s_F)\, p_t^A C_{A,t}^{\bar{F}} = s_F p_t^M \left(C_{M,t}^F + \tau_V \frac{(V_t^F)^{\phi_V}}{\phi_V}\right)$

By using conditions #5, #14 and #17 in #7, to get rid of prices and imposing the steady state, under the special case of zero trend inflation, the condition describing the optimal choice of land accumulation at the decentralized equilibrium is given by

$$\beta \frac{\alpha_A (H_t^F)^{1+\eta_H}}{(1-\alpha_A)\, L^F} = [1 - \beta(1-\delta_L)] \frac{(H_t^{\bar{F}})^{1+\eta_H}}{(1-\alpha_M)\, Y_t^M} \tau_V \left(V^F\right)^{\phi_V - 1} \frac{\theta}{\theta - 1} \frac{C^{\bar{F}}}{C^F}. \tag{B-18}$$

From condition #20, which is the New Keynesian Phillips curve, we observe that at zero inflation, the real marginal cost of producing the manufacturing good is $\Phi^R = p^M(\theta-1)/\theta$. This is equivalent to $\Phi = P^M(\theta-1)/\theta$ when expressed in nominal terms. Noting that the gross markup, $\mathcal{M}^p$, is by definition equal to P^M/Φ and, therefore, to $\mathcal{M}^p \equiv \theta/(\theta-1)$, and that $\mathcal{H} \equiv C^{\bar{F}}/C^F$, we obtain the equivalent of equation (23) in the main text.

The Phillips Curve and the Inflationary Effects of an Adverse Weather Event

In order to understand how an adverse weather event hitting the agriculture sector propagates in the manufacturing sector leading to inflation also in this sector, it is sufficient to inspect the New Keynesian Phillips curve #20. By log-linearizing #20 around a zero-inflation steady state and using #1 and #19, we obtain what follows:

$$\pi_t^M = \frac{\theta - 1}{\chi^P} \hat{\Phi}_t^R + \beta \mathbb{E}_t \pi_{t+1}^M + \frac{\theta - 1}{\chi^P} \frac{\varphi}{1-\varphi} \hat{p}_t^A, \tag{B-19}$$

where hatted variables are in log deviation from their steady-state counterparts, and π_t^M denotes the core inflation rate. The above result shows that a change in the relative price of agricultural goods acts as a cost-push shock for the manufacturing sector, leading to inflation in that sector as well.[25] Following an adverse weather shock that affects only agriculture, farmers increase their demand for manufacturing inputs needed to restore the land. This excess of demand in the manufacturing sector generates inflationary pressure. However, since, at least initially, the adverse weather event causes a contraction in demand for manufacturing goods from households operating in this sector, there is a short-lived decline in marginal cost, which explains why, at least in the decentralized equilibrium under the non-optimal policy, core inflation initially decreases.

[25] This is consistent with Aoki (2001) who shows that an increase in the relative price of the flexible-price good enters as a positive shifter in the dynamic equation determining inflation in the sticky price sector.

Appendix C

In the present appendix, we derive the efficient allocation and show the dynamics of the economy in response to an adverse weather event. This will prove a useful benchmark for the analysis of the optimal policy mix discussed in the main text.

The Social Planner's Problem

The first-best allocation in any given period can be described as the solution to the following social planner's optimization problem: the social planner chooses $\{C^F_{A,t}, C^F_{M,t}, C^F_t, Y^A_t, C^{\bar{F}}_{A,t}, C^{\bar{F}}_{M,t}, C^{\bar{F}}_t, Y^M_t, I^{\bar{F}}_t, K^{\bar{F}}_t, H^{\bar{F}}_t, H^F_t, V^F_t, L^F_t\}$ to maximize the social welfare function:

$$\mathcal{U}_t = s_F \mathcal{U}^F_t + (1 - s_F)\,\mathcal{U}^{\bar{F}}_t, \tag{C-1}$$

where $\mathcal{U}^F_t$ and $\mathcal{U}^{\bar{F}}_t$ are the lifetime utility functions of farmers and non-farmer households defined in (7) and (13), subject to the following set of constraints:
(i) consumption baskets

$$\begin{aligned} C^F_t &= [\varphi^{\frac{1}{\mu}} {C^F_{A,t}}^{\frac{\mu-1}{\mu}} + (1-\varphi)^{\frac{1}{\mu}} {C^F_{M,t}}^{\frac{\mu-1}{\mu}}]^{\frac{\mu}{\mu-1}}, \\ C^{\bar{F}}_t &= [\varphi^{\frac{1}{\mu}} {C^{\bar{F}}_{A,t}}^{\frac{\mu-1}{\mu}} + (1-\varphi)^{\frac{1}{\mu}} {C^{\bar{F}}_{M,t}}^{\frac{\mu-1}{\mu}}]^{\frac{\mu}{\mu-1}}, \end{aligned}$$

(ii) available technologies

$$\begin{aligned} Y^A_t &= B_A(\Omega(\varepsilon^w_t)L^F_{t-1})^{\alpha_A}(H^F_t)^{1-\alpha_A}, \\ Y^M_t &= B_M(K^{\bar{F}}_{t-1})^{\alpha_M}(H^{\bar{F}}_t)^{1-\alpha_M}, \end{aligned}$$

