STUDIES

Impact of climate change mitigation actions on food prices in developing countries

Agus Dwi Nugroho
(corresponding author)
Faculty of Agriculture,
Universitas Gadjah Mada,
Yogyakarta, Indonesia
Email: agus.dwi.n@mail.ugm.ac.id

Mária Fekete-Farkas
Institute of Agricultural and
Food Economics,
Hungarian University of
Agriculture and Life Sciences,
Gödöllő, Hungary
Email:
Farkasne.Fekete.Maria@uni-mate.hu

Zoltán Lakner
Institute of Agricultural and
Food Economics,
Hungarian University of
Agriculture and Life Sciences,
Gödöllő, Hungary
Email:
Lakner.Zoltan.Karoly@uni-mate.hu

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Mitigation is a crucial action in reducing the effects of climate change. However, it is frequently debated in developing countries because mitigation not only improves the environment but also reduces food production, which can increase food prices. Therefore, this study examines the impact of climate change mitigation actions on food prices in developing countries. The vector error correction model (VECM) was used to examine data collected between 1990 and 2020 from 87 developing countries. The current food price in Africa and Latin America and the Caribbean (LAC) have experienced short and long-term increases due to previous year's inflation. However, the current food prices in Asia have decreased in the short-term. The inefficient use of nitrogen nutrients in the previous year have also increased food prices in Africa in both the short and long-term but only in the short-term in Asia and LAC. Other climate mitigation efforts, such as water productivity in the previous year briefly lowered food prices in Asia in the short term and renewable energy can lower food prices in Africa and LAC in the short term. Thus, our study shows that climate change mitigation actions can lower food prices in developing countries.

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Introduction

Population growth without income growth will reduce per capita food production and real income (Schneider et al. 2011). This phenomenon occurred in the 1960s and 1970s when there were global constraints on the per capita food supply and food prices. However, today's problems are different. The number of people living in poverty, the global population, and the price of agricultural inputs have increased significantly (de Fraiture et al. 2010). This problem can be addressed by enhancing economic activity, especially in developing countries (Mberu–Ezeh 2017). Efforts are ongoing to elevate individuals from poverty by promoting investments and subsidies that boost their income. Concurrently, innovation in agricultural production is being fostered to increase food availability and reduce prices (Schneider et al. 2011).

With the remarkable growth in population, economic, and energy consumption, several adverse effects have emerged, such as overexploitation of natural resources, water scarcity, extinction of some local varieties or ancient peoples, and increased CO_2 emissions (Darko et al. 2016, Meo et al. 2020, Jaber 2022). Conversion of forested areas to agricultural land and infrastructure uses has increased, resulting in land degradation and a significant loss of soil organic carbon stocks (Abbas et al. 2017). Foreign direct investment in developing countries increases CO_2 and methane emissions and has a significant harmful impact on the environment (Ahmed et al. 2022). For example, the growing demand for biomass has resulted in a loss of natural forest cover and a rise in greenhouse gas emissions (Nong et al. 2020). This phenomenon is consistent with the environmental Kuznets curve (EKC), which states that economic growth leads to environmental degradation in developing countries. Furthermore, the agricultural and food sectors are affected environmental damage, leading to reduced market supply and increased prices (Nugroho et al. 2023).

Humans have been significantly affected by various environmental damages, such as natural disasters, rise in sea level, and intense salinity, which adversely affect the economic, environmental, and social well-being of the global population (Bradu et al. 2023). The predicted climate change by 2060 will lead to welfare and export losses in developing countries (Wesseh–Lin 2017). Important food crops such as corn and soybean production declined, resulting in losses for farmers (Casali et al. 2022). Problems in developing countries are worsening due to political crises, poor resource support, and steady environmental degradation (Mulyo et al. 2023). Therefore, more people in developing countries are experiencing the negative effects of climate change, particularly in terms of the severity of incidents, morbidities, and mortality (Bhuiyan 2015).

Several methods have been adopted to mitigate environmental damage. Governments worldwide implement policies, such as carbon taxes and feed-in-tariffs (FIT), to reduce carbon (dioxide) emissions and control climate change on both the local and global scales (Zhang–Wang 2017). The EKC theory emphasizes the effectiveness of developed countries in reducing environmental harm during periods of rapid economic expansion because of changes in lifestyle, efforts to mitigate climate change, and increase environmental awareness (Nugroho et al. 2023). Unfortunately, the situation for developing countries is different because their current political and economic realities may hinder their ability to adapt to climate change (Bhuiyan 2015). They also tend to be less successful in conservation policies compared with developed countries (Imamoglu 2019).

Delaying actions to mitigate climate change could have catastrophic consequences for ecosystems, soils, and food supplies (Hasegawa et al. 2021). Many developing countries are vulnerable to drought, floods, storms, and extreme temperature disasters (Ward–Shively 2017). Any further delay is expected to result in developing countries losing a significant portion of their income, which could exacerbate the gap with developed countries (Mulyo et al. 2023). Hence, numerous global agreements have been established to mitigate climate change and its adverse effects. These agreements aim to reduce the rise in global temperature and encourage environmentally friendly consumption behaviour. Many countries with stronger commitment ties have approved the Paris Agreement, which facilitates the transfer of funds from developed to developing countries to support their efforts in fighting climate change. The outcomes of this transfer of capital are still debated because it greatly increases the economic risks for developing countries. However, the situation is expected to improve as the political scenario stabilizes in developing countries (Zhao et al. 2022). Although the agreement has been shown to significantly reduce CO_2 emissions, many countries are not fully committed to upholding it (Kim et al. 2020).

