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Weather or not? The role of international sanctions and climate on food prices in Iran

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Introduction: The scarcity of resources have affected food production, which has challenged the ability of Iran to provide adequate food for the population. Iterative and mounting sanctions on Iran by the international community have seriously eroded Iran's access to agricultural technology and resources to support a growing population. Limited moisture availability also affects Iran's agricultural production. The aim of this study was to analyze the influence of inflation, international sanctions, weather disturbances, and domestic crop production on the price of rice, wheat and lentils from 2010 to 2021 in Iran.

Method: Data were obtained from the statistical yearbooks of the Ministry of Agriculture in Iran, Statistical Center of Iran, and the Central Bank of Iran. We analyzed econometric measures of food prices, including CPI, food inflation, subsidy reform plan and sanctions to estimate economic relationships. After deflating the food prices through CPI and detrending the time series to resolve the non-linear issue, we used monthly Climate Hazards group Infrared Precipitation with Stations (CHIRPS) precipitation data to analyze the influence of weather disturbances on food prices.

Results and discussion: The price of goods not only provides an important indicator of the balance between agricultural production and market demand, but also has strong impacts on food affordability and food security. This novel study used a combination of economic and climate factors to analyze the food prices in Iran. Our statistical modeling framework found that the monthly precipitation on domestic food prices, and ultimately food access, in the country is much less important than the international sanctions, lowering Iran's productive capability and negatively impacting its food security.

KEYWORDS

international sanctions, food inflation, staple food prices, commodity crops, precipitation

1. Introduction

Global food security is often noted as a prerequisite for sustainable development (FAO and WHO, 2019). Adequate supplies of food is a fundamental aspect of human societies, and is considered one of the pivotal factors of individual and social health (Tutunchi et al., 2020). In the last 10 years, the frequency and intensity of conflict, climate variability and extremes, and economic slowdowns have increased and are undermining

food security and nutrition around the world (FAO, IFAD, UNICEF, WFP, and WHO, 2021). Of particular concern are low- and middle-income countries because the negative impacts on food security and nutrition are greatest in these countries (FAO, 2021b). Most of the world's undernourished, food insecure that suffer from one or more forms of malnutrition live in low-income countries (FAO, IFAD, UNICEF, WFP, and WHO, 2021). Findings of a systematic review and meta-analysis on climate and food prices by Birgani et al. (2022) show that increases in food price will significantly affect food accessibility in lower-income countries, primarily through 2050.

Iran is an upper middle-income country (FAO, IFAD, UNICEF, WFP, and WHO, 2021). Restrictions on imports and exports have generated hurdles for food transportation, while consumers and producers have faced difficulties that ultimately led to declining farmers' income, damaging the agricultural sector (FAO, 2020). The Food and Agriculture Organization of the United Nations (FAO) reports that from 2018 to 2020 the prevalence of moderate or severe food insecurity in the approximate total population of 84 million in Iran was 42.5%, with the prevalence of undernourishment at 5.5% (FAO, 2021a). Fiscal policies should promote the ability of households to meet their nutritional needs (Behzadifar et al., 2016). The scarcity of resources and lack of food production with high population growth are challenging the ability of the country to provide adequate food (Iran Economy News, 2021). Northern Iran is the most important domestic agricultural region, with the largest share of domestic food production (Sharifi, 2021). For the majority of the country, the climate is arid or semi-arid, with long-run average annual rainfall estimates ranging from 200 to 230 millimeters per year (The World Bank, 2021; World Bank, 2021) and therefore, local weather disturbances inevitably affect food markets, resulting in increased food prices (Mbow et al., 2019).

The purpose of this study was to explore the impact of precipitation anomalies and trade sanctions on food prices, and ultimately food security, in Iran. This 120-month, 10-year study of four commodity crops describes the impact of weather disturbances on food prices in the context of inflation, changes in the exchange rate and ongoing sanctions. The paper is organized by first describing the current economic situation in Iran, specifically the impact of trade sanctions on the country, inflation on food affordability, and current climate trends. We then present our data, the methods used in the analysis and our results. We finish with a discussion of the implications of climate and trade sanctions on agricultural productivity over a period of a decade. In the past decade, a few papers have analyzed the impact of climate and food prices in Iran separately (Karbasi and Sayyadi, 2015; Afzali et al., 2020; Kiani Ghalehsard et al., 2020; Fatahi Ardakani et al., 2022). In this study, we provide a novel analysis that seeks to include a wide range of variables related to the price of domestic commodity crops. The main study question is: to what extent are food prices impacted by the international sanctions, food inflation and climate change?

2. Background

2.1. Agriculture in Iran

Agriculture in Iran is one of the three main sectors of the economy, playing an important role in food supply, social welfare, and gross domestic product (GDP). Due to its extensive connections with other economic sectors, the agriculture sector provides the basis for wealth production, market creation and currency generation [Statistical Center of Iran (SCI)., 2019]. In Iran, rice has a special place in the daily diet. Many agricultural processing activities and supplementary industries (e.g., rice bran oil and rice hull factories) result from the rice crop (Mardani Najafabadi et al., 2022). The head of Agricultural Mechanization Development Center of the Ministry of Agriculture Jihad (hereafter referred to as the Ministry of Agriculture), emphasized that rice cultivation should be stopped in low-water provinces, allowing and promoting rice production in the Gilan and Mazandaran provinces of northern Iran (Iran Economy News, 2021). According to the Ministry of Agriculture-Jihad in Iran Yearbook (2019), Golestan Province (also in northern Iran) produces about 10% of the total wheat output with high quality as well as 14% of total rice production after Mazandaran and Gilan provinces. Therefore, northern Iran is the main region of producing domestic rice (∼ 84% of domestic production providing by Mazandaran and Gilan provinces) and wheat (∼ 14% of sharing domestic production is in Golestan province as well as the self-sufficiency in wheat production to meet the needs of Mazandaran province) and an important region of the country in terms of food security and food sovereignty (Zamanialaei et al., 2022). Figure 1 shows examples of pest management in wheat and barley fields (a) and a rice field (b) in northern Iran.

2.2. Food inflation

Iran's economy has been trying to control its chronic inflation by creating discipline in monetary and fiscal policies (Zaroki and Yousefi-Barfurushi, 2021). In the past decade, inflationary pressures in Iran have been particularly high due to a limited supply of foreign exchange and economic uncertainty (The World Bank, 2021). Food inflation in Iran has averaged 22.88 percent from 2012 until 2021, reaching 59.20 percent in August of 2020 over the same month in the previous year (Figure 2) (Trading Economics., 2021). The inflation rate is the measure of the increase or rate of increase in the general price of selected goods and services over a determined period of time, and can indicate a decline in the purchasing power or value of a nation's currency (FEWS NET, 2009).