(iii) accumulation equations of land and physical capital

$$\begin{aligned} L^F_t &= (1-\delta_L)\Omega(\varepsilon^w_t)L^F_{t-1} + V^F_t, \\ K^{\bar{F}}_t &= (1-\delta_K)K^{\bar{F}}_{t-1} + I^{\bar{F}}_t, \end{aligned}$$

(iv) resource constraints

$$\begin{aligned} s_F Y^A_t &= s_F C^F_{A,t} + (1-s_F)\,C^{\bar{F}}_{A,t}, \\ (1-s_F)\,Y^M_t &= s_F \left(C^F_{M,t} + \tau_V \frac{\left(V^F_t\right)^{\phi_V}}{\phi_V} \right) + (1-s_F)\,C^{\bar{F}}_{M,t} + (1-s_F)\,I^{\bar{F}}_t. \end{aligned}$$

It can be easily shown that at the optimum, the social planner allocates resources to rule out any possible misallocation of consumption. It follows that farmers and non-farmers benefit from the same level of consumption, so that $C^F_t = C^{\bar{F}}_t$, $C^F_{A,t} = C^{\bar{F}}_{A,t}$, and $C^F_{M,t} = C^{\bar{F}}_{M,t}$. Let $\lambda^{C_A}_t$ and $\lambda^{C_M}_t$ denote the marginal utility households derive from the consumption of agricultural and manufacturing goods. Then, at the optimum, the following conditions must hold:

$$\lambda^{C_A}_t\,(1-\alpha_A)\,\frac{Y^M_t}{H^F_t} = \chi_H (H^F_t)^{\eta_H}, \tag{C-2}$$

$$\lambda^{C_M}_t\,(1-\alpha_M)\,\frac{Y^A_t}{H^{\bar{F}}_t} = \chi_H (H^{\bar{F}}_t)^{\eta_H}, \tag{C-3}$$

$$\alpha_M \beta \mathbb{E}_t \lambda_{t+1}^{C_M} \frac{Y_{t+1}^M}{K_t^{\bar{F}}} + \beta(1-\delta_K)\mathbb{E}_t \lambda_{t+1}^{C_M} = \lambda_t^{C_M}, \tag{C-4}$$

$$\alpha_A \beta \mathbb{E}_t \lambda_{t+1}^{C_A} \frac{Y_{t+1}^A}{L_t^F} + \beta(1-\delta_L)\mathbb{E}_t \lambda_{t+1}^{C_M} \tau_V \left(V_{t+1}^F\right)^{\phi_V - 1} \Omega(\varepsilon_{t+1}^w) = \lambda_t^{C_M} \tau_V \left(V_t^F\right)^{\phi_V - 1}, \tag{C-5}$$

where (C-2) and (C-3) determine the optimal allocation of the two specific labor inputs in each sector, while (C-4) and (C-5) determine the optimal accumulation equation of physical capital and land.

A close inspection of the above conditions helps us understand the specific features of this economy. Consider the two conditions (C-2) and (C-3). Since labor is sector-specific, at the optimum, the disutility that farmers and non-farmers derive from labor (right-hand side of both conditions) must equalize the benefit derived from working more in each sector (left-hand side of both conditions). This benefit, in turn, depends on the marginal utility households derive from consuming the specific good that labor is able to produce.

Condition (C-4) equates the present discounted value of the expected marginal benefit derived from purchasing an additional unit of capital to the marginal cost, measured in terms of the utility loss from consuming fewer manufactured goods. The benefits on the left-hand side depend on the marginal product gains and the increased availability of capital in the following period.

Condition (C-5) describes the optimal accumulation equation of land. Since improving the quantity of usable land requires goods from manufacturing, the marginal cost of increasing land depends on the utility loss from consuming fewer manufactured goods. The benefits depend on the utility gains associated with larger agricultural production and the next-period marginal benefit derived from the resources saved due to the increased land accumulated in the current period. This last component is measured in terms of the utility gains from manufacturing goods.

By substituting (C-2) and (C-3) in (C-5), at steady state we obtain that the efficient condition of land accumulation is