Although challenging, several studies have recommended climate change mitigation actions in developing countries (Brüssow et al. 2017, Mashi et al. 2022, Acevedo-Ramos et al. 2023). First, many people are unaware of the negative impacts of climate change and the importance of mitigation (Mashi et al. 2022). Farmers failing to respond to changes in temperature, rainfall, and especially atmospheric CO_2 levels can lead to inaccurate conclusions about the environmental impact. Second, climate change mitigation does not always benefit human life as such actions increase the amount of land used for energy crops and thus reduce GDP, thereby increasing the risk of food insecurity, especially in developing countries (Wesseh–Lin 2017, Kim et al. 2020, Hasegawa et al. 2021). Third, global climate change mitigation agenda does not prioritize national/regional contexts and vulnerabilities, especially in developing countries. This oversight results in suboptimal stakeholder involvement and implementation of this strategy. Moreover, complexity of many institutions in developing countries poses significant challenges to implement and manage climate change mitigation measures (Alves et al. 2020).

This gap persists because several studies have shown that the adoption of a climate-smart strategy typically leads to increased food security because users of this strategy tend to have diverse food consumption patterns, higher protein intake, and better economic access to food (Brüssow et al. 2017). However, some studies have found contrasting results: the same actions (such as carbon tax for natural gas and greenhouse gasses) were found to have caused welfare losses and poverty (Renner 2018).

No study so far has proven the impact of climate change mitigation actions on food price inflation in many developing countries (Spiertz–Ewert 2009). This study gains significance when linked to a key objective of the 2030 sustainable development goals (SDGs): climate action. Increased food prices resulting from climate change mitigation actions threatens two other key objectives of the SDGs: eradicating poverty and reducing inequalities. A reduced food supply in developing countries also affects developed countries because of import dependencies on basic foods.

Hence, whether climate change impacts food prices in developing countries needs to be examined. In this study, we hypothesize that use nitrogen use inefficiency per value of agricultural production will increase food price inflation, while indicators of climate change mitigation factors such as water use productivity, renewable energy consumption, and naturally regenerating forests will reduce food price inflation in developing countries. This study has global implications, especially for developing countries, to implement optimum measures to mitigate climate change with the least negative impact on food prices.

Literature review

The world has experienced increasing competition for land and water since decades because of economic activities through agriculture, industry, urbanization, and infrastructure development, leading to a shortage of both land and water (Schneider et al. 2011). Moreover, the demand for raw materials derived from plants and forests in the chemical industry is expected to increase sharply by 2050; for example, the demand of for wheat is expected to rise by 327%. In terms of agricultural food, the price of vegetable oil will grow by 3.5% and that of sugarcane by 3.9% in developing countries (Nong et al. 2020). These economic activities have raised concerns about climate change and its negative impacts. Therefore, mitigation efforts and commitments have emerged in the form of efficiency of production factor, improved freshwater resource management and distribution, use of renewable energy, as well as preservation of climate, ecosystems, and biological diversity (Schneider et al. 2011).

At the producer level, efficient use of resources not only helps to mitigate climate change but also enhances food production to meet the rapidly increasing demand for food, feed, and fuel (Deng et al. 2024). For example, increasing the efficiency of soil N uptake can reduce both short- and long-term loss of nitrogen and pollution. Hence, increasing soil N uptake efficiency contributes to developing countries' strategic goals of zero growth in N fertilizer consumption (Wang et al. 2023). This strategy also balances people's dietary habits in developing countries, which are shifting toward consuming foods that produce a significant amount of nitrogen. The percentage of grain-based nitrogen consumption in the diets of developing countries is gradually decreasing. Conversely, the consumption of nitrogen from dairy products and poultry meat is increasing (Yang et al. 2012). For instance, overall dietary nitrogen consumption in Beijing (China) has increased over time from 37 Gg in 1979 to 70.77 Gg in 2019. Chinese rural residents' dietary patterns are similarly changing, shifting toward high nitrogen animal-based consumption patterns. High food nitrogen consumption implies not only high nitrogen input in food but also substantial amount of nitrogen waste that could pollute the ecosystem (Yang et al. 2022).

Hypothesis 1: Nitrogen use inefficiency per value of agricultural production will increase food price inflation in developing countries.

Furthermore, water availability is also an important factor related to climate change. Water scarcity is becoming a significant issue due to the increasing demand from non-agricultural uses and intense crop management to meet the needs of a growing global population (Darko et al. 2016, Nadee et al. 2023). Trends in production, consumption, and environmental patterns will also lead to increased use of water globally (de Fraiture et al. 2010, Meo et al. 2020). This is in addition to the role of water as a provider of food, other goods, and services, which must be considered in any food production systems (Elzaki–Al-Mahish 2024).

The strategies that combine elements such as providing poor people with access to water, offering multiple ecosystem services, managing rainwater, adapting irrigation to new needs, increasing water productivity, and encouraging the use of low-quality water on farms should be reconsidered in both the current situation and long-term (de Fraiture et al. 2010). One of the main strategies to reduce water scarcity is increasing water productivity (Schneider et al. 2011). This can help produce more food, earn more money, improve livelihoods, and provide more ecosystem services while using less water (de Fraiture et al. 2010). Efficient use of water in developing countries helps achieve higher levels of food security. This will support the building of resilient and reliable food production systems to combat climate change and other triggers (Badawy et al. 2022).

Hypothesis 2: Water use productivity lowers food price inflation in developing countries.