Soaring food prices and subsidy cuts directly affected the food security situation among the poor and vulnerable population in Iran [World Food Programme (WFP)., 2016]. Both controlling the price of goods and monopoly pricing are

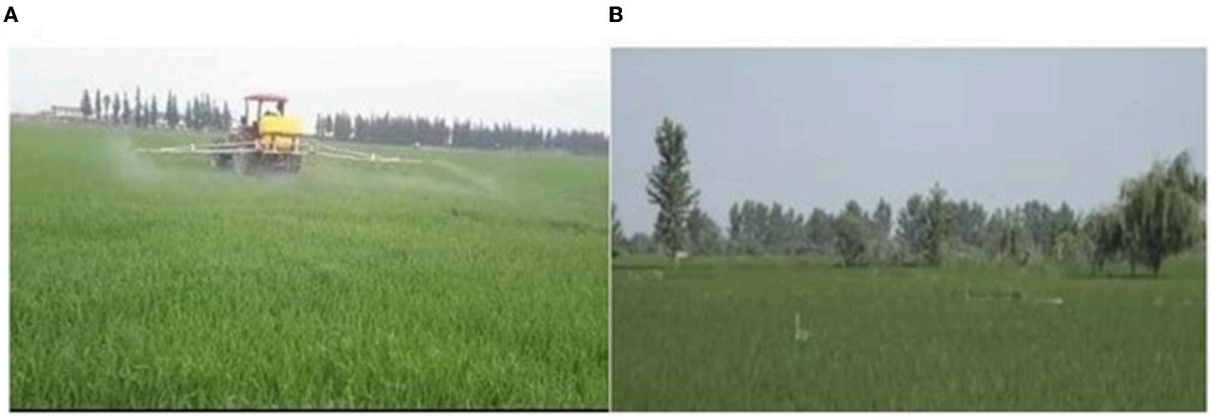
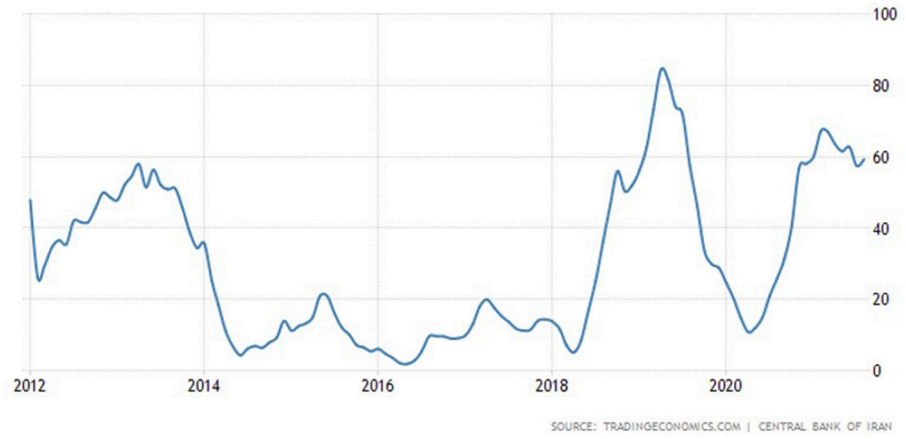


FIGURE 1
(A) Technology of pest management in wheat and barley fields in Golestan province (March 2022, Source: https://kesht-sanat.ir/?p=5219).
(B) Rice farm in Amol, Mazandaran province (March 2017 by Maryam Zamanialaei).



Actual	Previous	Highest	Lowest	Dates	Unit	Frequency
59.20	57.40	84.40	1.80	2012-2021	%	Monthly

FIGURE 2
Monthly percentage of food inflation in Iran 2012–2021, with 2011 as the base year to calculate inflation rate (Source: Central Bank of Iran, www.cbi.ir).

severe problems for Iran's economy (Shakeri et al., 2015). Social safety nets, which included food and energy subsidies, have supported the food security of the population (Devereux, 2016). Iran passed a targeted subsidy plan in December 2010 (Persian: یارانه‌ها هدفمندسازی طرح) also known as the subsidy reform plan, which replaces subsidies on food and fuel (80% of total) with targeted social assistance in accordance with a 5-year economic development plan (Salamatbakhsh, 2020). Unfortunately, like many other programs in the region, this targeted social assistance is low and inaccurately applied, resulting in far less support and leading to substantial food price inflation (Harrigan, 2014).

The latest official information available from Iran's Central Bank indicates that, in the period from 19 February 2019 to 20 March 2019 (corresponding to اسفند 1398), food and beverages price inflation index climbed to 72 percent on a yearly basis, driven by the devaluation of its currency related to the full re-imposition of economic sanctions in November 2018. The sanctions severely limit export earnings. By comparison, in the same period in 2018, the food price inflation stood at 7 percent on a year-on-year basis. The Central Bank of Iran maintains a dual tier exchange rate system. The fixed rate of IRR (Iranian Rial) 42 000 per 1 USD is used to finance imports of essential goods. For

other transactions, the official exchange was IRR (Iranian Rial) 135 000 per 1 USD (FAO, 2019).

2.3. International sanctions

Iran has gone through an economic downturn over the past two decades due to prolonged international sanctions (Congressional Research Service., 2021). Garshasbi and Yusefi (2016) assessed the international sanctions' influence on Iranian macroeconomic variables for the years 1978–2010 and found that the direct effects of sanctions have affected the growth of trade and the terms of trade. Similarly, between 1981 and 2014, international sanctions have had direct and significant effects on the inflation rate in Iran through increasing the exchange rate and raising the budget deficit. Due to the significant decrease in foreign exchange reserves of the central bank due to international sanctions in 2012–2014, the central bank encountered restrictions in supplying foreign exchange to the market and therefore a sharp increase in the exchange rate occurred. The increase in the exchange rate led to rise the prices of imported agricultural goods (e.g., livestock inputs such as corn for livestock feed, as well as oil seeds, hybrid seeds, fertilizer and pesticides) and, consequently, to an increase in the price of commodities, and finally to an increase in the rate of inflation (Sadeghi and Tayebi, 2018).

Torbat (2005) uses an exhaustive approach to assess the costs of sanctions on Iran. He estimates the costs to be ∼1.1% of GDP annually, which is a non-trivial amount given that the average growth rate of per capita income in Iran in the past 10 years (1995–2005) has been about 3 percent. He also shows that financial sanctions have been more consequential than those imposed on trade.

Between 2011–2015, global economic sanctions reflecting US foreign policy contributed to the shrinking of Iran's economy as its crude oil exports fell by more than 50% and lack of access to its foreign exchange assets abroad (Congressional Research Service., 2021). Sanctions did contribute to Iran's decision to enter into a 2015 agreement that put limits on its nuclear program—the Joint Comprehensive Plan of Action (JCPOA). On May 8, 2018, President Trump ended US participation in the JCPOA and reimposed all secondary sanctions in November 2018. As a result of the re-enactments of US sanctions against Iran in 2018, Iran's currency (the Rial) collapsed, losing two-thirds of its value. Coupled with the social safety net reform passed in the same year (2018), Iran experienced unprecedented inflation in the food market (Hejazi and Emamgholipour, 2022). Table 1 shows the economic impacts of the international sanctions' seven phases and the main outcome for each phase as well as our use of the labels Sanction 1, Sanction 2 and Sanction 3 in this paper. Other countries and international organizations like the European Union and the United Nations have sanctions against Iran (EU Sanctions Map)[1], but our study focuses on US sanctions as they are often viewed as the most impactful by non-governmental organizations (Iran Watch., 2019) and the scientific literature (Amuzegar, 1997; Torbat, 2005; Garshasbi and Yusefi, 2016; Heidary, 2018; Mahdiloo and Rezaei-Mirghaed, 2018; Rabi'I and Takrosta, 2021; Hejazi and Emamgholipour, 2022).

2.4. Climate change

In the context of these economic upheavals, Iran has experienced increasing climate variability and extremes, linked to climate change, which are negatively affecting the stability of domestic food prices (Brown and Kshirsagar, 2015). Drought, floods, and extreme temperatures significantly affect the economy and affect approximately a third of the variability of agricultural yields globally (Ray et al., 2015). Countries with limited agricultural resources are particularly vulnerable to these climatic extremes.

