Staff memo

Adverse weather shocks and monetary policy in Rwanda

Magnus Jonsson, Callixte Kamanzi, Placide Aime Kwizera, and Jean Claude Niyonsenga

November 2024

SVERIGES RIKSBANK

Contents

Summary

This paper examines whether central banks should stabilize CPI or core inflation – defined as the change in the CPI excluding food prices – following an adverse weather shock. We evaluate this in a small open economy model with an agriculture sector and a non-agricultural sector calibrated to fit some stylized facts of the Rwandan economy. We first establish empirically that an adverse weather shock in Rwanda leads to higher agriculture prices and lower agriculture output, which is in line with the mechanisms in the macroeconomic model. We then show that following an adverse weather shock, a central bank can reduce the loss from a loss function where inflation is measured by CPI inflation by stabilizing core inflation instead of CPI inflation. We also show that changes in labor mobility between the agriculture and non-agriculture sectors, the elasticity of substitution between agriculture and non-agriculture products, and higher cost of land maintenance have small inflationary effects.

Authors: Magnus Jonsson (Sveriges Riksbank), Callixte Kamanzi (National Bank of Rwanda), Placide Aime Kwizera (National Bank of Rwanda), and Jean Claude Niyonsenga (National Bank of Rwanda).[1]

Keywords: Weather shocks, relative prices, price indices, inflation, monetary policy.
JEL classification: C6, E5, Q11.

---

[1] We thank seminar participants at the National Bank of Rwanda and Sveriges Riksbank, in particular we thank Mikael Apel, Mattias Erlandsson, Thierry Kalisa, Mathias Karangwa, Paulina Tamme, Gauthier Vermandel, and Anders Vredin for valuable comments, discussions, and other input. This study is part of the Riksbank's technical assistance program and support from The Swedish International Development Cooperation Agency is gratefully acknowledged. The opinions expressed in this article are the sole responsibility of the authors and should not be interpreted as reflecting the views of the National Bank of Rwanda or Sveriges Riksbank.

1 Introduction

Extreme weather events such as floods, droughts, and heatwaves often cause considerable damage, not least to agriculture production. Countries with large agriculture sectors are thus particularly vulnerable. Moreover, climate change is likely to make the frequency and intensity of extreme weather more severe, see Mendelsohn et al. (2000). In addition to damages to agricultural production, extreme weather leads to higher prices on agriculture products and changes in relative prices.

Inflation is defined as an equal increase of all nominal prices in the economy and should ideally not be affected by relative price changes, see Bryan (2002). However, it is not straightforward to define an inflation measure unaffected by relative prices. Central banks almost uniformly specify their inflation measure in terms of a consumer price index (CPI), which is a living cost index and is by definition affected by relative price changes. This is a well-known issue and central banks also examine other measures, for example, various measures of core inflation. These measures are in many cases variants of the CPI where some prices that normally give rise to substantial relative price changes are excluded, most notably food and energy prices. Core measures are not ideal measures of inflation but they can under certain circumstances give a better signal of the underlying inflation pressure than CPI inflation. This was pointed out by Bryan and Cecchetti (1994):

> *“During periods of poor weather, for example, food prices may rise to reflect decreased supply, thereby producing transitory increases in the aggregate index. Because these price changes do not constitute underlying monetary inflation, the monetary authorities should avoid basing their decisions on them.”*

Furthermore, Bernanke et al. (1999) claim that core inflation generally provides a better guide to monetary policy than CPI inflation:

> *“Although the particular choice of the price index used in constructing the inflation target is perhaps not critical, we lean towards the use of a “core” CPI measure that excludes food, energy and other volatile items from the price index. The core CPI is likely to provide a better guide to monetary policy than other indices, since it measures the more persistent underlying inflation rather than transitory influences on the price level.”*

This paper examines whether a central bank should stabilize CPI or core inflation following an adverse weather shock. We first estimate a Bayesian Vector Autoregression (BVAR) model on Rwandan data to establish the empirical effects of an adverse weather shock on agriculture prices and agricultural production. The impulse responses from the BVAR model show that a weather shock leads to higher agriculture prices and lower agriculture output.

We then construct a small open dynamic stochastic general equilibrium model with an agriculture sector and a non-agriculture sector to examine whether the central bank should stabilize CPI or core inflation. The agriculture sector is based on Gallic and Vermandel (2017, 2020) and is characterized by perfect competition and flexible prices, while the non-agriculture sector is a standard New Keynesian model with price and capital adjustment costs. When calibrating the model to some stylized facts of the Rwandan economy, we make sure that the impulse response of an adverse weather shock approximately is in line with the empirical evidence from the BVAR model.

We consider two different central bank loss functions to quantify the effects of stabilizing CPI versus core inflation, see Svensson (2010). In the first loss function, the central bank has a single mandate to stabilize CPI inflation. This loss function reflects the National Bank of Rwanda's (NBR's) inflation mandate. However, since the model lacks financial frictions and a financial sector, we cannot capture the financial stability mandate of the NBR. In the second loss function, the central bank has a dual mandate to stabilize CPI inflation and output, which is a common mandate in many countries.

If the central bank has a single mandate to stabilize CPI inflation, the loss can be reduced by 17 percent by stabilizing core inflation instead of CPI inflation. In the case of a dual mandate, the loss can be reduced by 53 percent. For both loss functions, the loss depends on the price adjustment cost in the non-agricultural sector. If prices become more flexible, the benefit from stabilizing core inflation instead of CPI inflation is reduced.

We also show and discuss the propagation mechanisms of an adverse weather shock on inflation and the economy more generally. Among other things, we show that the main effect of higher labor mobility across the sectors is an increase of labor supply in the agriculture sector. This increases agriculture production and puts downward pressure on agriculture prices. However, the overall effect on CPI inflation and monetary policy is small. The effect of higher elasticity of substitution between agriculture and non-agriculture products and higher cost of land maintenance on CPI inflation is also small.

The rest of the paper is organized as follows. In the next section, we discuss papers related to our study. Section 3 establishes the empirical effects of an adverse weather shock in Rwanda. Section 4 presents the macroeconomic model and calibration, while section 5 shows the propagation mechanisms of an adverse weather shock and provide some sensitivity analysis. In section 6, we present the results of the policy analysis. Finally, section 7 concludes with some suggestions for future research.

2 Related literature

This paper is related to an emerging literature studying the economic impact of weather shocks. A seminal paper in this literature is Gallic and Vermandel (2020). They construct a model with a weather-dependent agricultural sector where endogenous land productivity is a key feature to examine the business cycle effects of weather shocks in New Zealand. Among other things, they show that weather shocks play a non-trivial role in driving the business cycle in New Zealand. Although, the potential implications for inflation and monetary policy of weather shocks are not examined.

The framework developed by Gallic and Vermandel (2020) has been used in many recent papers. Milivojevic (2022) studies the climate-fiscal nexus and highlights the role of structural resilience in limiting the impact of extreme weather events. Another paper by Romdhane and Bouaziz (2021) show that weather shocks have an important impact on the Tunisian economy and that a significant spillover mechanism from the agricultural sector to the rest of the economy generates large business cycle fluctuations. Romero et al. (2023) incorporate a monetary sector in the Gallic and Vermandel (2020) model and fit the model to the characteristics of the Colombian economy. They show that the model predicts that a weather shock leads to a decrease in agricultural production and an increase in food and headline inflation, which is in line with the Colombian experience. They conclude that if the weather shocks persistently impact inflation – as the simulations demonstrate – monetary policy would need to take this into account.

Okot (2020) constructs a model where the production factors in the agriculture sector are labor and land. The size of land is assumed to be fixed but exogenous weather shocks affects the productivity of land through its effects on soil moisture. The model is estimated on Ugandan data and investigates to what extent weather shocks matter for macroeconomic fluctuations. The results show that weather shocks are the main driver of Uganda's business cycle through their impact on agricultural production and relative prices. Moreover, monetary policy has a limited impact on fluctuations arising from weather shocks.

Other studies on weather shocks include Acevedo et al. (2020), who find that the negative effect of temperature on output in countries with hot climates goes through reduced investment, depressed labor productivity, poorer human health, and lower agricultural and industrial output. The analysis also suggests that the adverse consequences are borne disproportionately by countries with hot climates, i.e., most low-income countries. Romero and Naranjo-Saldarriaga (2022) finds that extreme weather shocks such as the strong El Niño event can have an important role in the dynamics of both inflation and inflation expectations and that this fact should be considered by central banks when assessing the monetary policy stance.