Education programs should prioritize promotion of and highlight the use of renewable energy sources, encourage the development of the nation's renewable energy resources, and provide the public with opportunities to select the best renewable energy sources (Chel–Kaushik 2011). There has also been a recent significant increase in the promotion of renewable resources (solar energy, wind energy, biomass, tidal, geothermal, small-scale hydro, biofuels, and wave energy) to replace fossil fuels and combat climate change. The use of renewable energy sources and cleaner technologies in the agricultural and industrial sectors is a key factor for developing countries' economic growth without damaging the environment

(Acevedo-Ramos et al. 2023). Renewable energy is a strategy for dealing with rising temperature in developing countries (Nugroho et al. 2023).

Hypothesis 3: Renewable energy consumption will lower food price inflation in developing countries.

Finally, there is a negative relationship between forest cover and food prices. Rising food prices lead to conversion of forests into agricultural land (Simmons et al. 2018). However, programs implemented to protect forest and woodland protection have significantly reduced the maximum amount of land available for agricultural production. For example, agricultural land use under reducing emissions from deforestation and forest degradation (REDD) program is 28% lower in southern Africa, 24% lower in Indonesia, and 14% lower in Central and South America and Southeast Asia compared with the renewable energy directives (RED) scenario. Because of the implementation of REDD, land availability is significantly reduced compared with the land use under RED. Consequently, the cost of renting land in Southern Africa has dramatically increased (160% increase post-REDD implementation than the rental prices under RED). The REDD mandates a 55% reduction in land availability below land usage under RED, resulting in 121% increase in land rental prices in Indonesia (Dixon et al. 2016). Meanwhile, limiting deforestation significantly impacts land costs and water resources but has minimal global impact on the food production quantity and prices (Schneider et al. 2011). Consequently, food prices increase while food consumption decreases in developing countries.

Hypothesis 4: Naturally regenerating forests will lower food price inflation in developing countries

Research methods

Theory and variable selection

Several theories explain why inflation occurs across time and in various locations. Some well-known theories include quantity theory, Keynesian theory, the “cost-push“ theory, and structural theory. However, this study only applies the “cost-push“ theory because climate change mitigation results in more intense competition for resource utilization, which results in rising prices.

Initially, inflation was associated with excessive monetary growth, i.e., the money supply grows faster than the rate of growth in real output. However, non-monetary experts link inflation to the consequence of rising costs and prices to maintain high levels of production and employment. That is, regardless of demand, prices will only increase when costs increase. According to the “cost-push“ theory, producer costs and ultimately prices rise because of sellers of productive inputs (including labor) continually and unilaterally increasing their selling prices (Batten 1981). This theory claims that the main sources of inflation include the competitive struggle for relative income shares, labor and capital immobility (and the resulting wage/price rigidities), a lack of job information, and "ratchet effects" arising from inflexibility of specific prices to changes in the composition of demand. Recent global economic conditions indicate that inflation is driven by random non-monetary shocks (special factors), such as crop failures, commodity shortages, and OPEC-managed increase in oil price (Humphrey 1976).

These developments demonstrate how the adaptive cost-push theory applies to the most recent conditions (Fujimori et al. 2022). Climate change is one of the factors affecting the global food condition. This phenomenon raises production costs, decreases global food supplies, disrupts food distribution, and increases food prices. The main step to overcome rising production costs and food supply shortages is to mitigate climate change (Nugroho et al. 2023). Several important steps in climate change mitigation can then be associated with agricultural activities as a source of food. The first step is the efficient use of agricultural production factors, especially fertilizers and water, which can minimize environmental damage and produce maximum food (Wang et al. 2023). Second, the effective use of technology is crucial for minimizing the harmful effects of human activities on the environment and preserving the stability of food production. Renewable energy is expected to be the technology that best exemplifies this aspect (Acevedo-Ramos et al. 2023). Third, the availability of land is a crucial component of food production. However, efforts to mitigate climate change have increased the competitiveness for land use. Therefore, humans continue to exploit forest areas that can reduce environmental temperature and CO_2 and ensure proper food availability (Schneider et al. 2011).

Data source

This study uses panel data that combines cross-sectional and time-series data. These data were obtained from the World Bank and FAO. This study used cross-sectional data from 87 developing countries, and the time-series data ranged from 1990 to 2020. The countries were categorized into three regions: Africa, Asia, and Latin America and the Caribbean (LAC) (Table A1, see in Appendix). The number of countries for each region varies based on the completeness of the data from each country. We included 36 countries in Africa, 27 in Asia, and 24 in LAC. The country samples are selected based on the availability of data in each database. Many developing countries cannot be used as subjects in this study as they have not released data. Meanwhile, a three-decade timeframe is ideal for observing the massive impacts of climate mitigation measures, particularly implemented through various international agreements.

Five variables were analyzed in this study (Table 1): (1) food price inflation is the annual price change of a basket of food items in 87 developing countries,

(2) the inefficient use of nitrogen per value of agricultural production, (3) water use productivity is determined by dividing GDP at a constant price by the total annual water withdrawal, (4) renewable energy consumption is the share of renewable energy in total final energy consumption, and (5) naturally regenerating forests are ecological processes of forest regeneration that are not significantly disturbed by humans.

