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Abstract

In this paper, we investigate the impact of adverse weather shocks on Colombian economic activity, with a particular emphasis on the effects on agricultural output, food and headline inflation. Existing literature and empirical evidence suggest that adverse weather shocks, such as those related to the El Niño event in 2015-2016, lead to decreases in agricultural output and increases in inflation without significantly affecting total GDP growth. To further assess this result, we evaluate the impact of ENSO fluctuations using a BVAR-X model. Based on these findings, we propose a small open economy New Keynesian model that introduces a novel channel through which relative prices (agricultural vs. non-agricultural) are affected by weather shocks, allowing us to incorporate this empirical evidence into a structural model for Colombia.

Keywords: Weather shocks, El Niño Southern Oscillation (ENSO), Small Open Economy New Keynesian Models.

JEL: Q54, E52, E31.

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1 Introduction

Understanding the impact of weather shocks on the economy has become increasingly relevant, as these phenomena can affect GDP growth, agricultural sector performance, and inflation. This increased relevance is underscored by a recent surge in studies within the economic research agenda examining these impacts (e.g., Berg et al., 2023, Gallic and Vermandel, 2020, Mohaddes et al., 2023, Callahan and Mankin, 2023, Berg et al., 2023, Cevik and Jalles, 2023,Gallic and Vermandel, 2020,Andersson et al., 2020, Acevedo et al., 2020, Matthes and Phan, 2022, Natoli, 2023, Romero and Naranjo-Saldarriaga, 2022). Nonetheless, due to the heterogeneous nature of weather-related shocks and their varying impacts across sectors and geographies, no consensus has been reached on whether these shocks predominantly affect the supply or demand side of the economy. From a policy perspective, as climate change potentially alters the frequency and intensity of adverse weather events, these shocks could become a more frequent source of business cycle fluctuations in the coming years (Gallic and Vermandel, 2020). This highlights the importance of studying the various transmission mechanisms of these shocks to the economy.

In the case of Colombia, weather fluctuations associated with the El Niño Southern Oscillation (ENSO) can trigger both droughts (during El Niño phases) and floods (during La Niña phases). Previous ENSO episodes have significantly impacted Colombia's economy, mainly affecting food prices, inflation, and agricultural output.

The primary objective of this study is to investigate the macroeconomic implications of ENSO weather shocks in Colombia. To achieve this, we employ a BVAR-X model and a two-sector Small Open Economy New Keynesian (SOE-NK) model specifically designed for a small open economy. The model incorporates weather shocks, allowing us to investigate their influence on agricultural output and inflation. Our study's contribution to the literature is threefold: it adds to the existing empirical literature on the macroeconomic effects of weather shocks; introduces these shocks into a macroeconomic model that helps us dissect the transmission channels of these shocks; and the model is suitable for short-term policy analysis and understanding the trade-offs that these shocks may impose. Notably, the model's structure aligns with the small open economy DSGE models routinely used at central banks in emerging markets.

The remainder of this study is organized as follows. In section 2, we present a brief overview of the significance of ENSO fluctuations and review the recent empirical literature linking weather shocks to GDP growth and inflation. In section 3, we outline the primary stylized facts regarding ENSO fluctuations, economic activity, and inflation in Colombia. We employ a BVAR-X model to observe that adverse ENSO shocks result in increased food prices and headline inflation, along with a decrease in agricultural production, while their impact on the overall GDP appears negligible.

Section 4 introduces a SOE-NK model with several notable features. It integrates the impact of weather shocks on the agricultural sector, following the approach of Gallic and Vermandel, 2020, by incorporating a damage function. It assumes price rigidities in both the agricultural and non-agricultural sectors through the inclusion of intermediate firms, aggregate firms, capital producers for each sector, and Calvo Pricing, resulting in prices that do not coincide with marginal costs. The model also factors in the total aggregate firms and includes a monetary policy rule as an integral part of its structure. It assumes imperfect pass-through, influencing the pricing of imported goods for each sector. In section 5, we present the dynamics of the model in response to ENSO shocks. Lastly, section 6 outlines the conclusions.

2 Significance of ENSO Fluctuations, Weather Shocks, and Economic Activity

The El Niño Southern Oscillation (ENSO) is a recurring climatic pattern involving temperature changes in the waters and shifts in atmospheric pressure in the Pacific Ocean. Figure 1 depicts the sea-surface temperature anomalies during the potent 2015-2016 El Niño episode, one of the strongest occurrences since 1950 (L'Heureux, 2016). Figure 2 presents the evolution of the Oceanic Niño Index (ONI), which measures sea surface temperature anomalies in the Pacific Ocean, based on a threshold of +/- 0.5 degrees Celsius.

This phenomenon influences global weather and climate patterns, resulting in widespread environmental and societal consequences, thereby underscoring its significance (McPhaden et al., 2020). However, it is essential to understand that ENSO's characteristics are shaped by the long-term average background climatic conditions within which it evolves (Masson-Delmotte et al., 2021; McPhaden et al., 2020). Since the Industrial Revolution in the mid-18th century, these background conditions have significantly transformed, largely due to human activities. This shift has accelerated in recent decades, with human activities pushing heat-trapping greenhouse gas concentrations in the atmosphere to unprecedented levels (McPhaden et al., 2020).

In this context, the risks and uncertainties underscore the need to understand the potential mechanisms through which ENSO fluctuations will evolve and how they may impact the economy. According to the 2021 IPCC report (Masson-Delmotte et al., 2021), climate models do not provide a consensus on a systematic change in the amplitude of ENSO sea surface temperature variability under medium confidence scenarios. However, it is very likely that rainfall variability related to ENSO will significantly increase by the latter half of the 21st century. Recent research by the US National Oceanic and Atmospheric Administration (NOAA) suggests that under

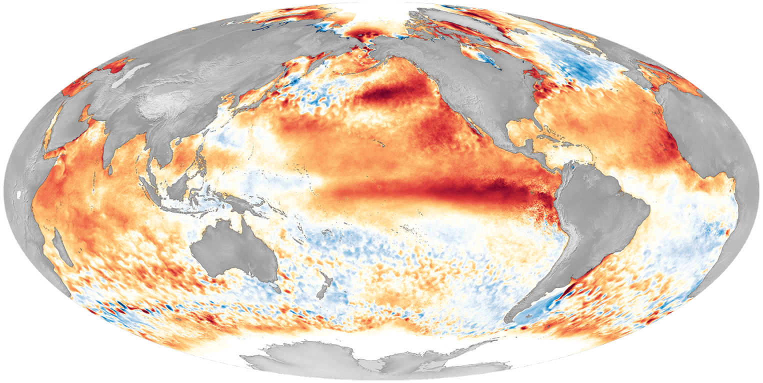

Figure 1: A very strong El Niño in 2015-2016 – large 'red tongue' in equatorial Pacific. Source: NOAA/NESDIS.

aggressive greenhouse gas emission scenarios, the frequency of extreme El Niño and La Niña events could potentially double by the end of the century, changing from approximately one event every 20 years to one every 10 years. Furthermore, the intensity of these events may become even stronger than those witnessed today (McPhaden et al., 2020).