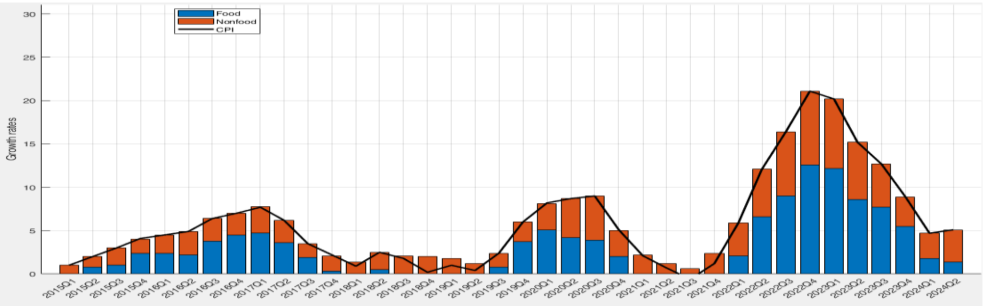
This paper is also related to the literature on relative price changes and measures of inflation. An issue that recently came into light after the sharp increase of CPI inflation in 2021 and 2022. An important factor for the increase was in many cases relative price changes, primarily higher energy and food prices. A well-known result in the New Keynesian literature is that in a two-sector economy with one sticky and one flexible price sector, monetary policy should stabilize the prices of the sticky price sector to implement a first-best allocation, see Aoki (2001). Variants of this result can be found in different papers. Olovsson and Vestin (2023) show that monetary policy should see through increases in energy prices during the green transition and stabilize some measure of core inflation. In a similar paper, del Negro et al. (2023) show that the green transition implies that the central bank should keep inflation down in the sticky price sector and make sure the adjustment in relative prices occurs with an overall inflation level in line with the inflation target.

However, the former president of the Federal Reserve Bank of St. Louis James Bullard, argues against “the relative price argument” as well as other arguments in favor of stabilizing core inflation, see Bullard (2011). Regarding the relative price argument, he points out that in the case of higher energy prices, households will spend more on energy consumption and then less on all other consumption products, which would put downward pressure on all other prices.[2] Ignoring energy prices understates the true inflation rate, as one would be focusing only on the prices facing downward pressure.

3 Weather shocks in Rwanda

Agriculture is a large part of the Rwandan economy. In terms of GDP, the agriculture sector is 27 percent and the weight of food prices in the CPI is 28 percent. The importance of food prices for CPI inflation can be illustrated by the contribution of food prices to CPI inflation during the last 10 years, see Figure 1. Food prices have often contributed more than its share of 28 percent, in particular during the inflation surge in 2022. Adverse weather conditions are often a factor behind higher food prices but suboptimal agricultural practices can also play a role. Beyond agriculture, extreme weather disrupt transportation networks, infrastructure projects, and other non-agricultural economic activities with negative effects on the economy more generally.

Figure 1. Contributions of food and non-food prices to the CPI



Note. Non-food prices include furnishings, recreation, alcohol, health, education, clothing, transport, housing, restaurants, communication, and miscellaneous items.

Source: Authors' computations.

Rwanda has four distinct climatic seasons, see Table 1. First an extended rainy season from March to May and then a brief rainy season from September to November. In between these rainy seasons, there is a protracted dry season from June to August and a concise dry season from December to February. However, rainfall is a consistent feature throughout the year with the months June, July and August being notable exceptions.

To empirically examine the effects of weather shocks, we compute the so-called Rainfall Anomaly Index (RAI). This index was originally formulated by Rooy (1965) – and subsequently modified by de Sousa Freitas (2005) – to assess the occurrence and strength of unusually dry and rainy events in specific regions by quantifying deviations from normal rainfall patterns. The formulas for calculating the RAI are given by $3((N-\overline{N})/(\overline{M}-\overline{N}))$ for positive anomalies, and $3((N-\overline{N})/(\overline{X}-\overline{N}))$ for negative

---

[2] This is also the case in our model but it is still the case that the central bank should stabilize core inflation, given the evaluation method we use.

anomalies, where N is the rainfall in the in the current quarter, $\overline{N}$ is the quarterly average rainfall of the historical series, $\overline{M}$ is the average of the ten highest quarterly rainfalls of the historical series, and $\overline{X}$ is the average of the ten lowest quarterly rainfalls of the historical series.

Table 1. Distribution of rainfall from Jan 2019 to Dec 2023 across the yield cycle

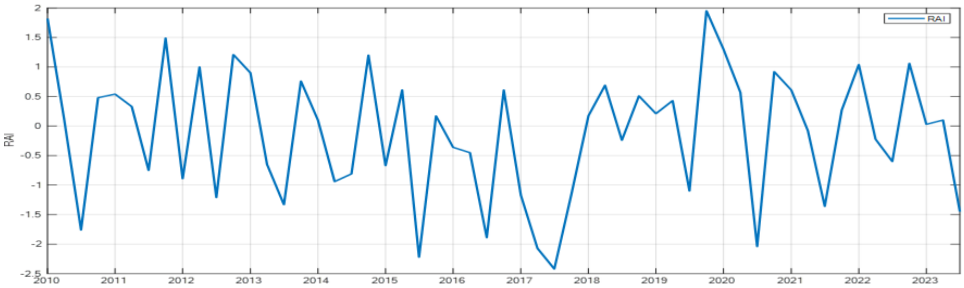
	December to February	March to May	June to August	September to November
Average mean	124	142	24.9	134
Average min	61.3	37.4	0	73.8
Average max	218	255	111	197
Total mean	1737	2137	374	2015

Note. Rainfall in mm per month.

Source: Authors' computation.

Positive anomalies indicate values above the average, while negative anomalies are values below the average. Specifically, regions with RAI values above 4 are classified as "Extremely Humid", indicating significant surplus rainfall compared to historical averages. Values between 2 and 4 are classified as "Very Humid", signifying above-average rainfall. Regions with values ranging from 0 to 2 are classified as "Humid", experiencing normal or slightly above-average rainfall conditions, and regions with values between −2 and 0 are classified as "Dry" indicating below-average rainfall. Values between −4 and −2 are classified as "Very Dry" suggesting significant deficit rainfall compared to historical norms. Finally, regions with values below −4 are classified as "Extremely Dry" and are experiencing severe and prolonged drought conditions. The RAI for Rwanda varies between −2.5 and 2, see Figure 2.

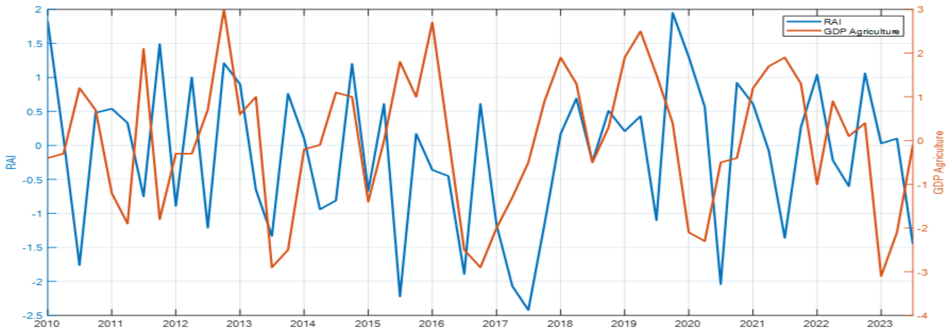
Figure 2. The rainfall anomaly index for Rwanda



Source: The Rwanda Meteorological Agency and authors' computations.

Figure 3 shows the pattern of adverse weather events measured by the RAI and agricultural production. Negative RAI values are on specific occasions associated with low agriculture production, providing evidence of the vulnerability of agricultural production to adverse weather conditions. For example, during 2013Q3, the RAI fell to −1.3, signalling a substantial deviation below the average rainfall while agriculture production experienced a significant decrease. Similarly, in 2017Q2, the RAI dropped to −2.07, indicating an even more severe deficit in rainfall and noticeable decline in agriculture production. Another example is 2020Q3, where a notably negative RAI coincided with a substantial decrease in agriculture production. These occasions are indicative of the negative impact of below-average rainfall on agricultural production.

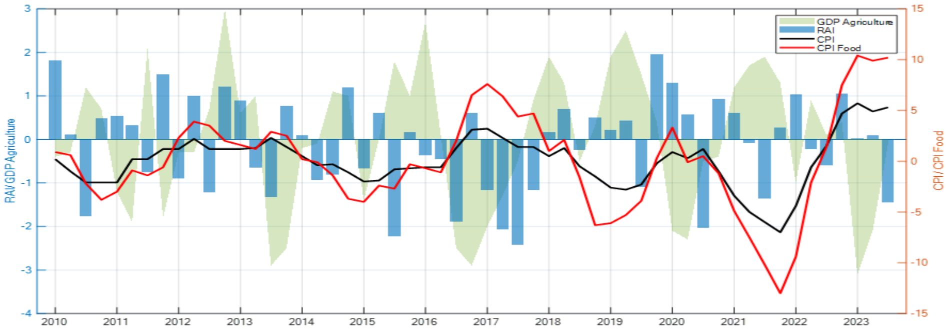
Figure 3. Relationship between the RAI and agriculture production



Source: Authors’ computations

Figure 4 shows that periods of low agriculture production are associated with periods of high food prices and CPI inflation. The correlation between agriculture production and food prices is −0.47 and between agriculture production and the CPI it is −0.48. Adverse weather events typically lead to an imbalance between supply and demand of agriculture products, leading to a rise in food prices and CPI inflation.