Over the past 15 years, Iran has seen prolonged drying conditions, resulting in vanishing lakes and wetlands along with excessive water stress across the country. The resulting long-standing issues with the inefficiency of its water distribution network has particularly affected the agricultural sector (Ashraf et al., 2021). Iran's average annual precipitation over the last 10 years is 250 mm with most of the country receiving <100 mm of rain per year (Atashi et al., 2019). Madani et al. (2016) showed that rapid population growth, migration and urbanization, inadequate water distribution infrastructure, water quality degradation, inefficient agriculture, and drought all affect water availability for agriculture.

Sudden and irregular rainfall is also a significant threat that affects agriculture through floods in Iran [Islamic Parliament Research Center (IPRC)., 2019]. At the end of April 2020, seasonal flooding due to heavy rainfall affected 18 provinces, particularly in central and eastern parts of the country. Localized damage to crops (especially wheat, garlic and orchards) and significant damage to agricultural infrastructure were reported in the agricultural provinces. These floods also damaged about 10,000 km of roads (FAO, 2020).

3. Methodology

3.1. Study area

Given their importance in agricultural production, Mazandaran, Gilan and Golestan provinces in northern Iran were the focus of this study (Figure 3). Northern Iran is bordered

1 https://www.sanctionsmap.eu/#/main

TABLE 1 The economic impact of the US sanctions on Iran.

	Sanctions phases	Implemented date	Highlighted outcomes
Before study time frame	Phase 1	November 1979	The United States imposes sanctions which result in ban the Iranian imports to the United States and $12 billion in Iranian assets are frozen.
	Phase 2	April 8, 1992	The US Congress passes the Iran-Iraq Arms Non-proliferation Act of 1992.
	Phase 3	August 5, 1996	The US Congress passes the Iran-Libya Sanctions Act, later known as the Iran Sanctions Act.
	Phase 4	March 24, 2007 March 3, 2008 June 2010	The US Treasury Department revokes Iran's "U-turn" license "further restricting Iran's access to the U.S. financial system."
Sanction 1	Phase 5	January 23, 2012	The nuclear- related sanctions on Iran. Sanctions imposed on the central bank of Iran and oil industry.
Sanction 2	Phase 6	July 14, 2015	Signing of the Joint Comprehensive Plan of Action (JCPOA).
Sanction 3	Phase 7	November 5, 2018	The Trump administration reimposes nuclear-related sanctions on Iran.

by the Caspian Sea to the north and the Alborz Mountains to the south. The elevation of Iran ranges from <-28 m at the Caspian Sea to 5,610 m at the Damavand Peak of Alborz Mountains (Vaghefi et al., 2019). Work by Mesgaran et al. (2017), estimating the spatial distribution of suitability agrarian classes, shows that northern Iran has good and very good suitability for agriculture. According to the latest census in Iran, the total population was estimated at 84 million people in 2020 [Central Bank of Iran (CBI)., 2021]. The population of the three provinces in northern Iran is equivalent to ∼9% of the total population: Mazandaran with 3.2 million, Gilan with 2.5 million and Golestan with 1.8 million. The total area of these three provinces is 58,167 square kilometers [Statistical Center of Iran (SCI)., 2021], which is slightly larger than the Republic of Croatia.

3.2. Data collection

The agricultural data such as domestic production for rice, wheat, barley and lentil was obtained from the Ministry of Agriculture in Iran and the economic variables, like exchange rate, inflation and CPI and food prices were obtained from the statistical center of Iran, Central bank of Iran and FAO. Financial sanctions are derived from the US Congressional Research Service (Congressional Research Service., 2021) and published literature (Amuzegar, 1997; Torbat, 2005; Garshasbi and Yusefi, 2016; Heidary, 2018; Mahdiloo and Rezaei-Mirghaed, 2018; Rabi'I and Takrosta, 2021; Hejazi and Emamgholipour, 2022). Table 2 summarizes the data we used in the study. Sections 3.2.1 through 3.2.4 provide more detailed information on the consumer, economic, and climatic data used.

3.2.1. Price data

We used monthly prices from January 2010 to October 2021 for domestic rice, imported rice, domestic wheat and domestic lentils which derived from the statistical center of Iran (Figure 4). According to the Agricultural Planning, Economic and Rural Development Research Institute (APERDRI) the food basket for Iranian households highly depends on domestic production and availability of food, with 50% of energy supply in the food basket is provided by cereals—mostly wheat and rice. Beans, especially lentils, are important to the diet after wheat and rice (Agricultural Planning, 2016). Therefore, in this study we considered the domestic wheat, rice and lentils prices as well as imported rice prices because of the importance of rice in food security, sustainability and water resources in Iran.

3.2.2. Domestic production annually

Statistics of production, import, and export of agricultural products and foodstuffs were obtained from the Statistical Center of Iran (SCI). Restrictions on cultivable lands, the semi-desert position of Iran, the lack of mechanization of farms, and the imbalance of domestic supply and demand are the important factors of the high amount of food imports in Iran (Mardani Najafabadi et al., 2022) (the statistics of food imports are available in Supplementary Table S2). Therefore, efforts to increase the production of commodity crops are needed immediately (Iran's Crop Calendar as well as the statistics for crop production, yield and commodity crop areas, including wheat, rice and barley, are available in Supplementary Figure S1 and Supplementary Table S1. In January 2019, a deal among the Islamic Republic of Iran, Kazakhstan and the Russian Federation was struck to supply wheat *via* the Caspian Sea in order to increase the utilization of the Iranian wheat flour mills with excess

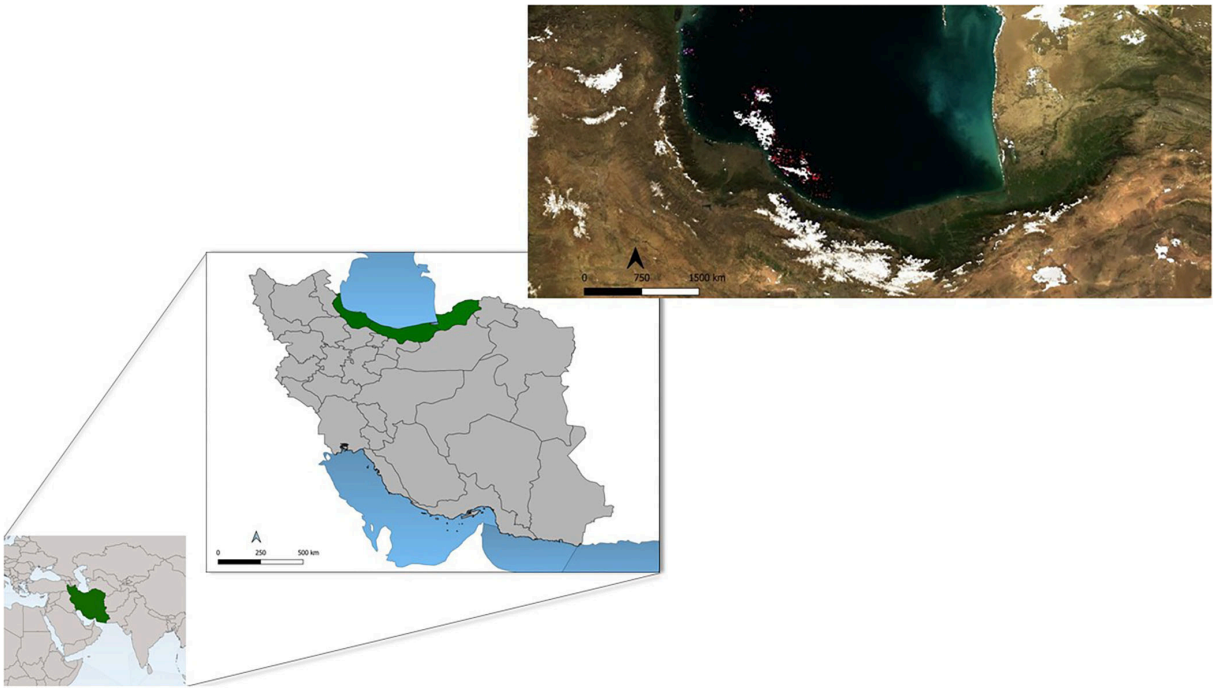


FIGURE 3
Map of Iran highlighting the three provinces in northern Iran include: Mazandaran, Gilan, and Golestan provinces using QGIS V.3.18 and true-color Sentinel-2 satellite imagery from https://www.sentinel-hub.com/.