Recent research has highlighted the heterogeneous effects that ENSO fluctuations, and particularly strong El Niño events, can have on economic activity. For instance, Callahan and Mankin, 2023 shows that El Niño persistently reduces economic growth and that national economies are sensitive to El Niño even when warming is taken into account, arguing that future global economic growth could decline due to the anthropogenic intensification of ENSO variability. Cashin et al., 2017 show evidence of considerable heterogeneities in the responses of different countries to El Niño shocks. While Australia, Chile, Indonesia, India, Japan, New Zealand, and South Africa face a short-lived fall in economic activity in response to an El Niño shock, other countries (including the United States and the European region) experience a growth-enhancing effect. Furthermore, most countries in their sample experience short-term inflationary pressures as both energy and non-fuel commodity prices increase.

In Colombia, ENSO fluctuations typically lead to decreases in agricultural output and increases in food and headline inflation, without significantly affecting total GDP growth. Given the country's heavy reliance on hydroelectric energy generation, these fluctuations also have a significant impact on electricity prices. Key studies documenting these stylized facts for Colombia, particularly the effects of El Niño on prices, are encapsulated in works by Bejarano-Salcedo et al., 2020, Romero et al., 2017, Abril-Salcedo et al., 2020, and Romero and Naranjo-Saldarriaga, 2022. These studies have consistently found that adverse weather events associated with El Niño tend to significantly escalate food and headline inflation. Furthermore, Romero

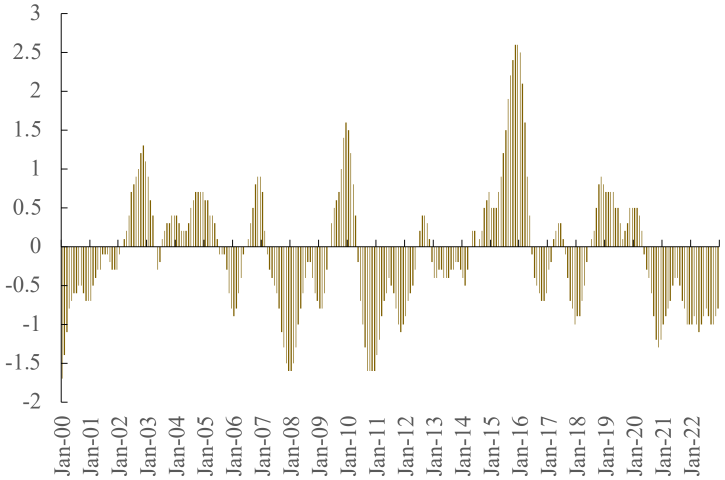

Figure 2: ENSO fluctuations. Sea surface temperature anomalies in Celsius degrees. Source: NOAA/NESDIS.

et al., 2017 projected that an adverse El Niño event could result in a 0.6% negative impact on GDP.

There is also an expanding literature on specific crops that may be affected by these fluctuations. For example, Bastianin et al., 2018 demonstrate that despite the overall agricultural sector being affected by El Niño, La Niña events (i.e., negative shocks to ENSO) depress Colombian coffee production and exports while increasing prices, underscoring the complex nature of these shocks. To synthesize the stylized facts regarding overall economic activity and prices since 2000, the subsequent section presents a BVAR-X model, enabling us to assess the recent historical impact of ENSO fluctuations on Colombia's agricultural sector and inflation.

3 Some Stylised Facts

In order to better understand the impact of ENSO shocks on the Colombian economy, we employ an empirical approach using a Bayesian Vector AutoRegressive model with exogenous variables (BVAR-X). The model we propose is of the following form:

$$y_t = Ay_{t-1} + Bx_t + \mu_t \tag{1}$$

In this model, the vector y_t comprises:

$$y_t = \begin{pmatrix} \tilde{y}_t^* \\ \tilde{z}_t^* \\ \widetilde{inv}_t \\ \widetilde{cons}_t \\ \tilde{y}_t \\ \widetilde{agri}_t \\ \tilde{\pi}_t^{food} \end{pmatrix} \qquad (2)$$

Here, $\tilde{y}_t$, $\tilde{z}_t$, $\widetilde{inv}_t$, $\widetilde{cons}_t$, $\tilde{y}_t$, and $\widetilde{agri}_t$ correspond to external output, real exchange rate, investment, consumption, total output, and agricultural sector gaps respectively. Each variable is presented as a deviation from a long-term trend.[1] The variable $\tilde{\pi}_t^f$ represents food inflation, detrended using the inflation target.[2]

The exogenous matrix X_t in our model includes the ENSO fluctuations. For the rest of the system, we identify shocks using Cholesky decomposition, positioning the agricultural output and food inflation as the most contemporaneously endogenous variables. We estimate our model using quarterly data from 2000Q1 to 2019Q4. Inclusion of data from the post-COVID-19 period did not significantly impact the results related to activity. However, the effect on inflation series may require further exploration.[3] Standard information criteria were used to determine the lag structure, which in most cases suggested four lags for our quarterly model. Our BVAR-X models were estimated using an independent Normal-Wishart prior, with the assumption that the variance-covariance matrix Σ is unknown. This kind of BVAR-X models have been previously used to study the impact of ENSO fluctuation in Colombia, particularly regarding its influence on different meassures of inflation expectations (Romero & Naranjo-Saldarriaga, 2022).

Our BVAR-X model reveals several stylized facts about the impact of ENSO shocks on the Colombian economy. Figure 4 illustrates the response of selected variables to a 1-degree Celsius shock in the ENSO index. Our findings suggest a substantial increase in inflation, indicating a significant effect on consumer prices. This observation aligns with existing Colombian literature. We also note a decline in agricultural output, thereby highlighting the vulnerability of the agricultural sector

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[1] The empirical exercise results shown here use the HP filter. Additional exercises employing alternative detrending methods, such as the Hamilton filter, lead to similar qualitative results.

[2] Alternative specifications using food inflation $\tilde{\pi}_t^f$ were also performed. Generally, and in accordance with the literature for Colombia, ENSO fluctuations—particularly those related to El Niño—tend to impact inflation.

[3] There are several elements complicating the analysis of the relation between ENSO, inflation, and food inflation in 2021 and 2022, including the strong pick-up in global inflation during 2021-2022, the impact of relative prices of foodstuffs, and an unusually long and intense La Niña event during this period.

