RESEARCH ARTICLE

Co-inventions, uncertainties and global food security

Christian Urom[1] · Khaled Guesmi[1] · Ilyes Abid[2] ·
Immaculata Nnenna Enwo-Irem[3]

Abstract
This paper examines the effects of international collaborative efforts on climate-friendly agricultural technologies on global food security. In particular, we use patent data on environmental technological innovations for OECD countries and global food prices from the period 1990 to 2016. Also, we investigate the impact of uncertainties in weather conditions in terms of rising global temperature created by climate change using data on global surface temperature from the Energy Information Administration and the Goddard Institute for Space Studies (GISS) Surface Temperature Analysis of the National Aeronautics and Space Administration (NASA). We used both impulse response functions and variance error decomposition from a panel Vector Auto-Regressive (VAR) model to examine both the response of global food prices to shocks on the concerned variables and the decomposition of error variance in global food prices. First, our results show that international collaborative efforts on climate-friendly agricultural technologies reduce global food prices while increasing global surface temperature increases food prices. Regarding the variance decomposition of global food prices, results show that surface temperature followed by international collaborations in climate-friendly innovations and other environment-related technologies are the main drivers of forecast error variance in global food prices. The food price variance share associated with greenhouse gas emissions is less when compared to that of technological innovations.

✉ Christian Urom
  sainturom@gmail.com

1 Paris School of Business, 54 Rue Nationale, Paris, France

2 ISC Paris Business School, Paris, France

3 Alex-Ekwueme Federal University, Ndufu-Alike, Ikwo, Nigeria

1 Introduction

In the twenty-first century, providing sufficient, safe and nutritious food for over 7.5 billion people has become one of the major global concerns. In this regard, recent data from (FAO 2019) shows that over 2 billion people are deprived of regular access to safe, nutritious, and sufficient food while (FAO 2018) suggest that about 821 million people can not afford sufficient food to meet their minimum dietary energy requirements. Even more, as noted in United Nations (2019), the objective of the second United Nations Sustainable Development Goal is to eliminate hunger and all forms of malnutrition by 2030. However, there is a gradual increase in hunger after decades of decline. Gregory et al. (2005) note that the rapidly changing interactions between and within the biophysical and human environments bring about the production, processing, distribution, and consumption of food, leading to food systems that underpin food security. In this regard, food systems envelop food availability (with elements related to production, processing and distribution), food access (relating to affordability, allocation and preference) and food utilisation (relating to nutrition, values and safety) and food stability denoted by food self-sufficiency ratio (Hasegawa et al. 2020). Food security describes a situation in which all people have both physical and economic access to sufficient, safe and nutritious food that satisfies their dietary needs and food choices for a healthy life (FAO 2016; Allee et al. 2021). Thus, food security contracts when the food system is stressed following serious defects in the global food system due to such factors as urbanisation, globalisation, climate change and other agents of environmental change.

It is in this context that the recently diminishing global food security has been largely attributed to the already precarious and vulnerable situation created by the complex links between climate change and agricultural production. Although, these effects, while extensive, have been observed to be locally specific, the multiple drivers of environmental change interrelate, leading to a situation of "differentiated vulnerability" across countries and regions (see e.g. Kasperson and Kasperson 2001; Adger 2006; Brooks and Loevinsohn 2011; Thomas et al. 2019). Put differently, Gregory et al. (2005) argue that given the complex interactions among the multiple socio-economic and bio-physical drivers of food systems and hence, food security, the strategies to adapt food systems to reduce their vulnerability to climate change are not consistent across regions. Despite these inconsistencies, the provision of local adaptive capacity are necessary. However, the dynamic interactions among food security, agricultural practices and climate change, which compounds existing vulnerabilities across regions require collaborative and concerted efforts. These efforts may be generated through collaborations among governments, non-governmental and international agencies.

Innovation and the deployment of agriculture-related technologies will substantially drive farmers' adaptation to climate change (Chhetri et al. 2012), and contribute to increased food production without increasing environmental pressures (Sayer and Cassman 2013). Indeed, a large body of reviews document that the capacity to adapt to climate change depends on knowledge dissemination

and the ability of both public, private and international organisations to function collectively at varying scales (see e.g. Adger et al. 2003; Lasco et al. 2006; Agrawal 2010; Shahbaz et al. 2018, 2020). These studies note that acknowledging the dynamic nature of innovations and technologies will help in promoting innovations that increase agricultural production while protecting the environment. Besides, recognizing the variety of actors involved in the innovation process and the institutional complexities within which they interrelate helps to establish the necessary policies and incentives to stimulate such interactions. Therefore, International collaborations are also very crucial to the adoption and diffusion of environmental related innovations to solve the impact of climate change on food security for several reasons, including institutional obstacles.

This paper examines the effects of international collaborations on climate-friendly technologies used in agricultural production and uncertainties on global food security. In this regard, we rely on patent data on innovations in environment-related technologies created through international collaborations, and global food prices. More so, we assess the impact of uncertainties in weather conditions such as rising temperature created by climate change using the global surface temperature from Energy Information Administration and the Goddard Institute for Space Studies (GISS) Surface Temperature Analysis of the National Aeronautics and Space Administration (NASA). Alarcón and Bodouroglou (2014) note that crucial lessons from the green revolution indicate that improving agricultural production for the present food security is far more complex than in the past and demands radical innovation and the diffusion of new climate-friendly technologies. This may be achieved through a long term support for research and development within an environment of international collaborations and free flow of information and an enabling policy framework involving both national and international stakeholders.

Although the effects of innovations in climate-friendly technologies and surface temperature on agricultural production and food prices are somehow already documented, this paper advances our knowledge of the interactions among environmental innovation, climate change and global food security in the following ways. To our best knowledge, this is the first study that focuses on climate-friendly innovations used in agricultural production developed following international collaborations and the impacts of such innovations on global food prices while accounting for the effects of changes in surface temperature. This research question is worth investigating for several reasons. First, Premanandh (2011) argues that in this globalized era of the 21st century, many determinants of food security are trans-national and depend upon multilateral collaborations and actions for an effective solution. Besides, given the adoption of the Sustainable Development Goals (SDGs) by all nations in 2015 as a commitment towards a world development path, Herrero et al. (2021) argue that innovations in the global food system will be crucial to achieving multiple SDGs and that collaborative innovations are required to achieve positive outcomes over multiple sustainability dimensions. Hence, results from our analysis have crucial implications for improving estimates of the level of international collaborative effects needed in the development of technological innovations that are required to ensure global food security without compromising earth system resilience.

Secondly, as noted in Lewis (2014), partnerships in international clean energy innovation vary widely in scope, targeting the deployment of clean energy technologies at different stages and across sectors, findings from this study will be useful in assessing the effects of existing collaborative efforts on global food security as well as in mobilizing inter-governmental and joint organizational subsidies to attract more collaborations on clean energy technologies associated with the food system. Lastly, results from this study will be useful in formulating proactive strategy for maintaining global food security for a post-COVID-19 recovery without increasing emissions from the global food system. Specifically, as noted in Falkendal et al. (2021), the global food security has been threatened by the effects of COVID-19 pandemic on international agricultural supply chains and locusts destroying crops, which have impacted the global supply and prices of main food crops including wheat, maize and rice, especially in Africa and South Asia. As major economies, regional bodies and international organisations implement different economic measures to stimulate the global economy towards a recovery path, findings from this study will be crucial in estimating the extent of cross-national and joint organisational collaborations that is required to maintain global food security through technological innovations which can be helpful in moderating the effects of the global food system on environmental quality.

To preview the results from our empirical estimations, following the impulse response functions, we document that food prices respond positively to its previous levels but decreases and become negative after the impact period. Also, we find that shocks on international collaborations as well as total technological innovations on climate-friendly technologies drive down food prices while food prices respond positively to shocks on greenhouse gas emissions after the first impact period. These suggest that although greenhouse gas emission drives up global food price, such effect may not be instantaneous but passes through negative effects on agricultural production due to harsh weather conditions, which may not occur immediately. Confirming this, a shock on global surface temperature has a positive and instantaneous impact on food prices. Regarding the error-variance decomposition, results suggest that surface temperature, followed by international collaborations in climate-friendly innovations and other environment-related technologies are the main drivers of error-variance in the forecast of food prices. Also, results show that the share of greenhouse gas emissions in food price variance are less compared to the shares associated with technological innovations.

The remainder of this paper is structured as follows. In the next section, we present the review of related literature while in Sect. 3, examine the trend in international collaborations in climate-friendly innovations and global food security. Section 4 contains the theoretical framework, model specification and data description. Empirical results are presented and discussed in Sect. 5 while the conclusion and policy recommendations are presented in Sect. 6.

