Three essays on food security, agricultural productivity, and commodity basis

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ABSTRACT

THREE ESSAYS ON FOOD SECURITY, AGRICULTURAL PRODUCTIVITY, AND COMMODITY BASIS

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The proposed research is constructed around the theme of food security, agricultural productivity, and commodity basis. The first paper analyzes the impacts of COVID-19 on the Bangladesh rice market within the framework of a partial equilibrium regime-switching model. We provide an initial estimate of the short- and long-run effects of COVID-19 on the Bangladesh rice market and food security sustainability by comparing baseline projections. We analyze the effect of shocks in policies related to trade, public stock, and productivity on rice supply, demand, and food security dimensions. Finally, we assess the effectiveness of these policies to smooth out shocks that may arise from a future pandemic like COVID-19. In the second essay, we analyze the relationship between women's empowerment in agriculture and Bangladesh rice farm productivity change and its components, which include efficiency change, technological change, and scale efficiency change. We employ the non-parametric Malmquist approach and bootstrap regression method. We find that improvements in women's empowerment in agriculture, specifically enhancing their ability to make independent choices regarding agricultural production, have a statistically significant positive association with productivity change, efficiency change, and technical change. We also find that lowering the gender parity gap is positively related to improving the productivity of the sample farms. In the third essay, we analyze the effect of precipitation variations, namely local, growing season, and

regional precipitation, on Missouri corn and soybean basis. We document statistically significant linear and nonlinear basis responses in corn and soybean models for local and growing season precipitation variations. We also find a statistically significant moderating effect of port distance measure on the curvilinearity of the association between regional precipitation and soybean basis.

Keywords: food security; policy analysis; women's empowerment; Malmquist; basis; corn; soybean; climate change; precipitation

Essay 1: COVID-19 and policy impacts on the Bangladesh rice market and food security

Abstract:

This research employs a partial equilibrium model to estimate the short- and long-run effects of COVID-19 and rice policies on Bangladesh's rice market and food security. We also analyze the impact of relevant policies in terms of their effectiveness in mitigating stresses stemming from a hypothetical pandemic with a COVID-19-like impact. The results indicate that the effect of COVID-19 on Bangladeshi food security during FY 2019/20 was mixed, as the indicators of food availability improved by 5%, and decreased by 17% for food stability, relative to what they would have been otherwise. Policy simulation results indicate that a higher import tariff improves self-sufficiency status but undermines rice availability and accessibility by bending the market toward a restrictive trade regime. Results also indicate that, unlike stock enhancement policy, closing the existing yield gap improves rice availability, accessibility, and moderates the depressing effect of a future event with repercussions similar to COVID-19, although the yield policy appears more speculative and could be too costly. The insights generated contribute to the understanding of policies that aim to achieve sustainable development goals related to aggregate food security, and build resilience against future shocks akin to COVID-19.

Keywords: Bangladesh, COVID-19, food security, partial equilibrium, rice

1. Introduction

There have been numerous studies on the concept of food security. Food security is relevant to the global policy agenda because of concern over issues such as growing population, rising production costs, declining agricultural production, and climate change [1,2]. Improved food security is also viewed as the key to achieving the sustainable development goal (SDG) [3]. Attention on food security was heightened after the global food price crisis of 2006-08, which pushed an additional 130 to 155 million people into poverty in 2008, and triggered riots in more than two dozen countries, including Bangladesh [4,5]. Similarly to the food price crisis of 2006-08, the COVID-19 pandemic could have a detrimental effect on food security. Containment measures such as lockdowns and social distancing imposed by governments around the globe to slow down the pandemic have amplified the risks of food insecurity directly through supply chain disruptions, and indirectly through decreases in purchasing power due to negative income shocks [6–8]. According to WFP [9], by the end of 2021 an additional 121 million people will be pushed into acute food insecurity due to the economic fallout of the pandemic. Bangladesh implemented a series of mitigation strategies to contain the pandemic, and the economic slump and supply chain disruptions triggered by such measures could have detrimental effects on agricultural production, trade, and price volatility. Rice availability, accessibility, and stability in Bangladesh could be affected, at least in the short run. Moreover, the current crisis seems unlikely to help Bangladeshi policymakers meet their stated objectives to increase food security and to achieve a transition toward sustainable development targets under the SDG agenda.

Our objective in this paper is to inform policy decisions relating to the Bangladesh rice market and food security indicators, and to conduct a COVID-19 impact analysis by comparing the baseline projections generated using pre-and post-COVID-19 exogenous macroeconomic, policy, and trade data. We also test the impact of different policy scenarios on the Bangladesh rice market, as well as the state of Bangladesh's food security during a hypothetical future pandemic after these policy options have been put in place. We do so by developing a partial equilibrium, structural-based model that incorporates Bangladesh's food and trade policies.

Despite the evidence of adverse effects from the food price increase, spikes, and income shocks on poverty and food security, little has been done to provide a long-term outlook on the food security status of Bangladesh [10–14]. To date, there have been insufficient efforts to examine the effects of food or trade policy changes or exogenous shocks on the Bangladeshi food market's fundamentals. The need for such analysis is even more compelling as the effects of the COVID-19 pandemic are likely to spill over into longer-run food security via income and food price impacts. In Bangladesh, food accounts for about 70% of total expenditures for the poor, defined as the bottom quintile of the income distribution, and the poor spend at least 35% of their income on staple foods [15]. Rice is the staple food of Bangladesh, which provides two-thirds of the calorie needs and half the protein consumption of the nation [16]. The rice sector is one of the key targets of the Government of Bangladesh's (GoB) food policy to ensure food security for all people at all times [17]. COVID-19 has the potential to jeopardize food security as it has already caused disruptions in food production, value chain, and access [18–20]. Therefore, estimates of the impact of COVID-19, future events with a COVID-19-like effect, and food

and trade policies on Bangladesh food security seem likely to be of relevance to the policymakers. If so, then there is a need for estimates of such effects to help policymakers formulate better policy responses toward the current and potential impact of COVID-19 on Bangladesh food security and to maintain rice market stability in the face of any future disruptions.

1.1. Literature review

Previous studies provided limited retrospective and prospective insights into the rice market and related food security concerns of Bangladesh. For example, Del Ninno et al. [21] analyzed the impact of the 1998 flood on Bangladesh's food security at national and household levels, and provided policy implications for managing future natural disasters in developing countries. Chen and Lu [22] measured the food security index (FSI) level changes in Bangladesh, and analyzed the contributions of factors such as total population, total cropping area, mean crop yield, and per capita consumption of rice and rice equivalents on FSI change during 1990-2013. Some studies provided projections for the Bangladesh rice market, and simulated supply and demand balance for rice under alternative scenarios [23–26]. There are studies that analyzed public stock requirement for stabilizing prices and mitigating future supply disruptions [27,28]. One common limitation of these studies is the omission of certain macroeconomic variables and trade policies (e.g., GDP, exchange rate, import tariff) in analyzing the rice market and food security. However, they do not explicitly employ any analytical tools that can capture the effect of shocks related to future events and policy changes on aggregate food security dimensions. Moreover, older studies might not relate well to the impacts of the COVID-19 pandemic, despite its potentially large impacts including at the intersection of food consumption and

online shopping [29,30], business innovation [31], working environments [32], agricultural and food markets, and trade more generally [33,34].

The partial equilibrium model developed in this study for the Bangladeshi rice market can fill this gap, as it quantifies the impact of a pandemic and certain policy options on key food security indicators. Although we found no studies of current Bangladeshi rice policy and food security that use the method employed here, several studies used a partial equilibrium framework to analyze and quantify agricultural and trade policies, examining their impact on different agricultural commodities in other parts of the world. Fathelrahman et al. [35] used a partial equilibrium framework to measure the welfare effect of food trade liberalization in India, Egypt, Pakistan, Saudi Arabia, and the United Arab Emirates (UAE). Others examined the effects of trade and agricultural policies on the rice sector in Madagascar [36], Japan [37], and Thailand [38]. Partial equilibrium models have also been used to estimate the effect of water subsidy policy on Banana farming in Jordan [39] and to analyze the effect of trade liberalization in the world wheat market on US wheat export demand elasticity [40]. Moreover, there are studies that simultaneously examined the impact of alternative policy responses on the Japanese and Indian rice and wheat markets [41,42].

1.2. Contribution

To the best of our knowledge, this research makes several unique contributions to the existing literature. First, this is a pioneering study in estimating the ex-post and ex-ante effects of COVID-19 on Bangladesh's rice market and food security using the partial equilibrium technique. Second, this is the first study to address the possibility of a trade regime switch in analyzing Bangladesh's rice market and related policies within a partial

equilibrium framework. There is evidence that the Bangladeshi rice market sporadically shifts between autarky and import parity regime [16,28]. Hence, the trade regime-switching mechanism employed in this research is more accurate in that it addresses the possibility of changing price formation under different market and policy conditions. Finally, we also evaluate the effectiveness of existing policies to cope with shocks that may stem from future events like COVID-19. The findings from this study will provide policymakers quantified insights regarding the current pandemic and help them to understand the potential effect of future pandemics on Bangladesh's rice market and the sustainability of food security.

2. Food and trade policies of Bangladesh

The current food policy framework in Bangladesh includes producer-oriented (e.g., public food stocks), consumer-oriented (e.g., public food grain distribution system), and trade and market-oriented (e.g., import tariff) policies whose stated purposes include ensuring an adequate and stable supply of food [43]. The current policy environment interlaces rice and food security policy, as discussed in this section, previewing our use of three policy instruments: import tariff, public stock, and yield gap closure. These are used to assess the impact of external shocks and variations on the dimensions of food security of Bangladesh.