Figure 4. Relationships of the RAI, agriculture production, and prices in Rwanda



Source: Authors’ computations

To quantify the effect of a weather shock on agriculture prices and production in Rwanda, we estimate a BVAR model. The Bayesian framework allows us to incorporate prior information and uncertainty in a consistent manner. This is important, since data availability is limited in Rwanda and we have a relatively small sample size. The BVAR model includes the following three endogenous variables:

- The RAI
- Agriculture production
- Food consumer price index

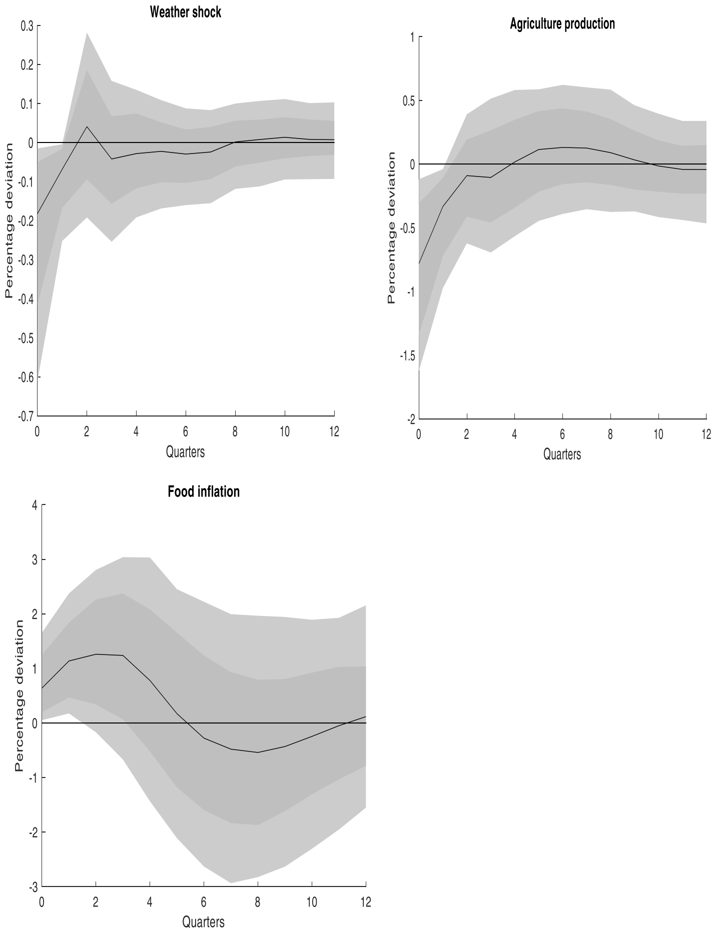
The general representation of the BVAR model is given by,

$$\boldsymbol{Y}_t = \boldsymbol{\alpha} + \sum\nolimits_{p=1}^{P} \boldsymbol{A}_p \boldsymbol{Y}_{t-p} + \boldsymbol{\varepsilon}_t, \tag{1}$$

where $\boldsymbol{Y}$ is the vector of the endogenous variables, $\boldsymbol{\alpha}$ is a vector of intercept terms, $\boldsymbol{A}_p$ is coefficient matrices for each lag p, P is the maximum lag order, and $\boldsymbol{\varepsilon}$ is a vector of error terms. To estimate the model, we do not assume any cointegration vectors and use quarterly data on growth rates. The data sample is 2010Q1 to 2023Q3. To identify the weather shock, we apply the sign-restricted method and the Akaike information criteria to determine the optimal lag structure, which is found to be four lags in our quarterly model. For the prior, we use the independent Normal-Wishart prior, assuming an unknown variance-covariance matrix.

Figure 5 shows the impulse responses to an adverse weather shock. There is a significant increase of food prices and a decrease of agriculture production. This is in line with the existing literature, see Bejarano-Salcedo et al. (2020), Abril-Salcedo et al. (2020), Romero and Naranjo-Saldarriaga (2022), as well as research on Uganda by Okot (2020).

Figure 5. Impulse responses to an adverse weather shock (RAI)



Note. The grey areas represent 95 percent and 68 percent confidence intervals.

4 The model

We construct a small open economy with an agriculture and a non-agriculture sector. The features of the agriculture sector is based on Gallic and Vermandel (2017, 2020). Farmers in this sector use labor and land to produce food and other agriculture products. A novel feature of this framework – compared to the neoclassical literature where land is a fixed factor – is the interpretation of land as "land productivity". Land is in other words a production factor that can be improved upon by spending more resources on it, for example fertilizers, pesticides, herbicides, seeds, water etcetera.

The agriculture sector in Rwanda involves many small farms that produce nearly identical products. This sector is therefore well described by perfect competition and flexible prices. The weather shock – specific to the agriculture sector – has a negative impact on land productivity that could last for several quarters. The non-agriculture sector has standard New Keynesian features. Firms operate under monopolistic competition and are subject to quadratic price and capital adjustment costs. The production factors are labor and capital.

Households maximize utility that includes consumption and leisure, subject to an intertemporal budget constraint. Labor is supplied to both sectors but the mobility between the sectors is imperfect. It is costly for a farmer to switch from the agriculture sector to the non-agriculture sector following an adverse weather shock, and vice-versa for workers in the non-agricultural sector.

Given the focus on a domestic weather shock, the small open economy part of the model involves a number of simplifying assumptions to get a reasonable trade-off between simplicity and complexity. We assume full exchange rate pass-through. Exports only involve non-agriculture products, so all the domestically produced agriculture products are consumed by domestic households. The imported consumption products can be thought of as including both agriculture and non-agriculture products since we do not separate imported agriculture products from non-agriculture products. The key open economy equation is the uncovered interest rate parity (UIP) condition. This condition is central for the determination of the real exchange rate, which in turn is the main determinant of imports and exports.

4.1 Households

There is a continuum of $j \in [0,1]$ identical and infinitely-lived households that have preferences $\mathcal{U}$ over an aggregate consumption bundle C_j and hours worked H_j over an infinite horizon,

$$\mathbb{E}_t \sum_{t=1}^{\infty} \beta^t \mathcal{U}(C_{j,t}, H_{j,t}), \tag{2}$$

where $\mathbb{E}$ denotes the expectation operator, $\mathcal{U}$ the period utility function, and the parameter $\beta < 1$ is the subjective discount factor.

The period utility function takes the following functional form,

$$\mathcal{U}(C_{j,t}, H_{j,t}) = \ln(C_{j,t}) - \frac{H_{j,t}^{(1+1/\eta^F)}}{1+1/\eta^F}, \tag{3}$$

where η^F is the Frisch intertemporal elasticity of substitution. Households maximize expected utility subject to an intertemporal budget constraint given by,

$$P_t^C C_{j,t} + P_t^N I_{j,t}^N + B_{j,t} + S_t B_{j,t}^* = R_t^{K,N} K_{j,t-1}^N + W_t^N H_{j,t}^N + W_t^A H_{j,t}^A + R_t B_{j,t-1} + S_t R_t^* B_{j,t-1}^* + P_t^C \mathbb{C}_{j,t}^{B^*} + D_{j,t}^N, \tag{4}$$

where the price of the aggregate consumption bundle is the numeraire and denoted by P^C.[3] The superscripts N and A denote the non-agriculture sector and agriculture sector, respectively. The stock of domestic and foreign bonds are denoted by B and B^*, respectively, S is the nominal exchange rate, defined as the price of foreign currency in terms of domestic currency, W is the wage rate, R^K, R and R^* are interest rates on capital, domestic bonds and foreign bonds, respectively, D^N denotes dividends, and I^N denotes investments. A portfolio adjustment cost function is introduced to ensure stationarity and is denoted by $\mathbb{C}^{B^*}$. This function is quadratic and has the following functional form,

$$\mathbb{C}_{j,t}^{B^*} = \frac{\kappa^{B^*}}{2}\left(B_{j,t}^* - \bar{B}^*\right)^2, \tag{5}$$

where $\kappa^{B^*}$is an adjustment cost parameter and a bar above a variable denotes a steady state value. Investment is implicitly determined from the law of motion of capital given by,

$$K_{j,t}^N = I_{j,t}^N + (1-\delta^N) K_{j,t-1}^N - \mathbb{C}_{j,t}^{K,N}, \tag{6}$$

where $\delta^N \in [0,1]$ is the depreciation rate of capital. The capital adjustment cost function $\mathbb{C}^K$has the following quadratic functional form,

$$\mathbb{C}_{j,t}^{K,N} = \frac{\kappa^K}{2}\left(\frac{I_{j,t}^N}{K_{j,t-1}^N} - \delta\right)^2 K_{j,t-1}^N, \tag{7}$$

where κ^K is the adjustment cost parameter. To capture that the degree of labor mobility between the agriculture and non-agriculture sectors is imperfect, we assume a constant-elasticity-of-substitution specification of aggregate labor, i.e., aggregate labor supply is determined according to,

$$H_{j,t} = \left[\left(H_{j,t}^N\right)^{(1+\eta^H)} + \left(H_{j,t}^A\right)^{(1+\eta^H)}\right]^{\frac{1}{1+\eta^H}}. \tag{8}$$

---

[3] In general, a nominal price is denoted by an uppercase letter, and a relative price by a lowercase letter.