Table 1

Variable in this study

Variable	Symbol	Source
Food price inflation (%)	INF	World Bank
Inefficient use of nitrogen per value of agricultural production (kg/1,000 USD)	NUT	FAO
Water productivity, total (constant 2015 USD GDP per cubic meter of total freshwater withdrawal)	WAT	World Bank
Renewable energy consumption (% of total final energy consumption)	REN	World Bank
Naturally regenerating forest (1,000 ha)	FOR	FAO

Data analysis

The impact of climate change mitigation actions on food prices in developing countries (*i*) every year (*t*) is assessed using the following model:

$$INF_{it} = A_0 + A_1 NUT_{it} + A_2 WAT_{it} + A_3 REN_{it} + A_4 FOR_{it} + \varepsilon_i \qquad (1)$$

Equation (1) can be written as

$$INF_{it} = A_0 + \sum_{i=1}^{p} A_1 NUT_{it-1} + \sum_{i=1}^{p} A_2 WAT_{it-1} + \sum_{i=1}^{p} A_3 REN_{it-1} + \sum_{i=1}^{p} A_4 FOR_{it-1} + \varepsilon_{it} \qquad (2)$$

A stochastic process is said to be stationary if its mean and variance always remain constant. However, most macroeconomic series are non-stationary. Therefore, the first step of this study is the unit root test to determine the stationarity of the variable. This test can prevent a regression model from producing "t-ratios" that do not follow a standard t-distribution and spurious regression, indicating a significant relationship between two variables when there should be none. The Levin Lin Chu (LLC) unit root test is considered in this study (Choi 2001):

$$\Delta y_t = \mu + \delta y_{t-1} + \sum_{i=1}^{k} A_i \, \Delta y_{t-i} + e_t \qquad (3)$$

where $\delta = \alpha - 1$; α = coefficient of y_{t-1}; Δy_t = first difference of $y_t, i.e. \, y_t - y_{t-1}$.

The results of the unit root analysis show variations between variables and models (Table 2). The INF is a stationary variable at the level in every model; however, many variables are not stationary at that level. The non-stationary variables can be made stationary by taking the first and second differences. Consequently, NUT, WAT, REN, and FOR are stationary at the first or second difference.

Table 2

LLC unit root test

Variable	Africa		Asia		LAC	
	level	sign	level	sign	level	sign
INF	at level	−8.939***	at level	−5.196***	at level	−5.891***
NUT	1st difference	−17.321***	at level	−2.578***	at level	−4.097***
WAT	1st difference	−4.159***	2nd difference	−7.174***	2nd difference	−1.768***
REN	1st difference	−13.401***	at level	−2.458***	at level	−3.959***
FOR	2nd difference	−19.014***	at level	−2.482***	2nd difference	−14.201***

*** significance level=0.01.

Following the unit root test, the Akaike information criteria (AIC) was used to determine the optimal lag length. The smallest absolute value of the AIC will produce the optimal lag length. The AIC results show that the length of lag for every model in this study is optimal at level 3 (lag 1.3) (Table 3).

Table 3

AIC results

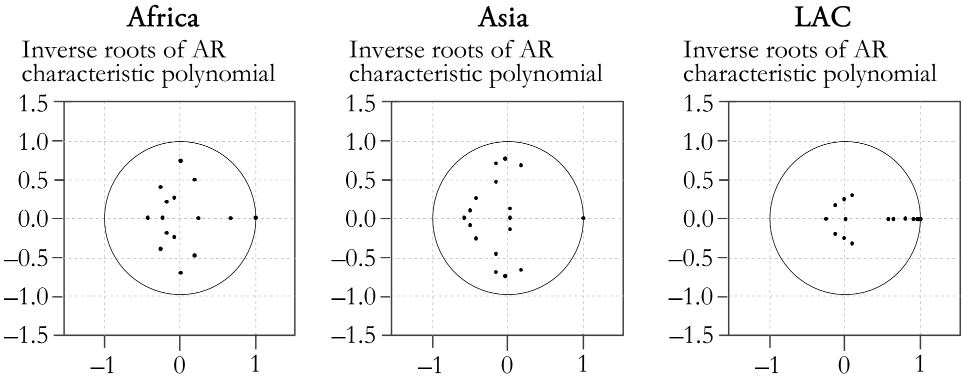
Lag	Africa	Asia	LAC
0	64.488	64.114	63.205
1	40.539	45.498	40.767
2	39.272	42.859	38.788
3	39.049*	42.643*	38.773*

* significance level=0.1.

Some studies suggest stability tests, especially for vector autoregression (VAR) or the vector error correction (VECM) models. Stability implies that the cointegrated vectors, cointegrated rank, and adjusted coefficients remain unchanged. The results of the stability test modulus of less than one for each model are shown in Figure 1. Thus, the fit of the third lag of the Africa, Asia, and LAC models remains stable.

Figure 1

Results of stability tests in Africa, Asia, and LAC



Next, the relationships between non-stationary variables should be analyzed using a cointegration test. Cointegration occurs when two or more variables are linked to form a long-term equilibrium relationship. Cointegration generally includes the following: (1) heterogeneity, (2) unbalanced panels, (3) cross-sectional dependence, (4) cross-unit cointegration, and (5) asymptotic N and T (Im et al. 2003). In this study, the Johansen cointegration test was conducted by comparing the trace statistic and maximum eigenvalue values. The following is the Johansen cointegration equation (Shrestha–Bhatta 2018):

$$Y_t = A_1 Y_{t-1} + \varepsilon_t, \tag{4}$$

so that

$$\Delta Y_t = A_1 Y_{t-1} - Y_{t-1} + \varepsilon_t \tag{5}$$

$$= (A_1 - I)\, Y_{t-1} + \varepsilon_t \text{ can be written as} \tag{6}$$

$$= \Pi Y_{t-1} + \varepsilon_t \tag{7}$$

where Y_t and ε_t are (n.1) vectors; A_1 = an (n.n) matrix of parameters; I = an (n.n) identify matrix; $\Pi = A_1 - I$.