The initial trade liberalization process in Bangladesh was started in the early 1980s with a new industrial policy in 1982. Major trade reforms were started in 1991, with the elimination of non-tariff import restrictions on most of the agricultural products and with the legalization of rice import by the private sector in 1994. Since then, governments have used import tariffs as a crucial policy instrument to develop the domestic rice market,

stabilize prices, and provide price incentives to producers and consumers. For example, to cover the production losses caused by the 1998 flood, the government removed import tariffs to encourage private sector import to avoid a food supply shortage. Such short-term policy action, along with the prompt port clearance, prevented domestic market price from rising above import parity level price. Del Ninno et al. [44] stated that such initiatives allowed the private sector to import a substantial amount of rice and proved to be less costly compared to the production shortfall following the 1988 flood, which was mainly handled through government commercial imports. We had observed similar policy actions following the 2004 monsoon flood and the 2007/08 world food crisis when the government quickly reduced rice import tariffs from 23% and 5% to 8% and 0%, respectively. At the end of the financial year (FY) 2018/19, the government nearly doubled (from 28% to 55%) import tariff to boost producer price after rice production hit an all-time high of 36 million metric tons (mmt) in FY 2017/18. Such flexibility in trade policies is also perceived as useful from a food security perspective, and there are certainly important implications. For example, studies indicate that Madagascar's 2004 rice crisis was aggravated by the government's reluctance to lower import tariff rates [45,46].

Public food grain stock policy is another instrument that is intended to help maintain food security. Due to the inelasticity of food grain demand in the short run, even a small disruption in food grain output can cause massive fluctuation in the market price without the ready availability of government buffer stocks for price stabilization [47,48], at least in the absence of private stocks and fully liberalized trade. Under the current public stock policy, GoB seeks to stabilize food grain prices by responding to both positive and negative supply disturbances through food grain purchases and sales [49]. Goletti [50]

stated that such interventions by the government influence market expectations about price. Del Ninno et al. [44] stated that despite smaller production shortfalls, the rise in nominal rice price was much bigger after the 1974 flood compared to the 1988 and 1998 floods as the government's ability to intervene in the domestic market was hampered by low public stock. Currently, GoB mandates maintaining a minimum public stock of 1 mmt of food grain to smooth out price volatility associated with supply disturbance and handle emergency offtake requirements [49].

Godfray et al. [51] stated that low yield results from a lack of technical knowledge, skills, or from constraints that limit investment in productivity-enhancing measures. Achieving yield improvements that close the gap between realized yield and the best possible yield is proposed by some as a factor that would contribute to improved food security [52]. The feasibility of such yield improvements and the cost of significant steps in this direction is unknown. For example, since the scope for production growth through area expansion is very limited, GoB has focused on improving current yield status through the adoption of the System of Rice Intensification (SRI), which involves better management of plants, soil, water, and nutrients [53]. Although important, we are not aware of any study that relates exact yield increase estimates and costs for this program.

3. Model design, elasticities, and historical data

3.1. Model background

Since the trade liberalization in 1994, Bangladesh has consistently imported rice from the world market, as represented by the Thai export price. Such persistent trade indicates that changes in the world price might be transmitted to the domestic rice price through spatial arbitrage. Dorosh and Rashid [28] found evidence of long-run transmission

from the subsidized below-poverty-line price of India to the domestic price during 2002–2007. Following Dorosh and Rashid [28], we employ the co-integration method to examine the spatial price linkage between Bangladesh domestic price and external price. We update the model with additional monthly data ranging from January 2000 to October 2020 and world reference price (Thailand free on board 5% broken rice). Our findings indicate that there exist at least two co-integrating relationships between Bangladesh and world price, implying a long-run equilibrium relationship (see supplement S2). However, the increase in the import tariff from 28% to 55% in FY 2019/20 proved to be high enough to eliminate import almost entirely. This indicates that such a tariff level can influence the correlation between domestic and world price and cause the Bangladesh rice market to be autarkic. Since the Bangladeshi rice market can switch between imports with tariff and autarky, it is important to utilize a partial equilibrium approach that can capture the equilibrium pricing conditions under different trade regimes. Therefore, we employ a partial equilibrium model that solves for market equilibrium price under import and autarky regimes.

3.2. Modeling framework

The model developed here is a multi-equation partial equilibrium model and is divided into three blocks, namely: supply, demand, and price linkage. The blocks contain behavioral equations that are estimated based on the economic and production dynamics of the Bangladesh rice market, although key elasticities are drawn from the relevant literature (see supplement S1). Total domestic rice supply consists of production and beginning stocks. Production is estimated by multiplying total area planted and yield. Total rice demand of Bangladesh is determined by domestic demand, seed, feed, and wastage, ending stock, and export supply. In this study, we divided net domestic demand (domestic

demand minus seed, feed, and wastage) by the total population to obtain the per capita net domestic demand for rice. In the price linkage block, separate trade and price equations for different market regimes are estimated to formalize the relationship between world market prices, trade, and domestic prices.

Figures 1 and 2 depict the flow of the Bangladeshi rice market model's essential components with and without trade, respectively.

Figure 1. Model framework: import parity

Figure 2. Model framework: autarky

Under autarky, the model uses a price equilibrator framework to simulate equilibrium price through setting demand equal to supply. Unlike autarky, domestic price in import parity regime is determined by the world market price with the tariff and imports clear the market. The switching mechanism used in this model is triggered by the price levels and allows the model closure to switch between autarky and import parity. For example, the model switches to autarky when the import parity price stays above the

autarky price. Similarly, the model closes on net trade and switches to import parity when the import parity price is less than the autarky price.

3.3. Elasticity

The price and income elasticities of rice have not been estimated here; instead, they are borrowed from the existing literature. Table 1 reports elasticity estimates available in the relevant literature. As a rule, rice demand and supply are found to be inelastic with respect to rice price and income. Demand elasticities range fairly narrowly from -0.30 to -0.89 , and supply elasticities run from 0.20 to 0.50 . Income elasticities of rice demand are all positive in this literature, with values no lower than 0.30 and as high as 0.68 , suggesting a fairly uniform view that this is normal, but a necessity with decreasing budget share as income rises.

Table 1. Elasticity estimates

Author	Data type	Demand elasticity	Supply elasticity	Income elasticity
Hasan [54]	Survey		0.30	0.40 to 0.60
Hossain and Yunus [26]	Survey	-0.59 to -0.68		0.36 to 0.43
Dorosh and Rashid [28]	Literature survey	-0.30 to -0.50	0.20 to 0.30	0.30 to 0.50
World Bank [55]	Literature survey	-0.55 to -0.89	0.30 to 0.50	0.51 to 0.64
Del Ninno et al. [44]	Market	-0.45		0.35
Brennan [56]	Market	-0.50	0.40	
Ahmed and Shams [57]	Survey	-0.45		0.68

Source: Authors

For this study, we use a value of -0.50 for demand own-price elasticity, 0.30 for supply elasticity with respect to rice returns per acre, and 0.40 for income elasticity of demand. Real price, returns, and income are used. These values correspond to the elasticities found in the literature, with greater weight given to studies that are more recent.

3.4. Data

To study the Bangladeshi rice market, we use national level and yearly data from various sources. The historical period used in this research is FY 1995/96 to FY 2019/20. This period is considered to provide an adequate number of observations that are representative of current market conditions, because the liberalization of agricultural imports in Bangladesh started in 1990, and import procedures were deregulated in 1994. Table 2 presents descriptive statistics for key supply and demand variables. The time series data used in the analysis may not possess constant mean due to the deterministic trend. Therefore, to remove the effect of factors such as technology, market and trade policies, we detrend the data by regressing each variable on constant and a trend variable and obtain the time trend removed residuals.

Table 2. Descriptive statistics

Descriptive statistics					
Variable	Unit	Mean	Std. Dev	Min	Max
Area planted	thousand acres	27,041	1349	24,567	29,388
Yield	ton/acre	1.06	0.18	0.72	1.32
Production	thousand metric ton	28833	6245	17687	38724
Net domestic demand	thousand metric ton	26475	5258	16824	34970
Imports	thousand metric ton	903	968	4	3889
Seed, feed and wastage	thousand metric ton	3237	953	1769	4647
Ending stocks	thousand metric ton	627	266	123	1256
Price	BDT*/metric ton	20,953	8435	9820	37,570
Thailand 5% parboiled price	USD/metric ton	375	134	187	616
Descriptive statistics after detrending					
Area planted	thousand acres	0.00	629	-1328	1037
Yield	ton/acre	0.00	0.04	-0.07	0.05
Production	thousand metric ton	0.00	1287	-2503	2217
Net domestic demand	thousand metric ton	0.00	1213	-2521	2365
Imports	thousand metric ton	0.00	965	-974	3082
Seed, feed and wastage	thousand metric ton	0.00	235	-380	411
Ending stocks	thousand metric ton	0.00	239	-647	454
Price	BDT*/metric ton	0.00	3086	-5316	5951
Thailand 5% parboiled price	USD/metric ton	0.00	111	-134	230

Source: Authors' calculation

Note: *Bangladeshi Taka

Imports appear the most volatile component of supply if assessed by comparing the standard deviation to the mean, or comparing maximum and minimum values. However, domestic production is many times higher than imports, as implied by the product of mean area and mean yield. Although area and yield both vary, if assessed by the standard deviations, the ranges seem small as compared to the mean values. Most production and imports go to food use, but a share is assumed in the government statistics to go to seed and feed uses or waste. Demand-side variability is a mirror of domestic production because, although ending stocks could in principle moderate the impact of supply shocks on domestic use, the mean stock level represents a small share of the market quantities in

historical data. The ranges of prices, both domestic and border, have been substantial in this period.