This functional form allows for different degrees of sectoral labor mobility by means of just one parameter, i.e., the intratemporal elasticity of substitution of labor across sectors η^H. The aggregated first-order conditions that summarize the household's intertemporal decisions are as follows,

$$\frac{R_t}{r_t} = \mathbb{E}_t \pi_{t+1}^{CPI}, \tag{9}$$

$$\frac{r_t}{r_t^*} = \mathbb{E}_t \left[\frac{S_{t+1}}{S_t}\right] \left(1 + \mathbb{C}_t^{B^*}\right)^{-1}, \tag{10}$$

$$p_t^N \left(1 - \frac{\partial \mathbb{C}_t^{K,N}}{\partial I_t^N}\right)^{-1} = \frac{1}{r_t} \mathbb{E}_t p_{t+1}^N \left[r_{t+1}^{K,N} + \left(1 - \delta^N - \frac{\partial \mathbb{C}_t^{K,N}}{\partial K_t^N}\right)\left(1 - \frac{\partial \mathbb{C}_{t+1}^{K,N}}{\partial I_{t+1}^N}\right)^{-1}\right], \tag{11}$$

$$\frac{p_t^N w_t^N}{p_t^A w_t^A} = \left(\frac{H_t^N}{H_t^A}\right)^{\frac{1}{\eta^H}}, \tag{12}$$

where π^{CPI} denotes CPI inflation. Equation (9) is the Fisher equation, which states that the difference between the nominal interest rate – the central bank's policy rate – and the real interest rate equals expected inflation. Equation (10) is the UIP condition, which states that the real interest rate difference between the domestic and foreign real interest rate equals an expected depreciation when the interest rate difference is positive, and an expected appreciation when the interest rate difference is negative.[4] Equation (11) is the optimal investment condition, which states that the marginal value of capital today equals the discounted value of the expected marginal product of capital plus the value in the next period. Finally, equation (12) gives the optimal labor supply condition for the two sectors, where p_t^N and p_t^A are the relative price of non-agriculture products and agriculture products, respectively.

The households also face an intratemporal decision problem, i.e., how to allocate their consumption between domestic produced products – non-agriculture and agriculture products – and imported consumption products. Formally, we solve this problem in two steps:

1. Households decide on how to allocate consumption between domestic and imported products
2. Households decide on how to allocate domestic consumption between non-agricultural and agricultural products

We assume an aggregate consumption index defined by a standard CES function over the domestic consumption index C_j^D and the imported consumption index C_j^M as follows,

---

[4] The portfolio cost is assumed to be negligible, and only matters to the extent that it ensures a determinate steady state.

$$C_{j,t} = \left[(\alpha^D)^{\frac{1}{\eta^D}} \left(C_{j,t}^D\right)^{\frac{\eta^D-1}{\eta^D}} + (1-\alpha^D)^{\frac{1}{\eta^D}} \left(C_{j,t}^M\right)^{\frac{\eta^D-1}{\eta^D}} \right]^{\frac{\eta^D}{\eta^D-1}}, \tag{13}$$

where the parameter $\alpha^D \in [0,1]$ can be interpreted as the level of trade openness or a measure of home bias in preferences. The parameter η^D measures the elasticity of substitution between domestic and imported consumption products. The aggregated demand for domestic and imported products can then be shown to be given by the following conditions,

$$C_t^D = \alpha^D \left(\frac{P_t^D}{P_t}\right)^{-\eta^D} C_t, \tag{14}$$

$$C_t^M = (1-\alpha^D) \left(\frac{P_t^M}{P_t}\right)^{-\eta^D} C_t, \tag{15}$$

where P^D and P^M are the price of domestic and imported products, respectively. The corresponding consumption price index is,

$$P_t = \left[\alpha^D (P_t^D)^{1-\eta^D} + (1-\alpha^D)(P_t^M)^{1-\eta^D}\right]^{\frac{1}{1-\eta^D}}. \tag{16}$$

In the second step, households allocate domestic consumption C_j^D between two types of consumption bundles produced by the non-agricultural and the agricultural sectors denoted by C_j^N and C_j^A, respectively. We assume that the domestic consumption index is given by a standard CES-function,

$$C_{j,t}^D = \left[(\alpha^N)^{\frac{1}{\eta^N}} \left(C_{j,t}^N\right)^{\frac{\eta^N-1}{\eta^N}} + (1-\alpha^N)^{\frac{1}{\eta^N}} \left(C_{j,t}^A\right)^{\frac{\eta^N-1}{\eta^N}} \right]^{\frac{\eta^N}{\eta^N-1}}, \tag{17}$$

where $\alpha^N \in [0,1]$ is the weight given to non-agricultural products in the domestic consumption bundle and η^N is the substitution elasticity between non-agricultural and agricultural products. The aggregated demand for each type of good is given by,

$$C_t^N = \alpha^N \left(\frac{P_t^N}{P_t^D}\right)^{-\eta^N} C_t^D, \tag{18}$$

$$C_t^A = (1-\alpha^N) \left(\frac{P_t^A}{P_t^D}\right)^{-\eta^N} C_t^D, \tag{19}$$

where P^N and P^A are the prices of non-agricultural and agricultural products, respectively.

The domestic consumption price index is given by,

$$P_t^D = \left[(\alpha^N (P_t^N)^{1-\eta^N} + (1-\alpha^N)(P_t^A)^{1-\eta^N}\right]^{\frac{1}{1-\eta^N}}. \tag{20}$$

4.2 Firms

The economy is populated by a unit mass $i \in [0,1]$ of representative firms in the non-agricultural and farmers in the agricultural sector.

Agricultural sector

To model the agriculture sector, we follow the approach developed by Gallic and Vermandel (2017, 2020). Labor and land are essential production factors in the Rwandan agriculture sector, while capital is less important. We therefore exclude capital as a production factor in this sector. Land should be interpreted as "land productivity" that can be improved upon by increasing spending on for example fertilizers, herbicides, and pesticides. Hence, farmers combine land productivity and labor to produce agriculture products. We assume a standard Cobb-Douglas production function,

$$Y^A_{i,t} = (L^A_{i,t-1})^{\theta^A} (H^A_{i,t})^{(1-\theta^A)}, \tag{21}$$

where Y^A_i is agricultural output, L_i land productivity, and H^A_i hours worked in the agricultural sector. The parameter $\theta^A \in [0,1]$ denotes the share of land in the production process. Land productivity varies over time according to the following law of motion,

$$L^A_{i,t} = J^N_{i,t} + (1-\delta^A)\, L^A_{i,t-1}\mathcal{F}_{i,t}, \tag{22}$$

where $\delta^L \in (0,1)$ is the decay rate of land productivity, J^A is spending on, for example, fertilizers, herbicides, and pesticides to improve land productivity. The damage function $\mathcal{F}_i$ is a function of the weather shock ω_i, and has the following functional form,

$$\mathcal{F}_{i,t} = \left(\omega_{i,t}\right)^{-\vartheta}, \tag{23}$$

where ϑ determines the elasticity of land productivity with respect to the weather shock. The weather shock follows a standard AR(1)-process,

$$\ln \omega_t = \rho \ln \omega_{t-1} + \sigma \epsilon_{t,} \tag{24}$$

where $\rho \in [0,1)$ denotes the persistence of the weather shock and $\sigma \geq 0$ the standard deviation of the innovation ϵ. The farmers maximize dividends D^A given by,

$$P^A_t D^A_{i,t} = P^A_t Y^A_{i,t} - W^A_{i,t} H^A_{i,t} - P^N_t \mathcal{M}^N_{i,t}. \tag{25}$$

We assume that there are increasing costs of investing in land productivity, given by a cost function $\mathcal{M}$,

$$\mathcal{M}^N_{i,t} = \frac{\tau}{1+\phi}\left(J^N_{i,t}\right)^{1+\phi}, \tag{26}$$

where $\tau > 0$ is scaling parameter and $\phi > 0$ implies that spending on land maintenance exhibits an increasing cost.

The aggregated first order conditions are summarized as follows,

$$1 = \frac{w_t^A}{\partial Y_t^A / \partial H_t^A}, \tag{27}$$

$$p_t^N \frac{\partial \mathcal{M}_t^N}{\partial J_t^N} = \frac{1}{r_t} \mathbb{E}_t \left[\left(p_{t+1}^A \frac{\partial Y_{t+1}^A}{\partial L_t^A} + p_{t+1}^N \frac{\partial \mathcal{M}_{t+1}^N}{\partial J_{t+1}^N} (1 - \delta^A) \mathcal{F}_{i,t+1} \right) \right]. \tag{28}$$

Equation (27) equalizes the wage rate with the marginal product of labor and equation (28) equalizes the marginal cost of land maintenance with the marginal product of land productivity and the value of land in the next period.