The hypothesis of the test:

$H_0 : A_i = A_0$, there is no cointegration,

$H_a : A_i \neq A_0$, there is a cointegration.

The cointegration test results show that the variables in the models have a long-term relationship (Table 4), implying that the INF, NUR, WAT, REN, and FOR variables are cointegrated in Africa, Asia, and LAC. This is shown by the trace statistics value that is higher than the critical value at the 1% confidence level. Once cointegration has been established, the non-stationary variables (INF, NUR, WAT, REN, and FOR) will have a long-term relationship that always returns the variables to their long-term equilibrium path.

Table 4

Cointegration test

Hypothesized number of CE (s)	Africa	Asia	LAC
None	1,129.229***	263.638***	258.347***
At most 1	638.478***	170.447***	169.705***
At most 2	317.018***	109.678***	112.262***
At most 3	94.340***	59.685***	60.499***
At most 4	5.891***	4.820**	5.017**

*** significance level=0.01, ** significance level=0.05.

The preliminary findings show that the three models were stationary in the data differentiation process and had a long-term relationship, indicating that the VECM was most suitable. The estimation of the VECM equations is as follows:

Long-term equation:

$$ECT_{it-1} = A_0 + A_1 NUT_{it-1} + A_2 WAT_{it-1} + A_3 REN_{it-1} + A_4 FOR_{it-1} \tag{8}$$

Short-term equation:

$$\Delta INF_{it} = \alpha ECT_{it-1} + A_0 + A_1 \Delta NUT_{it-1} + A_2 \Delta WAT_{it-1} + A_3 \Delta REN_{it-1} + A_4 \Delta FOR_{it-1} \tag{9}$$

Results

Impact of climate change mitigation actions on food prices in Africa

The model's validity is confirmed by an error correction term (ECT) coefficient of 0.018, significant at 0.01 alpha (Table 5). The ECT coefficient determined how quickly equilibrium was restored. An ECT of 0.018 implies that its equilibrium and the change in the previous year's food price in Africa were adjusted for the current period by 0.018%.

Table 5

Impact of climate change mitigation actions on food prices in Africa

Long-term	
cointegrating equation	CointEq1
D(FOR(−1))	1.000
D (INF(−1))	0.001*** (0.0004) (2.349)
D(NUT(−1))	2.709*** (0.993) (2.728)
D(REN(−1))	0.455 (0.375) (1.213)
D(WAT(−1))	−0.211 (0.271) (−0.779)
C	−32.408
Short-term	
error correction	D(INF,2)
CointEq1	0.018*** (0.001) (25.037)
D(FOR(−1),2)	0.003 (0.255) (0.011)
D(FOR(−2),2)	−0.009 (0.216) (−0.042)
D(FOR(−3),2)	0.009 (0.178) (0.051)
D(INF(−1),2)	0.913*** (0.060) (15.322)
D(INF(−2),2)	0.271*** (0.043) (6.337)
D(INF(−3),2)	0.293*** (0.031) (9.357)
D(NUT(−1),2)	15.464*** (1.925) (8.032)
D(NUT(−2),2)	12.574*** (2.326) (5.401)
D(NUT(−3),2)	2.882* (1.912) (1.508)
D(REN(−1),2)	−20.212*** (3.395) (−5.953)
D(REN(−2),2)	−16.107*** (3.918) (−4.111)
D(REN(−3),2)	−9.446*** (3.446) (−2.741)
D(WAT(−1),2)	−2.339 (3.395) (−0.689)
D(WAT(−2),2)	−1.293 (3.683) (−0.351)
D(WAT(−3),2)	0.288 (3.349) (0.086)
C	0.392 (8.637) (0.045)
Adjusted R-squared	0.643
F-statistic	106.040
Akaike AIC	14.006
Schwarz SC	14.094
Determinant residual covariance	2.66E+10
Log-likelihood	−17,875.28
Akaike information criteria	38.387
Schwarz criteria	38.853

*** significance level=0.01, ** significance level=0.05, * significance level=0.1.

In the long-term, the previous year's food prices and inefficient use of nitrogen affect the food prices in Africa. Both independent variables increase food prices by 0.001% (inflation) and 2.709% (the inefficient use of nitrogen). The other independent variables, such as renewable energy, water productivity, and naturally regenerating forests, have no significant impact on food prices in Africa.

The previous year's food price, the inefficient use of nitrogen, and renewable energy affected short-term food prices in Africa (Table 5). In the current year, food prices increased because of inflation and the inefficient use of nitrogen in the preceding year. Food prices increased in the current year by 0.913%, 0.271%, and 0.293% because of food prices in the previous year, two years ago, and three years ago. Increased inefficiency in the use of nitrogen in the previous year, two years ago, and three years ago led to increases in food prices by 15.646%, 12.574%, and 2.882%, respectively. Meanwhile, renewable energy in the previous year, 2 years ago, and 3 years ago could briefly reduce food prices in African countries in the current year by 20.212%, −16.107%, and −9.446%. This finding supports the theory and hypothesis that wasteful resource usage increases production costs. Thus, food inflation can be controlled through efficient resource utilization.

Impact of climate change mitigation actions on food prices in Asia

The model's validity is indicated by an ECT coefficient of 0.001, significant at 0.01 alpha (Table 6). An ECT of 0.001 means that its equilibrium and the change in the previous food price in Asia were adjusted for the current period by 0.001%.