2 Literature review

2.1 International collaborations on environment technological innovations and global food prices

According to Lee et al. (2012), the concept of technological innovation is very broad and may connote scientific inventions, patents, technological break-throughs, or simply, a new way of doing things. Innovation generally relates to value creation through the application of a new idea or approach for the advantage of stakeholders or even, the general good of humanity. It also includes the global environmental problems such as global warming, increasing CO_2 concentration and water shortages. New ideas and approaches for mitigating the adverse effect of global environmental issues generally known as green technologies have received vast attention globally over the past two decades. Climate-friendly technological inventions is on the increase and these innovations happen across the world. The increasing global challenge of climate change mitigation calls for the necessity to develop technological innovations and adoption for sustainable practices that have no detrimental consequences such as global warming.

Given its environmental externality, Hall and Helmers (2010) argue that patent protection is one of the necessary aspects of green technological innovations and adoption. This is because the new networks of global businesses and the increasing interdependence among individuals, institutions, governments, and economies necessitate a new innovation model for green technologies. This model, according to Lee et al. (2012) may only strive on a platform where internal, external, collaborative, co-creative ideas can be assembled and new ideas and approaches created to facilitate the sustainability of agricultural practices that are dependent to a large extent on the environment and therefore, vulnerable to climatic change. Also, addressing the externalities associated with green technologies and the huge uncertainties from climate change individually poses some challenges. This is because the interaction between these two externalities complicates the formulation of appropriate policy interventions to mitigate the impact of adverse weather events and also adapt to climate change (see e.g. Heal and Kriström 2002; Jaffe et al. 2005). The existence of dual externality issues in the process of addressing environmental technologies and its diffusion demands at least two different policy instruments.

The co-invention framework is premised on the need to assemble ideas, collaborative arrangement, and the co-creation of diverse experiences (Lee et al. 2012). International collaborative networks and alliances have been identified as most attractive to offer this platform and has been strongly advocated for the development and diffusion of green technological innovations (see e.g. Levi et al. 2010; Benioff et al. 2010; de Coninck et al. 2010). Substantial economics of scale in agricultural research generated through international collaborations, the organisational structure and institutional flexibility that characterize research networks as well as the narrow focus and agenda are key features of international collaborations. Brown (2013, p. 173) notes that one of this platform may be seen in the

Consultative Group on International agricultural Research (CGIAR) which laid the foundation for the green revolution.

The recent incentive structure for agricultural innovation system has manifested in the current evolution of 'open-source' collaborations or globalization of innovation characterized mostly by an increasing interaction among governments, private and global institutions as well as evolving laws and regulations concerning the ownership and use of inventions, notably patents. This trend has been illustrated by an increasing annual growth in share of R &D financing as well as international patents. For instance, Philibert (2004) notes that there was an annual average growth rate of about 13% in international patents during the decade from 1985 and 1995 whereas the share of R &D financing in OECD countries from abroad doubled between 1985 and 2001. Figure 1 shows the evolution of international patents through collaborations over the last two decades from 2000 to 2016 expressed as percentage of total patents in each country. The figure shows an average annual increase from about 6.7% in 2000 to about 12.6% and 11.8% in 2011 and 2016 respectively. Denmark appears to lead in the percentage of international patents reaching about 23.7% in 2011 whereas Ireland has the least over the entire period with about 3.6% in 2016

On the other hand, Fig. 2 presents the historical trend in international food prices. Panel A shows aggregated nominal and deflated food price indices from 1990 to 2016 while Panel B presents the good prices of main global food commodities including meat, cereals, sugar, diary products and oils. A look at both the aggregate
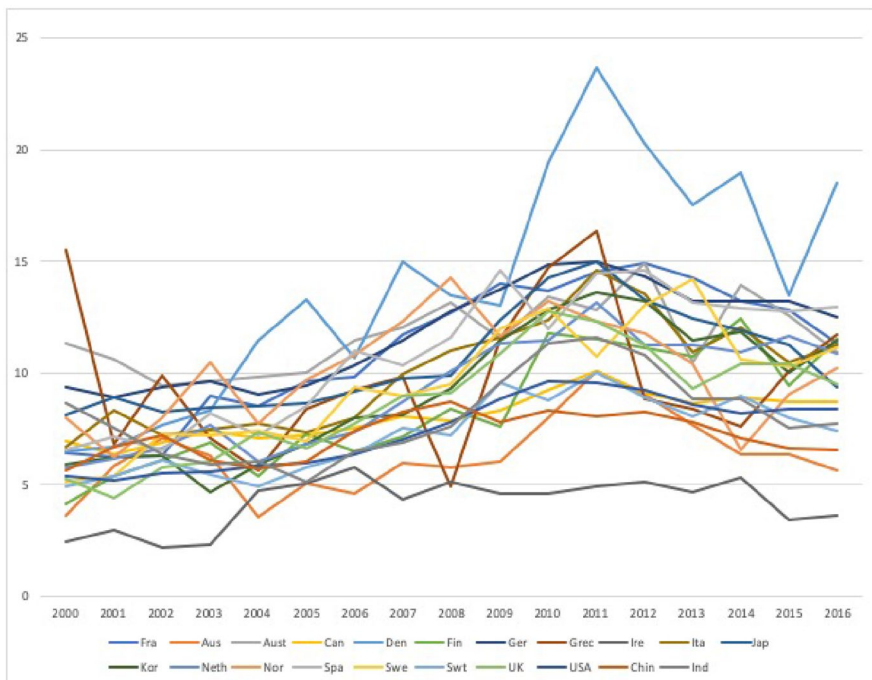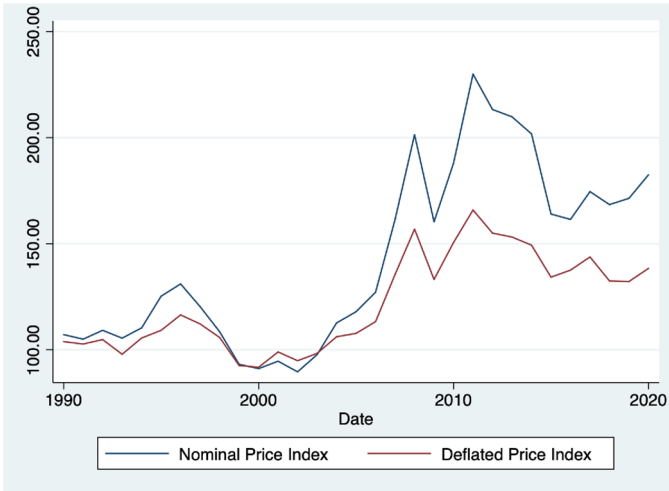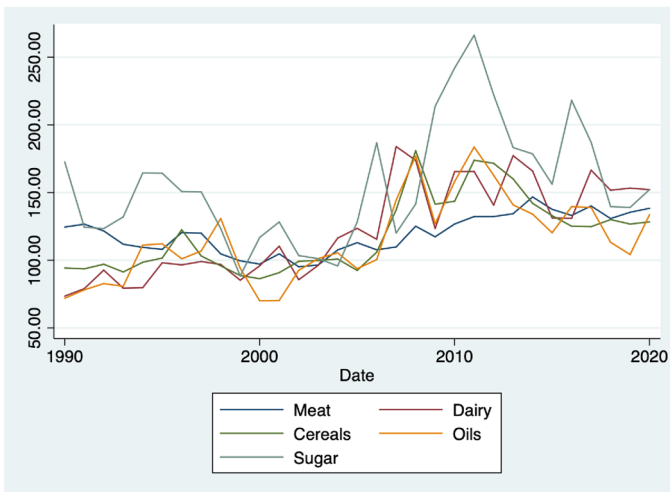

Fig. 1 Patent from international collaborations % of total patent for each country

(a) Global food prices 1990-2016, (2000=100)

(b) Global food commodity prices, 1990-2016

Fig. 2 The state of international food prices

as well as the decomposed trends shows evidence of sharp increase in prices over the period considered. Specifically, aggregate international food prices rose quickly, notably in two periods namely 2007–2008 and 2010–2011. Regarding decomposed food prices into main food commodities, all the food commodities have maintained an upwards trend since the end of 2000. Specifically, the most frequently demanded food crop namely cereals has the highest increase in prices over the study period. During the two episodes of food price spikes, the price of main cereals such as wheat, maize and rice rose significantly, with rice rising up to five-fold in 2008.

Agricultural food price is a main aspect of food security because food prices especially prices of grains and oil constitute large share of popular diets, especially for middle and low-income class. As noted in Cedrez et al. (2020), local food prices are main indicators of food security. Thus, increases in food prices due to climate effects, which negatively impact global food stocks diminishes access to food and nutritional needs, thus reducing food security.