Market data, including production, area planted, yield, imports, feed and residual, ending stock, world market price (Thailand 5% parboiled rice price), and exports, were collected from the Food Planning and Monitoring Unit (FPMU) of the Ministry of Food of Bangladesh Government. Historical GDP, exchange rate, consumer price index, and population data were collected from the World Bank. Policy data, certainly including the import tariff rate, were collected from the Bangladesh Ministry of Agriculture, the International Fertilizer Development Center [58], and the World Trade Organization's Tariff Analysis Online database, respectively.

4. Food security indicators, exogenous assumptions, and scenarios

4.1. Food security indicators

Food security is a broad term that includes both macro dimensions, such as price stability that ensures availability and access to food, and micro dimensions that allow individuals to produce or purchase food according to their dietary preferences. Our approach is focused on the macro dimensions of Bangladesh's food security, and thereby relevant to policymakers who consider the implications of their strategies for aggregate rice demand, supply, and price in terms of their food security implications. Thompson et al. [59] analyzed food security characteristics of developing countries using the macro food security dimensions, namely availability, stability, and accessibility. One concern is that the macro approach does not necessarily capture the underlying dynamics of food security between and within households. Nonetheless, macro analysis of food security is still crucial in that insufficient per capita food availability would affect the market price and, thereby,

food access at the individual level [60]. Therefore, we measure the implications of market shocks for availability, stability, and accessibility dimensions of Bangladesh food security. GoB's national food policy plan of action also articulated food availability, supply stability, and access as core food security objectives [49].

Quantitative measures of the availability, accessibility, and stability dimension of food security that respond to markets, and more specifically to policy impacts on markets, require indicators. Ideally, each indicator reflects the characteristics of a specific dimension, and together a set of such indicators can provide an unbiased assessment of the impacts of policy options on food security. There are no definitive measures of food security dimensions. Thus, our proposed measures (Table 3) are developed based on the definition of these dimensions, variables widely used to represent market conditions, and previous studies that developed the framework for indicators of food security dimensions.

Table 3. Food security indicators

Dimension	Indicators
Availability	Per capita consumption ratio
Accessibility	Real price ratio
Stability	Self-sufficiency ratio, stocks-to-consumption ratio

Source: Authors

We use the per capita consumption ratio, a comparative indicator which measures the deviation of projection year per capita rice consumption from the base periods (FY 2017/18 to FY 2019/20) mean per capita consumption, for an indicator of availability [59]. Per capita income is a useful measure for the accessibility or economic affordability of food. Since GDP is exogenous to the model and no shocks are planned on this variable, we have not used per capita GDP as an indicator of accessibility despite its appropriateness. As an alternative, we use the ratio of projection year average real price relative to the

average real price in the base period (FY 2018/19 to FY 2019/20) as a measure of accessibility as price relates to consumer's food accessibility. We use the self-sufficiency ratio and stocks-to-consumption ratio as measures of stability [59]. The self-sufficiency ratio is the ratio of domestic production relative to the available supply. The stocks-to-consumption ratio is an indicator of supply buffer by expressing what part of needs at going prices could be met through stock release in the event of a production or import shock. These indicators do not support conclusive statements about food security outcomes, however. For example, having large public stocks might be less effective in reducing price shocks under import parity regime as compared to the case of autarky regime. Once sufficiently built, the government can use the stock to check the domestic price from rising during the period of scarcity, but this requires additional policy decision making regarding stock release. Similarly, the scope for self-sufficiency to reflect stability of food depends on the sources of shocks to supply, in particular whether domestic or foreign shocks are more important.

4.2. Model assumptions

Variables and assumptions used in the model include GDP growth to back-calculate nominal GDP level, yearly population growth, consumer price index (CPI) inflation (Bangladesh and the U.S.), and Thailand free on board (FOB) 5% broken rice (Table 4).

Table 4. Variables and assumptions

Variable	With-COVID Simulation	Without-COVID Simulation
Real GDP growth	1.6% FY 2020/21 and 1% in FY 2021/22	7.8% in FY 2019/20 and 7.4% from FY 2020/21 onward
Population projections	UN's medium variant projections	Same as with-COVID model
CPI Bangladesh	5.7% in FY 2020/21 and 5.6% from FY 2021/22 onwards	5.5% from FY 2019/20 onwards
CPI U.S.	0.6% in FY 2020/21 and 2.2% from FY 2021/22 onwards	2.2% in FY 2019/20 and 2.3% from FY 2020/21 onwards
Exchange rate	Constructed based on the difference between Bangladesh and the U.S. consumer price	Same as with-COVID model
World price	Thailand 5% FOB Bangkok; forecasts are taken from World Bank's commodity markets outlook, April 2020	Thailand 5% FOB Bangkok; forecasts are taken from World Bank's commodity markets outlook, October 2019
Import tariff	55% from FY 2021/22 onward	Same as with-COVID model
Fertilizer subsidy	Moving average of past three years subsidy per ton	Same as with-COVID model

Source: International Monetary Fund [61,62], United Nations [63], and World Bank [64–67]

4.3. COVID-19 and policy scenario analysis

In this section, we explain the assumptions and mechanisms used to analyze the impact of COVID-19 and the current policy environment on the Bangladesh rice market and food security.

COVID-19: To estimate the effect of COVID-19, we compare with- and without-COVID-19 results. Holding all else constant, we generate different baseline values by changing macroeconomic projections and world price to reflect the changing conditions caused by the pandemic. We do this by replacing projections (estimated by the World Bank and IMF as of October 2020) with forecasts made in January 2020 and October 2019. We assume that the changes in World Bank projections of the world rice price were dominated by COVID-19. However, changes after the first few years might reflect other factors, such as changes in long-run expectations of global productivity or demand growth, not COVID-

19. Indeed, the World Bank updated projections suggest a higher long-run price that could be a residual effect of COVID-19 but might be caused by other factors as well. Nevertheless, we use these projected world rice prices directly here.

Scenario 1- Import tariff: This scenario explores one mechanism that might be suggested by the self-sufficiency goal of the Seventh Five Year Plan (2016-2020) of the Bangladesh government [68], namely, increasing the import tariff to a level that eliminates arbitrage between domestic and world prices. At this tariff, import becomes nonexistent. In our policy experiment, we raise the current 55% import tariff to 90%; a rate that is not beyond the realm of possibility given past values, yet high enough to make import unfeasible.

Scenario 2- Public stocks: As of FY 2019/20, the public food grain storage capacity of Bangladesh stands at 2.3 mmt, and the GoB has a target of expanding public storage capacity to 3 mmt [69]. Moreover, IFPRI recommended a 2.4 mmt rice stock level to avoid shortfall as seen in 2007-2008 [28]. Under this scenario, we assume that over the next ten years, the GoB will gradually increase its rice stock to 3 mmt.

Scenario 3- Import tariff and public stocks: This scenario tests the combined effect of protectionist trade policy and greater rice stocks on Bangladesh rice market and food security.

Scenario 4- Yield gap closure: In this scenario, we explore the idea of ensuring food security by closing the gap between realized yield and attainable rice yield. Timsina et al. [70] stated that Bangladesh's current rice yield is not enough to meet future demand. They estimated that the average yield potential of three major rice crops of Bangladesh could be 3.51 tons/acre. Alam et al. [71] stated that the adoption of best management

practices, along with appropriate nitrogen management options, could reduce the yield gap by 45%. Since we find no stated government policy goals for future rice production levels or estimates of yield increase as a result of current production enhancement programs, we use the estimate from Alam et al. [71]. We increase the yield by 4.5% in all years of the projections to reflect an incremental step towards the hypothetically possible 45% increase over the long run.

We represent the above policy scenarios as though they are costless. Our primary objective is to quantify the shifts in the Bangladesh food security dimensions using these policy tools, not to evaluate these policies' costs or to provide a complete benefit-to-cost assessment.

5. Results

5.1. COVID-19 and Bangladesh's rice market

The results of the effect of COVID-19 on Bangladesh's rice market are reported in Table 5. To conserve space, we only report ex-post and ex-ante short and long-run effects.

Table 5. COVID-19 impact (% change relative to without-COVID-19 baseline)

	2019/20	2020/21	2021/22	2029/30	2030/31
Area	0%	−1%	−1%	3%	3%
Yield	0%	0%	0%	0%	0%
Production	0%	−1%	−1%	3%	4%
Net import	0%	0%	0%	−67%	−52%
Total domestic demand	0%	−1%	−1%	−2%	−2%
Ending stocks	−17%	0%	1%	−1%	−1%
Price/KG	−5%	−1%	−6%	10%	11%
Food security indicators (absolute change)					
Per capita consumption ratio	0.00	−0.01	−0.01	−0.03	−0.03
Real price ratio	−0.05	−0.01	−0.07	0.09	0.09
Self-sufficiency ratio	0.00	0.00	0.00	0.05	0.05
Stocks-to-consumption ratio	−0.01	0.00	0.00	0.00	0.00

Source: Authors' calculation

We did not assume any shocks in FY 2019/20's rice area and yield, as monsoon season rainfed and dry season irrigated rice varieties are usually planted by early February. Therefore, no production effect is reported. The net import status of the country is also unaffected, mostly due to the prohibitive import tariff imposed at the onset of FY 2019/20, which pushed the world price above the autarkic price. Except for ending stock and price, COVID-19 appeared to have little to no impact (mostly zero or less than 1%) on the Bangladeshi rice market during FY 2019/20. Results (Table 5) show that domestic rice price in FY 2019/20 would have been 5% higher had there been no pandemic. Such a depressed rice price could be due to the dampened rice demand or the slow pace of the public rice procurement program due to lockdown, which contributed little to raise producers' price. Total domestic demand in FY 2019/20 increased slightly by 0.4%. This is mainly due to the low-income growth caused by COVID-19 related lockdown and mobility restrictions that imposed additional constraints on income-generating activities. The largest immediate impact is on ending stocks, at least in relative terms, which is 17% lower than in the case of without-COVID-19 levels. The price response reflects how public stocks tend to be used. FAO [72] reports that GoB's special open market operations sell rice at a subsidized price to vulnerable groups, which lends credence to the relative higher starting stocks assumption that we made in the without-COVID-19 model.