Food prices in Asia in the short-term were influenced by food prices, the inefficient use of nitrogen, and water productivity in the previous year. Food prices reduced in the current year by −0.491%, −0.569%, and −0.311%, respectively, because of the rise in food prices in the previous year, two years prior, and three years prior. The inefficient use of nitrogen in the previous year, 2 years prior, and 3 years prior led to an increase in Asian food prices by 1.034%, 0.630%, and 0.202%, respectively. Meanwhile, food prices may reduce due to an increase in water productivity in the previous year (−0.129%), 2 years prior (−0.080%), and 3 years prior (−0.033%). This finding supports our hypothesis that inefficient use of nitrogen leads to an increase in food prices, whereas water productivity is an appropriate measure to lower food inflation. In contrast to short-term circumstances, none of the climate change mitigation variables included in this study have any effect on food prices in Asia over the long-term.

Table 6

Impact of climate change mitigation actions on food prices in Asia

Long-term	
cointegrating equation	CointEq1
D(FOR(−1))	1.000
D (INF(−1))	−0.00005 (0.00004) (−1.242)
D(NUT(−1))	0.099 (0.062) (1.596)
D(REN(−1))	−0.058 (0.036) (−1.625)
D(WAT(−1))	−0.010 (0.007) (−1.483)
C	12.075
Short-term	
error correction	D(INF,2)
CointEq1	−0.001*** (0.0001) (−6.606)
D(FOR(−1),2)	−0.004 (0.010) (−0.396)
D(FOR(−2),2)	0.005 (0.010) (0.481)
D(FOR(−3),2)	0.001 (0.005) (0.248)
D(INF(−1),2)	−0.491*** (0.045) (−10.875)
D(INF(−2),2)	−0.569*** (0.037) (−15.463)
D(INF(−3),2)	−0.311*** (0.033) (−9.332)
D(NUT(−1),2)	1.034*** (0.185) (5.586)
D(NUT(−2),2)	0.630*** (0.169) (3.732)
D(NUT(−3),2)	0.202* (0.141) (1.428)
D(REN(−1),2)	0.153 (0.567) (0.271)
D(REN(−2),2)	−0.145 (0.677) (−0.214)
D(REN(−3),2)	−0.507 (0.575) (−0.881)
D(WAT(−1),2)	−0.129*** (0.021) (−6.233)
D(WAT(−2),2)	−0.080*** (0.015) (−5.296)
D(WAT(−3),2)	−0.033*** (0.009) (−3.865)
C	0.132 (0.910) (0.146)
Adjusted R-squared	0.474
F-statistic	40.520***
Akaike AIC	9.224
Schwarz SC	9.335
Determinant residual covariance	5.42E+12
Log-likelihood	−15,229.10
Akaike information criteria	43.664
Schwarz criteria	44.228

*** significance level=0.01, ** significance level=0.05, * significance level=0.1.

Impact of climate change mitigation actions on food prices in LAC

The model's validity is shown by an ECT coefficient of 0.038, significant at 0.01 alpha. An ECT of 0.038 means that its equilibrium and the change in the previous food price in LAC were adjusted for the current period by 0.038%.

Table 7

Impact of climate change mitigation actions on food prices in LAC

Long-term	
cointegrating equation	CointEq1
D(FOR(−1))	1.000
D (INF(−1))	0.0005*** (0.0002) (3.209)
D(NUT(−1))	−0.471 (1.264) (−0.373)
D(REN(−1))	1.248 (0.868) (1.439)
D(WAT(−1))	−0.932 (0.993) (−0.939)
C	24.234
Short-term	
error correction	D(INF,2)
CointEq1	0.038*** (0.001) (30.217)
D(FOR(−1),2)	0.020 (0.032) (0.615)
D(FOR(−2),2)	0.021 (0.032) (0.649)
D(FOR(−3),2)	0.020 (0.032) (0.634)
D(INF(−1),2)	0.411*** (0.036) (11.356)
D(INF(−2),2)	0.090*** (0.018) (4.905)
D(INF(−3),2)	0.059*** (0.009) (6.614)
D(NUT(−1),2)	1.321*** (0.312) (4.228)
D(NUT(−2),2)	0.832** (0.397) (2.092)
D(NUT(−3),2)	0.440* (0.312) (1.408)
D(REN(−1),2)	−2.312** (1.096) (−2.108)
D(REN(−2),2)	−1.214 (1.282) (−0.946)
D(REN(−3),2)	−0.630 (1.096) (−0.575)
D(WAT(−1),2)	−1.364 (1.965) (−0.694)
D(WAT(−2),2)	−1.677 (2.121) (−0.791)
D(WAT(−3),2)	−0.134 (1.980) (−0.068)
C	0.185 (3.053) (0.061)
Adjusted R-squared	0.691
F-statistic	87.987
Akaike AIC	11.521
Schwarz SC	11.642
Determinant residual covariance	1.03E+11
Log-likelihood	−12,294.27
Akaike information criteria	39.693
Schwarz criteria	40.333

*** significance level=0.01, ** significance level=0.05, * significance level=0.1.

Food prices in the LAC in the long-term are only affected by food prices in the previous year, while other independent variables have no effect. Meanwhile, food prices and the inefficient use of nitrogen in the previous year affected food prices in the LAC in the short-term (Table 7). Food prices in the previous year, 2 years prior, and 3 years prior led to an increase in food prices in the current year in the LAC by

0.411%, 0.090%, and 0.059%, respectively. Food prices also increased due to an increase in the inefficient use of nitrogen in the previous year (1.321%), 2 years prior (0.832%), and 3 years prior (0.440%). Only the previous year's renewables impacted food prices (−2.312%), whereas those from the previous two and three years had no impact. These findings, like those from Africa and Asia, support our hypothesis that inefficient use of nitrogen lead to increased food prices, whereas renewable energy is beneficial in lowering food inflation.