2.2 Empirical evidence

Climate change characterized by changes in temperature, precipitation and climate variability which alters the timing and duration of growing seasons impacts agricultural food systems in several ways including direct effects on yields, changes in markets, international food prices as well as distribution networks (Amthor 2001; Fuhrer 2003; Jones and Thornton 2003; Long et al. 2005; Gregory et al. 2005; Shardul & Samuel, eds., 2008; Von Braun et al. 2008; Sayer and Cassman 2013; Cammarano et al. 2020; Ye et al. 2020; Wang et al. 2021; Kogo et al. 2021). An increasing amount of studies have demonstrated that increasing temperature and diminishing precipitation are likely to impact negatively on the yields of important food types such as wheat, rice, corn, oil and livestock products over the next two decades (see e.g. Gregory et al. 1999; Jones and Thornton 2003; Long et al. 2005; Lobell et al. 2008; Brown and Funk 2008; Falconnier et al. 2020; Hussain et al. 2020; Ahmed et al. 2020; Ureta et al. 2020; Godde et al. 2021). This is therefore expected to exert significant impact on the global food systems. For instance, in an experimental findings, Gregory et al. (1999) observed that diminished crop duration (and thus yield) due to global warming would lead to 5% of wheat and rice yield in about $°C^{-1}$ rise above 32°C while Rosenzweig et al. (2020) argue that 8–10% of total anthropogenic GHG emissions leads to food loss and waste of about 25–30% of global food production.

Thus, over the next decades, sustainably meeting the food requirements of the globally expanding population within a finite resource base while safeguarding the environment has become one of the most challenges confronting humanity (Barrera and Hertel 2021). However, the unsettling reality concerning global food production systems is that agricultural production itself is a major contributor of global environmental change. Several reviews have identified that over the past half century, existing technology and agricultural practices have contributed significantly both directly and indirectly to the increase in atmospheric carbon dioxide (CO_2), greenhouse gas methane (CH_4), nitrous oxide (N_2O) emissions due to increased nitrogen fertilizer use, animal manure production, use of farm machinery, production and use of pesticides and irrigation systems (see e.g. FAO 2002; Mosier and Kroeze 2000; Gregory et al. 2005; US-EPA 2006; Bellarby et al. 2008; Alarcón and Bodouroglou 2014; UNCTAD 2017; Kim et al. 2021). This has led to increase in land degradation and extensive water pollution. Specifically, Tubiello et al. (2021) estimated the total GHG emissions from the global food system to be about 16 CO_2eq yr^{-1} or one-third of the global anthropogenic total in 2018 while FAO (2002) notes that by 2030, nitrous oxide (N_2O) emissions from agriculture is projected to increase from 35% to

50% whereas Mosier and Kroeze (2000) claim that this would increase by 50% in 2020. Moreover, Rosenzweig et al. (2020) argue that about an additional 21%–37% of total anthropogenic emissions are contributed by supply chains and consumption activities from agriculture. Following this, Rockström et al. (2017) argue that agricultural practices have become both the single most important driver of global environmental change as well as the most affected of the change while Rosenzweig et al. (2021) note that improved estimates of GHG emissions from the global food system is very crucial in identifying effective policy solutions.

Around the world, earlier international collaborations in technological innovations have been targeted to address the climate change constraints on food security in specific regions. Lipton (2010) opines that in recent years, the challenge of increasing agricultural production for food security has become even more complex and will require improved systems of innovation that offer the flexibility to respond to regional specific needs in a divergent ecological and socio-economic contexts. Without recourse to its political context, the success of the green revolution is largely attributed to a large and inter-connected network of collaborations on research and development sustained through contributions from governments of both developed and developing countries, private organisations as well as international institutions (Alarcón and Bodouroglou 2014). The high dependence on food aid due to widespread food insecurity in Asia and Latin America in the 1960s – 1970s gave impetus to concerted collaborative efforts for technological innovations in agricultural productivity. Even more, the fear of repeated famines in India triggered more innovative agriculture through the adoption of high yield seed varieties, chemical nutrients, irrigation systems and reduced agricultural cycles (IFPRI 2002; Lipton 2010).

Results from collaborations on agricultural technological innovations during the green revolution were impressive especially between 1975 and 1995 and this halted the looming global food crisis. There were rapid expansions in the production of highly demanded food crops such as wheat, rice and maize. For instance, cereal production in Asia increased from 310 million tons per year in 1970 to 650 million tons in 1995 (Hazell 2009). This led to an increase in availability and accessibility of foods due to reduced food prices, which impressively increased food security during this period. Lipton (2010) noted that increased food productivity following the green revolution was largely driven by public sector research response to incentives other than profit from sales. However, it has been severally noted that the gains from the green revolution may have been significantly undermined following the recent hikes in major global food prices over the last two decades. Particularly, the prices of corn, oil, wheat and rice have escalated since the mid-2007, prompting the doubling of public expenditure on safety-nets such as the annual budget of World Food Program from $3 billion in 2007 to over $6 billion in 2008 (Timmer 2008).

Indeed, many other factors have been identified to impact the price formation of major foods including speculative activities in the commodity markets, developments in energy prices, biofuel production as well as exchange rate movements. However, dwindling global stocks due to yields damaged by drought, rising temperature and other forms of weather disruptions as well as diseases have generally been identified as the main drivers of food prices (Trimmer 2008). The yield gap caused by slow increases in global food production and diminishing yield growth rates are therefore

the main threats to global food security (Von Braun et al. 2008). Many studies have emerged focusing on inter-governmental collaborations to address the complex relation between food security and climate change both at national, regional and global levels. This is mainly because inter-governmental collaborative efforts are thought to be an optimal approach to slow down or reverse the current adverse effects of climate change on food security. However, most of these studies focus on political and economic corporations to facilitate the development and execution of climate policies, especially at regional levels. For instance, Islam and Kieu (2020) focused on international collaborative efforts across three regional organizations, including the Association of Southeast Asian Nations (ASEAN) the Pacific Islands Forum (PIF) and South Asia Association for Regional Cooperation (SAARC) to mitigate climate change risks and food security. Thus, this paper examines the collaborative efforts of regional organizations in dealing with climate change and food security risks by emphasizing the political and economic obstacles to effective management of climate change and food security.

Furthermore, Lee (2017) demonstrate that international collaboration is crucial for the adoption of climate-smart agriculture in Kenya through the provision of necessary resources and successful implementation while Modi and Venkatachalam (2021) focused on the transformation of agriculture in Africa within the framework of international cooperation in knowledge sharing; value addition; food security augmentation through trade in agro-commodities; and the financing of agriculture and allied sectors. Fixing the complex challenge of achieving global food security in a sustainable manner underscores the need for significantly increased international collaborations in the creation of climate-friendly technologies. Trimmer (2008) argues that essentially, yield growth in major food crops from existing technologies have remained at similar levels over the past decades due to inadequate investment in research and that closing the present yield gaps are only expected through the introduction of new technologies to enable a more sustainable food system. As stated in Agnusdei and Coluccia (2022), these technologies are necessary for agricultural transformations needed to promote sustainable food systems, waste reduction and to facilitate a change towards healthy sustainable diets. Given that most of such new technological innovations may best be generated through collaborations both across disciplines and the globe, this study contributes to the literature by examining how innovations made through international collaborations affect global food prices in the presence of rising global temperature. Co-inventions are optimal approaches for dealing with the complex nature of environmental technologies because they serve as important modes of inter- and trans-disciplinary knowledge sharing and co-production across borders. They also serve as better avenues for generating huge financial resources from relevant stakeholders such as international organizations, corporate bodies and national/regional governments while reducing the institutional complexities involved in such ventures.

3 The model and data

3.1 Model specification

In our empirical analysis, we focus on consumer food prices, where food prices are determined by changes in technology and climate change. Therefore, the panel VAR with which we consider the effects of co-inventions, emissions and climate uncertainty on agricultural food prices is formulated following Abrigo and Love (2015). Indeed, this econometric framework comes with some notable advantages over some other methodologies. First, as noted in Grossmann et al. (2014), Vector Auto-regressive (VAR) models are particularly useful in modelling empirical relationships among variables where there is minimal theoretical information about the relationships to inform the model specification. Secondly, the econometric design of VAR models explicitly accounts for endogeneity problems, which is one of the most serious drawbacks of empirical analysis on food prices. For example, using the Auto-regressive Distributed Lags (ARDL) model, Chen et al. (2010) raised the issue of endogeneity, which led to an explicit division into sample periods as an attempt to deal with the issue. However, the panel VAR enables us to treat all variables as essentially endogenous and explicitly capturing feedback effects among the variables. Besides, the impulse response functions derived from VAR models allow us to explore potential delayed effects among the variables, which is not enabled by panel regressions.

We consider a k-variate panel VAR denoted by the linear equations below:

$$Y_{it} = Y_{it-1}A_1 + Y_{it-p}A_p + X_{it}B + \phi_{it},$$
$$i \in \{1, 2, ..., N\}, t \in \{1, 2, ..., T_i\},$$ (1)

where Y_{it} denotes agricultural food prices; $Y_{it-p}A_p$ are lags of the dependent variable to be chosen using appropriate information criteria. X_{it} is a vector of exogenous covariates whereas ϕ_{it} is the vector of idiosyncratic errors specific to each dependent variable. $A_1, A_p,$ and B are the matrices of parameters to be estimated. Equation 1 above assume that the innovations in $E[\phi_{it}] = 0$, $E[\phi'_{it}\phi_{it}] = \sum$ and $E[\phi'_{it}\phi_{is}] = 0$ for all $t > s$. The vector of exogenous variables for this study includes *ICERT*, *GST* and *GHG* which denote International collaborations on environment related technology used in agricultural process, global surface temperature and green house gas emissions respectively. Also, *ERT* and *GHGPC* indicate total patent on climate-friendly technological innovation and greenhouse gas emission per capita respectively.