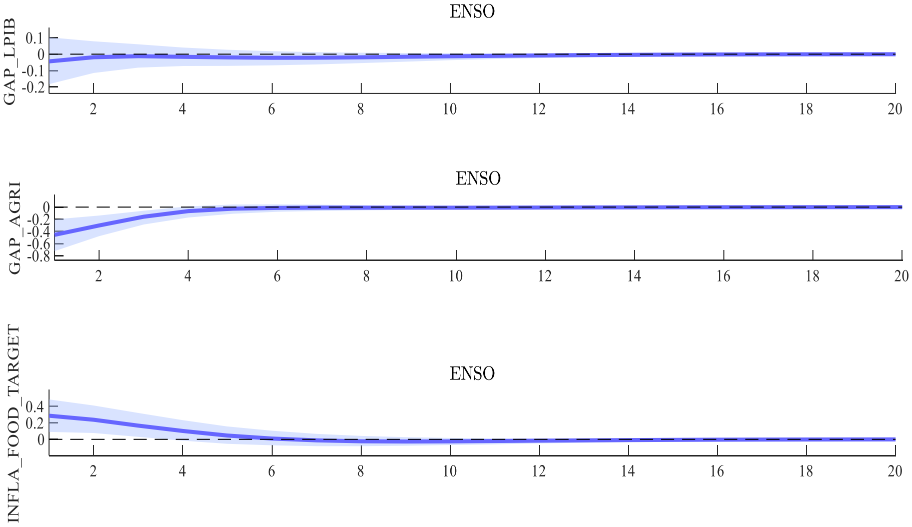

Figure 3: Impulse responses of selected variables to a 1 Celsius degree shock in the ENSO index (68% confidence intervals). Source: Authors' calculations.

to weather shocks. Despite these observable impacts on the agricultural sector, the overall effect on GDP seems relatively muted and is not statistically significant in our sample, underscoring the complex nature of weather shocks' effects on different economic sectors. Nonetheless, the impulse responses reveal a slight decrease in our measure of economic activity. In summary, ENSO shocks in Colombia can be viewed as supply (cost-push) shocks where increases in the ENSO index (evidenced by higher sea surface temperatures in the Pacific Ocean) lead to inflation, reductions in the agricultural sector, and a slight impact on overall economic activity (included as an output gap in our BVAR-X model).

In our exercises, and for the estimation sample, we find small and statistically insignificant negative variations in investment and consumption. Furthermore, excluding these variables from the BVAR-X model did not alter our results. In the Appendix, we present the complete impulse responses to an ENSO shock with BVAR-X specifications that utilize food inflation and an alternative specification that uses headline inflation. Nonetheless, is important to highlight that these estimations only cover a relatively recent period and they could change in the future.

4 Model

Our model is a two-sector, two-good economy in a small open economy setup with a flexible exchange rate regime. In our analysis of the macroeconomic implications of weather shocks, we further refine the model established by Gallic and Vermandel, 2020, by incorporating a number of important new features. Firstly, we acknowledge the presence of price rigidities in both sectors under consideration, namely the agricultural and non-agricultural sectors. This is achieved by introducing intermediate firms, aggregate firms, and capital producers for each sector, leading to a model where prices are not equivalent to marginal costs. We demonstrate this by the incorporation of Calvo Pricing.

Additionally, we introduce a monetary policy rule, specifically adopting a Taylor Rule, which has been calibrated in line with prior studies conducted in the Colombian context. Lastly, we acknowledge the influence of an imperfect pass-through effect, which is particularly evident in the imported goods of each sector. This effect arises due to a combination of the small open economy (SOE) setup of our model and the aforementioned price rigidities. This inclusion helps us to capture more realistically how changes in international prices translate into domestic prices, a factor that can be highly influential in the context of weather-related shocks.

A simplified structure of the model is depicted in Figure 4, where households receive revenues from agricultural and non-agricultural firms, as well as transfers from the government. The households consume locally produced agricultural and non-agricultural goods, as well as imported goods. They also pay taxes and invest in local and external bonds. The two sectors, agricultural and non-agricultural, maximize their profits in the first stage of production, while distributors create price rigidities. The agricultural sector is directly affected by weather shocks, which increase marginal costs of production, leading to higher food inflation and decreased agricultural output. In the next subsection, we will present the main structure of our model.

4.1 Households

Following Gallic and Vermandel, 2020, we use a standard household maximization process. The economy consists of a continuum of identical households indexed by $j \in [0, 1]$. These households consume, save, and work in the two productive sectors. The representative household maximizes its expected sum of utilities given by:

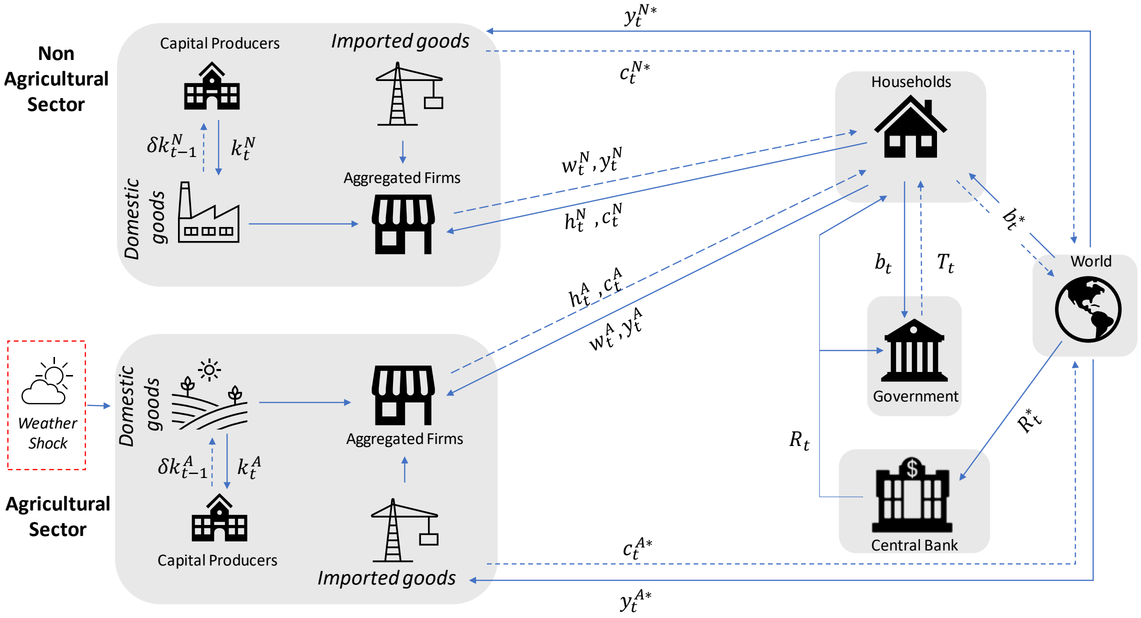

Figure 4: Model structure. Source: Authors' design.

$$E_t \sum_{\tau=0}^{\infty} \left[\frac{1}{1-\sigma}(C_{JT+\tau} - bC_{t-1+\tau})^{1-\sigma} - \frac{\chi \varepsilon^H t + \tau}{1+\sigma H} h_{jt+\tau}^{1+\sigma_H} \right] \tag{3}$$

Here, $\in [0,1]$ represents the discount factor, C_{jt} is the consumption index that aggregates domestic and imported agricultural and non-agricultural consumption, $b \in [0,1]$ represents consumption habits, h_{jt} is a labor effort index for the agricultural and non-agricultural sectors, and $\sigma > 0$ and $\sigma_H > 0$ denote consumption aversion and labor disutility coefficients, respectively. The labor supply between the agricultural and non-agricultural sectors exhibits imperfect substitutability, which is captured by a Constant Elasticity of Substitution (CES) labor disutility index of hours worked in the non-agricultural and agricultural sectors:

$$h_{jt} = \left[(h^N jt)^{1+\iota} + (h^A jt)^{1+\iota} \right]^{\frac{1}{1+\iota}} \tag{4}$$

The parameter $\iota \geq 0$ represents the substitutability between sectors, accounting for the costs associated with labor reallocation.