Non-agricultural sector

Firms producing the final non-agricultural product are perfectly competitive. They use a CES-aggregator to aggregate intermediate products into a final non-agricultural product. The CES-aggregator is given by,

$$Y_t^N = \left[\int_0^1 \left(Y_{i,t}^N \right)^{\frac{\eta - 1}{\eta}} di \right]^{\frac{\eta}{\eta - 1}}, \tag{29}$$

where Y^N is the non-agricultural product, Y_i^N is an intermediate product produced by intermediate firm i, whose price is P_i^N and η is the elasticity of substitution between intermediate products. The demand for the intermediate products is given by,

$$Y_{i,t}^N = \left(\frac{P_{i,t}^N}{P_t^N} \right)^{-\eta} Y_t^N, \tag{30}$$

and the price level as a function of intermediate products is,

$$P_t^N = \left[\int_0^1 \left(P_{i,t}^N \right)^{1 - \eta} di \right]^{\frac{1}{1 - \eta}}. \tag{31}$$

Firms producing the intermediate products combine capital and labor using a Cobb-Douglas production function,

$$Y_{i,t}^N = (K_{i,t-1}^N)^{\theta^N} (H_{i,t}^N)^{(1 - \theta^N)}, \tag{32}$$

where $\theta^N \in [0,1]$ is the share of capital in production. These firms operate in a monopolistic competition environment and maximize dividends given by,

$$P_{i,t}^N D_{i,t}^N = P_{i,t}^N Y_{i,t}^N - R_t^k K_{i,t-1}^N - W_t^N H_{i,t}^N - P_{i,t}^N \mathbb{C}_{i,t}^{N,P}. \tag{33}$$

When maximizing dividends, firms set the price of their own good subject to the demand of the good and they pay a quadratic price adjustment cost $\mathbb{C}^{N,P}$ whenever they adjust a price, see Rotemberg (1982). The quadratic cost function is given by,

$$\mathbb{C}_{i,t}^{N,P} = \frac{\kappa^P}{2}\left(\frac{P_{i,t}^N}{P_{i,t-1}^N} - \bar{\pi}\right)^2 P_t^N Y_t^N. \tag{34}$$

where κ^P is the adjustment cost parameter. The aggregated first order conditions can be summarized as follows,

$$mc_t^N = \frac{r_t^k}{\partial Y_t^N / \partial K_t^N}, \tag{35}$$

$$mc_t^N = \frac{w_t^N}{\partial Y_t^N / \partial H_t^N}, \tag{36}$$

$$mc_t^N = \frac{\eta-1}{\eta} + \frac{\kappa^P}{\eta}\left(\frac{\pi_t^N}{\bar{\pi}} - 1\right)\frac{\pi_t^N}{\bar{\pi}} - \frac{1}{r_t}\mathbb{E}_t\left[\frac{\kappa^P}{\eta}\left(\frac{\pi_{t+1}^N}{\bar{\pi}} - 1\right)\frac{\pi_{t+1}^N}{\bar{\pi}}\frac{Y_{t+1}^N}{Y_t^N}\right], \tag{37}$$

where mc denotes the marginal cost.

4.3 Monetary policy

Monetary policy is modeled by a simple Taylor rule, see Taylor (1993). The Taylor rule is often used as a benchmark in monetary policy discussions since it is consistent with many of the principles on how optimal monetary policy should be conducted in a standard New Keynesian model, see Clarida et al. (1999). For example, the Taylor rule calls for a gradual adjustment of inflation to its target, it has the property that the policy rate should be adjusted by more than one-for-one with the inflation rate, and the policy rate responds to the output gap, as opposed to the level of output, which means that, at least approximately, the rule calls for a countercyclical response to demand shocks and accommodation of shocks to the natural level of output. Moreover, in contrast to optimal policy rules, the Taylor rule is robust to different model assumptions.

Formally, the policy rate R reacts to deviations of inflation, π, from the target (the inflation gap) and deviations of output from steady state (the output gap),

$$\frac{R_t}{\bar{R}} = \left(\frac{\pi_t}{\bar{\pi}}\right)^{\rho_\pi}\left(\frac{Y_t}{\bar{Y}}\right)^{\rho_Y}, \tag{38}$$

where ρ_π shows the strength by which the policy rate stabilizes inflation and ρ_Y the strength by which the policy rate reacts to the output gap. In the analysis, we examine two different measures of inflation, i.e., CPI and core inflation.

The central bank objective or mandate is modeled by specifying a central bank loss function, see Svensson (2010). This approach is consistent with the common practice of giving central banks a simple objective that only involves a small number of economic variables. A simple objective is easy to communicate to the public, which increases transparency. It also facilitates the evaluation of monetary policy and enhances accountability. From a modeling perspective, a simple objective is robust to model and parameter uncertainty.

We evaluate two loss functions that represent two different central bank objectives. In the first loss function $\mathcal{L}_1$, the central bank has a single objective to stabilize CPI inflation. This loss function captures the NBR's inflation mandate. We cannot capture the financial stability mandate of the NBR, since the model lacks financial frictions and a financial sector. Formally, the loss consists of the quadratic sum of current and future CPI inflation gaps,

$$\mathcal{L}_1 = \sum_{t=0}^{\infty}(\pi_t^{CPI} - \bar{\pi})^2. \tag{39}$$

According to the second loss function $\mathcal{L}_2$, the central bank has a dual objective that stipulates the stabilization of both CPI inflation and output with equal weights. This loss function is common as many central banks also have a mandate to support sustainable economic growth or more generally supporting the government's broader economic policies. In this case, the loss function has following quadratic form,

$$\mathcal{L}_2 = \sum_{t=0}^{\infty}\left[(\pi_t^{CPI} - \bar{\pi})^2 + \left(\frac{Y_t - \bar{Y}}{\bar{Y}}\right)^2\right]. \tag{40}$$

4.4 Foreign economy

Households and firms in the small open economy take foreign variables as given. Foreign output is normalized to domestic steady state output,

$$Y_t^* = \bar{Y}. \tag{41}$$

The foreign real interest rate is set equal to the domestic steady state real interest rate,

$$r_t^* = \bar{r}. \tag{42}$$

The foreign price level is normalized to one,

$$P_t^* = 1. \tag{43}$$

4.5 Trade and market clearing conditions

We assume that a condition similar to domestic demand of foreign products (imports) also holds for foreign demand of domestic good, i.e., the condition for exports is given by,

$$X_t^N = (1 - \alpha^*)\left(\frac{P_t^N}{S_t P_t^*}\right)^{-\eta^*} Y_t^*, \tag{44}$$

where α^* and η^* are the foreign equivalents to the domestic parameters α and η. The market clearing conditions for non-agriculture and agriculture are, respectively,

$$Y_t^N = C_t^N + I_t^N + \mathcal{M}_t^N + X_t^N + \mathbb{C}_t^{N,P}, \tag{45}$$

$$Y_t^A = C_t^A, \tag{46}$$

and the aggregate resource constraint is,

$$Y_t = C_t + I_t + \mathcal{M}_t + X_t - C_t^M + \mathbb{C}_t^P. \tag{46}$$

4.6 Benchmark calibration

We summarize the calibrated parameter values in Table 2. The length of a time period is one quarter. We set the discount factor β to 0.9926, which implies an annual long-run real interest rate of about three percent in line with the historical average on Rwandan short-term treasury bills.

The Frisch elasticity η^F is set to 2. Estimates of the Frisch elasticity often vary between two and four in macroeconomic models, see Peterman (2016), while microeconomic evidence suggests lower values.

The parameter $\alpha^D$is set at 0.7, which is in line with values used in the open economy literature, see e.g., Adolfson et al. (2007). In accordance with Rwandan evidence, we set the weight on non-agriculture consumption in the CES-function α^N to 0.7.

Estimates of the elasticity of substitution between domestic and foreign (imported) products are around 5–20 in micro data (see references in Obstfeld and Rogoff (2000) and others). Estimates using macro data are, however, lower, see Collard and Dellas (2002). We therefore set the elasticity of substitution parameter η^D at the lower range of the estimates from the micro data.

The substitution elasticity of labor across sectors η^H and the substitution elasticity between non-agriculture and agriculture products η^N are judged to be low. When the value of elasticity is greater than 1.0 the demand for a good or service is more than proportionally affected by the change in the price. A value less than 1.0 thus suggests that the demand is relatively insensitive to price changes, or inelastic. We set both η^N and η^H to 0.5.

The price markup in the non-agriculture sector is set to 20 percent in line with estimates in Bayoumi, Laxton, and Pesenti (2004). To calibrate the price adjustment cost parameter κ^P, we use the fact that under certain conditions there is a simple relationship between this parameter and the so-called Calvo parameter, which measures the duration between price changes. Standard estimates of the duration between price changes is about 3–4 quarters, see Nakamura and Steinsson (2008). This implies a Calvo parameter of 0.75, which in our model corresponds to a price adjustment cost parameter of 59.