Discussion

Climate change mitigation programs have conflicting impacts on food security. The scarcity of land, cost of production, and food prices increase because of incentive-based mitigation measures such as preserving carbon-rich forests or implementing low-emission production methods. Preference-based mitigation, such as reducing household waste or consuming fewer animal products, can reduce land scarcity and reduce food prices (Stevanović et al. 2017). The long-term benefits of climate change mitigation include lower food prices, reduced risk of hunger, and a decrease in the need for irrigation water. However, short-term climate change mitigation increases the amount of land used for energy crops, thereby increasing the risk of food prices and insecurity (Hasegawa et al. 2021). Hence, the implementation of climate change mitigation is much debated, especially in developing and less developed countries.

Many low- or middle-income countries still hold unfavourable opinions about climate change mitigation. High mitigation costs increase the risk of hunger in these countries due to changes in income and food prices (Hasegawa et al. 2015). Many countries then provide international aid, bioenergy taxes, or reallocate domestic incomes to protect the poor and prevent famine from the economic impact of climate-focused policies alone (Fujimori et al. 2018).

The previous year's food price increased the current food price in Africa and LAC in the short and long-term but reduced the current Asian food price in the short-term. This variable plays a significant role in increasing current food prices in the three regions although it will decrease in the future. Government policies to control inflation are not always effective because of several factors and may be effective only in the short-term. Targeting inflation using monetary policy rates and interest rates was an ineffective tool for addressing inflation in Africa (Širůček–Galečka 2017). In addition, developing countries, especially in Africa, often experience monetary and fiscal (captured by public debt) policy shocks that increase inflation in the short and long-term (Mndebele et al. 2023, Olaoye et al. 2023). Other non-policy factors also affect food inflation in the short and long-term. Climate change has a significant continuous impact on food price inflation (Chari et al. 2022, Iliyasu et al. 2023). Meanwhile, countries in Asia could implement effective fiscal and monetary policies to control food price inflation as they produce food in large quantities to meet market demand and stop ongoing food inflation. Exchange rate policy also plays a major role in controlling Asian consumer price inflation (Jongwanich et al. 2019).

The inefficient use of nitrogen in the previous year increased food prices in Africa in the short and long-term but only increased food prices in Asia and LAC in the short-term. Specifically, food prices will reduce when nitrogen is used efficiently. The role of the inefficient use of nitrogen in the three regions in current food prices will continue to increase in the future and increase production costs as well. Nitrogen is an essential nutrient for agricultural development to meet the global increasing food demand. For example, the consumption of nitrogenous food has gradually increased in China's rural and urban areas in the last 40 years as the population and GDP have grown. Beijing's total dietary nitrogen intake increased from 37 Gg in 1979 to 70.77 Gg in 2019, switching to a pattern of high animal-based nitrogen consumption (Yang et al. 2022). The consumption of high nitrogen foods has led to an increase in food prices in China (Yang et al. 2012). A similar case occurred in developed countries where the combination of bioeconomic and dietary shifts toward animal-based foods high in nitrogen led to an increase in food prices (3.0%) (Imran et al. 2021).

The excessive and inefficient use of nitrogen results in low land productivity and vast agricultural land, which harms the environment and food security (Wang et al. 2023). Our analysis shows that higher food prices were a result of inefficient or excessive nitrogen use. Plant N use efficiency increases by synchronizing plant N demand and supply. The result is a stimulation of root architecture by producing plant hormones, thereby increasing the plant's overall ability to absorb more nutrients and water (Imran et al. 2021). Increasing the efficiency of N fertilization significantly reduces the side effects of bioenergy production, including changes in land use, unsustainable water extraction, and food prices (Humpenöder et al. 2018). The efficient use of nitrogen is one of the most successful technological advancements for reducing food prices and food insecurity in developing countries. According to current projections, this technology can reduce food insecurity by 36% when used in combination with other modern agricultural technologies (IFPRI 2014).

Water productivity in the previous year lowered food prices in Asia in the short-term. According to Spiertz–Ewert (2009), the rapidly growing demand for food, feed, and fuel will require combining yield growth (about 2% annually) and doubling or tripling resource use efficiencies, especially nitrogen use efficiency and water productivity in production systems with high external inputs, over the next 20–30 years. Without increasing global water productivity, grain prices will double globally, disrupting global economic progress, which in turn can be a world warning. Hence, increasing water productivity can increase food production so that the food supply will meet the needs of the global population and lower food prices (de Fraiture et al. 2010).

Finally, renewable energy can lower food prices in Africa and LAC in the short-term. Increased consumption of renewable energy has minimized the use of crude oil. Fluctuations in crude oil prices have caused food prices to increase. That is, reducing reliance on crude oil and increasing the consumption of renewable energy are significant steps to avoid fluctuations in food prices (Smyth et al. 2010). Haji Esmaeili et al. (2020) also emphasized that renewable energy does not always lead to an increase in food prices.