As regards food security in FY 2019/20, COVID-19 had a much smaller impact on rice market food stability than on accessibility. The real price ratio dropped by 5%, indicating consumers improved access to rice. The stocks-to-consumption ratio declined marginally and could be explained by GoB's effort to stabilize the market by expanding

targeted food grain distribution and relief programs that required the additional release of rice from public reserves.

As noted earlier, caution should be exercised as the changes in post-COVID-19 price projections by World Bank might not just because of the pandemic alone. There seems resurgence in world demand and/or a reduction in world supply that causes long-run world prices to be higher in post-COVID-19 projections. These world market patterns projected by the World Bank could be related to other factors.

The ex-ante short-run (FY 2020/21–FY 2021/22) effect of COVID-19 on rice production is negative, but in the long run (FY 2029/30–FY 2030/31), production increases by an average of 3%. The supply response occurring mostly through acreage change can be explained by the changes in domestic price. In the short run, price is determined endogenously in the domestic market, and no net import changes are reported. In the long run, domestic price trades at import parity level triggering demand for import. However, with-COVID-19, net imports are, on average, 60% smaller than that of the without-COVID-19 model. This is due to the relatively improved self-sufficiency caused by the fall in domestic demand compared to without-COVID-19 levels during the projection periods. The dampening effect of eroding purchasing power due to income loss coupled with price hikes in later baseline years explains such a fall in domestic demand. On the other hand, the pandemic's effect on ending stock is relatively negligible and attributable to the domestic price change. With regard to food security indicators in the future, COVID-19 negatively affects rice availability, as per capita consumption of rice is projected to fall by an average of 2% during the projection period. The effect on rice accessibility is mixed, as the real price ratio improves in the short-run but reverses in the end by an average of 9%.

The long-run self-sufficiency ratio increases by an average of 5%, indicating an improvement in rice market stability, whereas the stocks-to-consumption ratio remains unchanged.

5.2. Baseline projections

A 10-year rice supply and demand outlook is developed for FY 2020/21 to 2030/31 with-COVID-19 macroeconomic and world price assumptions. We also assume normal weather and continuation of macro and trade policies in place in Autumn 2020.

The results (Table 6) indicate that rice production in Bangladesh is projected to reach 48 mmt in FY 2030/31, reflecting a gradual increase in acreage and yield during the projection period. A steady rise in nominal rice price from BDT (Bangladeshi Taka) 34/Kilogram (KG) in 2021/22 to BDT 57/KG in FY 2030/31 induces farmers to increase their land allocation, on average, by 0.6% annually. Influenced by higher domestic price and positive long-run trends, rice yield is also projected to increase from 1.4 ton/acre in FY 2021/22 to 1.6 ton/acre in FY 2030/31. Despite production improvements, a gradual increase in domestic demand fueled by positive income growth outpaces the increase in production. Although a continuation of the 55% import tariff appears to be sufficiently large to drive net import to zero until FY 2027/28, the evolving market conditions eventually cause the price to rise to the import parity level allowing trade to pass over the current tariff in the later baseline years. Net import and domestic demand reach 2.4 mmt and 50 mmt by FY 2030/31, respectively. Ending stock, on the other hand, remains steady around one mmt during the projection period.

Table 6. Baseline projections

	2021/22	2022/23	2023/24	2024/25	2025/26	2026/27	2027/28	2028/29	2029/30	2030/31
Area	28,427	28,516	28,572	28,929	29,234	29,432	29,647	29,912	30,110	30,099
Yield	1.36	1.39	1.41	1.44	1.46	1.49	1.52	1.54	1.56	1.59
Production	38,633	39,527	40,383	41,621	42,797	43,852	44,945	46,083	47,073	47,766
Net import	0	0	0	0	0	0	0	335	1292	2393
Total domestic demand	38,624	39,532	40,388	41,621	42,798	43,854	44,946	46,416	48,360	50,155
Ending stocks	1051	1046	1041	1041	1041	1039	1038	1039	1044	1047
Price/KG	34	37	40	43	45	48	52	54	55	57
Food security indicators (absolute change)										
Per capita consumption ratio	0.98	0.99	1.00	1.02	1.04	1.06	1.08	1.11	1.15	1.19
Real price ratio	0.97	1.00	1.03	1.03	1.03	1.04	1.06	1.05	1.02	0.99
Self-sufficiency ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.97	0.95
Stocks-to-consumption ratio	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02

Source: Authors' calculation

With regards to food security, rice availability appears to improve as the per capita consumption ratio increases from 0.98 in FY 2021/22 to 1.19 in FY 2030/31. Results for rice accessibility, proxied by the real price ratio, are mixed. The real price ratio increases during autarky years and reverses with the start of imports, implying net rice consumers' terms of access to rice will be positively affected by the change of trade regime. The effect of regime change is opposite for the stability dimension as the self-sufficiency ratio is projected to fall during the later baseline years. The stocks-to-consumption ratio, another proxy for Bangladesh's rice market stability, does not change significantly, only marginally decreasing from 0.03 in 2021/22 to 0.02 in 2030/31. It should be noted that such a trend in ending stock is determined exclusively by the modeling approach, where we assumed domestic price is the key driver of the GoB's stock behavior. We considered alternative approaches, but the historical estimates of the impact of price on public stocks appeared to

support this representation. We subject this assumption, as well as other policy assumptions, to additional analysis in the next section.

5.3. Scenario analysis

5.3.1. Scenario 1– Import tariff

Under this scenario, we increase the current 55% import tariff to 90%. The estimated effects of a high import tariff on the Bangladeshi rice market are reported in Table 7.

Table 7. Changes from baseline projections- higher import tariff

	2021/22	2022/23	2029/30	2030/31
Area	0%	0%	0%	1%
Yield	0%	0%	0%	0%
Production	0%	0%	1%	2%
Net import	0%	0%	–100%	–100%
Total domestic demand	0%	0%	–2%	–3%
Ending stocks	0%	0%	–1%	–1%
Price/KG	0%	0%	6%	10%
Food security indicators (absolute change)				
Per capita consumption ratio	0.00	0.00	–0.03	–0.04
Real price ratio	0.00	0.00	0.06	0.10
Self-sufficiency ratio	0.00	0.00	0.03	0.05
Stocks-to-consumption ratio	0.00	0.00	0.00	0.00

Source: Authors' calculation

No effects are reported in the early baseline years due to the absence of imports at that time since the tariff is already prohibitive. However, in the later years, a 90% import tariff eliminates net import, resulting in higher domestic production, lower domestic consumption, and lower ending stocks. Although tariff escalation improves the stability dimension, if judged based on the food security indicators presented here, the effects are negative for rice availability and accessibility. The findings are consistent with that of Minten et al. [45]. Compared to baseline values, the per capita consumption ratio is reduced

by an average of 4%, and the real price ratio increases by an average of 8%, indicating the waning food security status of Bangladesh by these measures due to the higher import tariff.

5.3.2. Scenario 2: Public stocks

In this scenario, we gradually increase the ending stock level to achieve the rice stock holding target of 3 mmt by FY 2030/31. Simulation results are reported in Table 8. It is important to note that some of the reported changes are big such as 170% increase in ending stock in FY 2029/30; this is due to the small baseline values and large relative changes.

Table 8. Changes from baseline projections- public stocks

	2021/22	2022/23	2029/30	2030/31
Area	0%	0%	0%	0%
Yield	0%	0%	0%	0%
Production	0%	0%	0%	0%
Net import	0%	0%	10%	7%
Total domestic demand	0%	0%	0%	0%
Ending stocks	33%	51%	170%	186%
Price/KG	1%	1%	0%	0%
Food security indicators (absolute change)				
Per capita consumption ratio	0.00	0.00	0.00	0.00
Real price ratio	0.01	0.01	0.00	0.00
Self-sufficiency ratio	0.00	0.00	0.00	0.00
Stocks-to-consumption ratio	0.01	0.01	0.04	0.04

Source: Authors' calculation

The results show that shocks in public stocks increase the price by an average of 1%. In the long run, the domestic price is driven by the world price and arbitrage, independent of domestic supply and demand. Therefore, except for net import, no other changes are reported. However, looking at the food security indicators, we observe some improvements in the stability dimension, mainly due to the improvement in the stock level.

5.3.3. Scenario 3: Import tariff and public stocks

This scenario simulates the impact of the simultaneous implementation of a protectionist policy and stock build-up on the Bangladeshi rice market and food security. Results (Table 9) indicate that in the long run, Bangladesh's rice market switches from import parity to autarky in response to the dual shocks in tariff and stocks. Such shocks effectively eliminate trade and put downward pressure on domestic demand by raising the price.