Table 2. Benchmark parameter values

Parameter	Description	Value
α^D	Weight on domestic consumption in CES-function	0.7
α^N	Weight on non-agriculture consumption in CES-function	0.7
β	Discount factor	0.9926
η^F	Frisch elasticity	2
η^H	Substitution elasticity of labor across sectors	0.5
η^D	Substitution elasticity between domestic and imported consumption	2
η^N	Substitution elasticity between non-agriculture and agriculture goods	0.5
η	Substitution elasticity between non-agriculture products	6
θ^N	Weight on capital in non-agriculture production function	0.33
δ^N	Depreciation rate capital	0.025
κ^P	Price adjustment cost	59
κ^K	Capital adjustment cost	5
θ^A	Weight on land productivity in agriculture production function	0.2
δ^A	Decay rate land productivity	0.04
τ	Cost of land maintenance scaling parameter	6
ϕ	Cost of land maintenance elasticity parameter	0.5
κ^{B^*}	Foreign bond adjustment cost	0.001
$\bar{B}^*$	Foreign bond holdings to output	0.4
$\bar{\pi}$	Inflation target (percent)	5
ρ	Persistence of weather shock	0.6

5 Economic implications of weather shocks

To illustrate how weather shocks can affect the Rwandan economy, we show the impulse responses to an adverse weather shock of 10 percent in Figure 6.[5] The shock decays gradually and reaches zero after about a year. There is a direct and negative impact on land productivity, which drops by almost 4 percent. The effect on hours worked is relatively small. This means that the decrease of agriculture production of about 3 percent is almost entirely due to lower land productivity.

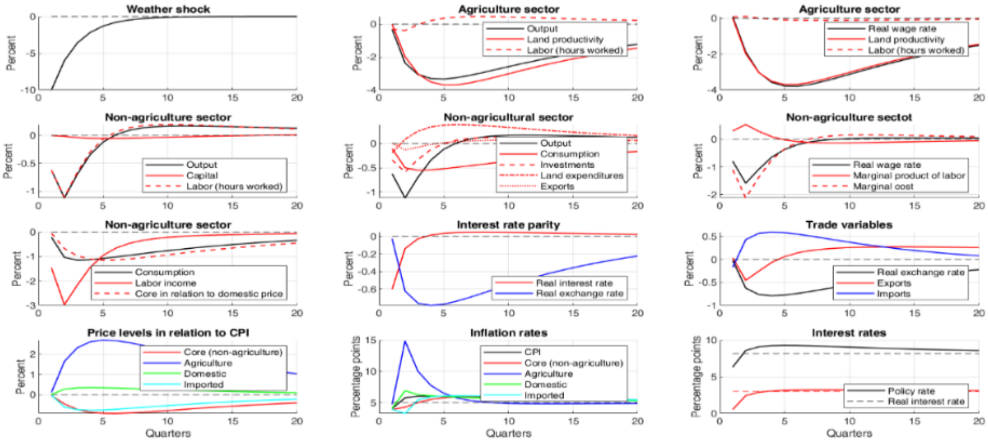
---

[5] Monetary policy follows a Taylor rule where inflation is measured by the CPI and the parameters $\rho_\pi = 1.5$ and $\rho_Y = 0.125$.

The real wage in the agriculture sector is determined by the marginal product of labor, i.e., the ratio of land productivity to hours worked. Lower land productivity puts a downward pressure on the marginal product of labor and consequently the real wage.

The non-agricultural sector is indirectly affected by the weather shock. Non-agriculture production decreases by about 1 percent, which from the supply side is driven by fewer hours worked. From the demand side, the expenditure components – consumption, investments, land maintenance, and exports – initially fall. Although, spending on land maintenance rises quickly in the following quarters as farmers restore damages from the weather shock.

Figure 6. Economic implications of an adverse weather shock



Note. The diagrams show percentage (where indicated) deviations from steady state or percentage points (where indicated) deviations from steady state to an adverse weather shock.

The price adjustment cost in the non-agricultural sector implies a time-varying real marginal cost and that the real wage depends on both the marginal product of labor and the marginal cost. The slight increase of the marginal product of labor is counteracted by a lower marginal cost, which leads to a fall of the real wage also in this sector.

In the aggregate, lower wages and fewer hours worked imply a lower labor income for the households, limiting their consumption possibilities. Consumption of both agriculture and non-agriculture products decrease, but decrease of agriculture products is larger due to the higher relative prices of these products.

The uncovered interest rate parity condition provides an additional channel through which the economy is affected. The real interest rate falls initially, which implies an expected appreciation of the real exchange rate. This gives households an incentive to substitute domestic consumption for imported consumption goods. At the same time, the appreciating real exchange discourages exports.

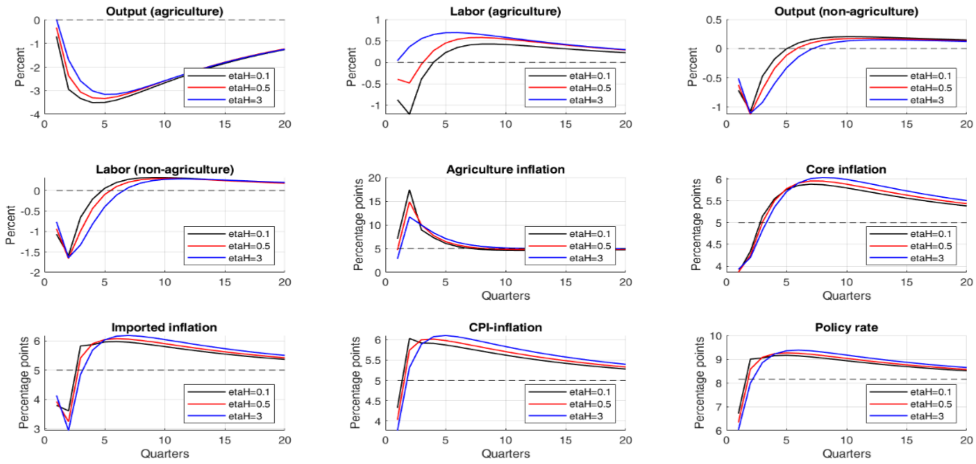
The CPI is a weighted average of prices for agriculture, non-agriculture, and imported products. On one hand, the weather shock drives up prices on agriculture products by almost 15 percent. On the other hand, there is a downward pressure on prices of non-agriculture products from lower marginal costs and lower prices of imported products due to the appreciating real exchange rate. The total effect is a decrease of CPI inflation. Monetary policy follows a standard Taylor rule with CPI as the inflation measure. The policy rate is initially lowered, since both CPI inflation and output fall but as the CPI increases in the next quarters the policy rate is raised above its long-run value.

5.1 Sensitivity analysis

Labor mobility across sectors

The substitution elasticity of labor between the two sectors is calibrated to a relatively low value of 0.5 in the benchmark. To examine how the impulse responses are affected by this value, we examine a lower elasticity and a higher elasticity, i.e., $\eta^H = 0.1$ and $\eta^H = 3$. The impulse responses for these values together with the benchmark value are shown in Figure 7.

Figure 7. Sensitivity analysis with respect to labor mobility across sectors



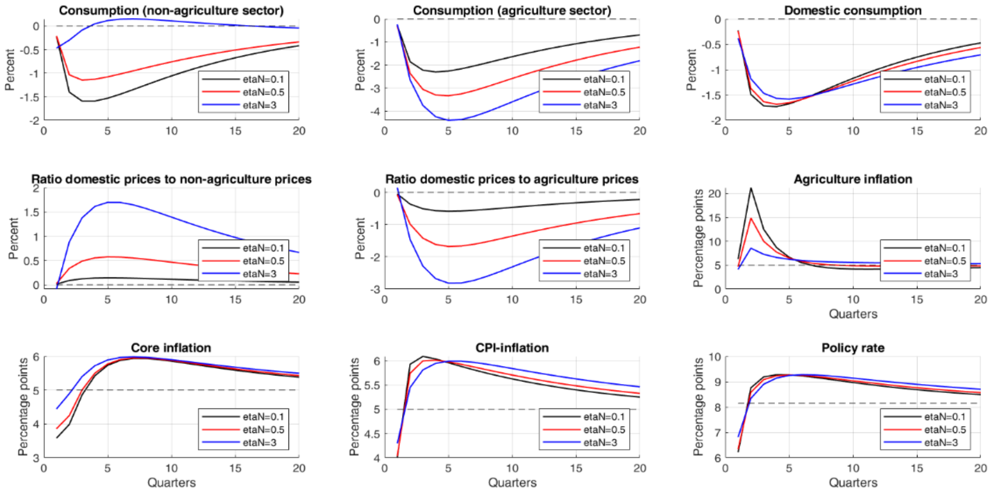
Note. The diagrams show percentage (where indicated) deviations from steady state or percentage points (where indicated) deviations from steady state to an adverse weather shock.

The primary effect of higher labor mobility is an increase of labor supply in the agriculture sector. This increases agriculture production and puts downward pressure on agriculture prices. However, this has relatively small spillover effects on CPI inflation and the policy rate is almost unaffected.

Substitution elasticity between non-agriculture and agriculture products

The willingness to substitute away food for non-agriculture products is generally low in lower income countries and is set to a low value in the benchmark calibration, i.e., $\eta^N = 0.5$. Figure 8 shows how an even lower and a higher substitution elasticity affects the results.

Figure 8. Sensitivity analysis with respect to the substitution elasticity between non-agriculture and agriculture products



Note. The diagrams show percentage (where indicated) deviations from steady state or percentage points (where indicated) deviations from steady state to an adverse weather shock.