Efficiency in renewable energy production is key to reducing its negative impact on the economy, society, and future development. Meanwhile, the lack of R&D activity on renewable energy in developing countries, which can lead to several problems in agriculture such as microscale food security, agricultural policy instability, high food price inflation, and food fraud (Keskin–Güneş 2023). This case occurred in Brazil, where an increase in ethanol production has impacted the prices of sugar, wheat, corn, and barley (Maitah et al. 2019). Developed countries also face a similar situation where the usage of renewable energy from plants has resulted in lower food production. However, there has never been a fall in food consumption, which in turn results in an increase in food costs (Calvin et al. 2014, Lajdova et al. 2016). Several countries have used perennial plants as a source of renewable energy. These plants produce oil in large quantities and does not disturb the land used for food production. Hence, it will not affect food prices or contribute to the debate between food and fuel (Riayatsyah et al. 2022).

Appropriate policies play a crucial role in ensuring that renewable energy has a positive impact on food security and help control the increase in food price. One of the most important policies is regulating the volume of biofuels so that their production aligns with the growing local and global needs for food, feed, and fiber (Beach et al. 2017). Agricultural intensification policies and the efficient use of fertilizers are appropriate for the synergy between food prices and renewable energy (Popp et al. 2014). Canada's policy on renewable energy is a good example. Bioenergy crops cultivated on marginal land with biofuel production will be 33 million tons (under switchgrass) or 380 million tons (under hybrid poplar). Thus, Canada's production of bioenergy on marginal land can contribute to the security of its food and energy supply (Liu et al. 2012).

Conclusion

Policymakers, academics, and international organizations should regularly examine and adjust climate change mitigation measures to ensure that they have a net positive impact on society. In the long-term, the increase in food prices in Africa was a result of an increase in food prices and the inefficient use of nitrogen in the preceding year. Short-term increases in food prices are also caused by a rise in both variables and decline in renewable energy. Meanwhile, there are currently no long-term climate change mitigation efforts variables that affect food prices in Asia. However, in the short-term, food prices were reduced due to improved water productivity and decreased food prices in the previous year. whereas a harmful impact was seen from the inefficient use of nitrogen. Food prices in the LAC in the long-term are only affected by the previous year's food prices. Meanwhile, in the short-term, food prices and the inefficient use of nitrogen in the previous year increased LAC food prices. Only the previous year's use of renewable energy impacted food prices, whereas those from the previous two and third years had no impact.

Our study shows that almost every aspect of human life, particularly food prices, benefits from climate change mitigation actions. We recommend that policy makers should be more ambitious in implementing climate change mitigation policies, especially resource efficiency and the use of renewable energy. These policies must be designed within the scope of domestic policies and international agreements. The crucial aspect of implementing this policy is the role and collaboration of scholars and industry in developing environmentally friendly technology that promotes resource efficiency. However, climate change mitigation policy must be designed wisely to ensure that the global community, especially in developing and less developed countries, derives economic benefits. Meanwhile, developed countries cannot enforce all climate change mitigation actions because the negative impacts endanger the economies of developing countries and the world at large. The global community and business must promote and collaborate to regularly assess the effectiveness of climate change mitigation actions.

Our study results will raise a debate amid climate change mitigation efforts. The main limitation of this study is that the conclusions are generalized to developing countries without considering their diverse characteristics (heterogeneity). Moreover, several countries have inelastic food markets due to poor price transmission. This study may increase stakeholder awareness of the importance of maintaining global food security while making significant efforts to mitigate climate change. Future research could consider simulating the number of food inflations with and without climate change mitigation efforts and with "wise climate change mitigation efforts" to assess the level of inflation under each scenario. Further studies should consider every country's situation and use current data to determine the impact of Covid-19 pandemic on climate change mitigation actions. Hence, future studies can use fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) as data analysis methods.

Appendix

Table A1

List of countries included in this study

Africa	Asia	Latin America and the Caribbean
1. Algeria	1. Afghanistan	1. Argentina
2. Angola	2. Bangladesh	2. Barbados
3. Benin	3. Bhutan	3. Belize
4. Botswana	4. Brunei Darussalam	4. Bolivia
5. Burkina Faso	5. Cambodia	5. Brazil
6. Burundi	6. China	6. Chile
7. Cameroon	7. Cyprus	7. Colombia
8. Central African Republic	8. India	8. Dominica
9. Congo	9. Indonesia	9. Dominican Republic
10. Côte d'Ivoire	10. Iran	10. Ecuador
11. Democratic Republic of the Congo	11. Iraq	11. El Salvador
12. Ethiopia	12. Jordan	12. Guatemala
13. Gabon	13. Lebanon	13. Guyana
14. Gambia	14. Malaysia	14. Honduras
15. Ghana	15. Maldives	15. Jamaica
16. Guinea	16. Mongolia	16. Mexico
17. Kenya	17. Myanmar	17. Nicaragua
18. Madagascar	18. Nepal	18. Panama
19. Malawi	19. Pakistan	19. Paraguay
20. Mali	20. Philippines	20. Peru
21. Mauritius	21. Saudi Arabia	21. Saint Lucia
22. Morocco	22. Sri Lanka	22. Suriname
23. Mozambique	23. Syrian Arabic Republic	23. Trinidad and Tobago
24. Namibia	24. Thailand	24. Uruguay
25. Niger	25. Turkey	
26. Nigeria	26. Vietnam	
27. Rwanda	27. Yemen	
28. Senegal		
29. Seychelles		
30. South Africa		
31. Togo		
32. Tunisia		
33. Uganda		
34. United Republic of Tanzania		
35. Zambia		
36. Zimbabwe		

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