Expressed in nominal terms, the budget constraint for the representative household is represented as:

$$\sum_{s=(N,A)} W_t^s h_t^s + R_{t-1}B_{o,t-1} + s_t R_{t-1}^* B_{t-1}^* - T_t + \\ P_t^N \xi_t^N + P_t^A \xi_t^A + P_t^{CN}\xi_t^{CN} + P_t^{CA}\xi_t^{CA} \geq P_t C_t + B_t + s_t B_t^* + P^N s_t \phi(B_t^*) \tag{5}$$

In this equation, W_t^s represents wages in sector s at time t, h_t^s denotes labor effort in sector s at time t, R_{t-1} represents the nominal return on domestic bonds, $B_{o,t-1}$ represents the holdings of domestic bonds, s_t is the nominal exchange rate, R_{t-1}^* represents the nominal return on foreign currency-denominated bonds, B_{t-1}^* represents the holdings of foreign currency-denominated bonds, T_t represents government taxes, $P_t^N \xi_t^N$ and $P_t^A \xi_t^A$ represent benefits coming from the non-agricultural and agricultural sectors, respectively, $P_t^{CN}\xi_t^{CN}$ represents benefits associated with non-agricultural consumption, $P_t^{CA}\xi_t^{CA}$ represents benefits associated with agricultural consumption, $P_t C_t$ represents the cost of consumption, B_t represents savings, $s_t B_t^*$ represents foreign currency savings and $\phi(B_t^*) = 0.5\Xi_\beta (b_t^*)^2$[4] represent a bond premium risk cost.

The representative household allocates total consumption C_{jt} between two types of consumption goods produced by the non-agricultural (N) and agricultural (A) sectors determine by a CES bundle:

$$C_{jt} = \left[(1-\varphi)^{\frac{1}{\mu}}(C_{jt}^N)^{\frac{\mu-1}{\mu}} + (\varphi)^{\frac{1}{\mu}}(C_{jt}^A)^{\frac{\mu-1}{\mu}}\right]^{\frac{\mu}{\mu-1}} \tag{6}$$

Each index C_{jt}^N , C_{jt}^A is also a composite consumption subindex composed of domestically and foreign produce goods:

$$C_{jt}^{d,s} = (1-\alpha_s)\left(\frac{P_t^{d,s}}{P_t^s}\right)^{-\mu_s} C_{jt}^s \tag{7}$$

$$C_{jt}^{s*} = \alpha_s \left(e_t^* \frac{P_t^{s*}}{P_t^s}\right)^{-\mu_s} C_{jt}^s \tag{8}$$

Where α is the share of foreign goods, μ is the elasticity of substitution between home and foreign goods and $s = N, A$. The demands can be expressed as a fraction of the total consumption index adjusted by their respective relative prices:

$$C_{jt}^N = (1-\varphi)\left(\frac{P_t^N}{P_t}\right)^{-\mu} C_{jt} \tag{9}$$

$$C_{jt}^A = \varphi\left(\frac{P_t^A}{P_t}\right)^{-\mu} C_{jt} \tag{10}$$

Where φ represents the share of every sector consumption over the total.

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[4] the parameters $\xi_\beta > 0$ denotes the magnitude of the cost paid by the domestic households when purchasing a foreign bond

4.2 Non-agricultural sector

In our Non-agricultural sector we have a standard setup. There are 4 types of good producers:

1. **Producers of domestic goods:**

   In each period t, the domestic good Y_t^N is produced by a perfectly competitive firm combining intermediate goods according to the production function:

   $$Y_t^N = \left(\int_0^1 Y_{j,t}^{N(1-\frac{1}{\epsilon_{Nd}})} dj \right)^{\frac{\epsilon_{Nd}}{\epsilon_{Nd}-1}} \tag{11}$$

   where ϵ_{Nd} is the elasticity of substitution between goods varieties.

   As a result, the demand for the intermediate good j and the price of the domestic good are determined by:

   $$Y_{j,t}^N = \left(\frac{p_{j,t}^{Nd}}{p_t^{Nd}} \right)^{-\epsilon_{Nd}} Y_t^{Nd} \tag{12}$$

   $$p_t^{Nd} = \left(\int_0^1 (p_{j,t}^{Nd})^{1-\epsilon_{Nd}} dj \right)^{\frac{1}{1-\epsilon_{Nd}}} \tag{13}$$

   Where Y_t^{Nd} is the demand of the domestic non agricultural final good.

2. **Producers of intermediate goods:** They operate in monopolistic competition and set prices as in Calvo, 1983. Their output is a homogeneous good that we call domestic output, they use labor and capital as production inputs, the first one is demanded to the households and second one is rented to capital producers.

   $$Y_{j,t}^N = z_{y,t}^N (K_{j,t-1}^N)^{\alpha} \left(h_{j,t}^N \right)^{1-\alpha} \tag{14}$$

   where $\alpha, \in (0, 1)$. α is the capital share of total output, K_{t-1}^N is the capital,$1-\alpha$ is the share of labor in production and $z_{y,t}^N$ is an exogenous transitory productivity shock.

3. **Producers of intermediate imports goods:** There is a continuum $z \in (0,\ 1)$ of imports good producers that use homogeneous imports goods to produce differentiates intermediate good. They act in monopolistic competition environment and produce imported goods for consumption and use non-transformed imports as input. Their production function is given by:

$$Y_t^{Nf}(z) = Im_t(z) \tag{15}$$

The demand for the good z is:

$$Y_{t+s}^{Nf}(z) = \left(\frac{P_{t+s}^{Nf}(z)}{P_{t+s}^{Nf}}\right)^{-\epsilon_{Nf}} Y_{t+s}^{Nf} \tag{16}$$

Where ϵ_{Nf} is the elasticity of substitution across z goods in the production of a final imported good. It can also be define as: $Y_t^{Nf} = C_t^{Nf}$.

4. **Non agricultural capital producers:** These firms seek to maximize profits and operate in a perfectly competitive market. At the end of the period they buy the depreciated physical capital stock $(1-\delta)k_{t-1}$ from the intermediate firms and use I_t^N to produce a new stock k_t^N, which is sold to intermediate firms that is used for production in the next period.