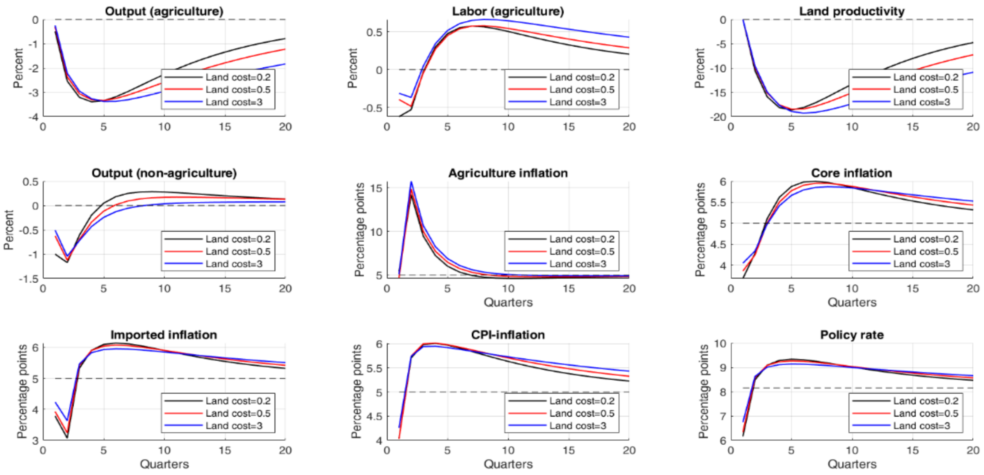
The adverse weather shock drives up prices of agricultural products. The easier it is to substitute between agricultural and non-agricultural products, the larger becomes the relative price increase. A higher substitution elasticity thus gives households incentive to consume more non-agriculture products and less agriculture products. These sector effects are quantitatively significant, but the implications for CPI inflation and the policy rate are small.

Land maintenance cost

Spending resources on land maintenance exhibit an increasing cost determined by the parameter ϕ. In the benchmark calibration, this parameter is set to 0.5. Figure 9 shows how a lower and a higher value of the land maintenance cost affect the impulse responses.

A higher cost has first and foremost a negative effect on land productivity. However, this effect takes place gradually over time according to the law of motion for land productivity and it takes about a year until there are any visible effects. Lower land productivity affects agricultural production negatively, but this can to some extent be mitigated by higher labor input. This, however, leads to fewer hours worked in the non-agricultural sector. Consequently, non-agriculture production decreases when the cost of land maintenance increases. CPI inflation and output are, however, hardly affected and there are only small effects on the policy rate.

Figure 9. Sensitivity analysis with respect to cost of land maintenance



Note. The diagrams show percentage (where indicated) deviations from steady state or percentage points (where indicated) deviations from steady state to an adverse weather shock.

6 Weather shocks and monetary policy

This section examines whether the central bank should stabilize CPI or core inflation following an adverse weather shock. To do this, we evaluate how the central bank's loss is affected when the central bank reacts to either CPI inflation or core inflation in the Taylor rule. We consider a single and a dual mandate loss function.

6.1 Single mandate loss function

When the central bank has a single mandate to stabilize CPI inflation, we set the weight on output stabilization to zero in the Taylor rule,

$$\frac{R_t}{\bar{R}} = \left(\frac{\boldsymbol{\pi}_t}{\bar{\pi}}\right)^{1.5}, \tag{47}$$

where $\boldsymbol{\pi}_t$ is a vector of inflation measures, i.e., $\boldsymbol{\pi}_t = [\pi_t^{CPI}, \pi_t^{core}]$. The rule where CPI is the inflation measure is called the CPI rule and the rule where agriculture prices are excluded from the CPI is called the core rule. For the benchmark calibration, the central bank's loss is reduced by 17 percent when the central bank follows the core rule instead of the CPI rule, see Table 3. However, the benefit from following a core rule decreases as prices become more flexible, but the benefit is always positive. When prices are perfectly flexible, the benefit is 7 percent.

These results are in line with the well-known result in the New Keynesian literature that the central bank should stabilize prices of the sticky price sector in a two-sector model. This result relies on central banks maximizing the utility of a representative household, while our results are based on evaluating a simple rule in terms of a central bank loss function.

Table 3. Central bank loss for the core rule relative to the CPI rule under different degrees of price stickiness

Price stickiness	Central bank loss
$\kappa^P = 58.7$ (corresponds to a Calvo parameter of 0.75)	−17 percent
$\kappa^P = 9.9$ (corresponds to a Calvo parameter of 0.50)	−15 percent
$\kappa^P = 2.2$ (corresponds to a Calvo parameter of 0.25)	−10 percent
$\kappa^P = 0.0$ (corresponds to a Calvo parameter of 0.00)	−7 percent

Note. The central bank loss for the core rule is computed as the percentage deviation from the CPI rule. A negative value therefore indicates a benefit of the core rule over the CPI rule.

The transmission channel of monetary policy in the model can be divided into an interest rate channel and an expectation channel. Price stickiness is the key feature of the interest rate channel. When nominal prices are slow to adjust, changes in the policy rate translate into movements in the real interest rate that affect supply and demand conditions in the goods and labor markets, and in turn inflation.

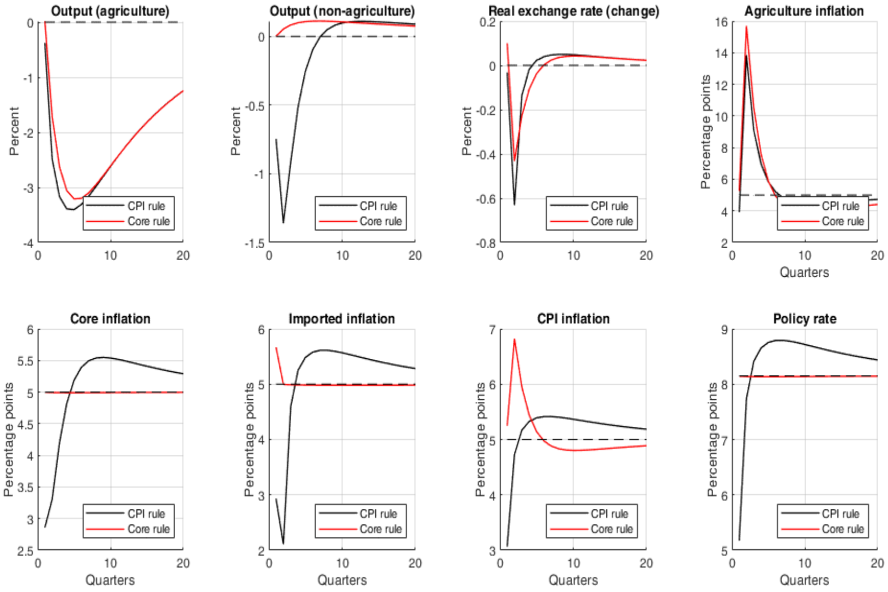
The expectation channel relies on households' and firms' expectations of future inflation. These expectations are a function of the monetary policy rule, in particular the weight on inflation stabilization in the rule matters. A higher weight increases households' and firms' expectations that the central bank is committed to stabilize inflation around the target. If the weight is high enough, inflation can in principle be fully stabilized without the central bank even moving the policy rate. Other factors in the policy rule – such as output stabilization – weaken the commitment to stabilize inflation, and affect inflation expectations negatively.

The central bank's possibility to stabilize prices in the agriculture and non-agriculture sectors depends on (i) in which sector the shock has its main impact and (ii) the strength of the transmission channels in the two sectors. The weather shock directly affects the agricultural sector through its impact on land productivity. Prices are also flexible in this sector, which means that the interest rate channel is absent.

Prices in the non-agricultural sector are only indirectly affected by the weather shock. Moreover, prices in this sector are affected by both the interest rate and expectation channels. These factors taken together imply that the possibilities to stabilize non-agricultural prices or core inflation are better than agricultural prices. This is illustrated in Figure 10. When the central bank follows the core rule instead of the CPI rule, core inflation is fully stabilized without even the need to move the policy rate.

Importantly, the stabilization of core inflation does not come at the expense of higher variations in the CPI. On one hand, variations in agricultural prices increase somewhat, since they are not included in the inflation measure. On the other hand, non-agriculture prices are fully stabilized and they comprise a larger part of the CPI. These effects outweigh the somewhat higher variations in agriculture prices.

Figure 10. Impulse responses to an adverse weather shock for the CPI rule and the core rule



Note. The diagrams show percentage (where indicated) deviations from steady state or percentage points (where indicated) deviations from steady state.

It would in principle be possible for the central bank to fully stabilize agriculture prices following the adverse weather shock. This would, however, have severe negative consequences for the rest of the economy. Higher prices for agriculture products provide an important signal that these products are scarce. Households should be incentivized to substitute for other products when they can and farmers should be incentivized to quickly restore farming. When distributional consequences are important, the government should compensate those negatively affected by fiscal transfers and let the price signal affect behavior.

More generally, resources should be allocated by supply and demand conditions in a well-functioning market economy. Changes in relative prices act as signals, directing resources to where they are most valued. This allows for efficient resource allocation as it reflects the scarcity and value placed on resources by households and firms. The central bank should avoid interfering with those price signals. When there are large relative price changes, this can be done by also considering core measures of inflation.