Table 9. Changes from baseline projections- higher import tariff and public stocks

	2021/22	2022/23	2029/30	2030/31
Area	0%	0%	0%	1%
Yield	0%	0%	0%	0%
Production	0%	0%	1%	2%
Net import	0%	0%	-100%	-100%
Total domestic demand	0%	0%	-2%	-3%
Ending stocks	17%	33%	170%	186%
Price/KG	1%	1%	7%	11%
Food security indicators (absolute change)				
Per capita consumption ratio	0.00	0.00	-0.03	-0.05
Real price ratio	0.01	0.01	0.07	0.11
Self-sufficiency ratio	0.00	0.00	0.03	0.05
Stocks-to-consumption ratio	0.01	0.02	0.04	0.05

Source: Authors' calculation

With regard to food security indicators, rice availability and accessibility deteriorate as a consequence of protectionist measures and larger rice stockpiles. The per capita consumption ratio declines by an average of 4%; this is mainly due to the adjustment in rice consumption in order to buffer price shocks. The real price ratio increases by an average of 9%, leading to a fall in longer-run access to rice. The stability of Bangladesh food security is enhanced as both the self-sufficiency and stocks-to-consumption ratio improve relative to the baseline levels. The self-sufficiency ratio increases in the long run,

indicating greater domestic supply and reduced dependency on trade for meeting demand. Gradual improvement in the stocks-to-consumption ratio indicates an enhancement in the GoB's capacity to cope with market demand and supply shocks.

5.3.4. Scenario 4: Yield gap closure

In this scenario, we implicitly assume that ongoing government initiatives (e.g., input subsidy, soil management, land improvement, extension services) to boost productivity affect rice yield positively. This hypothetical case assumes that such policies successfully increase rice yield and yet ignores the costs of these policies. Nevertheless, because improved productivity is a stated goal, the implications for the rice market and food security are relevant.

Results (Table 10) indicate that domestic price decreases by an average of 6% in the first few years but remains unaffected in the later baseline years. This indicates that the effect of yield shocks on price is more pronounced when the market operates under autarky and has no price effect when arbitrage through trade links domestic and world price. The resultant decline in price triggers market adjustments, such as less acreage planted. Production, consumption, and ending stocks are greater in these early years. Domestic price in later baseline years is predetermined by the world price, so no response in price is possible since downward pressure caused by greater production affects the amount traded rather than global rice prices. In the absence of price shocks, changes in domestic supply or demand relative to the baseline are not expected. Nonetheless, the long-run negative acreage response found here is not contrary to the theoretical expectations. There are delays between price changes and eventual crop production due to evolving expectations and lags inherent in crop production. As such, the lower crop returns in the early years cause

sustained area reduction relative to the baseline. However, the area effects are dissipating by the end of the projection period and would likely reverse in time if producers were motivated by the combination of higher yield and unchanged price to plant more rice area than in the baseline.

Table 10. Changes from baseline projections- yield gap closure

	2021/22	2022/23	2029/30	2030/31
Area	–1%	–2%	–2%	–1%
Yield	4%	4%	5%	5%
Production	3%	2%	3%	4%
Net import	0%	0%	–94%	–67%
Total domestic demand	3%	2%	0%	0%
Ending stocks	1%	1%	0%	0%
Price/KG	–7%	–5%	0%	0%
Food security indicators (absolute change)				
Per capita consumption ratio	0.03	0.02	0.00	0.00
Real price ratio	–0.07	–0.05	0.00	0.00
Self-sufficiency ratio	0.00	0.00	0.03	0.03
Stocks-to-consumption ratio	0.00	0.00	0.00	0.00

Source: Authors' calculation

In the short run, the positive yield shock improves rice availability and accessibility. The per capita consumption ratio increases by an average of 3%, and the real price ratio drops by 6%, indicating an expansion in rice consumption and improved market access. Regarding long-run food security, the rise in the self-sufficiency ratio indicates an improvement in the rice market stability.

5.4. Pandemic, policies, and Bangladesh food security

This section evaluates the impact of a hypothetical pandemic on Bangladesh food security in the event that the policies mentioned above are put in place. We do this by replicating shocks, similar to COVID-19 in FY 2027/28 and FY 2028/29 in terms of macroeconomic variables and world price effects. In other words, we estimate the impacts

of another, similar pandemic on the Bangladesh rice market with each of these policies in place as well as without any of them implemented. The hypothetical future pandemic is represented by repeating the percent changes in macroeconomic variables and world rice prices that our data sources estimate in FY 2019/20 and FY 2020/20 in the future period. Table 11 reports changes in food security indicators caused by a hypothetical pandemic starting in FY 2027/28 with and without the above listed policies in place. Detailed results are outlined in Supplement S3. Results indicate that the hypothetical pandemic without policy changes shifts the trade regime from import parity to autarky, puts downward pressure on domestic production, consumption, and price, and increases ending stocks. The last year effects are, however, different because the lower prices lead to less area as compared to the baseline, which after being priced out of world markets, combines to raise the domestic price as compared to baseline levels. Since the Bangladesh rice market becomes autarkic due to the hypothetical pandemic, we only considered policy options (public stockholding and yield gap closure) that can influence price when determined by domestic supply and demand.

Table 11. Food security, hypothetical future pandemic, and policies– % change relative to baseline

<u>Hypothetical future pandemic- no pre-existing policy</u>				
	2027/28	2028/29	2029/30	2030/31
Per capita consumption ratio	0%	–2%	–5%	–7%
Real price ratio	–5%	–9%	–2%	3%
Self-sufficiency ratio	0%	1%	3%	5%
Stocks-to-consumption ratio	1%	3%	6%	7%
<u>Hypothetical future pandemic- pre-existing stock policy</u>				
Per capita consumption ratio	0%	–2%	–5%	–7%
Real price ratio	–4%	–8%	–1%	4%
Self-sufficiency ratio	0%	1%	3%	5%
Stocks-to-consumption ratio	139%	160%	186%	209%
<u>Hypothetical future pandemic- pre-existing yield gap closure policy</u>				
Per capita consumption ratio	2%	0%	–3%	–5%
Real price ratio	–10%	–14%	–7%	–2%
Self-sufficiency ratio	0%	1%	3%	5%
Stocks-to-consumption ratio	0%	2%	4%	6%

Source: Authors' calculation

Table 11 (hypothetical future pandemic: no pre-existing policy) indicates that during the period FY 2027/28 to FY 2030/31, the per capita consumption ratio and real price ratio decrease by an average of 4% and 3%, respectively. The self-sufficiency ratio and stocks-to-consumption ratio, on the other hand, increase by an average of 2% and 4%. The table (hypothetical future pandemic- pre-existing stock policy scenario) also shows a pre-existing stock policy improves only rice stability, not rice availability or accessibility when compared to estimates obtained under no policy or production enhancement policy scenario. A pre-existing production enhancement policy, on the other hand, better smooths the effect of the pandemic on rice availability and accessibility as the per capita consumption ratio and real price ratio decrease by an average of 1% and 9%, respectively. Furthermore, with the exception of the stocks-to-consumption ratio under the stock policy

scenario, such a policy yields estimates of the stability indicators, which is quite similar to that of estimated under other scenarios.

6. Conclusions

This paper analyzed the impacts of COVID-19 on the Bangladeshi rice market within the framework of a partial equilibrium regime-switching model, and is the first such exercise of which we are aware. We provided an initial estimate of the short- and long-run effects of COVID-19 on the Bangladeshi rice market and food security sustainability by comparing baseline projections. We analyzed the effect of shocks in policies related to trade, public stock, and productivity on rice supply, demand, and food security dimensions. Finally, we assessed the effectiveness of these policies to smooth out shocks that may arise from a future pandemic similar to COVID-19.

The analysis showed that COVID-19 causes a shift in the rice trade regime, supply, and demand in the coming years. We found that the pandemic has had a mixed impact on the Bangladeshi rice market and food security. The short-run domestic prices are lower than they would be otherwise. Long-term prospects for post-COVID-19 rice supply, demand, and trade indicate a weakened Bangladeshi food security. Income shocks reduce per capita domestic demand during the projection period. The lower short-run prices cause sluggish production growth in later years, which, when combined with slower but continued growth in domestic demand, result in a higher price in later baseline years. COVID-19 improves self-sufficiency in rice by causing a reduction in imports. With regards to aggregate food security, the findings appear mixed. Rice availability improves due to the rise in per capita consumption. The real rice price remains relatively constant, indicating access to rice is not jeopardized during the projection period given the

assumptions. However, the rice market stability indicators deteriorate largely due to the rise in imports in the later baseline years and slow public stock growth.

With regard to policy experiments, a higher import tariff helps to improve self-sufficiency status but undermines rice availability and accessibility by bending the market toward a restrictive trade regime. The experiment with public stock policy reveals that increasing the ending stock incrementally, even up to the targeted level of 3 mmt, has limited implications for rice market fundamentals and food security indicators, particularly as long as stocks can be increased through greater imports. The results also indicate that having such a policy does not necessarily provide a large buffer against future market disruptions stemming from an event with repercussions similar to COVID-19. Conversely, combining public stock and import tariff policy was shown to improve rice market stability, however doing so also curbs the consumer demand by raising the domestic price. The results of the yield gap closure scenario indicate that yield increase positively affects rice availability, accessibility, and stability and hence improves the short- and long-run food security of Bangladesh. The analysis also shows that such a policy better insulates the Bangladesh rice market from the depressing effect of a COVID-19 like pandemic compared to other scenarios considered. However, as noted earlier, policies that successfully increase yields could be costly and have apparently been elusive.

Bangladesh's food security has already been challenged by growing population, reduced acreage supply, and climate change [73,74]. COVID-19, however, posed policy challenges that policymakers have not experienced before, namely responding simultaneously to demand-side shocks triggered by declining income levels and to supply-side shocks caused by disruption in trade. Apart from relying on short-run policies such as

expanding social safety net programs to deal with transitory food insecurity, policymakers may also focus on long-run food and trade policies to sustain food security and build resilience against future shocks. Policy recommendations aligned with the findings of this study are to recognize the scope for an open trade regime that permits rice imports to offset domestic production shortages and price volatility, to bear in mind the potential for productivity improvement to bridge the supply gap between demand and domestic production, and to balance the benefits from strategic grain reserves in terms of stabilizing prices and consumption with the cost of rice procurement, storage, and administration.