TABLE 2 Data used in this study.

Data	Years and time step	Source	Purpose
Domestic and imported rice, domestic wheat and domestic lentil prices	Monthly, January 2010 to October 2021	Statistical center of Iran	Measure of food affordability in Iran
Domestic production of rice, wheat, barley, and lentils	Annual, 2010–2020	Statistical yearbook, ministry of agriculture	Measure of food availability
Exchange rate (official)	Annual, 2010–2021	Central bank of Iran	Measure of access to international commodities
CPI	Monthly percent increase, January 2010 to October 2021	Statistical center of Iran	Deflating the food prices
International sanctions	January 2012, July 2015 and November 2018	Congressional research service and publications	Assess Iranian macroeconomic variables
$0.05^{\circ} \times 0.05^{\circ}$ degree Precipitation data	Monthly, January 2008 to Dec 2021	CHIRPS	Estimate weather variability

capacity and, consequently, expand the Iranian exports of flour to third parties *via* the Persian Gulf (FAO, 2019). The Iranian private millers are not allowed to use the domestic wheat destined to supply the domestic market for these flour exports. All wheat imports are meant to be re-exported, while domestic wheat is only consumed in the country (FAO, 2019). We do not consider this complexity in our model, such that reported domestic production is assumed to be consumed in Iran and not exported. Figure 5 shows the annual domestic production for four commodity crops from 2010 to 2020, with detailed data on annual domestic production and imported commodities available in Supplementary Tables S1, S2.

3.2.3. Consumer price index

The Consumer price index (CPI) is the measure of the average price changes of goods and services consumed by Iranian households (Karshenas and Pesaran, 1995) as well as the most common measure of inflation (Baker,

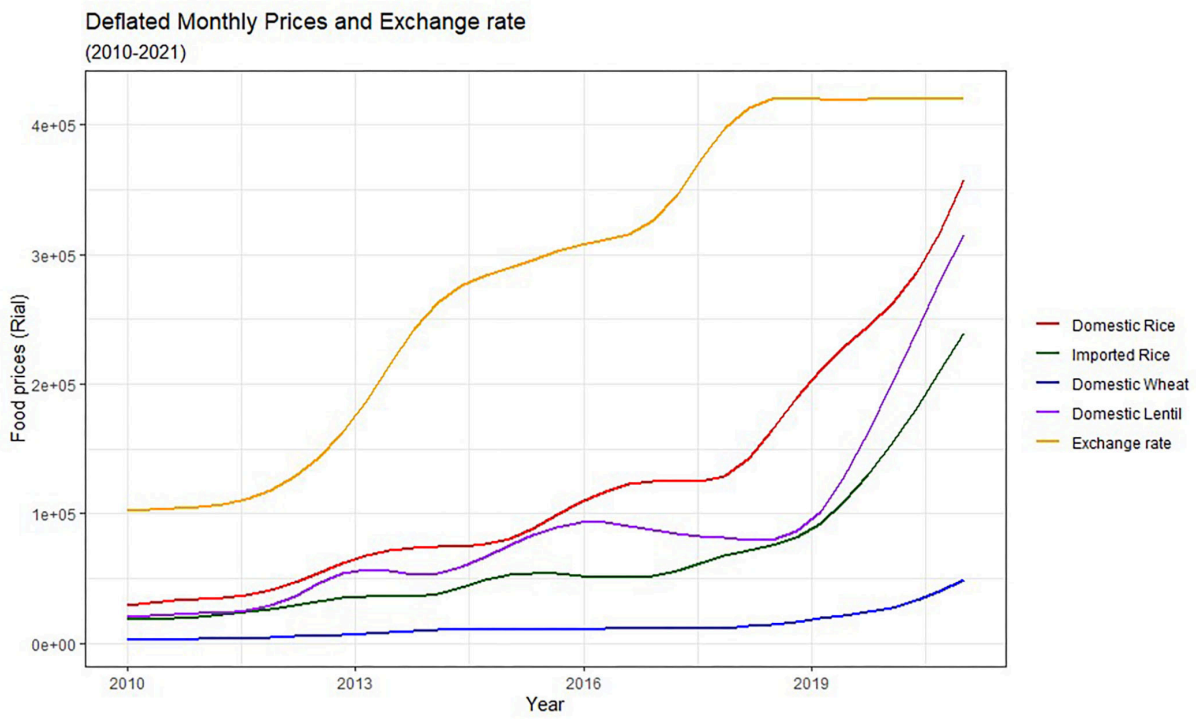


FIGURE 4
Monthly food price for domestic and imported rice, domestic wheat and domestic lentils along with exchange rate 2010–2021 (Source: https://www.amar.org.ir/).

2016). CPI, as a tool for measuring general price level of goods and services consumed by households, is one of the best criteria for measuring changes in purchasing power of national currency (Rogoff, 1996). Deflating food prices with the CPI results in understating price affordability changes through time given the importance of food prices within the index (Alderman and Shively, 1996). The most important categories in the consumer price index in Iran are housing, water, electricity, gas and other fuels (29 percent of total weight) and food and beverages (28.5 percent of total weight). Others include: transport (11.97 percent); furnishings, household equipment and routine household maintenance (6 percent); clothing and footwear (6 percent) and health (5.5 percent). The smallest groups are recreation and culture; education; restaurants and hotels; communication; tobacco and miscellaneous services and goods [Statistical Center of Iran (SCI), 2021]. Figure 6 shows the monthly CPI rate from January 2011 to October 2021.

3.2.4. Precipitation

This study used the monthly Climate Hazards group Infrared Precipitation with Stations (CHIRPS) data for the country of Iran for years 2008 to 2021 (Figure 7). The CHIRPS dataset builds on previous interpolation techniques and a high resolution, long term record of precipitation estimates based on infrared Cold Cloud Duration (CCD) observations. The CHIRPS algorithm (i) is built around a 0.05° climatology that incorporates satellite information to represent sparsely gauged locations, (ii) incorporates daily, pentadal, and monthly 1,981-present 0.05° CCD-based precipitation estimates, (iii) blends station data to produce a preliminary information product with a latency of about 2 days and a final product with an average latency of about 3 weeks, and (iv) uses a novel blending procedure incorporating the spatial correlation structure of CCD-estimates to assign interpolation weights (Funk et al., 2015). The density plots of average rainfall for the study area are also added to Supplementary Figure S2.