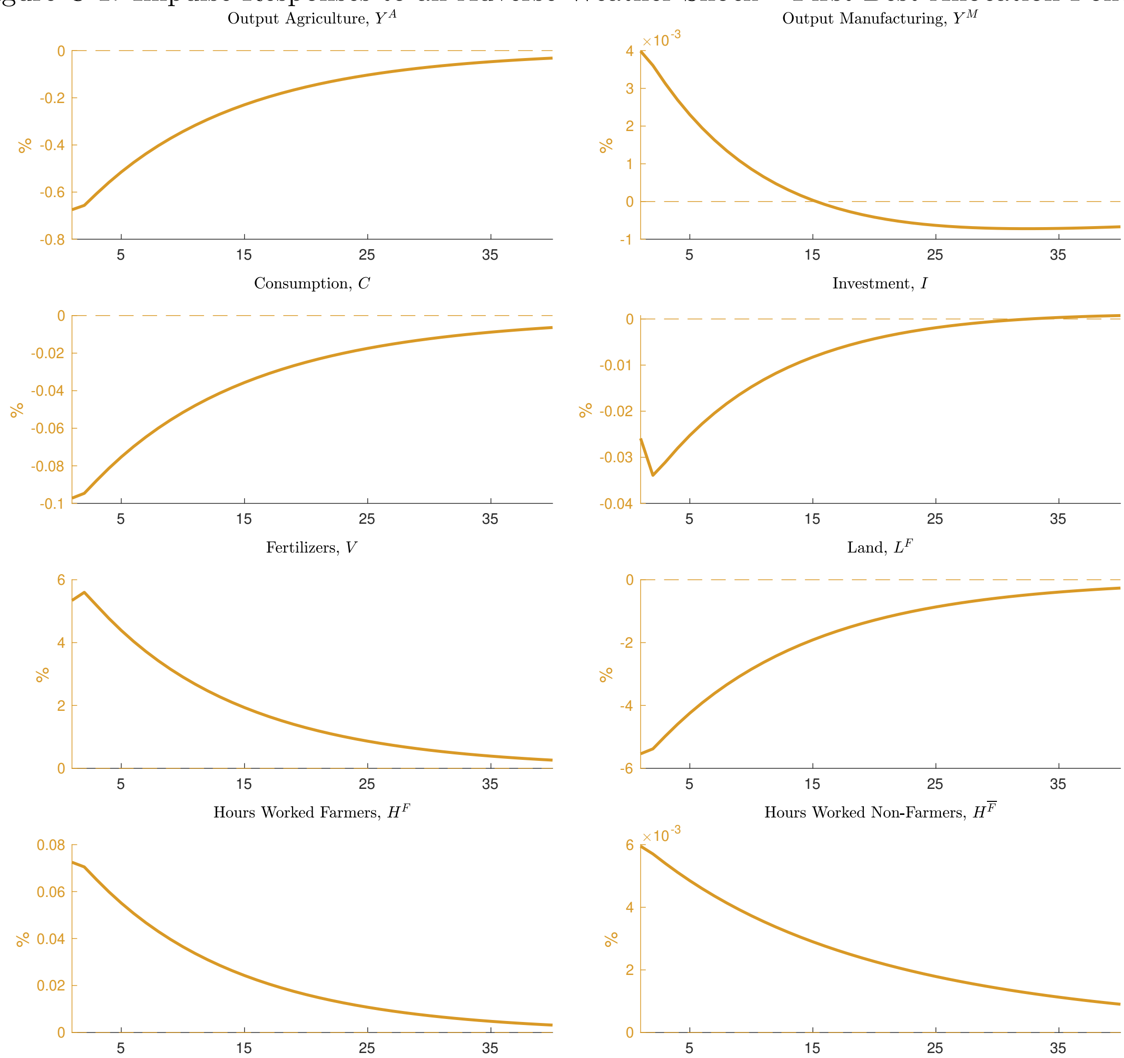
$$\beta \frac{\alpha_A (H_t^F)^{1+\eta_H}}{(1-\alpha_A)\, L^F} = \left[1 - \beta(1-\delta_L)\right] \frac{(H_t^{\bar{F}})^{1+\eta_H}}{(1-\alpha_M)\, Y_t^M} \tau_V \left(V^F\right)^{\phi_V - 1} \tag{C-6}$$

that is condition (22) in the main text.

Dynamics under the First-Best Allocation

We now characterize numerically the dynamic properties of the first-best allocation in response to an adverse weather shock by showing the impulse response functions of the main economic variables. Figure C-1 shows the results. In response to the weather shock, agricultural output shows a significant drop due to the reduction in the quality of the land. Clearly, the central planner allocates resources to repair and restore farmland. To do so, there is a need for an immediate increase in manufacturing output, which, in fact, goes up on impact. We observe that to facilitate the recovery, labor inputs increase in both sectors, while investments in physical capital slightly decline. By reducing investments in the manufacturing sector, the central planner reallocates resources to more immediate needs, such as supporting agricultural recovery and stabilizing consumption.

Figure C-1: Impulse Responses to an Adverse Weather Shock – First-Best Allocation Policy



Notes: The figure presents the impulse responses to a one standard deviation weather shock for the calibrated economy under the first-best allocation. All variables are reported as percentage deviations from their stochastic steady-state level.

Appendix D

The Ramsey Planner's Problem

In this appendix, we briefly describe the problem of the Ramsey planner and derive some of the results discussed in the main text. Consider the case in which the planner has access to both fiscal and monetary policies. The Ramsey optimal policy is determined by maximizing the social welfare function (26) with respect to the control variables, subject to the equilibrium constraints of the decentralized economy.

Since the size of the model does not allow us to combine all the constraints into a single implementability constraint, we follow a common approach in the literature. This involves a hybrid method where the competitive equilibrium conditions listed in Appendix B are summarized using a minimal set of equations that preserve analytical tractability. Let $\mathbf{\Lambda}_t$ be the set of Lagrangian multipliers associated with the constraints, $\{\lambda_{1,t},\ \lambda_{2,t},\ ...\lambda_{18,t}\}$ and $\mathbf{x}_t$ indicate the set of control variables $\{C_{A,t}^F,\ C_{M,t}^F,\ C_t^F,\ Y_t^A,\ C_{A,t}^{\bar{F}},\ C_{M,t}^{\bar{F}},\ C_t^{\bar{F}},\ Y_t^M,\ \Pi_t^M,\ \Phi_t^R,\ I_t^{\bar{F}},\ K_t^{\bar{F}},\ H_t^{\bar{F}},\ H_t^F,\ V_t^F,\ L_t^F,\ p_t^A,\ p_t^M,\ R_t,\ Tr_t^F\}$, then, consistent with a timeless perspective approach, the Ramsey problem can be stated as follows:

$$
\begin{aligned}
&\underset{\{\mathbf{\Lambda}_t\}_{t=0}^{\infty}}{Min}\ \underset{\{\mathbf{x}_t\}_{t=0}^{\infty}}{Max}\ \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ \left[s_F \left(\log(C_t^F) - \chi_H \frac{(H_t^F)^{1+\eta_H}}{1+\eta_H} \right) + (1-s_F) \left(\log(C_t^{\bar{F}}) - \chi_H \frac{(H_t^{\bar{F}})^{1+\eta_h}}{1+\eta_H} \right) \right] \right. \\
&+\lambda_{1,t} \left[1 - \left[\varphi (p_t^A)^{1-\mu} + (1-\varphi)(p_t^M)^{1-\mu} \right]^{\frac{1}{1-\mu}} \right] \\
&+\lambda_{2,t} \left[C_{A,t}^F - \varphi C_t^F \left(p_t^A \right)^{-\mu} \right] \\
&+\lambda_{3,t} \left[C_{M,t}^F - (1-\varphi)\, C_t^F \left(p_t^M \right)^{-\mu} \right] \\
&+\lambda_{4,t} \left[p_t^A Y_t^A + Tr_t^F - C_t^F - p_t^M \tau_V \frac{(V_t^F)^{\phi_V}}{\phi_V} \right] \\
&+\lambda_{5,t} \left[B_A (\Omega(\varepsilon_t^w) L_{t-1}^F)^{\alpha_A} (H_t^F)^{1-\alpha_A} - Y_t^A \right] \\
&+\lambda_{6,t} \left[C_t^F \chi_H (H_t^F)^{\eta_H} - p_t^A \left(1-\alpha_A\right) \frac{Y_t^A}{H_t^F} \right] \\
&+\lambda_{7,t} \frac{1}{C_t^F} p_t^M \tau_V \left(V_t^F \right)^{\phi_V - 1} - \lambda_{7,t-1} \frac{1}{C_t^F} \left[\alpha_A p_t^A Y_t^A \frac{1}{L_{t-1}^F} + (1-\delta_L) p_t^M \tau_V \left(V_t^F \right)^{\phi_V-1} \Omega(\varepsilon_t^w) \right] \\
&+\lambda_{8,t} \left[C_{A,t}^{\bar{F}} - \varphi C_t^{\bar{F}} \left(p_t^A \right)^{-\mu} \right] \\
&+\lambda_{9,t} \left[C_{M,t}^{\bar{F}} - (1-\varphi)\, C_t^{\bar{F}} \left(p_t^M \right)^{-\mu} \right] \\
&+\lambda_{10,t} \left[p_t^M Y_t^M - \frac{s_F}{1-s_F} Tr_t^F - \frac{\chi^P}{2} \left(\Pi_t^M - 1 \right)^2 p_t^M Y_t^M - C_t^{\bar{F}} - p_t^M I_t^{\bar{F}} \right] \\
&+\lambda_{11,t} \frac{p_t^M}{C_t^{\bar{F}}} - \lambda_{11,t-1} \left[\frac{1}{C_t^{\bar{F}}} \left((1-\delta_K) p_t^M \Theta(\varepsilon_t^w) + \alpha_M \Phi_t^R \frac{Y_t^M}{K_{t-1}^{\bar{F}}} \right) \right] \\
&+\lambda_{12,t} \left[C_t^{\bar{F}} \chi_H (H_t^{\bar{F}})^{\eta_H} - \Phi_t^R (1-\alpha_M) \frac{Y_t^M}{H_t^{\bar{F}}} \right] \\
&+\lambda_{13,t} \left[K_t^{\bar{F}} - (1-\delta_K) K_{t-1}^{\bar{F}} - I_t^{\bar{F}} \right] \\
&+\lambda_{14,t} \left[B_M (K_{t-1}^{\bar{F}})^{\alpha_M} (H_t^{\bar{F}})^{1-\alpha_M} - Y_t^M \right] \\
&+\lambda_{15,t} \left(1 - \theta - \chi^P \left(\Pi_t^M - 1 \right) \Pi_t^M + \frac{\Phi_t^R}{p_t^M} \theta \right) \frac{p_t^M Y_t^M}{C_t^{\bar{F}}} + \lambda_{15,t-1} \chi^P \left(\frac{p_t^M}{C_t^{\bar{F}}} \right) \left(\Pi_t^M - 1 \right) Y_t^M \Pi_t^M \\
&+\lambda_{16,t} \left[s_F Y_t^A - s_F C_{A,t}^F - (1-s_F)\, C_{A,t}^{\bar{F}} \right] \\
&+\lambda_{17,t} \frac{p_t^M}{C_t^{\bar{F}} R_t} - \lambda_{17,t-1} \frac{p_t^M}{\Pi_t^M C_t^{\bar{F}}}
\end{aligned}
$$

$$+\lambda_{18,t}\left[L_t^F-(1-\delta_L)\Omega(\varepsilon_t^w)L_{t-1}^F-V_t^F\right]\Big\}.$$

Consider the first-order condition with respect to inflation in the manufacturing sector, Π_t^M. At the steady state the condition reads as

$$\lambda_{10}\chi^P\left(\Pi^M-1\right)p^MY^M=0, \tag{D-1}$$

where we have used the fact that since the Ramsey planner controls the nominal interest rate, R_t, the constraint represented by the Euler's equation of the non-farmers is never binding, that is $\lambda_{17,t}=0$. This implies that at the Ramsey steady state, since $\lambda_{10}>0$, the optimal inflation rate is zero, that is $\Pi^M=1$.