Our modeling approach provides an objective assessment of rice market's fundamentals and the current policy environment. Nonetheless, there are limitations to our study and certain improvements can be made for a more nuanced assessment. For example, future research efforts could focus on capturing the impact of relevant economy-wide distortions on the Bangladeshi rice market, analyzing the impact of different scenarios reflecting altered macroeconomic assumptions and world price, and the dynamics between this market and other agricultural and non-agricultural sectors. Future research that aims to contribute to evidence-based policy decision-making could also consider distortionary and fiscal costs of policy interventions. Moreover, our results depend on the baseline conditions and also on the sources of future shocks (e.g., supply, demand, and pandemic). The regime switching caused by trade policy represents an important contribution of the model developed here, yet also suggests that market and food security effects of a shock can depend on initial conditions, particularly whether there is trade at the going border price (with tariff) or not. As such, long-run world price projections are one critical input, but the

future after the COVID-19 pandemic is uncertain and the future in the event of another global pandemic is even less clear.

To summarize, while there are limits to our assessment, this research can help concerned stakeholders, especially policymakers, to better understand the dynamics of the Bangladeshi rice market as well as improve the debate over policy choices to achieve goals relating to the food security of Bangladesh. More importantly, the insights generated can help devise policy options that aim to build resilience against shocks akin to COVID-19. Results for this case might be relevant for other developing countries whose staple foods are provided through a combination of domestic production and imports.

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Supplement S1

1. Rice supply

Total domestic rice supply consists of production and beginning stocks. Production is estimated by multiplying total area planted and yield. The area planted and yield equations are symbolized as ap_t and y_t as shown in Equation (1) and (3).

$$ap_t = \beta_0 + \beta_1 \frac{(expr_t + subs_t * y_t)}{pi_{t-1}} + \beta_2 ap_{t-1}, \quad (1)$$

where $expr_t$ is the expected return in period t , calculated by multiplying expected price and expected yield in t . Expected price is the average rice price in the period $(t - 1)$ and $(t - 2)$. Expected yield (ey) is the trend yield as shown in Equation (2):

$$ey = \beta_0 + \beta_1 trend \quad (2)$$

Fertilizer subsidy ($subs_t$) by GoB is multiplied by yield to express it in terms of per unit of output. In this and later equations, pi indicates the consumer price index of Bangladesh. Lagged area planted (ap_{t-1}) indicates a partial adjustment approach.

Rice yield (Equation 3) is estimated as a function of the trend, the real price of milled rice per ton in Bangladesh and subsidy in t :

$$y_t = \beta_0 + \beta_1 trend + \frac{\beta_2 (p_t + subs_t)}{pi} \quad (3)$$

Beginning stock (Equation 4) in the period t has been modeled as equal to the ending stock in the period $(t - 1)$:

$$bs_t = es_{t-1} \quad (4)$$

2. Rice demand

Domestic demand, seed, feed, and wastage, ending stock and export supply determine the total rice demand of Bangladesh. In this study, we divided net domestic

demand (domestic demand minus seed, feed, and wastage) by the total population to obtain the per capita net domestic demand for rice.

Per capita net domestic is estimated as follows:

$$\text{per capita net domestic demand}_t = \beta_0 - \beta_1 \frac{\text{price}_t}{pi_t} + \beta_2 \frac{\text{per capita bd gdp}_t}{pi_t} \quad (5)$$

Ending stock is a behavioral equation estimated as:

$$es_t = \beta_0 + \beta_1 \frac{1}{\left(\frac{\text{price}_t}{pi_t}\right)} \quad (6)$$

As discussed earlier, GoB has a minimum public stock holding policy. Thus, the curvilinear specification is necessary to partly describe this policy. Also, it generates a reasonably shaped stock demand curve in that the curve gets steeper as price increases and flatter if the price is low.

3. Model closure

In this section, we discuss the trade and price component of the model that are used to reach equilibrium.

3.1 Trade

Import demand has been estimated from an identity consisting of net import (import minus export in period t) and

The export supply (exp_t) in period t (Equation 7) is a behavioral equation specified as:

$$exp_t = \beta_0 - \beta_1 \left(\frac{\frac{\text{price}_t}{\text{ex.rate}_t}}{uspi_t} \right) + \beta_2 \left(\frac{\text{thai.p}_t}{uspi_t} \right), \quad (7)$$

here, ex.rate_t is the average exchange rate of United States dollar to Bangladeshi Taka in year t , deflated by United State General Price index ($uspi_t$). The other external price, thai.p_t , is the export parity price of 5% parboiled Thailand rice price.

3.2 Price and model closure

The model has two closure options namely import parity and autarky. Domestic price is estimated independently based on the given market conditions.

The import parity closure is based on the notion that there is a flow of trade between Bangladesh and the rest of the world rice markets. The use of the price linkage equation (Equation 8) formalizes this interaction and defines the degree of price transmission [40].

$$price_t = \beta_0 + \beta_1(thai.p_t * tariff_t * ex.rate_t) \quad (8)$$

Thus, the domestic price is a function of the Thai rice export price (*thai.p*), the tariff Bangladesh imposes on rice imports (*tariff*), and the exchange rate (*ex.rate*).

The estimated model closes on net trade (Equation 9) and the equilibrium condition is met when total market supply equals total market demand at the prevailing price. Thus,

$$net\ trade = total\ domestic\ demand + ending\ stock - production$$

$$- beginning\ stock \quad (9)$$

Under the autarky trade regime, price is used to close the model without imports. We use a price equilibrator framework to simulate equilibrium price by setting domestic demand equal to domestic supply, defined as follows:

$$total\ domestic\ demand + ending\ stock = production + beginning\ stock \quad (10)$$

Supplement S2

Supplement S2 Table 1. Augmented Dickey-Fuller test for unit root

	Bangladesh price	Thai 5% parboiled price
Exogeneous	Constant	Constant
Lag length (max lag 10)	4	8
P Value- Level	0.00	0.00
t- Statistics	-7.84	-6.44
1% level	-3.46	-3.46
5% level	-2.87	-2.87
10% level	-2.57	-2.57

Source: Authors' calculation

Supplement S2 Table 2. Lag length selection

Endogenous: Bangladesh price, Thai 5% parboiled price

Exogeneous: Constant

Lag	LL	LR	AIC	HQIC	SBIC
0	-1322.43		22.64	22.66	22.69
1	-1292.05	60.77	22.19	22.25	22.33
2	-1270.89	42.32	21.90	21.99	22.13
3	-1218.16	105.45	21.06	21.20	21.39
4	-1217.11	2.10	21.11	21.29	21.54
5	-1197.46	39.32	20.85	21.06	21.36
6	-1151.17	92.58	20.12	20.37	20.74
7	-1118.53	65.27	19.63	19.92	20.34
8	-1109.41	18.23	19.55	19.87	20.35
9	-1079.80	59.21*	19.11	19.47*	20.00*
10	-1075.62	8.38	19.10*	19.51	20.10

Source: Authors' calculation

*Indicates lag order selected by the criteria at 1% level

Supplement S2 Table 3. Co-integration test: Bangladesh price & Thai 5% parboiled price

Trend: constant			Number of observations: 239	
Sample: 2000m1 - 2020m10			Lags: 9	
Trace test			Maximum eigenvalue test	
	Trace statistic	1% critical value	Max test statistic	1% critical value
Ho: Rank=p				
P=0*	112.16*	19.94	88.63	18.52
P=1*	23.53*	6.63	23.53	6.63

Source: Authors' calculation

Note: *Denotes rejection of the hypothesis at the 1% level; Trace test indicates 2 cointegrating equations at the 1% level; Max-eigenvalue test indicates 2 cointegrating equations at the 1% level

Supplement S3

Supplement S3 Table 1. Hypothetical future pandemic – no policy changes (% change relative to baseline)

	2027/28	2028/29	2029/30	2030/31
Area	0%	-1%	-2%	-2%
Yield	0%	0%	0%	0%
Production	0%	-1%	-2%	-2%
Net import	0%	-100%	-100%	-100%
Total domestic demand	0%	-2%	-5%	-6%
Ending stocks	1%	1%	0.2%	-0.5%
Price/KG	-5%	-9%	-2%	3%
Food security indicators (absolute change)				
Per capita consumption ratio	0.00	-0.02	-0.06	-0.08
Real price ratio	-0.05	-0.09	-0.02	0.03
Self-sufficiency ratio	0.00	0.01	0.03	0.05
Stocks-to-consumption ratio	0.00	0.00	0.00	0.00

Source: Authors' calculation

Supplement S3 Table 2. Hypothetical future pandemic- with pre-existing public stock policy (% change relative to baseline)

	2027/28	2028/29	2029/30	2030/31
Area	0%	-1%	-2%	-2%
Yield	0%	0%	0%	0%
Production	0%	-1%	-2%	-2%
Net import	0%	-100%	-100%	-100%
Total domestic demand	0%	-2%	-5%	-7%
Ending stocks	138%	155%	170%	186%
Price/KG	-4%	-8%	-1%	4%
Food security indicators (absolute change)				
Per capita consumption ratio	-0.01	-0.02	-0.06	-0.09
Real price ratio	-0.04	-0.09	-0.01	0.04
Self-sufficiency ratio	0.00	0.01	0.03	0.05
Stocks-to-consumption ratio	0.04	0.04	0.05	0.05