3.3. Theoretical framework

Sharp increases in food prices also increase the number of people who fall into poverty, reduce the level and quality of nutrition, and decrease the consumption of non-food services such as education and healthcare, all of which adversely

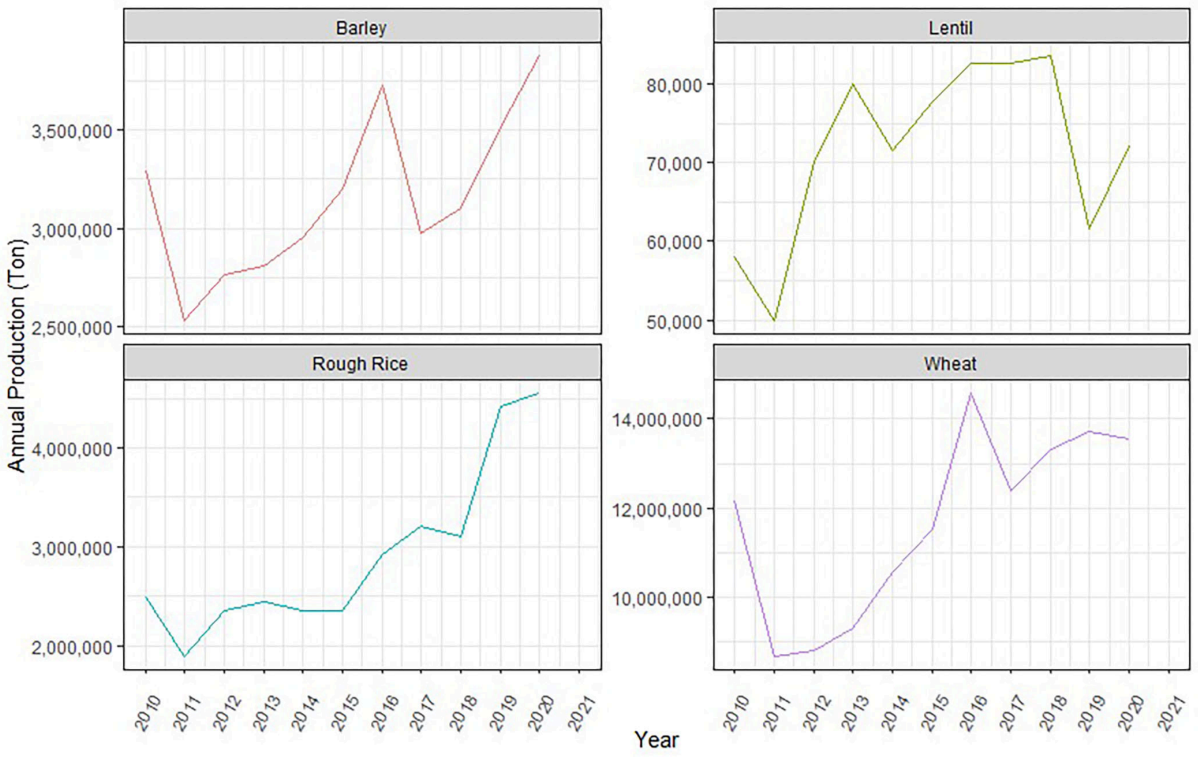


FIGURE 5
Annual domestic production for four commodity crops: rice, wheat, barley, and lentils [Source: Statistical Yearbooks, Ministry of Agriculture in Iran (https://maj.ir/)].

influence future growth of the global economy. In Iran several economic and climate indicators impact on food prices. Figure 8 shows the study framework with highlighting the variables included in the model. The variables in gray were initially considered but were ultimately not used in the final model. We considered economic measures, domestic production of commodity crops and climate change to analyze the food prices for domestic and imported rice, domestic wheat, and domestic lentils in Iran.

3.4. Statistical analysis

First, we deflated the food prices with CPI data and then the food prices were detrended with the use of Practical Numerical Math Functions (Borchers, 2022), then we analyzed the impact of sanctions and subsidy reform plans as well as the domestic production and finally we added the climate variables to see what impacts they had. Each of these are described below.

The monthly food prices were deflated to remove the impact of inflation by using the CPI as a deflator to adjust and normalize the food prices. Based on the information on CPI, we can adjust nominal prices in order to calculate real prices using the following formula (FEWS NET, 2009):

$$REAL\ PRICE\ current\ year\ = (CPI\ base\ year/CPI\ current\ year)^{*} nominal\ price\ current\ year$$

We then removed the trend using the Practical Numerical Math Functions (Pracma) in order to remove the effect of inflation over the period of interest on our price time series. By detrending, we can determine the probable relationship between food production, prices, and rainfall (Wu et al., 2007). In this study we used an additive method where the data is centered at zero. Detrended time series for food prices are added in Supplementary Figure S4.

A correlation matrix of detrended time series used to denote association between the food prices, inflation, international sanctions, domestic production and average monthly precipitation (Supplementary Figure S3).

To show the multicollinearity of the predictors, a Variance Inflation Factor (VIF) analysis was applied for the time series. The VIF of an explanatory variable indicates the strength of the linear relationship between the variable and the remaining explanatory variables (Forthofer et al., 2007). It can be used

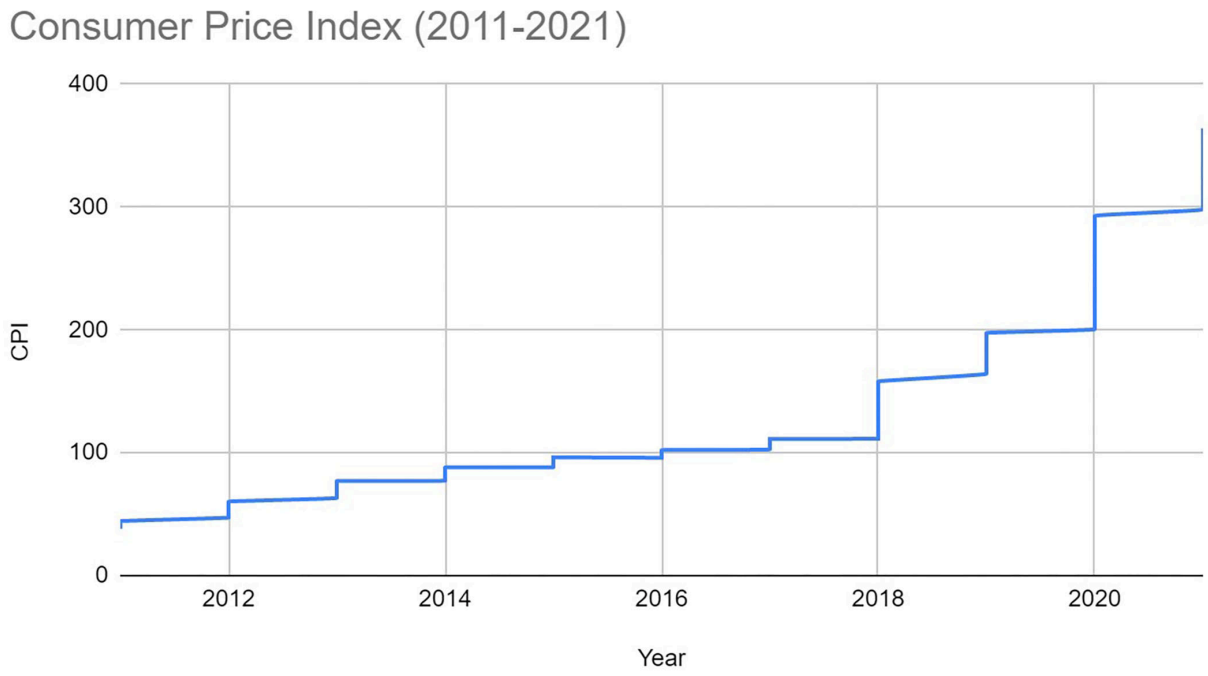


FIGURE 6
Monthly CPI in Iran 2011–2021 (Source: www.amar.org.ir).