   Their capital production technology is described by the following maximization problem:

$$maxE_t\left[\sum_{s=0}^{\infty}(\beta)^s\frac{\Lambda_{t+s}}{\Lambda_t}\left[r_{t+s}^{Nk}K_{t-1+s}^N - P_{t+s}^{Nd}I_{t+s}^N\right]\right] \tag{17}$$

   where K_{t-1}^N is per-capital the stock of non agricultural capital available at time t, δ is the depreciation rate. The stock of capital evolves accordingly to the following equation:

$$K_{t+s}^N = (1-\delta)K_{t+s-1}^N + z_{Nx,t+s}I_{t+s}\left(1 - f\left(\frac{I_{t+s}^N}{I_{t+s-1}^N}\right)\right) \tag{18}$$

   with $f(.)$ as a quadratic cost function given by $f\left(\frac{I_t^N}{I_{t-1}^N}\right) = \frac{a}{2}\left(\frac{I_t^N}{I_{t-1}^N} - 1\right)^2$. The investment first order condition is defined as:

$$\mathrm{P}_t^{Nd} = Q_t^N z_{x,t}\left[1 - f\left(\frac{I_t^N}{I_{t-1}^N}\right) - I_t^N f'\left(\frac{I_t^N}{I_{t-1}^N}\right)\right] - \beta E_t\left(\frac{\Lambda_{t+1}}{\Lambda_t}\right)Q_{t+1}^N z_{x,t+1}f'\left(\frac{I_{t+1}^N}{I_t^N}\right) \tag{19}$$

   And the optimal condition for capital is:

$$Q_t^N = \beta E_t\left(\frac{\Lambda_{t+1}}{\Lambda_t}\right)\left[r_{t+1}^{Nk} + (1-\delta)Q_{t+1}^N\right] \tag{20}$$

4.3 Agricultural sector

The agricultural sector in our model incorporates several key features based on the framework developed by Gallic and Vermandel, 2020. To account for the influence of ENSO fluctuations on agricultural goods' production, we assume that the weather shock variable related with ENSO, ϵ_t^W, follows a stochastic AR(1) process given by:

$$\log(\epsilon_t^W) = \rho_W \log(\epsilon_{t-1}^W) + \sigma_W \eta_t^W, \qquad \eta_t^W \sim N(0,1). \tag{21}$$

In 21 we proposed a simple AR(1) process for the ENSO fluctuation, where $\rho_W \in [0,1)$ is the persistent of the weather (ENSO) related shock and $\sigma_W \geq 0$ is the standard deviation. Analogously to the Non Agricultural sector, we have 4 types of good producers:

1. **Producers of domestic goods:** The domestic good Y_t^A is produced by a perfectly competitive firm combining intermediate goods according to the production function:

   $$Y_t^A = \left(\int_0^1 {Y_{j,t}^A}^{1-\frac{1}{\epsilon_H}} dj \right)^{\frac{\epsilon_{Ad}}{\epsilon_{Ad}-1}} \tag{22}$$

   where ϵ_{Ad} is the elasticity of substitution between goods varieties. The resulting demand for the intermediate good j and the price of the domestic good are:

   $$Y_{j,t}^A = \left(\frac{p_{j,t}^{Ad}}{p_t^{Ad}} \right)^{-\epsilon_{Ad}} Y_t^{Ad} \tag{23}$$

   $$p_t^A = \left(\int_0^1 (p_{j,t}^A)^{1-\epsilon_A} dj \right)^{\frac{1}{1-\epsilon_{Ad}}} \tag{24}$$

   Where Y_t^{Ad} is the demands of the domestic agricultural final good.

2. **Producers of intermediate goods:** They employ the Cobb-Douglas production function to describe the relationship between agricultural output (y_{it}^A), land (l_{it}), physical capital inputs (k_{it-1}), and labor inputs (h_{it}):

   $$y_{it}^A = [\Omega(\epsilon_t^W) l_{it-1}]^{\omega} \left[\epsilon_t^Z \left(K_{it-1}^A\right)^{\alpha_a} \left(\kappa_A h_{it}^A\right)^{1-\alpha_a} \right]^{1-\omega}, \tag{25}$$

   where $\Omega(\epsilon_t^W)$ represents a damage function capturing the influence of exogenous weather conditions on agricultural production, following the approach of Nordhaus (1991):

   $$\Omega(\epsilon_t^W) = (\epsilon_t^W)^{-\theta}, \tag{26}$$

where θ determines the elasticity of land productivity with respect to weather conditions. In the model, when the agricultural sector is affected by an ENSO shock, the damage function creates a decrease in agricultural output, and increase in the marginal cost of agricultural production and thus affecting agricultural (food) prices.

In line with Gallic and Vermandel, 2020 we include a time varying land productivity to capture the damage inflicted after this episodes, and the time require to recover the average productivity levels. We assume that each farmer owns his proportion of the land with a productivity that follows and endogenous law of motion:

$$\ell_{it} = \left[(1-\delta_l) + \nu(x_{it})\right]\ell_{it-1}\Omega(\epsilon_t^W) \tag{27}$$

Where x_{it} represents the farm's expenditure to maintain farmland productivity[5], and $\nu(.)$ denotes the associated cost function. There is not concrete studies or micro-evidence about the function form of the land cost but in line with Gallic and Vermandel, 2020 we adopt a conservative approach where: $\nu(x_{it}) = \frac{\tau}{\phi}x_{it}^{\phi}$ the parameters τ and ϕ represents the amount of per capita land, and the returns of the land, respectively.

Finally, the law of motion for physical capital in the agricultural sector is given by:

$$i_{it}^A = k_{it}^A - (1-\delta_k)k_{it-1}^A, \tag{28}$$

where δ_k represents the depreciation rate of physical capital.

3. **Producers of intermediate imports goods:** There is a continuum $z \in (0,1)$ of imports good producers that use homogeneous imports goods to produce differentiates intermediate good. The technology is given by:

$$Y_t^{Af}(z) = Im_t^A(z) \tag{29}$$

The demand for the good z is:

$$Y_{,t+s}^{Af}(z) = \left(\frac{P_{t+s}^{Af}(z)}{P_{t+s}^{Af}}\right)^{-\epsilon_{Af}} Y_{t+s}^{Af}$$

Where ϵ_{Af} is the elasticity of substitution across z goods in the production of a final imported good. It can also be define as: $Y_t^{Af} = C_t^{Af}$.

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[5] x_{it} represent all the spending used to maintain the farmland productivity such as pesticides, herbicides, seed, fertilizers, water and others

4. **Agricultural capital producers:** Similar to the Non Agricultural sector, capital production technology is described by the following maximization problem:

$$maxE_t \left[\sum_{s=0}^{\infty} (\beta)^s \frac{\Lambda_{o,t+s}}{\Lambda_{o,t}} \left[r^{Ak}_{t+s} K^A_{t-1+s} - P^N_{t+s} I^A_{t+s} \right] \right] \tag{30}$$

Their optimal investment decision is:

$$\mathrm{P}^N_t = Q^A_t z_{x,t} \left[1 - f\left(\frac{I^A_t}{I^A_{t-1}} \right) - I^A_t f'\left(\frac{I^A_t}{I^A_{t-1}} \right) \right] - \beta E_t \left(\frac{\Lambda_{t+1}}{\Lambda_t} \right) Q^A_{t+1} z_{x,t+1} f'\left(\frac{I^A_{t+1}}{I^A_t} \right) \tag{31}$$

And their optimal capital decision is:

$$Q^A_t = \beta E_t \left(\frac{\Lambda_{t+1}}{\Lambda_t} \right) \left[r^{kA}_{t+1} + (1-\delta) Q^A_{t+1} \right] \tag{32}$$

4.4 Price rigidities

Our modeling framework for price stickiness is analogous to the one employed in the primary Central Bank's structural model (PATACON, González-Gómez et al., 2011). We incorporate a Calvo pricing mechanism, which captures the behavior of firms in setting their prices. In our model, only a randomly selected fraction $(1-\theta)$ of firms have the ability to optimize their prices, while the remaining firms adjust their prices according to an inflation rule. Specifically, the price adjustment rule for these firms is given by the expression:

$$P^{Sf}_t(z) = P^{sf}_{t-1}(z) \pi^{\iota_{sf}}_{t-1} \bar{\pi}^{1-\iota_{sf}}, \qquad s = A, NA,$$

where ι_{Af} represents a parameter controlling the degree of price indexation. This approach allows for heterogeneity in price adjustment behavior among firms, which aligns with empirical evidence and introduces realistic dynamics into our model.