In estimating the model above, we apply a Generalized Method of Moments (GMM) estimator for the sample of 21 economies. We focus on the autoregressive structure of the panel VAR and estimated impulse response functions and forecast error variance decomposition. First, we conduct a series of preliminary tests including the unit root and cross-sectional dependence tests to determine the suitability and reliability of our chosen model and empirical approach. Abrigo and Love (2015) note that stability suggests that the panel VAR is invertible and has an infinite-order vector moving average representation, offering reliable interpretation to impulse responses and variance decomposition. A more detailed description of the

methodology allowing impulse-response functions and variance decomposition is presented in the Appendix (i).

3.2 Data sources and descriptive statistics

The data for this study were retrieved from the OECD *Stats* patent indicators database, the World Development Indicators (WDI) of the World Bank, the Food and Agriculture Organisation (FAO), the Energy Information Administration and the Goddard Institute for Space Studies (GISS) Surface Temperature Analysis of the National Aeronautics and Space Administration (NASA) covering the period from 1990 to 2016 for 21 economies comprising Australia, Austria, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Korea, Netherlands, Norway, Spain., Sweden, Switzerland, the United Kingdom and United States. We included India and China given the contributions of these countries to global food production, technological innovation, the size of their populations as well as strong working relationship with the OECD. The list of countries included in our analysis is presented in Appendix A. The variables for this study include agricultural food prices (consumer prices, food indices (2010 = 100)), patent on international collaboration on environment-related technology (% of total patent), environment-related technologies (% of total technologies), global surface temperature (global mean of Land-Ocean), total greenhouse gas emissions and emissions per capita.

Analyses of surface air temperature and ocean surface temperature changes are carried out by several groups, including the NASA Goddard institute of space studies (GISS). The NASA GISS Surface Temperature Analysis (GISTEMP) for estimating global temperature change takes both land and ocean temperature records from different sites and adjusts for urbanisation effects before computing the 12 month rolling mean global temperature. The GISTEMP is an open-source model based on data available from a large number of land based weather stations and ship data that forms an crucial source of measurement of global climate change. Uncertainties in the collected data from both land and ocean, with respect to their quality and uniformity, enables the analysis of both the land based station data and the combined data to estimate the global temperature change. Indeed, the estimation of long term global temperature change has crucial advantages over restricting the temperature analysis to regions with dense station coverage, providing a much better ability to identify phenomenon that influence the global climate change, such as increasing atmospheric CO_2.

As noted in Hansen et al. (2010), the fundamental objective of the NASA GISS data is to estimate global temperature change that could be compared with expected global climate change in response to both known or suspected climate forcing mechanisms including atmospheric carbon dioxide, volcanic aerosols, and solar irradiance changes. Hence, the analysis uses 1951–1980 as the base period and interpolates among station measurements and extrapolates anomalies as far as 1200 km into regions without measurement stations. Lastly, the analyses incorporates a homogeneity adjustment to minimize local (nonclimatic) anthropogenic effects on measured temperature change. Such effects have been noted by many past studies to be mainly

largest in urban locations where population, buildings and energy use often lead to a warming bias (see e.g. Pham et al. 2020). Basically, as noted in Hansen et al. (1999), the adjustment alters the long term temperature trend of an urban station to make it agree with the mean trend of nearby rural stations.

Table 1 above shows the basic descriptive statistics of the balanced panel dataset for this study. The table shows that food price index has a mean of about US $96 for the 21 countries considered. It also shows that the maximum food price index is about US $174 whereas the minimum is US $42 for the period under review. The difference between the minimum and the maximum values of food prices shows level of increase in food prices as well as the disparities in food prices between and within the countries in our panel. This is further implied by the high value of the standard deviation of about 15.5. The percentage of total patent from innovations through international collaborations has a mean of 9.22%. The maximum and minimum values are 23.7% and 2.22% respectively. This result imply that more needs to be done regarding international collaborations on innovations in climate-friendly technologies. This is because on average, less than 10% of innovations on green technologies results from collaborations among the countries. Figure 1 suggests that the maximum level in collaboration was achieved by Denmark in 2011 whereas the least collaboration may be seen in Ireland in 2002. This results does not necessarily imply that collaborations was highest in Denmark given that the data is expressed as percentage of annual patent granted. Therefore, this percentage may be smaller for a country that gained many patents in a particular year. Over the same period, we find that the mean global surface temperature has a mean value of 0.66 ^{0}C with a minimum value of 0.39 ^{0}C to about 1.02 ^{0}C maximum temperature.

Table 2 above shows results from a preliminary analysis using Pearson correlation coefficients between the variables in this study. Results show that the correlations among the variables are significant at different levels as shown by the simple contemporaneous correlation coefficients. With specific reference to correlations between global food price and other variables, the correlation between collaborations on climate friendly innovations is positively correlated with global food prices as shown by the positive and significant value of the correlation coefficient. As expected, we find the correlation between global surface temperature and food prices is strongly positive and statistically significant. This is also true concerning the correlation between surface temperature and innovations in climate friendly

Table 1 Descriptive statistics

Variable	Unit	Mean	Max.	Min.	Std. Dev.
FDPRN	US $ Consumer prices, food indices (2010 = 100)	96.2	174.4	42.1	15.5
ICERT	% of Total patent	9.22	23.7	2.22	3.21
GST	Global mean of Land-Ocean surface air in °C	0.66	1.02	0.39	1.43
GHG	Greenhouse gas emission in tonnes	28661.7	3246.1	23239.7	3246.1
GHGPC	Greenhouse gas emission per capita	12.94	25.95	5.34	5.68
ERT	Total patent	9.78	25.86	2.84	3.47

Table 2 Correlation coefficients among variables

	lFDPRN	lICERT	lGST	lGHG	lGHGPC	lERT
lFDPRN	1					
lICERT	0.39***	1				
	(0.0000)					
lGST	0.55***	0.29***	1			
	(0.0000)	(0.0000)				
lGHG	0.53***	0.49***	0.23***	1		
	(0.0000)	(0.0000)	(0.0000)			
lGHGPC	0.08***	0.09*	0.11**	0.19***	1	
	(0.0091)	(0.0783)	(0.0185)	(0.0003)		
lERT	− 0.27***	− 0.25***	− 0.34***	− 0.18**	− 0.06	1
	(0.0000)	(0.0000)	(0.0000)	(0.0112)	(0.2806)	

Note: *, **, and *** denote significance at 1%, 5% and 10% levels respectively. $p-values$ are in parentheses

technologies. It is expected that increasing temperature as a result of droughts impacts negatively on agricultural productivity, causing food prices to escalate due to diminishing global food stocks. As expected also is the correlation of greenhouse gas emission and food prices. Results show that global as well as emissions per capita have strong and positive correlations with food prices as well as with global surface temperature. Regarding environment-related technological innovations, as expected, it has a significant positive correlation on collaborations on climate-friendly technologies whereas it has negative correlations with surface temperature as well as emissions except with emissions per capita where it is statistically non-significant. Lastly, Table 3 shows results from the panel unit root test. The results show that all the variables become stationary after first difference.

4 Results

Having considered the necessary preliminary tests to improve the reliability and correctness of our empirical estimates, we proceed by examining the responses of food prices to shocks on international collaborations on climate-friendly innovations as well as other environmentally related technologies, changes in surface temperature and greenhouse gas emission. Plots of impulse response function are presented in Fig. 3 panel A-F in the Appendix. We find that all the response functions are statistically significant because the confidence band or interval does not contain zero at the chosen 95% significance level. Particularly, the last plot (Panel F) represents the response of current food price to a shock on its own lag. This implies that food prices respond to innovations in its own lags. The first period response from food prices to its own lag is positive but decreases sharply after the impact period. This impact changes to positive after the second period. However, after the fifth period, the response appears to become statistically insignificant. This shows that current

Table 3 Panel unit root test results

Variable	IPS t-value	Ho	Stationary
lFDPRN	1.452 (0.926)	Accept	No
D(lFDPRN)	8.603 (0.000)	Reject	Yes
lICERT	– 1.228 '(0.109)	Accept	No
D(lICERT)	– 3.707 (0.000)	Reject	Yes
lGST	– 0.795 (0.999)	Accept	No
D(lGST)	– 2.726 (0.003)	Reject	Yes
lERT	– 0.133 '(0.446)	Accept	No
D(lERT)	– 1.757 (0.039)	Reject	Yes
lGHG	–0.943 (0.460)	Accept	No
D(lGHG)	3.809 '(0.000)	Reject	Yes
lGHGPC	– 0.219 (0.399)	Accept	No
D(lGHGPC)	6.343 (0.000)	Reject	Yes

Note: IPS is the Im Persaran and Shin unit root test andH_0 is the null hypothesis that the series contain unit root. $p - values$ are in parentheses

food price responds positively to its previous levels but this decreases and becomes negative after the impact period.