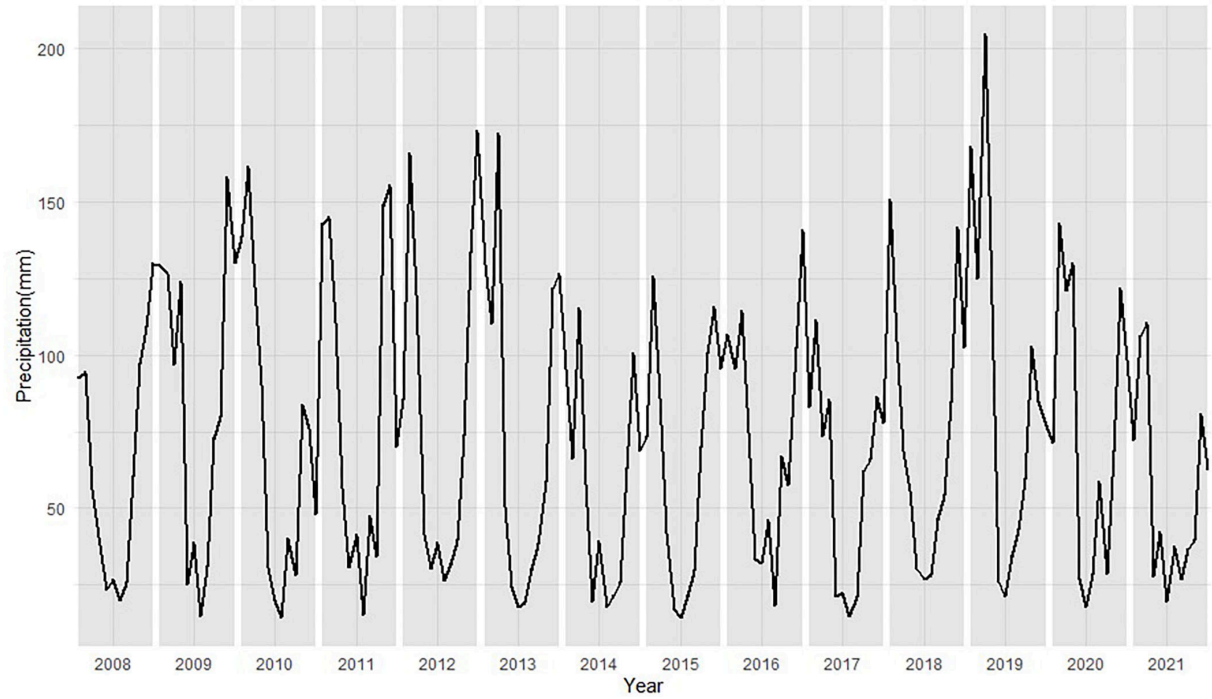


FIGURE 7
Monthly CHIRPS data spatially averaged across three northern provinces (Mazandaran, Gilan and Golestan) as the areas of interest in Iran from 2008 to 2021 for northern Iran.

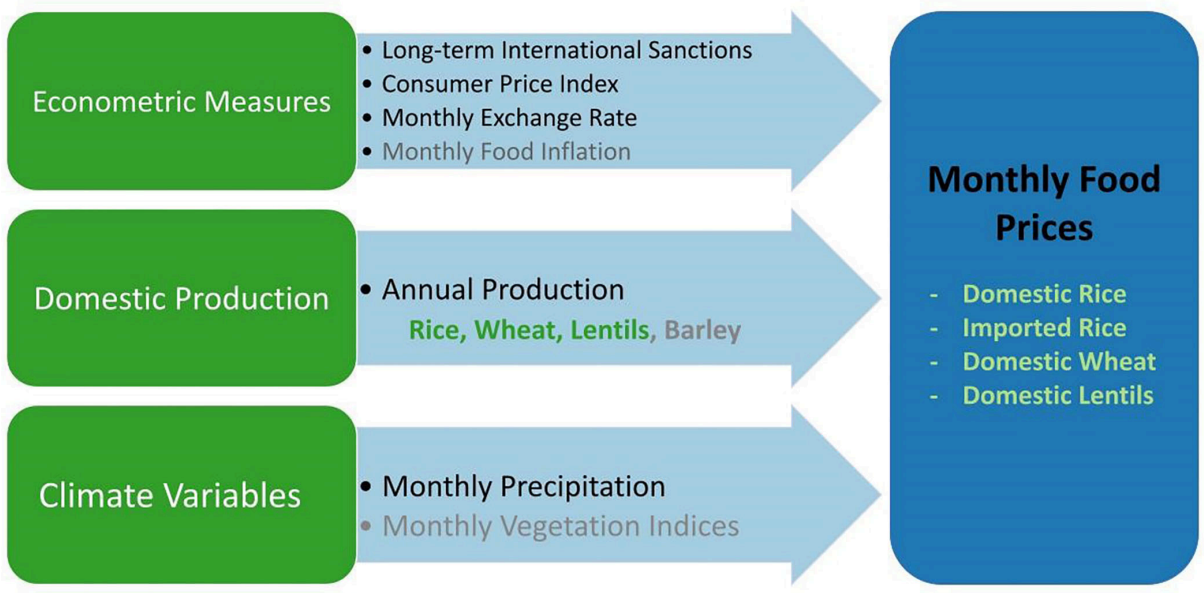


FIGURE 8
Paper's theoretical framework with all the variables included in the model.

as a general diagnostic measure of collinearity and represents a considerably better approach than studying the simple correlation values. An important advantage of the VIF is that it indicates which coefficients have collinearity. The results of VIF were as follows (Table 3).

The predictors represented in Table 3 shows a good measure of Variance Inflation Factor ($1 < \text{VIF} < 10$) for use in the model. We used a simple linear equation with the food prices including domestic rice, imported rice, domestic wheat, and domestic lentils as our dependent variables, and sanctions, detrended domestic production for rice, wheat and lentils as well as the average monthly precipitation as our predictors. In the equation, Y is domestic food prices (rice, wheat, and lentils) along with the imported rice prices. β_0 is intercept and β_1 through β_8 were the estimated regression coefficients (Supplementary Tables S3–S10). We used this equation to analyze the food prices based on the economic variables including sanctions along with the influences of domestic production and monthly precipitation.

Sanctions and reform plans were considered as dummy variables which were then separated into three different dummies based on the implemented date in the literature and the time period of this study. The first dummy variable was named "Sanction 1" which also included the subsidy reform plan. The second dummy variable was named "Sanction 2" and referred to the signing of the Joint Comprehensive Plan of Action (JCPOA) in July 2015. The third dummy variable was "Sanction 3" and highlighted the currency jumps after November 2018 due to economic sanctions (Table 1). In addition, barley was presented in Supplementary Tables S11, S12.

4. Results

Economic sanctions, particularly those that were imposed in 2018, were highly significant and increased domestic food prices in Iran (Figure 9). The sanctions imposed in 2011 and 2015 had significant negative impacts on food prices, with some financial relief and economic growth for a small period of time before 2018. We also found that domestic rice production has a negative impact on the prices of domestic and imported rice, wheat and lentils. The exchange rate also had a significantly negative correlation with prices for domestic and imported rice and domestic lentils. The currency exchange rate was an important determinant and critical to the price of food in Iran, demonstrating dependence on imports (Figure 9). When including the average monthly precipitation in the model, the results indicate no significant relationships between weather disturbances and food prices (Figure 10). These results also highlight the importance of sanctions (including the subsidy reform plan) and demonstrate that rice production, which is heavily irrigated, remains resilient to interannual rainfall changes, while also being an important driver of food prices. The exchange rate has a significant relationship with domestic rice and domestic lentil prices, but shows less significance for the imported rice price—highlighting

TABLE 3 VIF analysis results.

Exchange rate	Domestic rice production	Domestic wheat production	Domestic lentils production	Sanction 1, 2011	Sanction 2, 2015	Sanction 3, 2018
1.583	4.241	6.161	6.920	3.578	1.881	4.117

the impact of the government subsidized dollar exchange rate. The detailed results for non-climatic and climate impacts are as follows.