Moreover, the application of Calvo pricing is extended to foreign firms to introduce an element of imperfect pass-through (PT). By applying Calvo pricing to foreign firms, we capture the phenomenon where changes in international prices do not fully translate into domestic prices due to various factors. This imperfect pass-through effect arises from a combination of the small open economy (SOE) setup of our model and the price rigidities associated with Calvo pricing. The incorporation of imperfect pass-through allows us to more accurately represent how changes in international prices impact domestic prices, which is particularly relevant in the context of studying small open economy models. By accounting for these effects, our model captures a more realistic interplay between domestic and international price dynamics and provides valuable insights into the macroeconomic consequences of weather-related shocks.

4.5 Monetary policy

The monetary policy in our model is based on the same Taylor Rule employed in the primary Central Bank's structural model. Under the inflation targeting regime, the central bank controls the short-term nominal interest rate and sets it according to the following rule:

$$\frac{R_t}{\bar{R}} = \left(\frac{R_{t-1}}{\bar{R}}\right)^{\Phi R} \left[\left(\frac{\Pi_t}{\bar{\Pi}}\right)^{\Phi\Pi} \left(\frac{Y_t}{\bar{Y}}\right)^{\Phi Y}\right]^{1-\Phi R} \frac{1}{\epsilon^M}, \tag{33}$$

where R_t represents the current short-term nominal interest rate, R_{t-1} is the lagged short-term nominal interest rate, $\bar{R}$ represents the neutral interest rate, Π_t represents the current inflation rate, $\bar{\Pi}$ denotes the target inflation rate, Y_t represents the current output level, $\bar{Y}$ denotes the long term output growth, ΦR, $\Phi\Pi$, and ΦY are the policy rule coefficients, and ϵ^M represents the monetary policy shock. This rule allows the central bank to adjust the nominal interest rate based on the current and lagged values of interest rates, inflation, and output, contributing to the control and stabilization of the macroeconomic variables in our model.

4.6 Fiscal Policy

The public authority in our model consumes some non-agricultural output G_t, issues debt b_T at a real interest rate r_t and charges lump sum taxes T_t. Public spending is assumed to be exogenous $G_t = Y_t^N g_{\epsilon t}^G$, where $g \in [0, 1)$ is a fixed fraction of non-agricultural goods g affected by a standard AR(1) stochastic shock:

$$log(\epsilon_t^G) = \rho_G log(\epsilon_{t-1}^G) + \sigma_G \eta_t^G, \qquad \eta_t^G \sim N(0, 1), \tag{34}$$

where $1 \geq \rho_G \geq 0$ and $\sigma_G \geq 0$. This shock captures variations in absorption which are not taken into account in our setup such as political cycles and international demand in intermediate markets.

The government budget constraint equates spending plus interest payment on existing debt to new debt issuance and taxes:

$$G_t + r_{t-1} b_{t-1} = b_t + T_t \tag{35}$$

4.7 Foreign economy

Following Gallic and Vermandel, 2020 the external sector is represented by a set of four equations that determines an endowment economy with an exogenous foreign consumption. In each period foreign households solve the following optimization problem.

$$\max_{c_t^*, b_t^*} E_t \left[\sum_{\tau=0}^{\infty} \beta^{\tau} \epsilon_{t+\tau}^{*} log(c_{t+\tau}^{*}) \right] \tag{36}$$

$$s.t \qquad r_{t-1}^{*} b_{t-1}^{*} = c_t^{*} + b_t^{*} \tag{37}$$

Where $\epsilon_{t+\tau}^{*}$ is define as:

$$log(\epsilon_t^{*}) = \rho_{\epsilon^*} log(\epsilon_{t-1}^{*}) + \sigma_{\epsilon^*} \eta_t^{\epsilon^*} \tag{38}$$

The exogenous external consumption is determine as:

$$log(c_t^{*}) = (1 - \rho_c^{*}) log(\overline{c}_t^{*} + \rho_c^{*} log(c_{t-1}^{*}) + \sigma_c \eta_t^{c^*} \tag{39}$$

Where $\eta_t^{c^*} \sim N(0,1)$, and the standard deviation of the shock is represented by $\sigma_c > 0$ and $\overline{c}_t^{*}$ is the steady state of the foreign economy consumption.
An increase in the foreign demand induce a increment in the exportation of Colombian goods, and subsequently causing an appreciation of the foreign exchange rate. On the other hand a temporary preferences shock shock, $\eta_t^{e^*} \sim N(0,1)$ affects the household's discount factor, leading to a decrease in the foreign real interest rate and consequently the capital flows. The budget constraint comprises consumption and the purchase of domestic bonds, which are remunerated at a predetermined real rate r_{t-1}^{*}. Under the assumption of no specific sectoral shocks, all sectoral prices in the foreign economy are perfectly synchronized, denoted as $P_t^{*} = P_t^{A*} = P_t^{N*}$.

4.8 Aggregation and equilibrium conditions

The economy cleaning market conditions are determine when supply is equal to aggregate demand. For the non agricultural sector, it can be express in real terms as:

$$(1 - n_t) y_t^{N} = c_t^{d,N} + c_t^{exp,N} + g_t + i_t + n_t x_t + \phi(b_t^{*} \tag{40}$$

Where $c_t^{exp,N}$ are the non agricultural exports and are define as: $(1-\varphi)\alpha_N \left(\frac{p_t^{d,N}}{rer_t}\right)^{-\mu_N} c_t^{*}$.

For the agricultural sector, the cleaning market condition can be express in real terms as:

$$n_t y_t^{A} = c_t^{d,A} + c_t^{exp,A} \tag{41}$$

Where $c_t^{exp,A}$ are the agricultural exports and are define as: $\varphi \alpha_A \left(\frac{p_t^{d,A}}{rer_t}\right)^{-\mu_A} c_t^*$.

The total supply for non agricultural and agricultural sector is given by $\int_1^{n_t} y_i t^N \, di = (1 - n_t) y_t^N$ and $\int_{n_t}^0 y_i t^A \, di = n_t y_t^A$ respectively, and the aggregate real production is given by:

$$y_t = (1 - n_t) p_t^N y_t^N + n_t p_t^A y_t^A \tag{42}$$

Given the fact that we include intermediate inputs, as the land expenditures, we can define the GDP as:

$$gdp_t = y_t - p_t^N n_t x_t \tag{43}$$

Finally the total amount of real foreign debt depends on the real return of past debts, and the trade balance:

$$b_t^* = r_{t-1}^* \frac{rer_t^*}{rer_{t-1}^*} b_{t-1}^* + tb_t \tag{44}$$

$$tb_t = p_t^N \left[(1 - n_t) y_t^N - g_t - i_t - n_t x_t - \phi(b_t^*)\right] + p_t^A n_t y_t^A - c_t \tag{45}$$

4.9 Calibration

The primary parameters of the model were configured based on the PATACON model. This model, which has been routinely employed at the Central Bank of Colombia, provides a comprehensive characterization of the Colombian economy (González-Gómez et al., 2011). Acknowledging the distinctive structure of the two sectors in our model - agricultural and non-agricultural, we utilized the historical series of the Colombian national accounts and production function estimates specific to Colombia to determine sectoral ratios and shares. This approach assured that the calibrated model effectively emulates some of the main stilized facts of the Colombian economy captured by the PATACON model. However, the most challenging aspect of the calibration process was associated with the formulation of the damage function, intended to encapsulate the impact of weather shocks on the agricultural sector. The calibration of the damage function was derived from the impulse responses ascertained in the empirical section of our study. The main parameters of our model are shown in the Appendix A.