Appendix E

This appendix presents some extra results we refer to in the main text.

Stochastic Steady State Under Different Scenarios

Table E-1 reports the stochastic steady under different policy scenarios. The stochastic steady state is defined as the equilibrium at which agents would choose to stay in the absence of shocks, although they account for future volatility. On the concept of stochastic steady state, see Juillard and Kamenik (2005). Sometimes, this is also referred to as risky steady-state. See Coeurdacier et al. (2011). In the table, the last two columns represent scenarios where both policies are non-optimal, distinguishing between Taylor rules targeting headline and core inflation. In these scenarios, inflation target is set to zero, while the fiscal transfer to farmers is set to the optimal value as in the Ramsey steady state. This approach ensures that, in all cases considered in this table, the deterministic steady state aligns with the one presented in the first column of Table 2.

Table E-1: Stochastic Steady State Under Different Policy Scenarios

	Ramsey Mix	Ramsey Fiscal		Ramsey Monetary	Non-Optimal	
		HIT	CIT		HIT	CIT
Output in agriculture Y^A	2.7985	2.7987	2.7987	2.7988	2.7988	2.7988
Output in manufacturing Y^M	1.4488	1.4488	1.4488	1.4487	1.4487	1.4487
Land L^F	4.7574	4.7576	4.7573	4.7573	4.7573	4.7573
Physical capital $K^{\bar{F}}$	13.5382	13.5389	13.5386	13.5366	13.5377	13.5373
Labor of farmers H^F	0.2340	0.2340	0.2340	0.2340	0.2340	0.2340
Labor of non-farmers $H^{\bar{F}}$	0.3670	0.3670	0.3670	0.3670	0.3670	0.3670
Consumption of farmers C^F	1.3079	1.3077	1.3076	1.3075	1.3075	1.3075
Consumption of non-farmers $C^{\bar{F}}$	1.1601	1.1602	1.1602	1.1602	1.1602	1.1602
Headline inflation Π	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Core inflation Π^M	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Transfers to farmers Tr^F	0.8052	0.8049	0.8049	0.8048	0.8048	0.8048
Consumption heterogeneity $\mathcal{H}$	0.8870	0.8872	0.8873	0.8873	0.8873	0.8873
Gross markup $\mathcal{M}^P$	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
Total welfare $\mathcal{U}$	-17.2984	-17.3064	-17.3022	-17.3015	-17.3110	-17.3033
Welfare of farmers $\mathcal{U}^F$	33.6465	33.5491	33.5479	33.5493	33.5471	33.5489
Welfare of non-farmers $\mathcal{U}^{\bar{F}}$	-33.4039	-33.3836	-33.3777	-33.3772	-33.3891	-33.3795

Moments Under Different Scenarios

Tables E-2 and E-3 present the unconditional mean and volatility for a selection of variables under different policy scenarios. As in the previous section, the model in the non-optimal policy scenario is solved around the same deterministic steady state as in the Ramsey scenarios.

Table E-2: Means Under Different Scenarios

	Ramsey Mix	Ramsey Fiscal		Ramsey Monetary	Non-Optimal	
		HIT	CIT		HIT	CIT
Output in agriculture Y^A	2.8048	2.8050	2.8051	2.8051	2.8050	2.8051
Output in manufacturing Y^M	1.4488	1.4487	1.4487	1.4487	1.4487	1.4487
Land L^F	4.9043	4.9040	4.9041	4.9038	4.9037	4.9038
Physical capital $K^{\bar{F}}$	13.5378	13.5369	13.5368	13.5370	13.5372	13.5370
Labor of farmers H^F	0.2339	0.2340	0.2340	0.2339	0.2339	0.2339
Labor of non-farmers $H^{\bar{F}}$	0.3670	0.3670	0.3670	0.3670	0.3670	0.3670
Consumption of farmers C^F	1.3083	1.3077	1.3077	1.3078	1.3078	1.3078
Consumption of non-farmers $C^{\bar{F}}$	1.1605	1.1606	1.1606	1.1606	1.1605	1.1606
Headline inflation Π	1.0000	0.9999	0.9999	1.0000	0.9999	0.9999
Core inflation Π^M	1.0000	0.9999	0.9999	1.0000	0.9999	0.9999
Transfers to farmers Tr^F	0.8053	0.8047	0.8047	0.8048	0.8048	0.8048
Consumption heterogeneity $\mathcal{H}$	0.8870	0.8875	0.8875	0.8874	0.8874	0.8874
Gross markup $\mathcal{M}^P$	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
Total welfare $\mathcal{U}$	-17.2925	-17.3024	-17.2977	-17.2950	-17.3059	-17.2976
Welfare of farmers $\mathcal{U}^F$	33.6523	33.5333	33.5394	33.5565	33.5538	33.5558
Welfare of non-farmers $\mathcal{U}^{\bar{F}}$	-33.3980	-33.3734	-33.3691	-33.3710	-33.3844	-33.3741

Notes: The table reports the unconditional mean for a selection of variables under different policy scenarios.