4.1. Non-climatic impacts on food prices

The results of linear regression for deflated and detrended drivers of food prices are presented in a coefficient plot (Figure 9). The coefficient value signifies how much the mean of the dependent variable changes given a one-unit shift in the independent variable while holding other variables in the model constant (Fahrmeir et al., 2009). All regressors are centered and scaled in a numeric matrix (details of the regression can be found in Supplementary Tables S3–S10) to allow comparability across models. The results show that the third sanction in 2018 and domestic rice production are highly significant in the model.

Sanction 3, imposed in 2018, led to food price increases. After 2018, there was a severe budget deficit and exchange rate crisis in the country. However, Sanction 1 and Sanction 2, which occurred in 2011 and 2015, respectively, demonstrated negative impacts on food prices. These secondary sanctions contributed to the shrinking of Iran's economy as its crude oil exports fell by more than 50% and it could not access foreign exchange assets held abroad. We found that these first two sanctions depressed food prices (Supplementary Tables S3–S10) as a result of reduced purchasing power.

The exchange rate also has a significantly negative effect on prices of rice (both domestic and imported) and lentils. Because of Iran's economic dependency and productive structure on imported goods and inputs, exchange rate movements can be considered as one of the important factors of inflation (Zaroki and Yousefi-Barfurushi, 2021), therefore increasing food prices in Iran.

4.2. Climate impacts on food prices

The average monthly precipitation is not significant in the model (Figure 10). However, the results indicate that including the weather variable highlights the influences of economic sanctions and rice production in domestic food prices (Supplementary Tables S7–S10). Since rice production in Iran is irrigated, it is more resilient to interannual variability of precipitation than wheat or lentils.

We also show that domestic rice production has a negative relationship with food prices. In addition, wheat production shows weak relationship with prices, confirming the importance of rice in our model and more specifically in the study area, which is the main region of producing rice domestically. We found that although Sanction 3 caused significant increases in the price of domestic and imported rice and domestic lentils, wheat was more resilient to the imposition of sanctions. Wheat price regression results were similar with and without precipitation included in the model.

5. Discussion

Iran has moderate levels of inequality compared to most countries (World Bank, 2019), with gradually increasing inequality and growing concentrations of wealth in cities leading to a corresponding impoverishment in the countryside. Inequality is exacerbated by sanctions (Kuznar, 2019). Much of the population in Iran is considered to be just above the poverty line. Therefore, a further deterioration of the economy would push more of the vulnerable population into poverty (Salehi-Isfahani, 2017). Although US officials stated that food and medications are not subject to the sanctions, due to the problems that sanctions have created for trade and transfers of goods, sale of oil, and international financial exchanges of Iran, the sharp rise in the exchange rate has pushed up the price of imported goods, including imported food (Congressional Research Service., 2021). Furthermore, as imported goods have become more expensive, demand for domestic food products increased, but due to the increase in imported agricultural input prices (e.g., livestock inputs such as animal corn as well as oil seeds, hybrid seeds, fertilizer and pesticides) the supply of domestic food products that use these inputs has not been able to meet the demands (Hejazi and Emamgholipour, 2022). The lack of affordable food is likely to exacerbate food insecurity in low income Iranian people and make them more prone to chronic disease (Mohammadi Nasrabadi et al., 2014). This confirms the results of the study which indicate sanctions impacts on increasing food prices in Iran. Mahmoudinia (2021) shows that monetary policy, exchange rate and currency constraints affect food price inflation and are strongly linked to economic sanctions which also align with the results of this study.

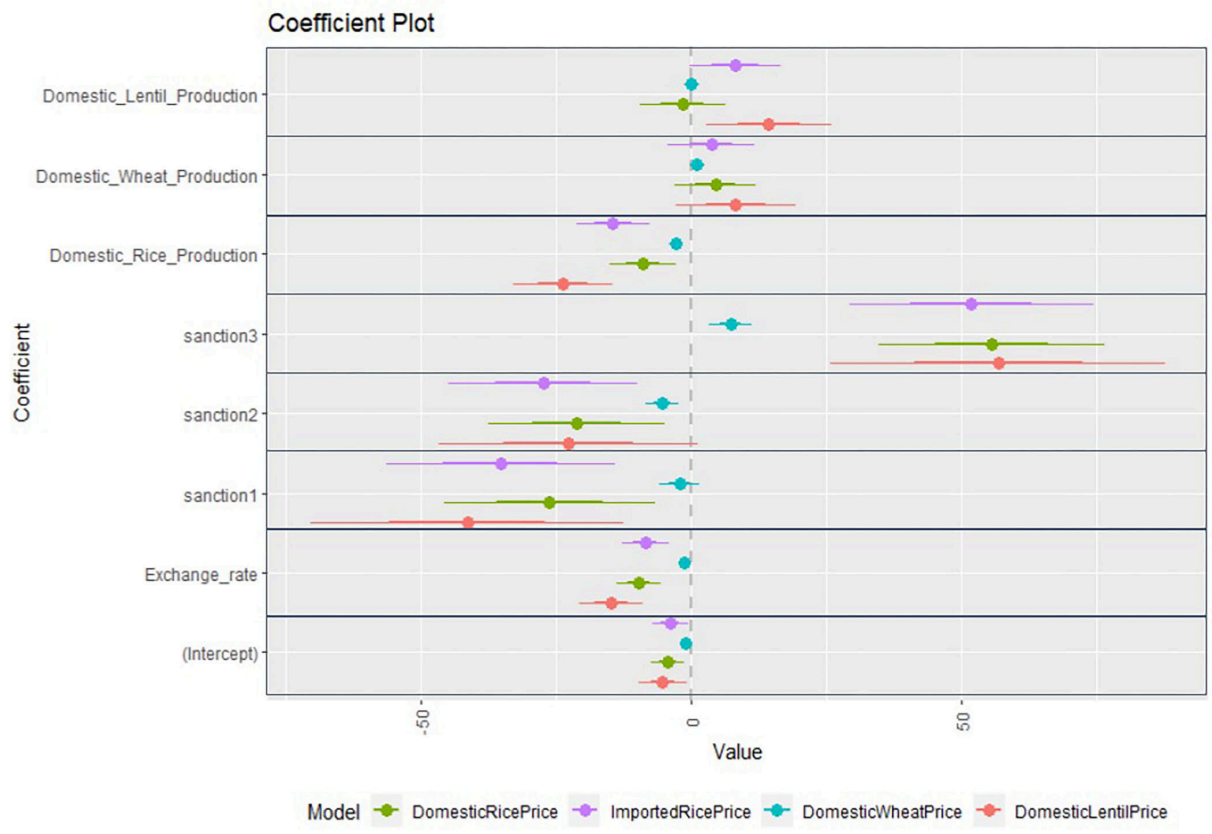


FIGURE 9
Linear regression results for detrended values and based on the regression coefficients.

Ninety percent of Iran is comprised of arid and semi-arid regions, with more than half of the country's water needs procured from aquifers. Our results showed that the average precipitation in the Caspian Sea coast was only marginally relevant to local food prices, despite the importance of this region to food production (Afzali et al., 2020). Iran's rising food demand is pushing against the limits of its own production capacity, which faces tight constraints from geography and climate (USDA, 2017).[2] Therefore, improving the climate will increase the country's economic potential and reduce costs, while adverse climate conditions will worsen the country's economic situation and, consequently, increase costs (Vatankhah et al., 2020).