Source: Authors' calculation

Supplement S3 Table 3. Impacts of a hypothetical future pandemic- with pre-existing yield gap closure policy (% change relative to baseline)

	2027/28	2028/29	2029/30	2030/31
Area	-2%	-3%	-4%	-4%
Yield	4%	4%	4%	5%
Production	2%	1%	0%	0%
Net import	0%	-100%	-100%	-100%
Total domestic demand	2%	0%	-3%	-4%
Ending stocks	2%	2%	1%	0%
Price/KG	-10%	-14%	-7%	-2%
Food security indicators (absolute change)				
Per capita consumption ratio	0.02	0.00	-0.03	-0.06
Real price ratio	-0.11	-0.15	-0.07	-0.02
Self-sufficiency ratio	0.00	0.01	0.03	0.05
Stocks-to-consumption ratio	0.00	0.00	0.00	0.00

Source: Authors' calculation

Essay 2: Women's empowerment in agriculture and productivity change: The case of Bangladesh rice farms

Abstract:

Using productivity change as a measure of farm economic performance, we analyze the relationship between women's empowerment in agriculture and farm productivity change and its components, which include efficiency change, technological change, and scale efficiency change. A non-parametric Malmquist approach is used to measure farm specific productivity change and its decomposition. We use a bootstrap regression to analyze factors that cause differences in productivity change and its components, testing, in particular, the role women's empowerment plays. The empirical application focuses on a sample of Bangladesh rice farms over the crop cultivation period 2011 and 2014. Results suggest that improvements in women's empowerment in agriculture were associated with higher levels of productivity change, efficiency change, and technical change, while they had no impact on scale efficiency change. We find that empowering women, specifically, improving their ability to make independent choices regarding agricultural production had a statistically significant positive association with productivity change, efficiency change, and technical change. We also find that lowering the gender parity gap is positively related with improving productivity of the sample farms.

Keywords: women's empowerment; productivity change, Malmquist index, rice farms, Bangladesh.

1. Introduction

Agricultural productivity growth is an important component of any development strategy [1,2]. At the farm level, productivity growth can be viewed as an indicator of a farm's ability to persist in an environment where market, regulatory, and environmental pressures may reduce its competitiveness and even lead to farm exit. Given the importance of agricultural productivity growth for development and agriculture's economic sustainability, extensive research has been put into measuring productivity change and understanding the factors that drive it. Prominent among the factors that have been investigated to better understand changes in productivity are farm and farmer characteristics, farm policies, and climatic conditions [3–5]. Women's empowerment and its relationship with farm-level productivity, have not been studied in depth so far, although they might be relevant, especially in developing countries where women make up for 43% of the agricultural labor force [6].

To date, a number of studies have looked at the effect of women's empowerment in agriculture on farm performance measures, but not specifically on farm productivity change. For example, studies by Bozoğlu and Ceyhanⁱ [7] and Seymour [8] examined the effect of women's empowerment on farm technical efficiencyⁱⁱ. Bozoğlu & Ceyhan [7] found that greater participation of women in decision-making and labor activities led to higher levels of farm technical efficiency. On the other hand, Seymour [8] found only a weak positive relationship between women's empowerment (as measured using Women's empowerment in Agriculture Index (WEAI) developed by Alkire et al. [10]) and technical efficiency. Besides technical efficiency studies, another stream of relevant literature has looked at the effect of women's empowerment on crop output quantity. More specifically,

Diirro et al. [11] employed an abbreviated version of WEAI to study the effect of women's overall empowerment and its individual indicators on maize yield of farm households in western Kenya and found a positive effect on yield. Another study [12] in this area used WEAI to examine the link between women's empowerment and crop output quantity of rural households in Niger and found a positive relationship between these variables.

Against this background, the objective of this study is to assess the effect of women's empowerment in agriculture on farm productivity change. To pursue this objective, and in line with other studies [8,11,12] in the literature, we use the WEAI and related measures of women's empowerment, and test their effect on productivity change of Bangladesh rice farms over the crop cultivation period 2011 and 2014. We focus on rice because rice is the largest crop of Bangladesh and crucial for the country's agricultural development. Rice production accounts for 69% of the total cultivated area in Bangladesh [13], contributes about 70% of the agricultural GDP, and provides 75% of the caloric needs of the nation [14]. We use the Malmquist productivity index to measure productivity change. We further decompose this index into three components: efficiency change, technical change, and scale efficiency change. Then, we use non-parametric bootstrap regression to examine the effect of women's empowerment, its individual domains, and other control variables on farm productivity change and its decomposition.

We contribute to the existing literature in two ways. First, we assess the role of different measures of women's empowerment in agriculture on farm productivity change and its components- a dynamic performance indicator by nature. We are aware of no other study of this type, particularly because so many past studies focus on static assessment presumably due to data limitations. Second, we consider the subjective value judgment of

the women's empowerment concept and employ alternative specifications of women's empowerment to reaffirm the association between women's empowerment and productivity change and its components. Our research is crucial because it enhances our knowledge about the consequences of promoting women's empowerment on the farm economic sustainability.

2. Literature Review

In this section, the relevant literature on productivity change in Bangladesh agriculture is reviewed. The theoretical background of the concept of women's empowerment is presented and discussed. Finally, the empirical literature that links women's empowerment in agriculture with agricultural production, nutrition, and food security is examined. In doing so, we focus attention on the most relevant studies rather than the broad literature on women's empowerment or the long and vast literature on agricultural productivity, including crop yields.

2.1. Productivity of Bangladesh agriculture

Growth in agricultural productivity is a fundamental precondition for sustainable economic development, and low agricultural productivity can substantially delay industrialization [15,16]. Agricultural growth is effective in reducing poverty, and it mostly affects the poorest of the poor [17,18]. A few studies have measured productivity change in Bangladesh agriculture, all at the regional level (greater district). Rahman and Salim [19] and Hossain et al. [20] used non-parametric techniques to measure regional productivity change in Bangladesh agriculture and reported a productivity growth of 0.57% and 2.95%, respectively. Coelli et al. [21], on the other hand, employed a parametric approach (stochastic frontier analysis) to measure regional productivity growth in

Bangladesh farming and reported a 0.23% decline in productivity. These studies also identified farm size, crop specialization, investment in agricultural research and development, extension contact, and extension expenditure as significant determinants of regional productivity change in Bangladesh. Although there are studies [8,22–25] that used farm-level survey data to analyze farm household technical efficiency until now no studies have measured the changes in farm-level productivity and its components of Bangladesh agriculture.

2.2. Women's empowerment and broader development issues

Because of the subjective nature of the women's empowerment concept, many definitions have been proposed in the literature. Mehra [26] defined women's empowerment as the expansion of choices and an increase in women's ability to exercise these choices. Kabeer [27] defined empowerment as the expansion in people's ability to make strategic life choices where this ability was previously denied to them. Kabeer's definition offers an extension to the previous definition in that it indicates a priori requirement for empowerment. The definition indicates that to be empowered, it is necessary to be disempowered first, more specifically, to be in a state where a woman had limited or no freedom of choices, expressions, and actions. Mosedale [28] discussed four characteristics of empowerment: first, the issue of empowerment arises because of the prevalence of disempowerment; second, the urge for empowerment comes from within, it cannot be bestowed by a third party such as government agencies or NGOs; third, being empowered means ability to make and implement decisions regarding aspects that matter most to individuals; and fourth, empowerment is an ongoing process in which people are empowered or disempowered relative to others or themselves in the past. Batliwala [29]

further extended the idea and conceptualized empowerment as a socio-political process, where political, social, and economic power shifts between and across both individuals and social groups. All these discussions lead us to two unique defining features of women's empowerment concept: the process, transformation towards greater freedom of choice, action, and equality; and the agency, woman as an agent of change influences important life outcomes by formulating strategic choices and controlling resources and decisions [30]. For the purpose of this study, we view the empowered woman as an assertive member of a farm household, and the degree of empowerment is contingent upon a woman's perceived belief in her ability to exercise control over various dimensions of agriculture (e.g., production, resources).

The importance of women's empowerment as a tool for development can be well approximated by the issue's inclusion in the United Nation's Sustainable Development Goals (SDGs), which calls for creating a conducive environment for women where they have higher decision-making power and control over political, economic and public life. Several studies [31,32] echoed this view as they reported that when women have control over cash income, expenditure patterns lean more toward human development inputs such as food and education. Duflo [33] stated that women's empowerment and economic development are bi-directional in the sense that economic development drives down gender inequality and gender bias hinder development.

One of the most well-known measures of farm households' women's empowerment is the index (WEAI) developed by Alkire et al. [10]. WEAI focuses on the agency aspect of the women's empowerment. It measures the ability of women in farm households to make decisions that relate directly to agriculture. WEAI has been used extensively in

various studies that documented the impact of women's empowerment in agriculture on agricultural production, nutrition, and food security. For example, Sraboni et al. [34] employed WEAI to examine the relationship between women's empowerment in agriculture and per capita calorie availability, dietary diversity, and adult body mass index (BMI) in Bangladesh. Malapit et al. [35] used WEAI to investigate the relationship between women's empowerment and dietary diversity and anthropometric outcomes of mothers and children in rural Nepal. Cunningham et al. [36] examined the link between women's empowerment in agriculture and child nutritional status in rural Nepal. Malapit and Quisumbing [37] used WEAI to investigate the association between women's empowerment and the nutritional status of women and children in northern Ghana. As discussed in the previous section, some studies [8,11,12] used WEAI to study the linkage between women's empowerment and technical efficiency or crop output quantity. In conclusion, the literature reviewed indicates an apparent gap in our understanding of the link between women's empowerment and farm-level productivity change. This study makes an important contribution to the literature by being the first to look at the relationship between women's empowerment and farm-level productivity and its components.