Table E-3: Volatility Under Different Policy Scenarios

	Ramsey Mix	Ramsey Fiscal		Ramsey Monetary	Non-Optimal	
		HIT	CIT		HIT	CIT
Output Y	0.0343	0.0455	0.0277	0.0341	0.0569	0.0309
Output in agriculture Y^A	0.5813	0.5510	0.5717	0.5712	0.5741	0.5705
Output in manufacturing Y^M	0.0020	0.0322	0.0081	0.0012	0.0377	0.0042
Consumption of farmers C^F	0.0336	0.1333	0.0640	0.0501	0.0520	0.0497
Consumption of non-farmers $C^{\bar{F}}$	0.0360	0.0319	0.0334	0.0331	0.0374	0.0323
Headline inflation Π	0.0097	0.0078	0.0112	0.0094	0.0114	0.0122
Core inflation Π^M	0.0000	0.0076	0.0053	0.0000	0.0117	0.0061
Transfers to farmers Tr^F	0.0186	0.0955	0.0378	0.0000	0.0000	0.0000

Notes: The table reports the unconditional standard deviation for a selection of variables under different policy scenarios.

Unconditional Welfare

Table E-4 presents the counterpart of Table 3 based on unconditional welfare measures. As can be seen, the results discussed in Section 5.4 hold using this metric.

Table E-4: Welfare - Unconditional Measures

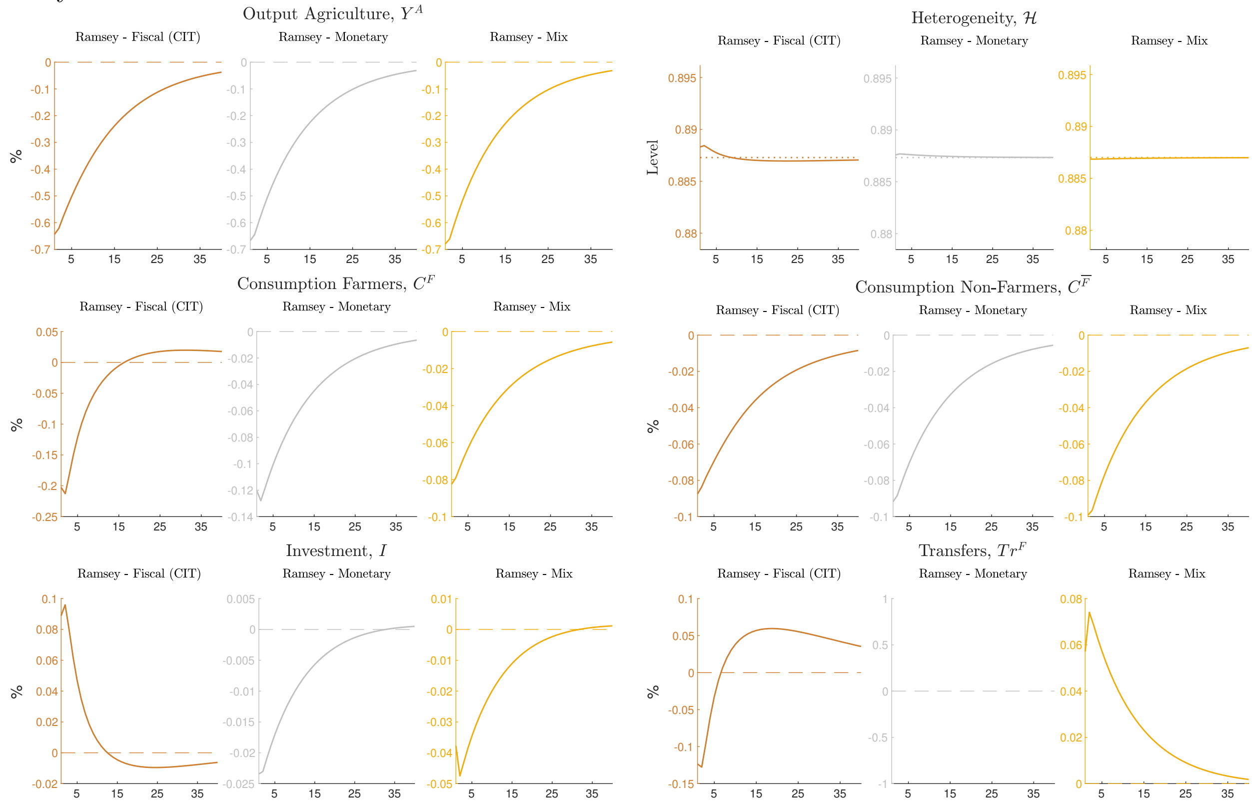
	Social		Farmers		Non-Farmers	
	level	cost	level	cost	level	cost
Ramsey Mix	-17.2925	0	33.6523	0	-33.3980	0
Ramsey Fiscal with HIT	-17.3024	0.0044	33.5333	0.0525	-33.3734	-0.0108
Ramsey Fiscal with CIT	-17.2977	0.0023	33.5394	0.0498	-33.3691	-0.0127
Ramsey Monetary	-17.2950	0.0011	33.5565	0.0423	-33.3710	-0.0119
Non-Optimal with HIT	-17.3059	0.0059	33.5538	0.0435	-33.3844	-0.0060
Non-Optimal with CIT	-17.2976	0.0022	33.5558	0.0426	-33.3741	-0.0105

Notes: Welfare costs are measured with respect to the Ramsey policy mix and are expressed in percentage. A positive figure indicates that welfare is higher under the Ramsey policy than under the alternative policy rules.