Concerning the response of food price to a standard deviation shock on total greenhouse gas emission and per capital emission, results show that after the first period, a shock in both total and per capita emission drives up food prices sharply. Before fading away after the fifth period, the response of food price decreased sharply into the negative region after the third period but this decrease was gradual when we consider total greenhouse emission. This result suggest that although emission has a negative effect on food price, such effect is not instantaneous because atmospheric gas emission impacts agricultural production through alterations in weather conditions which may not occur immediately. Confirming this, results show that a shock to global surface temperature has a positive and significant impact on food prices. This impact appears to be very sharp during the impact period (first period). After the first period, there is a gradual but negative impact till the third period when the impact becomes positive and briefly sharp again before becoming insignificant after the seventh period. These results suggest that uncertainty about weather conditions such as drought which raises global temperature as a result of emission is however found to have a positive and significant effect on food prices through adverse effect on agricultural production.

Lastly, results also show a similar pattern of response from food prices to a standard deviation shock on international collaborations as well as total technological innovations on climate-friendly technologies. The plots show that a shock to innovations on clean technologies drives down the prices of agricultural foods. These effects are both sharp but short-lived as they become insignificant after the fourth and fifth periods respectively. This suggests that as expected, innovations in environment-related technologies relevant to agricultural production has been effective in increasing food production and driving down food prices. This is true about
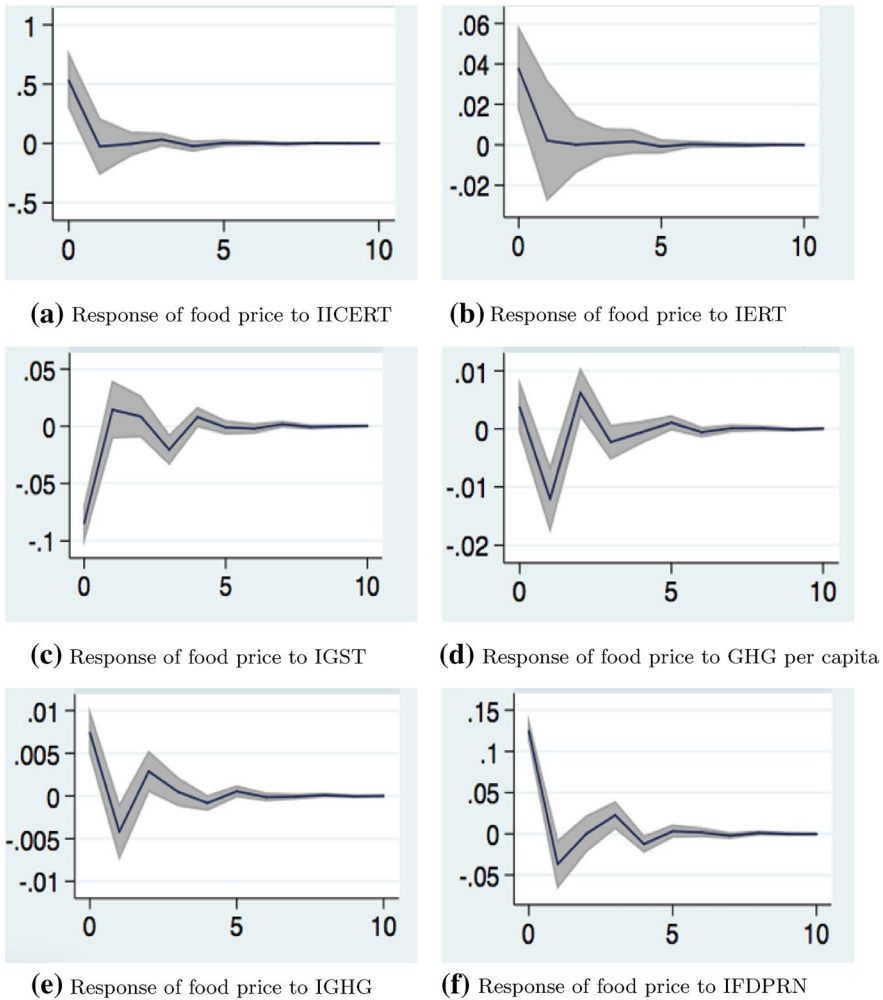
(a) Response of food price to IICERT

(b) Response of food price to IERT

(c) Response of food price to IGST

(d) Response of food price to GHG per capita

(e) Response of food price to IGHG

(f) Response of food price to IFDPRN

Fig. 3 Plots of food price responses

innovations developed through international collaborations as well as those without collaborations. Figure 4 in in Appendix (ii) shows that our analysis satisfied the stability condition required for our chosen econometric approach.

In order to offer more dynamic results beyond the impulse response functions in our analysis, Table 4 presents results from the variance decomposition of food prices forecast errors up to a ten period horizon. The results help us to shed more light about the explanatory power of surface temperature and climate-friendly technologies on the level of agricultural production (and hence, food prices). The results show the decomposition of the portion of variations in food prices that may be attributed to changes in global temperature and technologies relevant to sustainable agricultural production.

Table 4 Variance decomposition of food price

Period	lFDPRN	lICERT	lGST	lERT	lGHG	lGHGPC
1	100	0.00	0.00	0.00	0.00	0.00
2	79.9	1.41	17.9	0.72	0.22	0.120
3	49.8	6.36	38.3	3.77	0.93	0.84
4	27.9	11.9	47.9	6.71	3.12	2.47
5	15.5	16.7	49.1	8.19	6.26	4.25
6	8.74	21.1	45.2	10.32	7.81	6.83
7	5.14	25.2	38.1	11.38	13.3	6.88
8	3.74	28.3	28.4	14.43	15.9	9.3
9	9.62	17.5	23.4	18.12	16.7	14.66
10	10.28	20.71	26.8	15.1	16.86	10.26

Following the result in Table 4, the variance decomposition of food prices suggest that during the first two periods, variance in food prices is strongly driven by previous prices of food. However, the share of variance in food price attributable to its own lag diminishes throughout the forecast horizon whereas the predictive power of surface temperature and technological innovation and greenhouse gas emission increases. For instance, at the tenth period, the analysis show that the share of food prices on its own variance is about 10.28% whereas surface temperature becomes a strong and major driver of variance in food prices. The share of surface temperature in food price variance is about 26.8%. This implies that at the tenth period in our forecast horizon, changes in temperature such as drought or prolonged dry seasons which directly impacts negatively on food production contributes about 26.8% of the variance in food production. The share of temperature in food volatility in the second period is 17.9% but steadily increases to about 49.1% in the fifth period before decreasing till the end of the forecast horizon. This shows the strong effect of global warming on agricultural production and hence, food security.

The above findings are consistent with those of some past studies documented the negative effects of global warming due to increased surface temperature on crop yields (see e.g., Asseng et al. 2013, 2015; Martre et al. 2015; Asseng et al. 2019; Liu et al. 2019; Ye et al. 2020). Particularly, Asseng et al. (2015) suggest that globally, about 1 °C increase in temperature would lead to about 6% decrease in wheat production while Liu et al. (2019) argue that with reference to the 1980–2010 baseline, the projected global wheat production would change between – 2.3% and 7.0% under a global temperature increase of 1.5°C and between –2.4% to 10.5% under a 2.0°C increase in temperature. Even more, Mawejje (2016) focused on the effects of climate shocks on food prices in Uganda and found that increase in temperature significantly impacts on food price variability. These results suggest that risks associated with increased surface temperature will have adverse effects on food production, with access to food being negatively affected due to increasing aridity and lands suffering moisture stress. Thus, heat stress due to increase in temperature reduces the overall productivity of crops, increases food insecurity and malnutrition. This is in consonance with Battisti and Naylor (2009) which argues that heat due to

increased temperature will be the main cause of food insecurity in the tropics as well as temperate regions.

Next to surface temperature is the share of international collaborations in climate-friendly innovations and general environment-related technologies. Results show that agricultural related innovations due to collaborated efforts has a large share in food price variance. Innovations due to collaborations to address food security has a share of about 20.7% whereas the share of other climate-related technologies is about 15.1% at the end of our forecast horizon. This result shows that climate-friendly technological innovations applied in agricultural production has a sufficient share in the variance of global food prices through their impact on sustainable agricultural practices. Lastly, concerning the share of total and per capita emission, we find that the effect of both measures of environmental pollution are less compared to technological innovations. The share at the end of the forecast period are about 16.9% and 10.26% respectively. This is in line with expectations that technological innovations helps farmers mitigate the effects of climate change and improve yields from agricultural practices while minimising the level of environmental pollution.

Similar results have been documented in some past studies (see e.g., Webersik and Wilson 2009; Premanandh 2011; Vermeulen et al. 2012). Some crucial economic interpretations and intuitions may be drawn the above results. First, the maximization of agriculture's mitigation potential through collaborations in the development of climate-friendly technological innovations applied to food systems in the presence of uncertainties and climate change will lead to improved agricultural production and reductions in food prices. As noted in Hansen et al. (2011), increase in uncertainty associated with climate variability act as a disincentive to investments in advanced agricultural technology and market opportunities, influencing the risk-averse farmer to consider precautionary strategies that buffer against climate extremes over more profitable activities. Hence, without a collaborative effort towards adapting the global food systems to the current climate-related uncertainties, projected increases in climate variability is expected to impose more threat to the global food system, intensifying the cycle of poverty and could cause further vulnerability for achieving global food security (Field et al. 2014).