5 Results

This section shows the dynamics of the model to a transitory ENSO (adverse weather) shock in the model presented in Section 4[6]. As shown in Figure 5, the transitory ENSO shock makes land less productive, which in our structure is reflected by an increase in the cost of land and lower land efficiency. That is translated into higher marginal costs for the agricultural sector which result in a lower agricultural output and higher agricultural prices.

In our model, the shock in ENSO affects the relative prices[7] of the agricultural and non-agricultural sectors. Particularly, the ENSO shock increases agricultural relative prices, while the non-agricultural relative prices decreases. The magnitude in which this change in relative prices occurs have an impact on GDP growth and its composition given that there is some degree of substitution. This channel is important, since it also help explain, besides the agricultural sector share on overall output, why weather shocks related with ENSO have an small impact on output.

With our proposed parametrization, food inflation and headline inflation expectations increased approximately as a consequence of the shock. In these setting the monetary policy authority has to react to this shock by increasing the interest rates. In this model, there are is a small effect of the ENSO shocks on economic activity, so the decrease in the output gap is a result of the increase in monetary policy. Nonetheless, this impact is moderate in this parametrization.

It is important to highlight that these quantitative results correspond to a transitory, one standard deviation shock in the ENSO series. As we have seen, extreme weather events could be higher and more persistent as the episode in 2014 - 2016 in which sea surface temprature anomalies in the Pacific Ocean meassured in the ENSO index reached 2.4 degrees. In that context, the appendix show a simulation in which we increase the persistence and magnitude of ENSO shocks. In that simulation, a higher persistence of the ENSO shock create longer-lasting impacts on agricultural output, food and headline inflation. All in all, our proposed model effectively captures some of the primary stylized facts and impacts that adverse ENSO shocks may have on a small open economy like Colombia. Namely, ENSO shocks can be characterized as adverse supply shocks, wherein the Colombian economy experiences a decrease in agricultural production and heightened food and headline inflation. If the shocks persistently impact inflation, as demonstrated in our simulations, monetary policy would need to react partially.

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[6] That corresponds to 1 Celsius degree in ENSO's historical series of sea surface temperatures anomalies in the Pacific Ocean.

[7] In the model, relative prices are defined as the ratio between each of the sector prices and the overall price index.

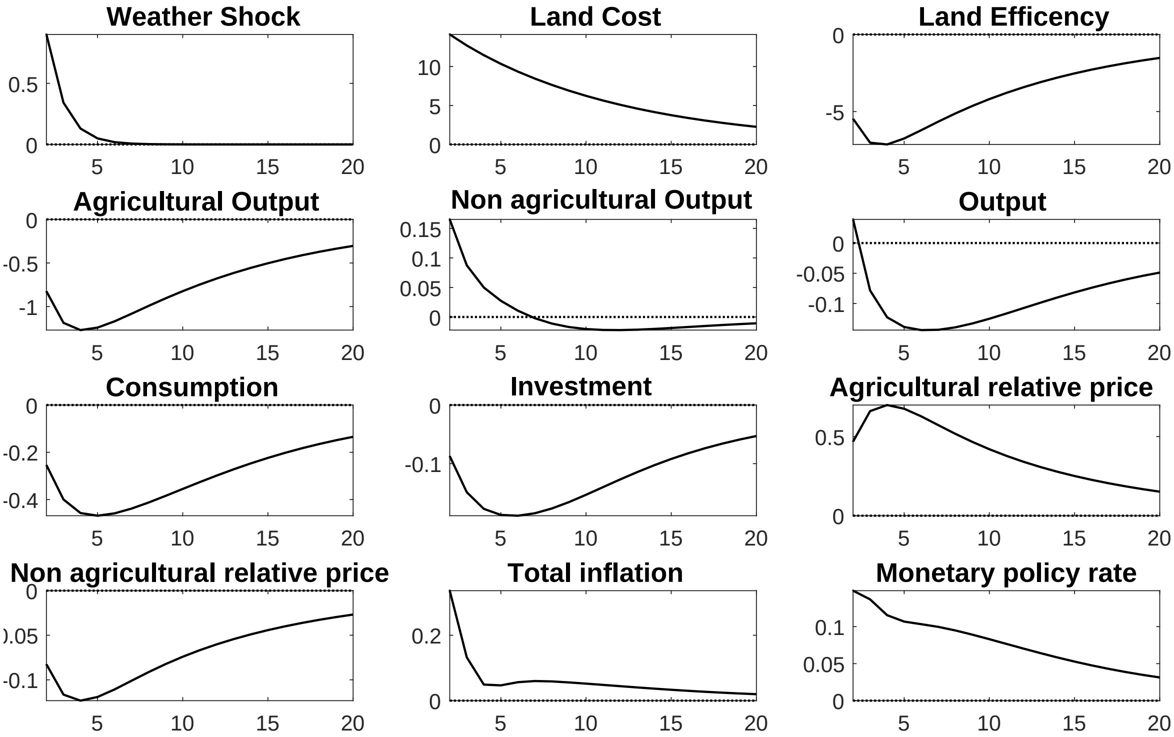

Figure 5: IRF to a one Celsius degree shock in the ENSO index.

6 Conclusions and Future Work

Our study provides an initial attempt at integrating ENSO-related weather shocks into a macroeconomic framework in the context of Colombia. The development of a two-sector DSGE model that accommodates these weather shocks, while maintaining significant compatibility with the Central Bank's main structural model, PATACON, lays a foundation for future research in this domain.

Our empirical observations through the BVAR-X model corroborate the importance of weather shocks in shaping the economic landscape of Colombia, particularly within the agricultural sector and its implications on inflation. This leads us to believe that incorporating such factors into macroeconomic models is important, especially given the intensifying climate-related issues. However, this research represents a starting point rather than a conclusion. Future research endeavors should aim at refining our initial model by focusing on possible extensions. In addition, it is important to highlight that the estimation and excercises done in this study only cover a relatively recent period and they could change in the future.

For one, while our model views weather shocks on a relatively aggregate level, future work should aim to distinguish between different types of weather events and their individual impacts. Second, expansion of the model to include other sectors vulnerable to weather shocks can provide a more comprehensive analysis. This would allow us to observe potential inter-sectoral effects and their implications on economic policy. Finally, future studies might explore alternative estimation approaches to the key parameters of the model. This would help us gain a better understanding of how market agents might adjust their behavior in the face of significant climate risks. To conclude, our study highlights the relevance of integrating weather shocks into macroeconomic modelling for a comprehensive understanding of the Colombian economy.