6.2 Dual central bank mandate

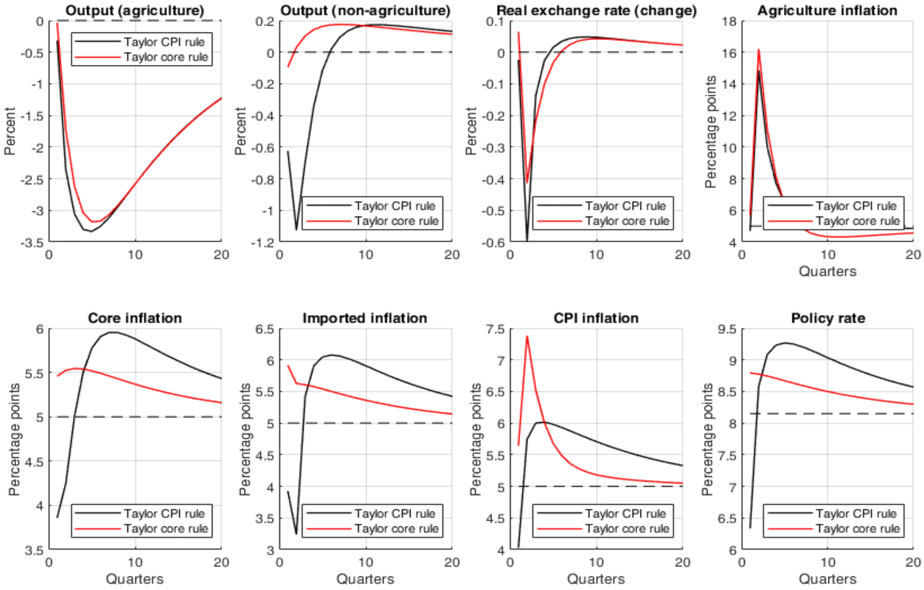
In the case of a dual mandate to stabilize both inflation and output, the weight on output stabilization is included in the Taylor rule,

$$\frac{R_t}{\bar{R}} = \left(\frac{\pi_t}{\bar{\pi}}\right)^{1.5} \left(\frac{Y_t}{\bar{Y}}\right)^{0.125}, \tag{48}$$

where $\boldsymbol{\pi}_t$ is a vector of inflation measures as in (47). The rule where the CPI is the inflation measure is called the Taylor CPI rule and the rule where non-agriculture prices is the inflation measure is called the Taylor core rule.

Figure 11 shows the impulse responses to the weather shock for the Taylor CPI rule and the Taylor core rule. Note that the Taylor core rule – in contrast to the core rule – does not fully stabilize core inflation, since adding output stabilization to the policy rule weakens the commitment to stabilize inflation through the expectation channel. Moreover, by reacting to output the fall in non-agriculture production is mitigated but the effect on agricultural production is very small.

Figure 11. Impulse responses to a weather shock for the Taylor CPI and core rules



Note. The diagrams show percentage (where indicated) deviations from steady state or percentage points (where indicated) deviations from steady state.

When the central bank follows the Taylor core rule instead of the Taylor CPI rule, the central bank's loss is reduced by 53 percent, see Table 4. When prices in the non-agriculture sector become more flexible, the benefit from stabilizing core inflation instead of CPI inflation decreases. Note that when prices are perfectly flexibility the benefit is zero.

Table 4. Central bank loss for the Taylor core rule relative to the Taylor CPI rule under different degrees of price stickiness

Price stickiness	**Central bank loss**
$\kappa^P = 58.7$ (corresponds to a Calvo parameter of 0.75)	−53 percent
$\kappa^P = 9.9$ (corresponds to a Calvo parameter of 0.50)	−14 percent
$\kappa^P = 2.2$ (corresponds to a Calvo parameter of 0.25)	−3 percent
$\kappa^P = 0.0$ (corresponds to a Calvo parameter of 0.00)	0 percent

Note. The central bank loss for the Taylor core rule is computed as the percentage deviation from the Taylor CPI rule.

7 Concluding remarks

This paper has examined whether a central bank should stabilize CPI or core inflation following an adverse weather shock. It was first shown that an adverse weather shock in Rwanda leads to lower agricultural production and higher agricultural prices, which aligns with the predictions of the macroeconomic model. It was then shown that in response to a an adverse weather shock, the central bank should follow a rule where inflation is measured by core inflation instead of CPI inflation to minimize the central bank's loss function, despite that inflation is measured by the CPI in the loss function.

This work can be extended in different directions. We have considered a relatively simple model to highlight some basic mechanisms and results. Future studies may extend the model to include additional features to better reflect the Rwandan economy. Fiscal policy and a financial sector are two important features that can be added. More frictions can also be added. We have considered price stickiness as the principal friction, but frictions such as wage stickiness and search and matching frictions in the labor market are potentially interesting. The open economy part of the model has been kept simple and can be extended to explore in more detail potential effects of trade and the exchange rate. Finally, we have examined a standard Taylor rule but extending the analysis to examine optimized simple rules or optimal monetary policy can also be of interest.

References

Abril-Salcedo, D. S., L. F., Melo-Velandia, and D. Parra-Amado, (2020), “Nonlinear relationship between the weather phenomenon El niño and Colombian food prices”, *Australian Journal of Agricultural and Resource Economics* 64.

Acevedo, S., M. Mrkaic, N. Novta, E. Pugacheva, and P. Topalova (2020), “The effects of weather shocks on economic activity: What are the channels of impact?”, *Journal of Macroeconomics* 65.

Aoki, K (2001), “Optimal monetary policy responses to relative price changes*”, Journal of Monetary Economics* 48.

Bejarano-Salcedo, V., E., Caicedo-García, N. F., Lizarazo-Bonilla, J. M., Julio-Román, and J. A. Cardenas-Cárdenas (2020), “The stylized facts of the relationship between El Niño, La Niña and inflation in Colombia”, Working Papers on Economics 1105, Banco de la Republica de Colombia.

Bernanke, B., T. Laubach, F. Mishkin, and A. Posen (1999), “Inflation targeting: Lessons from the international experience”, Princeton University Press.

Bryan, M. (2002), “Is it more expensive, or does it just cost more money?”, Economic Commentary 5/15/2002, Federal Reserve Bank of Cleveland.

Bryan, M. and S. Cecchetti (1994), “Measuring core inflation”, Editor: G. Mankiw, University of Chicago Press.

Bullard, J. (2011), “Measuring inflation: the core is rotten”, Federal Reserve Bank of St. Louis Review 93.

Clarida, R., J. Gali, and M. Gertler (1999), “The science of monetary policy: A new Keynesian perspective”, *Journal of Economic Literature* 37.

de Sousa Freitas, M. A., (2005), ”Um sistema de suporte à decisão para o monitoramento de secas meteorológicas em regiões semi-áridas”, Rev. Tecnol., suppl. 19.

del Negro, M., J. di Giovanni, and K. Dogra (2023), “Is the green transition inflationary?”, Federal Reserve Bank of New York Staff Report no. 1053.

Gallic, E. and G. Vermandel (2017), “Weather shocks, climate change and business cycles”, MPRA Paper No. 81230.

Gallic, E. and G. Vermandel (2020), “Weather shocks”, *European Economic Review* 124.

Mendelsohn, R., A., Dinar, and A. Dalfelt (2000), “Climate change impacts on African agriculture”, mimeo.

Milivojevic L. (2023), “Natural disasters and fiscal drought”, Policy Research Working Paper 10298, World Bank.

Nakamura, E. and J. Steinsson (2008) “Five facts about prices: A re-evaluation of menu cost models”, *Quarterly Journal of Economics* 123.

Okot, N. (2020), “Weather shocks and monetary policy: An empirical DSGE for Uganda”, Working Paper no. 27, Bank of Uganda.

Olovsson C. and D. Vestin (2023), “Greenflation?”, Sveriges Riksbank Working Papers Series 420.

Peterman, W. B., (2016), “Reconciling micro and macro estimates of the Frisch labor supply elasticity”, *Economic Inquiry* 54.

Romdhane, H. B. and R. Bouaziz (2021), “Climate change and business cycle: Case of Tunisia”, Working Paper Series no.1-2021, Central Bank of Tunisia.

Romero, J. V. and S. Naranjo-Saldarriaga (2023), “Weather shocks and inflation expectations in semi-structural models”, Latin American Journal of Central Banking 100112.

Romero, J. V., S. Naranjo-Saldarriaga and J.A. Muñoz (2023), “Assessing the macroeconomic impact of weather shocks in Colombia”, Working Paper HEIDWP14-2023, Graduate Institute of International and Development Studies.

Rooy, van A. (1965), “Rainfall anomaly index independent of time and space”, *Notos* 14.

Svensson, L. (2010), “Inflation targeting”, in Handbook of Monetary Economics, volume 3, Editors: B. Friedman and M. Woodford, chapter 22, Elsevier.

Taylor, J. (1993), “Discretion versus policy rules in practice”, *Carnegie-Rochester Conference Series on Public Policy* 39.

SVERIGES RIKSBANK
Tel +46 8 - 787 00 00
registratorn@riksbank.se
www.riksbank.se

PRODUCTION SVERIGES RIKSBANK