Even more, as noted in Premanandh (2011), the combined effects of population growth, urbanisation, climate change and reduced crops yields have resulted in increase in global food demand while food reserves are at their lowest in 35 years. Hence, with rising food prices projected to continue into the future due to climate-related risks and low crop yields, inadequate purchasing power could lead to non-affordability of foods in both cities and rural areas and may increase the global poverty level as a result of high food prices. Although, Vermeulen et al. (2012) argue that short-term international relief efforts in response to the effects of high food prices such as the World Food Program (WFP) and Global Food Crisis Response Program (GSRP) of the World Bank during the 2008 and 2011 food price hikes have been substantial and timely, we note that sustained increase in price and volatility of foods underscores some weaknesses in the global food supply system, which requires a longer-term response such as collaborative efforts in technological innovations. Increase in climate-friendly innovations through collaborative efforts has the potential to address food security by creating a new agricultural development

pathway by improving the technical potential for mitigation and agricultural GHG reductions. Lastly, it will reduce the expected cost of mitigation for smallholder farmers, lead to increased efficiency of inputs as well as increases in crop yields for smallholders while reducing negative environmental impacts.

5 Conclusion and policy implications

Providing adequate, safe and healthy food for the increasing global population is one of the major issues confronting the twenty-first century. Factors such as climate change, in terms of rising temperature and other manifestations impose significant adverse effects on agricultural production. This situation is even made more complicated by the current food systems, which contribute significantly to GHG emissions. In the context of this complex interactions among climate change, agricultural production and global food security, innovations in environment technologies used in agriculture is believed to be one of the best ways of increasing agricultural production to achieve food security without compromising environmental quality. This study contributes to this literature by examining the effects of international collaborations on environment-friendly technological innovations used in agriculture on global security. To measure international collaborations on environment-friendly technological innovations, we use patent data on international collaborative environment technological innovations while we use food prices to capture food security. Moreover, we assess the impact of uncertainties in weather conditions associated with the rapidly changing surface temperature due to climate change using the global surface temperature from Energy Information Administration and the Goddard Institute for Space Studies (GISS) Surface Temperature Analysis of the National Aeronautics and Space Administration (NASA)while also capturing the effects of other innovation and GHG emissions indicators. These effects are studied using both impulse response functions and variance decomposition derived from a panel VAR for 21 economies from the period 1990 to 2016.

Regarding our empirical estimations, first, results from the impulse response functions suggest that food prices react positively to its own past values while it responds negatively to a shock on international collaborations on agriculture-related environment-friendly technological innovations. Secondly, our results show that total technological innovations on climate-friendly technologies drive down food prices while food prices respond positively to shocks on greenhouse gas emissions after the first impact period. These suggest that although greenhouse gas emission drives up global food price, such effect may not be instantaneous but passes through negative effects on agricultural production due to harsh weather conditions, which may not occur immediately. Confirming this, a shock on global surface temperature has a positive and instantaneous impact on food prices. Regarding the error-variance decomposition, we document that surface temperature, followed by international collaborations in climate-friendly innovations and other environment-related technologies are the main drivers of error-variance in the forecast of global food prices. Also, results show that the share of

greenhouse gas emissions in food price variance are less compared to the shares associated with the indicators of technological innovations.

Findings from this paper underpin some important policy implications. For instance, our main finding of the negative effects of international collaborative efforts on climate-friendly innovation on food prices suggests that given the complexities in the development and diffusion of agriculture-related technological innovations, international collaborative efforts in the creation and diffusion of such innovations may be the best approach to achieve global food security through improved agricultural production without compromising environmental quality. In this regards, our study recommends that to reduce the complexities associated with the creation and diffusion of environment technologies, increased efforts should be made to improve inter-governmental collaborations at both the global, regional and local levels. Also, the global scientific community has an important role to play by collaborating with governments at all levels and international institutions to ensure the an increased output of relevant environment technologies. These technologies are essential for the transition of the current global food systems into safer and more climate-friendly food system that is capable of ensuring sufficient and healthy food without increasing GHG emissions from agriculture. Thus, our study offer support for policies that encourage increased, sustained and collaborative investments in environmental-friendly technological innovations. This is particularly essential to promote the desired changes in food production, the environment, human diet and global well-being. Lastly, the main limitation of this study is the current end date of the OECD data for patents on innovation, which does not permit us to explore the research objectives under the current situation created by the COVID-19 pandemic. As noted in Muthamilarasan and Prasad (2021), the pandemic is predicted to have increase the number of hungry people through its adverse effort on global supply chains, food systems, food security, and agricultural livelihoods which have resulted in global food price increases. Hence, we recommend that future research should offer updated perspectives by considering these research objectives in the post-COVID-19 pandemic period.

Appendix i: Impulse Response Function and Panel Variance Decomposition

Impulse-response functions

As noted in Hamilton (1994) and Lutkepohl (2005), the panel VAR for this study as defined in Eq. 1 is stable if all moduli of the companion matrix $\overline{A}$ are strictly less than one, where the associated matrix is formed as follows:

$$\overline{A} = \begin{bmatrix} A_1 & A_{11} & \dots & A_p & A_{p-1} \\ I_k & 0_k & \dots & 0_k & 0_k \\ 0_k & I_k & \dots & 0_k & 0_k \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0_k & 0_k & \dots & I_k & 0_k \end{bmatrix}. \tag{2}$$

Abrigo and Love (2015) note that stability suggests that the panel VAR is invertible and has an infinite-order vector moving-average (VMA) representation, offering known interpretation to estimated impulse-response functions and forecast error variance decomposition. Basically, the simple impulse-response function Φ_i may be estimated by re-writing the model as an infinite VMA, where Φ_i are:

$$\Phi_i = \begin{cases} I_k, & i = 0 \\ \sum_{j=1}^{i} \Phi_{t-j} A_j, & i = 1, 2, .. \end{cases} \tag{3}$$

However, the simple IRFs offer no causal interpretation given that innovations ϕ_{it} are correlated contemporaneously, a shock on one variable is likely to be followed by shocks in other variables, as well. Assume a matrix P, such that $P'P = \Sigma$. Hence P may be used to orthogonalize the innovations as $\phi_{it} P^{-1}$ and to transform the VMA parameters into the orthogonalized impulse-responses $P\Phi_i$. The matrix P apparently imposes identification restrictions on the system of dynamic equations.

The impulse-response function confidence intervals may be analytically realized using the asymptotic distribution of the panel VAR parameters and the cross-equation error variance-covariance matrix. However, Lutkepohl (2005) posits that the confidence interval may be computed based on Monte Carlo simulation as well as bootstrap resampling techniques.

Forecast-error variance decomposition

The h-step ahead forecast-error may be written as follows:

$$Y_{it+h} - E[Y_{it+h}] = \sum_{i=0}^{h-1} \phi_{i(t+h-i)}\Phi_i, \tag{4}$$

where Y_{it+h} denotes the observed vector at time $t + h$ while $E[Y_{it+h}]$ represents the h-step ahead predicted vector associated with time t. Similar to impulse-response functions, we orthogonalize the shocks based on the matrix P to separate each variable's contribution to the forecast-error variance. Thus, the orthogonalized shocks denoted by $\phi_{it} P^{-1}$ have a covariance matrix I_k which permits straightforward decomposition of the forecast-error variance.

Particularly, the contribution of a variable m to h-step ahead forecast-error variance of variable n may be estimated as follows:

$$\sum_{i=0}^{h-1} \theta^2 mn = \sum_{i=1}^{h-1} (i'_n P \Phi_i i_m)^2, \tag{5}$$

where i_s denotes the s-th column of I_k. However, in application, the contributions are often normalized relative to the h-step ahead forecast-error variance of variable n as:
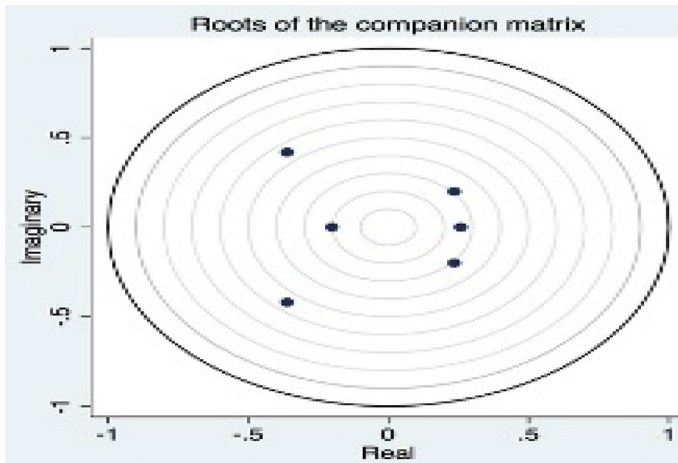
Fig. 4 Stability test

$$\sum_{i=0}^{h-1} \theta^2 . n = \sum_{i=1}^{h-1} i'_n \Phi'_i \Sigma \Phi_i i_n. \tag{6}$$

Lastly, just like the impulse-response functions, the confidence intervals may be realized analytically or based through various resampling techniques.