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A Calibration

Table 1: Calibrated parameters on a quaterly basis

Parameter	Economical Meaning	Value	Bibliography
β	Discount factor	0.9951	(González-Gómez et al., 2011)
δ_k	Capital depreciation rate	0.0138	(González-Gómez et al., 2011)
α	Share of capital in output	0.4	(González-Gómez et al., 2011)
g	Share of spending in in GDP	0.22	Commonly use in RBC literature
φ	Share of agricultural goods in consumption basket	0.15	Observed over the sample period
$\bar{H}^N = \bar{H}^A$	Hours worked	1/3	Commonly use in RBC literature
$\bar{l}$	Land per capita	0.11	Hectares of arable land (per person) FAO data from the World Bank
α_N	Opennesss of non-agricultural market	0.35	Author's calculation
α_A	Opennesss of agricultural market	0.22	Author's calculation
δ_N	Depreciation of non-agricultural capital	0.025	(González-Gómez et al., 2011)
δ_l	Depreciation of land	0.0466	Author's calculation
ϕ	Land expenditure cost	1.45	(Gallic & Vermandel, 2020)
ω	Share of labor in agricultural output	0.1289	(Gallic & Vermandel, 2020)

B Complemenatary BVAR-X Exercises

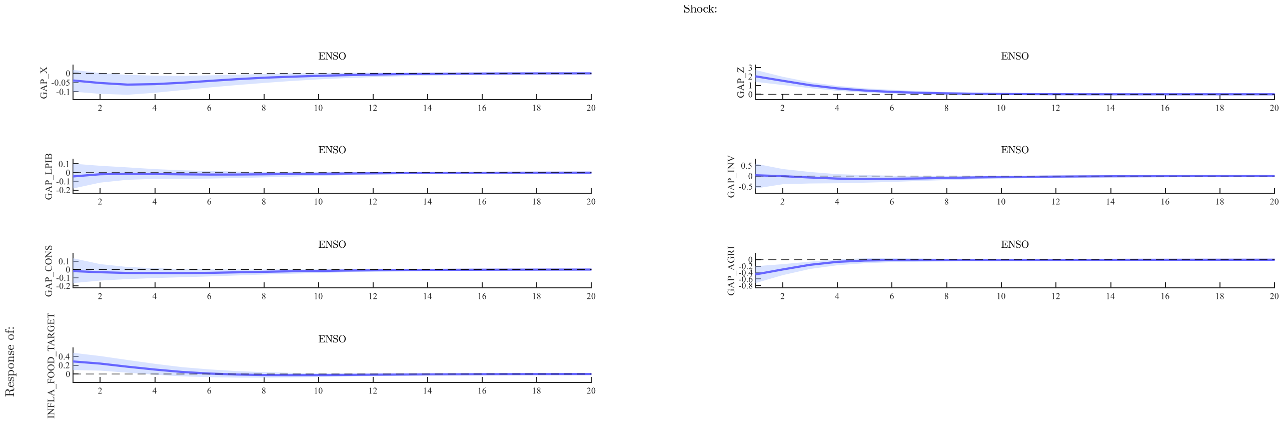

Figure 6: Impulse responses to a 1 Celsius degree shock in the ENSO index. BVAR-X estimated with food inflation (68% confidence intervals). Source: Authors' calculations.

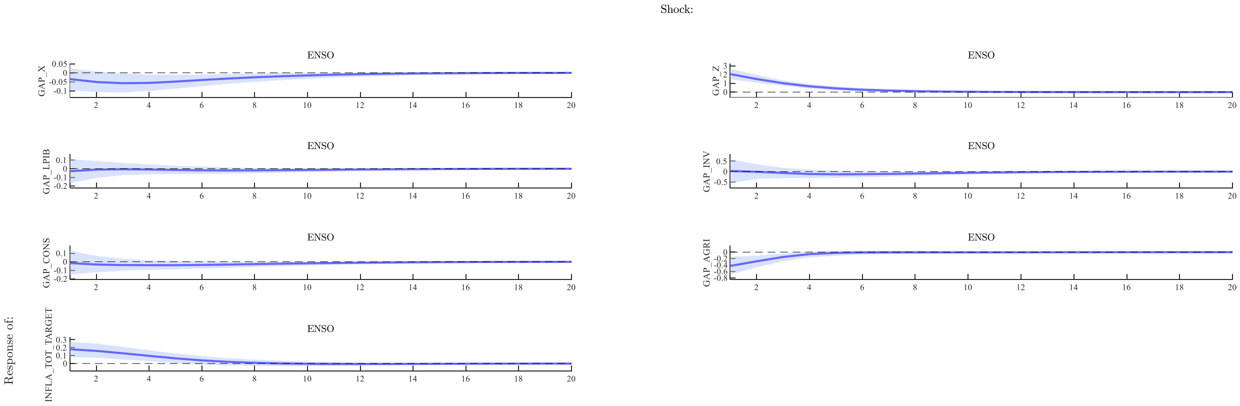

Figure 7: Impulse responses to a 1 Celsius degree shock in the ENSO index. BVAR-X estimated with headline inflation (68% confidence intervals). Source: Authors' calculations.

C Sensitivity analysis

We compared the parameter controlling the impact and the intensity of weather conditions (θ) with an alternate configurations. Particularly, in this exercises we double the magnitude and persistence in the ENSO process.

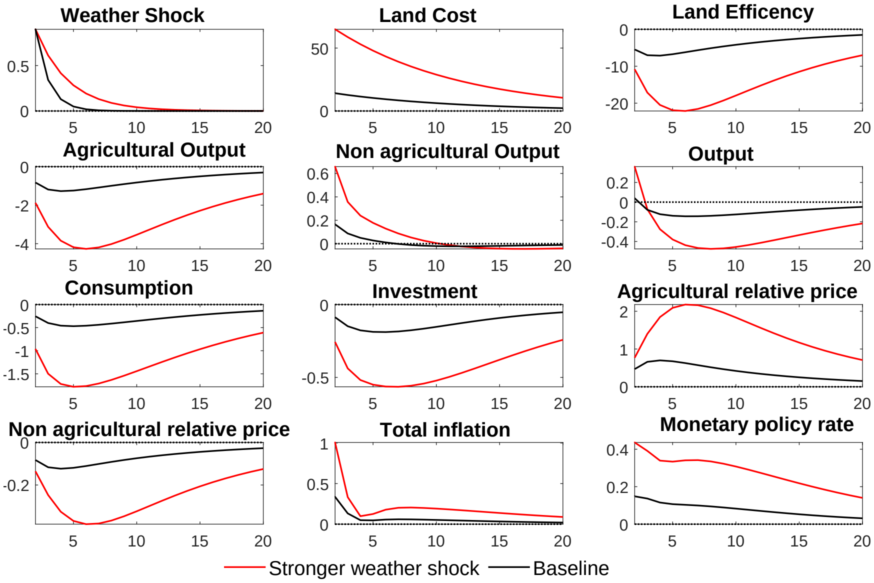

Figure 8: IRF: Weather shock