Results showed that domestic rice production has a negative relationship with food prices. Rice provides the main food supply to more than 50% of the population in Iran and increasing rice production is therefore an effective method to promote food security at the national-level (Zamanialaei et al., 2022). Rice production is highly affected by government policies, like the guaranteed purchase price. Approved in 1999, the guaranteed purchase of crops is the most important policy of the agricultural sector in Iran. The guaranteed purchase policy obliges the government to support the production of basic agricultural crops by guaranteeing the purchase of domestically produced wheat, rice and barley every year at a set price (Jafari Lisar et al., 2019). These policies resulted in some unwanted outcomes, such as changing the prices and production of other crops (e.g., wheat, barley, lentils), as well as working against the general objective of self-sufficiency in agricultural production (Najafi and Bakhshoodeh, 2002).

Although the experience of Iran with sanctions is unique, the analysis in this paper illuminates the potential harms and economic isolation that financial sanctions bring to countries and their populations. The impact of sanctions on the poor and vulnerable has been large, but the international community has not been able to affect the governments' policies or its decision making. Therefore, a need exists to transform sanctions from a "weapon" and punitive tool into a pressure mechanism that provides incentives to governments to carry out reforms. To ensure greater food security, Iran allocates subsidized foreign

2 https://www.ers.usda.gov/webdocs/outlooks/84408/aes-100.pdf?v=45.8

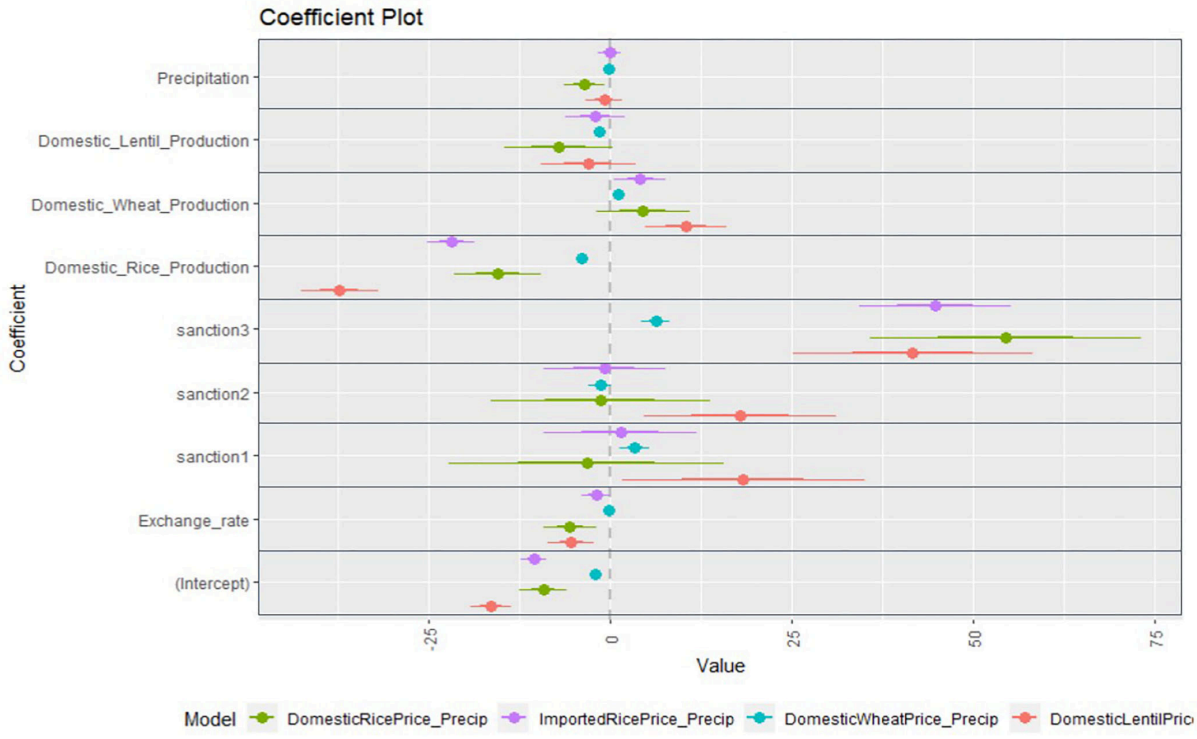


FIGURE 10
Linear regression results for detrended values including precipitation and based on the regression coefficients.

exchange to importing critical foods such as wheat and rice, promoting the optimum use of scarce inputs (e.g., livestock inputs, seeds, fertilizers and pesticides) in the agricultural sector, and relies on domestic production for the purpose of food security (Bodetti, 2019).

6. Conclusions

We show in this paper that during the past 10 years, irrigated rice production has underpinned agricultural production and provided stability to food prices in Iran. The first two US sanctions that were imposed in 2012 and 2015 actually reduced overall food prices, corresponding with a contraction of the broader economy. The third US sanction in 2018, however, caused further reductions in the ability of the government to import food, setting off an inflationary spiral which has affected the prices of both imported and domestic goods. We showed that despite being precipitation and temperature sensitive, wheat and lentil prices were not affected by monthly changes in precipitation, despite there being low rainfall totals in 2014–2016. All three sanction periods, but particularly the third, were more important drivers of Iranian food prices than weather variability. Weather, which is likely to become more unstable and less suitable for agricultural production in Iran with climate change, was not as statistically important as financial sanctions. In essence, while climate change may be a problem for food production, importation, and prices in the near to long term, the last decade's food price stability is driven by sanctions.

Economic and environmental issues confronting modern food systems threaten global long-term food security and natural resource management (El Bilali et al., 2019). As inflationary pressures rise, vulnerable populations in the Middle East and North Africa region are likely to remain food insecure. Furthermore, the Middle East countries are very vulnerable to climate change effects (Mansouri Daneshvar et al., 2019). Among the Middle East countries, Iran will experience an increase of 2.6°C in mean temperatures and a 35% decline in precipitation in the next decades (NCCOI, 2014). Based on recent scientific reports, an increased risk of drought will threaten water and food security especially for people who live in the highly populated cities of Iran (Karandish and Mousavi, 2018). Therefore, decision-makers should modify food policies by supporting transitions to sustainable energy, improved natural resource management and agricultural practices while helping to diversify and build a resilient economy. Also, restructuring guaranteed prices for specific crops (e.g., rice and wheat) in specific regions to reflect resource availability could

promote new cropping patterns more appropriate to land and water conditions.

Alongside rising prices, sanctions served to disrupt the supply chains on which the importation and domestic production of humanitarian goods, like food, depend (Batmanghelidj, 2022). Food price hikes, subsidy cuts and high levels of un- and under-employment due to economic downturn have limited the population's economic access to nutritious food in Iran [World Food Programme (WFP)., 2016]. High levels of inflation, coupled with population growth, urbanization and a constraint on food production are likely to push more people into food insecurity (Layani et al., 2020). Future work must consider financial sanctions, including expanding to consider the impact of conflicts on sanctions and food production, when determining impacts on food prices and thus food security for human populations. Geospatial products of long term climatic and agricultural variables exist, meaning now is the time to assess these multidisciplinary impacts—from policy and economic to sociocultural and international relations—in combination with spatially-explicit climatic and biophysical data.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

Author contributions

Data collection was conducted and the first draft of the manuscript was written by MZ. The material preparation and data analysis were performed by MZ, MB, JM, and JF. All authors contributed to the study conception and design, commented on previous versions of the manuscript, read, and approved the final manuscript.

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Conflict of interest

During the drafting and submission stage of the manuscript, JF was employed by Miami University. During the review, revision, and acceptance stages of the manuscript, JF is employed by ISciences, L.L.C., Burlington, Vermont, United States.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.998235/full#supplementary-material

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