Declarations

Competing interests Authors declare no competing interest regarding this study

Ethical approval There are no ethical issues regarding this study

References

Abbott PC, Hurt C, Tyner WE (2011) What's driving food prices in 2011? (No. 741-2016-51225)

Abrigo MR, Love I (2015) Estimation of panel vector autoregression in Stata: A package of programs. manuscript, February 2015 available on http://paneldataconference2015.ceu.hu/Program.Michael-Abrigo.Pdf

Adger WN, Huq S, Brown K, Conway D, Hulme M (2003) Adaptation to climate change in the developing world. Prog Develop Stud 3:179e195

Adger WN (2006) Vulnerability. Glob Environm Change 16(2006):268–281

Agnusdei GP, Coluccia B (2022) Sustainable agrifood supply chains: Bibliometric, network and content analyses. Science of The Total Environment, 153704

Agrawal A (2010) Local institutions and adaptation to climate change. In Mearns R, Norton N (eds.), Social dimensions of climate change: Equity and vulnerability in a warming world. New frontiers of social policy, . Washington D. C: The World Bank

Ahmed SM (2020) Impacts of drought, food security policy and climate change on performance of irrigation schemes in Sub-saharan Africa: The case of Sudan. Agricul Water Manag 232:106064

Ahmed N, Thompson S, Turchini GM (2020) Organic aquaculture productivity, environmental sustainability, and food security: insights from organic agriculture. Food Secur 12(6):1253–1267

Alarcón D, Bodouroglou C (2014) Agricultural innovation for food security and environmental sustainability in the context of the recent economic crisis: Why a gender perspective?. In Gender Perspectives and Gender Impacts of the Global Economic Crisis (pp. 255-277), Routledge

Allee A, Lynd LR, Vaze V (2021) Cross-national analysis of food security drivers: comparing results based on the Food Insecurity Experience Scale and Global Food Security Index. Food Secur 13(5):1245–1261

Amthor JS (2001) Effects of atmospheric CO2 concentration on wheat yield: review of results from experiments using various approaches to control CO2 concentration. Field Crops Res 73(1):1–34

Asseng S, Ewert F, Martre P, Rötter RP, Lobell DB, Cammarano D, Zhu Y (2015) Rising temperatures reduce global wheat production. Nat Clim Change 5(2):143–147

Asseng S, Ewert F, Rosenzweig C, Jones JW, Hatfield JL, Ruane AC, Wolf J (2013) Uncertainty in simulating wheat yields under climate change. Nat Clim Change 3(9):827–832

Asseng S, Martre P, Maiorano A, Rötter RP, O'Leary GJ, Fitzgerald GJ, Ewert F (2019) Climate change impact and adaptation for wheat protein. Glob Change Biol 25(1):155–173

Barrera EL, Hertel T (2021) Global food waste across the income spectrum: Implications for food prices, production and resource use. Food Policy 98:101874

Battisti DS, Naylor RL (2009) Historical warnings of future food insecurity with unprecedented seasonal heat. Science 323(5911):240–244. https://doi.org/10.1126/science.11643

Beddington JR, Asaduzzaman M, Clark ME, Bremauntz AF, Guillou MD, Jahn MM, Scholes RJ (2012) The role for scientists in tackling food insecurity and climate change. Agricul Food Secur 1(1):10

Beddington JR, Asaduzzaman M, Fernandez A, Clark ME, Guillou M, Jahn MM, Scholes RJ (2011) Achieving food security in the face of climate change: Summary for policy makers from the Commission on Sustainable Agriculture and Climate Change

Bellarby J, Foereid B, Hastings A (2008) Cool Farming: Clim Impacts Agricul Mitig Potent

Benioff R, de Coninck H, Dhar S, Hansen U, McLaren J, Painuly J (2010) Strengthening Clean Energy Technology Cooperation under the UNFCCC: steps toward implementation (No. NREL/TP-6A0-48596). National Renewable Energy Lab.(NREL), Golden, CO (United States)

Brooks S, Loevinsohn M (2011, August) Shaping agricultural innovation systems responsive to food insecurity and climate change. In Natural Resources Forum (Vol. 35, No. 3, pp. 185-200). Oxford, UK: Blackwell Publishing Ltd

Brown AE (Ed.) (2013) Environmental technologies, intellectual property and climate change: accessing, obtaining and protecting. Edward Elgar Publishing

Brown ME, Funk CC (2008) Food security under climate change. Science 319(5863):580–581

Cammarano D, Valdivia RO, Beletse YG, Durand W, Crespo O, Tesfuhuney WA, Antle J (2020) Integrated assessment of climate change impacts on crop productivity and income of commercial maize farms in northeast South Africa. Food Secur 12(3):659–678

Cedrez CB, Chamberlin J, Hijmans RJ (2020) Seasonal, annual, and spatial variation in cereal prices in sub-Saharan Africa. Glob Food Secur 26:100438

Chen ST, Kuo HI, Chen CC (2010) Modeling the relationship between the oil price and global food prices. Appl Energy 87(8):2517–2525

Chhetri N, Chaudhary P, Tiwari PR, Yadaw RB (2012) Institutional and technological innovation: Understanding agricultural adaptation to climate change in Nepal. Appl Geograp 33:142–150

Dawe D, Timmer CP (2012) Why stable food prices are a good thing: Lessons from stabilizing rice prices in Asia. Glob Food Secur 1(2):127–133

de Coninck HC, Tilburg XV, Vita AD (2010) Low-carbon technology cooperation in the climate regime. An exploration of opportunities, barriers and ways forward (No. ECN-B–10-002). ECN. 18c51

Falkendal T, Otto C, Schewe J, Jägermeyr J, Konar M, Kummu M, Puma MJ (2021) Grain export restrictions during COVID-19 risk food insecurity in many low-and middle-income countries. Nat Food 2(1):11–14

FAO (2002) World Agriculture: towards 2015/2030. FAO

FAO U (2016) The state of world fisheries and aquaculture 2016. Contributing to food security and nutrition for all, Rome (2016, pp 200)

FAO (2018) The State of Food Security and Nutrition in the World 2018. Building climate resilience for food security and nutrition. FAO. http://www.fao.org/3/I9553EN/i9553en.pdf

FAO (2019) The State of Food Security and Nutrition in the World 2019. Safeguarding against economic slowdowns and downturns. FAO. http://www.fao.org/3/ca5162en/ca5162en.pdf

Falconnier GN, Corbeels M, Boote KJ, Affholder F, Adam M, MacCarthy DS, Webber H (2020) Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa. Glob Change Biol 26(10):5942–5964

Field CB, Barros V, Stocker TF, Dahe Q (eds) (2012) Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Field B, et al (2014) Climate change 2014: impacts, adaptation, and vulnerability – IPCC. WGII AR5 summary for policymakers. pp. 1–32

Fuhrer J (2003) Agroecosystem responses to combinations of elevated CO2, ozone, and global climate change. Agricul Ecosyst Environm 97(1–3):1–20

Gerten D, Heck V, Jägermeyr J, Bodirsky BL, Fetzer I, Jalava M, Schellnhuber HJ (2020) Feeding ten billion people is possible within four terrestrial planetary boundaries. Nat Sustain 3(3):200–208

Godde CM, Mason-D'Croz D, Mayberry DE, Thornton PK, Herrero M (2021) Impacts of climate change on the livestock food supply chain; a review of the evidence. Glob Food Secur 28:100488

Gregory PJ, Ingram JS, Brklacich M (2005) Climate change and food security. Philosoph Transact Royal Soc B Biol Sci 360(1463):2139–2148

Grossmann A, Love I, Orlov AG (2014) The dynamics of exchange rate volatility: A panel VAR approach. J Int Financ Markets Institut Money 33:1–27

Hall BH, Helmers C (2010) The role of patent protection in (clean/green) technology transfer (No. w16323). Nat Bureau Econom Res

Hamilton JD (1994) Time Series Analysis. Princeton University Press, Princeton

Hansen J, Ruedy R, Sato M, Lo K (2010) Global surface temperature change. Rev Geophys 48(4)

Hansen JW, Zebiak S, Baethgen W, Ines AVM, Osgood D (2011) Climate risk, information and market participation for African farmers. In Proceedings of an international conference, Nairobi, Kenya, 13–15 May 2009, pp 157–175

Hasegawa T, Sands RD, Brunelle T, Cui Y, Frank S, Fujimori S, Popp A (2020) Food security under high bioenergy demand toward long-term climate goals. Clim Change 163(3):1587–1601

Hazell PB (2009) Transforming agriculture: The green revolution in Asia. Proven successes in agricultural development, Millions fed, pp 25–32