Dynamic Analysis Under Different Ramsey Policies

Figure E-1 complements the findings of Section 5.3 by comparing the dynamic behavior of additional macroeconomic variables in response to an adverse shock hurting agriculture, under different assumptions regarding the instruments available to the Ramsey planner.

Figure E-1: Impulse Responses to an Adverse Weather Shock - Ramsey Policy with Different Policy Instruments



Notes: The figure presents the impulse responses to a one standard deviation weather shock when the Ramsey planner has only access to fiscal policy with core inflation targeting (left-hand figures, bronze lines), to monetary policy (figures in the middle, silver lines) and to both instruments (right-hand figures, gold lines). All variables are reported as percentage deviations from their stochastic steady-state level, with the exception of consumption heterogeneity expressed in level.

The Optimal Policy Mix When Weather Shocks Adversely Affect Both Sectors

In this section of the appendix, we extend the analysis to examine the optimal policy mix when weather shocks negatively impact both the agriculture and manufacturing sectors. In particular, equations (11), (16) are now replaced by

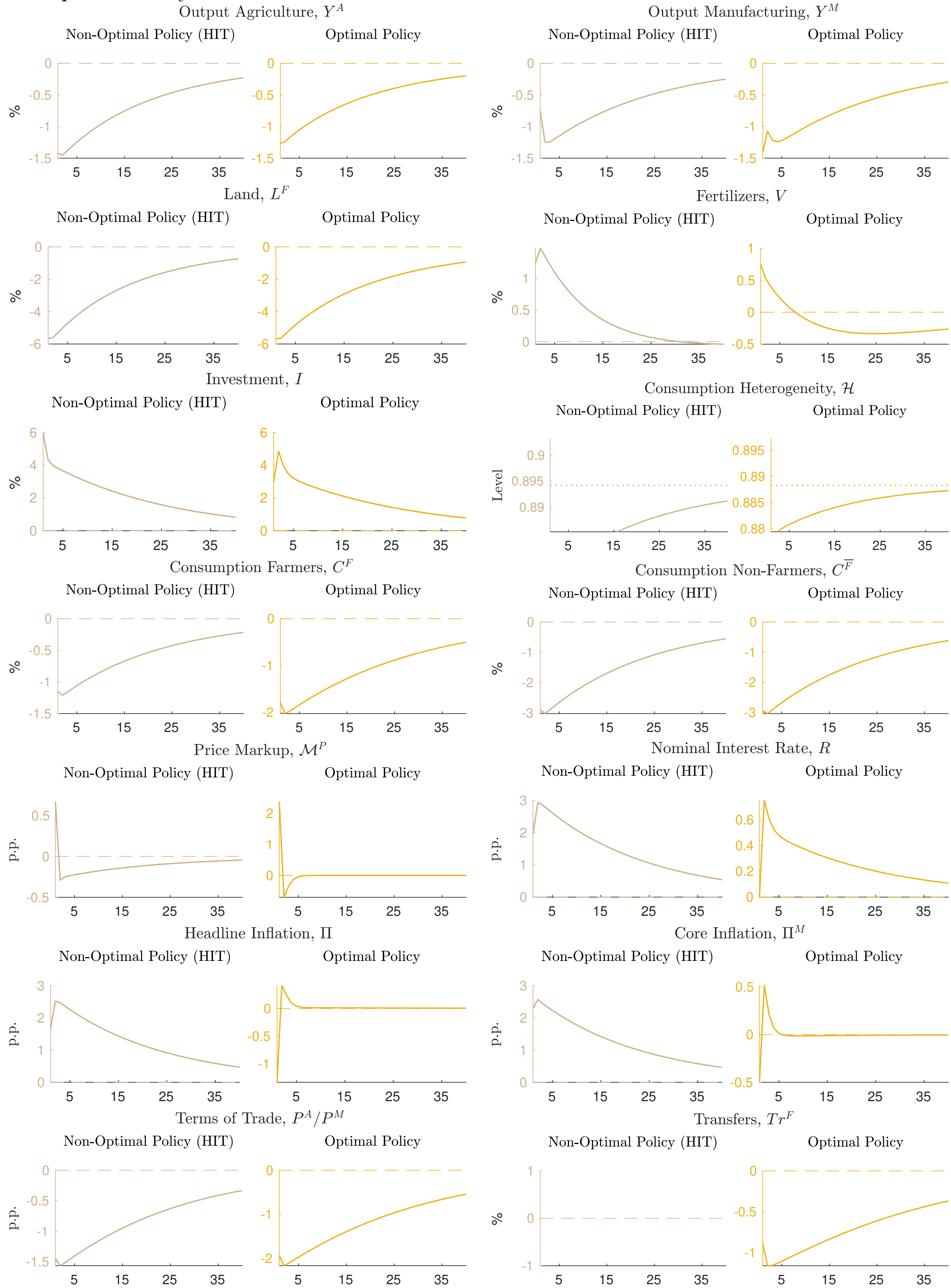
$$Y_{j,t}^{M} = B_M((\Omega(\varepsilon_t^w)K_{j,t-1}^{\bar{F}})^{\alpha_M}(H_{j,t}^{\bar{F}})^{1-\alpha_M} \tag{E-1}$$

and

$$K_t^{\bar{F}} = (1-\delta_K)\Omega(\varepsilon_t^w)K_{t-1}^{\bar{F}} + I_t^{\bar{F}}. \tag{E-2}$$

where $\Omega(\varepsilon_t^w)$ is the same as in (3) and (4) since we assume weather events symmetrically affect both sectors. Figure E-2 compares the dynamics of a selection of variables across the three Ramsey policy scenarios, while Table E-5 presents the corresponding results for welfare. As shown, deviating from the Ramsey policy mix is still more costly when the Ramsey planner has no access to monetary policy. However, unlike in the case of asymmetric shocks hurting only agriculture, targeting headline inflation is now less detrimental to welfare than targeting core inflation.

Figure E-2: Impulse Responses to an Adverse Symmetrical Weather Shock - Ramsey Policy v. Non-Optimal Policy



Notes: The figure presents the impulse responses to a one standard deviation weather shock affecting both sectors of the economy under the Ramsey equilibrium (right-hand figures, gold lines) and the non-optimal policy equilibrium with headline inflation targeting (left-hand figures, grey lines). All variables are reported as percentage deviations from their stochastic steady-state level, with the exception of the nominal interest rate and the inflation rates, which are reported as annualized percentage point deviations, the markup in percentage points deviations, and consumption heterogeneity expressed in level.

Table E-5: Welfare under Symmetric Shocks - Conditional Measures

	Social		Farmers		Non-Farmers	
	level	cost	level	cost	level	cost
Ramsey Mix	-14.4651	0	36.4864	0	-30.5727	0
Ramsey Fiscal with HIT	-17.0030	1.1256	29.5607	3.1015	-31.7235	0.5088
Ramsey Fiscal with CIT	-17.7289	1.4498	28.7375	3.4765	-32.4186	0.8174
Ramsey Monetary	-14.5899	0.0551	34.8804	0.7108	-30.2293	-0.1514
Non-Optimal with HIT	-18.3806	1.7418	34.0244	1.0917	-34.9477	1.9482
Non-Optimal with CIT	-18.6185	1.8486	33.9624	1.1194	-35.2412	2.0802

Notes: The table reports the results on welfare when adverse weather shocks hurt symmetrically both sectors. Welfare costs are measured with respect to the Ramsey policy mix and are expressed in percentage. A positive figure indicates that welfare is higher under the Ramsey policy than under the alternative policy rules.

Agents Can Borrow from Each Other

What if, in response to weather shocks, farmers are allowed to borrow from non-farmers? In this section of the appendix, we extend the analysis to consider the case in which agents of the economy can borrow from each other at the risk-free rate of R. This implies that equation (9), is now replaced by

$$P_t^A(Y_t^A - C_{A,t}^F) + P_t Tr_t^F + B_t^F = R_{t-1}B_{t-1}^F + P_t^M C_{M,t}^F + P_t^M \tau_V \frac{\left(V_t^F\right)^{\phi_V}}{\phi_V}, \tag{E-3}$$

where B_t^F, when negative, represents the amount of debt held by farmers. In equilibrium, the total amount of credit in the economy is zero:

$$s_F B_t^F + (1 - s_F) B_t^{\bar{F}} = 0. \tag{E-4}$$

It follows that condition (E-5) now determines the net debt (or credit) position of farmers:

$$(1 - s_F)\, P_t^A C_{A,t}^{\bar{F}} + s_F \left(B_t^F - R_{t-1}B_{t-1}^F\right) = s_F P_t^M \left(C_{M,t}^F + \tau_V \frac{\left(V_t^F\right)^{\phi_V}}{\phi_V .}\right) \tag{E-5}$$

It can be shown, that when the economy is hit by an adverse weather event, farmers borrow from non-farmers, ending up with a positive amount of debt that is rolled over indefinitely.

When we allow agents to borrow from each other, the Ramsey fiscal policy remains indeterminate, as time-varying fiscal transfers already allow the planner to immediately support farmers in response to the shocks, preventing them from taking on debt. Nonetheless, we are able to solve the model under optimal monetary policy, as well as under the two non-optimal policy scenarios with constant fiscal transfers and either core inflation targeting or headline inflation targeting. Table E-6 presents the conditional welfare measures and associated welfare costs relative to the scenario where both policies are optimally implemented but there is no borrowing. As we can observe, the results closely resemble those of Table 3, with core inflation targeting still outperforming headline inflation in terms of policy effectiveness.

Table E-6: Welfare when Agents Can Borrow from Each Other - Conditional Measures

	Social		Farmers		Non-Farmers	
	Level	Cost	Level	Cost	Level	Cost
Ramsey Monetary	-17.3017	0.0008	33.5476	0.0430	-33.3770	-0.0126
Non-Optimal with HIT	-17.3125	0.0055	33.5453	0.0440	-33.3905	-0.0067
Non-Optimal with CIT	-17.3042	0.0018	33.5471	0.0432	-33.3801	-0.0113

Notes: The table reports the results on welfare when adverse weather shocks hurt only the agriculture sector. Welfare costs are measured with respect to the Ramsey policy mix and are expressed in percentages. A positive figure indicates that welfare is higher under the Ramsey policy than under the alternative policy rules.