Herrero M, Thornton PK, Mason-D'Croz D, Palmer J, Bodirsky BL, Pradhan P, Rockström J (2021) Articulating the effect of food systems innovation on the Sustainable Development Goals. Lancet Planet Health 5(1):e50–e62

HLPE (2011) Price volatility and food security. Committee on World Food Security High Level Panel of Experts on Food Security and Nutrition, Report 1

Heal G, Kriström B (2002) Uncertainty and climate change. Environm Resour Econom 22(1):3–39

Hussain S, Huang J, Huang J, Ahmad S, Nanda S, Anwar S, Zhang J (2020) Rice production under climate change: adaptations and mitigating strategies. In: Environment, climate, plant and vegetation growth (pp. 659-686). Springer, Cham

International Food Policy Research Institute (IFPRI) (2002) "Green Revolution: Curse or Blessing?" Washington, DC, USA

Islam MS, Kieu E (2020) Tackling regional climate change impacts and food security issues: A critical analysis across ASEAN, PIF, and SAARC. Sustainability 12(3):883

Jägermeyr J (2020) Agriculture's historic twin-challenge toward sustainable water use and food supply for all. Front Sustain Food Syst 4:35

Jaffe AB, Newell RG, Stavins RN (2005) A tale of two market failures: Technology and environmental policy. Ecolog Econom 54(2–3):164–174

Jones PG, Thornton PK (2003) The potential impacts of climate change on maize production in Africa and Latin America in 2055. Glob Environm Change 13(1):51–59

Kasperson RE, Kasperson JX (2001) Global environmental risk. Earthscan, London

Kim DG, Grieco E, Bombelli A, Hickman JE, Sanz-Cobena A (2021) Challenges and opportunities for enhancing food security and greenhouse gas mitigation in smallholder farming in sub-Saharan Africa A review. Food Secur 13:457–476

Kogo BK, Kumar L, Koech R (2021) Climate change and variability in Kenya: a review of impacts on agriculture and food security. Environ Develop Sustain 23(1):23–43

Lasco RD, Cruz RVO, Pulhin JM, Pulhin FB (2006) Tradeoff analysis of adaptation strategies for natural resources, water resources, and local institutions in the Philippines. AIACC Working Paper No. 32. Washington, DC: International START Secretariat

Lee J (2017) Farmer participation in a climate-smart future: Evidence from the Kenya Agricultural Carbon Project. Land use policy 68:72–79

Lee SM, Olson DL, Trimi S (2012) Co-innovation: convergenomics, collaboration, and co-creation for organizational values. Manag Decis 50(5):817–831

Levi MA, Economy E, Shannon Kathleen ON, Segal A (2010) Energy innovation: Driving technology competition and cooperation among the United States, China, India, and Brazil. Council on Foreign Relations

Lewis JI (2014) Managing intellectual property rights in cross-border clean energy collaboration: The case of the US-China Clean Energy Research Center. Energy Policy 69:546–554

Lipton M (2010) From policy aims and small-farm characteristics to farm science needs. World Develop 38(10):1399–1412

Liu B, Martre P, Ewert F, Porter JR, Challinor AJ, Müller C, Asseng S (2019) Global wheat production with 1.5 and 2.0°C above pre-industrial warming. Glob Change Biol 25(4):1428–1444

Long SP, Ainsworth EA, Leakey AD, Morgan PB (2005) Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. Philosoph Transact Royal Soc B Biol Sci 360(1463):2011–2020

Lutkepohl H (2005) New Introduction to Multiple Time Series Analysis. Springer, New York

Martre P, Wallach D, Asseng S, Ewert F, Jones JW, Rötter RP, Wolf J (2015) Multimodel ensembles of wheat growth: many models are better than one. Glob Change Biol 21(2):911–925

Mawejje J (2016) Food prices, energy and climate shocks in Uganda. Agricul Food Econom 4(1):4

Modi R, Venkatachalam M (2021) South-South Collaborations in Agriculture: A Concluding Note. In: Modi R, Venkatachalam M (eds.), India–Africa Partnerships for Food Security and Capacity Building. International Political Economy Series. Palgrave Macmillan, Cham

Mosier A, Kroeze C (2000) Potential impact on the global atmospheric N2O budget of the increased nitrogen input required to meet future global food demands. Chemosphere Glob Change Sci 2:465–473

Muthamilarasan M, Prasad M (2021) Small millets for enduring food security amidst pandemics. Trends Plant Sci 26(1):33–40

Nelson GC, Rosegrant MW, Koo J, Robertson R, Sulser T, Zhu T, ... Magalhaes M (2009) Climate change: Impact on agriculture and costs of adaptation (Vol. 21). Int Food Policy Res Institute

Neufeldt H, Jahn M, Campbell BM, Beddington JR, DeClerck F, De Pinto A, LeZaks D (2013) Beyond climate-smart agriculture: toward safe operating spaces for global food systems. Agricul Food Secur 2(1):12

Pham NM, Huynh TLD, Nasir MA (2020) Environmental consequences of population, affluence and technological progress for European countries: A Malthusian view. J Environm Manag 260:110143

Philibert C (2004) International energy technology collaboration and climate change mitigation. OECD Environment Directorate and International Energy Agency, Paris (2004)

Premanandh J (2011) Factors affecting food security and contribution of modern technologies in food sustainability. J Sci Food Agricul 91(15):2707–2714

Pinstrup-Andersen P (2009) Food security: definition and measurement. Food Secur 1(1):5–7

Rockström J, Williams J, Daily G et al (2017) Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio 46:4–17. https://doi.org/10.1007/s13280-016-0793-6

Rosenzweig C, Mbow C, Barioni LG, Benton TG, Herrero M, Krishnapillai M, Portugal-Pereira J (2020) Climate change responses benefit from a global food system approach. Nat Food 1(2):94–97

Rosenzweig C, Tubiello FN, Sandalow D, Benoit P, Hayek MN (2021) Finding and fixing food system emissions: the double helix of science and policy. Environm Res Lett 16(6):1002

Sayer J, Cassman KG (2013) Agricultural innovation to protect the environment. Proc Natl Acad Sci 110(21):8345–8348

Shahbaz M, Nasir MA, Hille E, Mahalik MK (2020) UK's net-zero carbon emissions target: Investigating the potential role of economic growth, financial development, and R &D expenditures based on historical data (1870–2017). Technol Forecast Soc Change 161:120255

Shahbaz M, Nasir MA, Roubaud D (2018) Environmental degradation in France: the effects of FDI, financial development, and energy innovations. Energy Econ 74:843–857

Swinnen J, Squicciarini P (2012) Mixed messages on prices and food security. Science 335(6067):405–406

Thomas K, Hardy RD, Lazrus H, Mendez M, Orlove B, Rivera-Collazo I, Winthrop R (2019) Explaining differential vulnerability to climate change: A social science review. Wiley Interdisciplin Rev Clim Change 10(2):e565

Timmer CP (2008) Causes of high food prices. ADB Economics Working Paper Series 128, Asia Development Bank (ADB), Manila

Tubiello FN, Rosenzweig C, Conchedda G, Karl K, Gütschow J, Xueyao P, Sandalow D (2021) Greenhouse gas emissions from food systems: building the evidence base. Environm Res Lett 16(6):065007

UNCTAD (2017) The role of science, technology and innovation in ensuring food security by 2030. United Nations Conference on Trade and Development (UNCTAD)

United Nations (2019) The sustainable development goals report 2019. New York: United Nations https://unstats.un.org/sdgs/report/2019. Accessed 12 April, 2022

Ureta C, González EJ, Espinosa A, Trueba A, Piñeyro-Nelson A, Álvarez-Buylla ER (2020) Maize yield in Mexico under climate change. Agricul Syst 177:102697

US-EPA (2006) Global Anthropogenic non-CO2 greenhouse gas emissions: 1990-2020. United States Environmental Protection Agency EPA 430-R-06- 005, Washington DC

Vermeulen SJ, Aggarwal PK, Ainslie A, Angelone C, Campbell BM, Challinor AJ, Wollenberg E (2012) Options for support to agriculture and food security under climate change. Environm Sci Policy 15(1):136–144

von Braun J, Tadesse G (2012) Global food price volatility and spikes: an overview of costs, causes, and solutions. ZEF-Discussion Papers on Development Policy, (161)

Von Braun J, Fan S, Meinzen-Dick RS, Rosegrant MW, Nin Pratt A (2008) International agricultural research for food security, poverty reduction, and the environment: What to expect from scaling up CGIAR investments and "Best Bet" programs (No. 594-2016-39951)

Wang X, Müller C, Elliot J, Mueller ND, Ciais P, Jägermeyr J, Piao S (2021) Global irrigation contribution to wheat and maize yield. Nat Commun 12(1):1–8

Webersik C, Wilson C (2009) Achieving environmental sustainability and growth in Africa: the role of science, technology and innovation. Sustain Develop 17(6):400–413

Ye Z, Qiu X, Chen J, Cammarano D, Ge Z, Ruane AC, Zhu Y (2020) Impacts of 1.5 C and 2.0 C global warming above pre-industrial on potential winter wheat production of China. Eur J Agron 120:126149

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.