3. Methodology

3.1. Conceptual framework

Households can be viewed as a single production unit with a collective structure and members with dissimilar preferences [38,39]. This assumption of cooperative arrangements among members is more consistent as opposed to the unitary model that assumes a single set of household preference and representative altruistic household head [40,41]. Therefore, the relationship between productivity change and women's

empowerment can be conceptualized in terms of a collective bargaining model, where a household shares a stock of resources, and the allocation and use of which is influenced by bargaining power or gendered division of preferences and weights that are being placed on different intrahousehold decisions. Seen in this light, the women's empowerment in the household corresponds to their say in household decision making and can consequently affect the outcomes, including the decisions that determine the inputs used to generate output. In the context of Bangladeshi rice-producing households, women's empowerment could affect household productivity change through the effects on the number of size of plots used, the labor applied, or other inputs purchased, but this is speculation in the absence of focused study. Several studies [41–43] indicate that women's bargaining power positively affects household outcomes such as household food security, girls' school enrollment, and children's health status. Higher food security and improved health of the household members could in turn result in a more productive workforce when household members are working at the farm, leading to higher productivity. In another example, if more empowered women are involved in economic or social groups in rural areas, they may bring ideas about new farm practices and technologies that have the potential to increase productivity through, for example, more efficient use of farm resources. In theory, at least, a shift in bargaining power might reallocate resources and effort away from agricultural output and towards other household goals that are given newfound priority, although we are not aware of any empirical finding that would support such a claim. In what follows, the empirical methods used to estimate farm household productivity change and assess the relationship between productivity change and women's empowerment are presented.

3.2. Empirical framework

3.2.1. Measuring productivity change

Following the literature [19,24,44,45], we use the input-oriented Malmquist index to measure farm productivity change. The input orientation is appropriate since farmers have more control over inputs than outputs, which may be affected by external factors such as weather conditions. The input-oriented Malmquist index is based on the input distance function introduced by Shephard [46], which seeks the maximal proportional reduction of an observed input bundle for a given output bundle.

The production technology of a farm household using inputs x^t in period t to produce output y^t is represented by the following technology set:

$$T^t = \{(x^t, y^t): x^t \text{ can produce } y^t\} \quad (1)$$

Another equivalent set-wise characterization of the production technology can be given via the input requirement set of farm households as:

$$L(y^t) = \{(x^t: (x^t, y^t) \text{ is feasible})\} \quad (2)$$

The input requirement set in (2) represents all possible combinations of inputs that can produce a particular level of output.

A convenient generalization of the production technology, which is a key instrument of efficiency and productivity analysis, is the Shephard's input distance function. The Shephard's input distance function for period t can be defined as:

$$D_i^t(x^t, y^t) = \max \{\lambda: (x^t/\lambda) \in L(y^t)\}, \quad (3)$$

where λ is the value of the input distance function. We can obtain $D_i^{t+1}(x^{t+1}, y^{t+1})$ by substituting t for $t + 1$. $D_i^t(x^t, y^t)$ and $D_i^{t+1}(x^{t+1}, y^{t+1})$ are called single-period distance functions. One can also obtain the following mixed-period distance functions:

$D_i^t(x^{t+1}, y^{t+1})$ and $D_i^{t+1}(x^t, y^t)$. The first of these distance functions concerns the firms at time $t + 1$ in relation to the technology at time t . The second distance function concerns the firms at time t relative to the technology at time $t + 1$. Färe et al. [47] used single and mixed-period distance functions to compute the Malmquist productivity index. Assuming a constant return to scale, they defined the input-oriented Malmquist index as:

$$M(x^t, y^t, x^{t+1}, y^{t+1}) = \left[\frac{D_c^t(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)} \times \frac{D_c^{t+1}(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^t, y^t)} \right]^{1/2}, \quad (4)$$

where M is the input-oriented productivity index, which quantifies the changes in productivity originating from the efficiency change measured under period t technology and from the efficiency change measured under period $t+1$ technology. Following Ray and Desli [48], assuming a variable returns to scale (subscript v stands for VRS and c stands for CRS), we decompose the Malmquist index into efficiency change (EC), technical change (TC), and scale efficiency (SE) change:

$$\begin{aligned} M(x^t, y^t, x^{t+1}, y^{t+1}) &= \underbrace{\frac{D_v^{t+1}(x^{t+1}, y^{t+1})}{D_v^t(x^t, y^t)}}_{EC} \times \underbrace{\left[\frac{D_v^t(x^{t+1}, y^{t+1})}{D_v^{t+1}(x^{t+1}, y^{t+1})} \times \frac{D_v^t(x^t, y^t)}{D_v^{t+1}(x^t, y^t)} \right]^{1/2}}_{TC} \quad (5) \\ &\times \underbrace{\left[\frac{D_c^{t+1}(x^{t+1}, y^{t+1})/D_v^{t+1}(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^t, y^t)/D_v^{t+1}(x^t, y^t)} \times \frac{D_c^t(x^{t+1}, y^{t+1})/D_v^t(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)/D_v^t(x^t, y^t)} \right]^{1/2}}_{SE} \\ &= EC_i(x^t, y^t, x^{t+1}, y^{t+1}) \times TC_i(x^t, y^t, x^{t+1}, y^{t+1}) \\ &\times SE_i(x^t, y^t, x^{t+1}, y^{t+1}) \end{aligned}$$

EC is the relative efficiency change index which measures catch-up or the degree to which a Decision-Making Unit (DMU) improves or worsens its efficiency relative to the DMUs in the best practice frontier. It reflects a DMU's ability to use the available knowledge and technology to reach the best practice frontier. TC, often termed interchangeably with

technological change, indicates the frontier shift reflecting changes in the efficient frontiers between two time periods. Therefore, TC represents a DMU's level of innovativeness. SE change measures the closeness of a DMU to its most efficient (optimal) scale size. Technically, it may be interpreted as the relative contraction of inputs by producing at optimal scale on the best practice frontier for the observed input mix of a DMU whose technical inefficiency has been eliminated. Or geometrically, it may be defined as the ray average productivity after the observed mixture of inputs is projected to the best practice frontier relative to what is achievable at the optimal scale [49]. Values of $M(\cdot)$ or any of its components greater (less) than one implies productivity regress (improvement). Following Odeck [50], for the ease of interpretation, we take the inverse of productivity scores and its components, such that an index greater (less) than one implies productivity improvement (regress).

The distance functions defined above are empirically estimated using Data Envelopment Analysis. More specifically the distance function $D_i^t(x^t, y^t)$ is calculated by solving the following linear problem:

$$[D_i^t(x^t, y^t)]^{-1} = \min_{\lambda, \theta} \lambda$$

subject to

$$y_{m0}^t \leq \sum_{i=1}^k \theta_i y_{mi}^t, \quad m = 1, 2, \dots, M$$

$$\lambda x_{n0}^t \geq \sum_{i=1}^k \theta_i x_{ni}^t, \quad n = 1, 2, \dots, N \quad (6)$$

$$\theta_i \geq 0, \quad i = 1, 2, \dots, S$$

$$\sum_{i=1}^K \theta_i = 1,$$

where λ is a scalar that represents the efficiency score for the i^{th} household, and θ are household weights that define the best practice frontier. In a similar way, $D_i^{t+1}(x^{t+1}, y^{t+1})$ is computed by substituting t for $t + 1$.

The mixed period distance function $D_i^t(x^{t+1}, y^{t+1})$ which calculates the efficiency of firms observed in period $t + 1$ relative to the period t technology is given by:

$$[D_i^t(x^{t+1}, y^{t+1})]^{-1} = \min_{\lambda, \theta} \lambda$$

subject to

$$y_{m0}^{t+1} \leq \sum_{i=1}^k \theta_i y_{mi}^t, \quad m = 1, 2, \dots, M \quad (7)$$

$$\lambda x_{n0}^{t+1} \geq \sum_{i=1}^k \theta_i x_{ni}^t, \quad n = 1, 2, \dots, N$$

$$\theta_i \geq 0, \quad s = 1, 2, \dots, S$$

$$\sum_{i=1}^K \theta_i = 1$$

The mixed period distance function $D_i^{t+1}(x^t, y^t)$ is obtained analogously.

3.2.2. Modeling the relationship between productivity change and women's empowerment

After computing the household-specific TFP growth and its components, we use the following model to examine the association between productivity change and women's empowerment (and a set of control variables):

$$y_i = \alpha + z_i \beta + u_i, \quad (8)$$

where, y_i is the input-oriented Malmquist productivity change (or its components) for household i , α is an intercept and z_i is the base period vector of exogenous independent

variables that represents women's empowerment measures, and other control variables for the household i , β is the vector of coefficients to be estimated and u_i is an error term.

We follow the non-parametric bootstrap method of Kapelko et al. [51], as summarized here. We estimate equation (8) using an OLS bootstrap regression. A bootstrap regression is required to address the well-known problem of serial correlation among non-parametrically derived productivity and efficiency scores. This approach is a standard non-parametric bootstrap that involves randomly drawing, with replacement, a large number of subsamples from the original sample, and allows the computation of bootstrap regression coefficients and confidence intervals. Our computations involved 5,000 bootstrap replicates. Equation (8) was estimated separately for productivity change and each of its components.

3.2.3. Endogeneity issues

Two endogeneity issues complicate the estimation of the relationship between women's empowerment and productivity change. The first one is simultaneity or reverse causation. As Wouterse [12] argues, higher empowerment could increase productivity, but at the same time, higher productivity may result in higher income levels, and as a result, enhance household members' empowerment. However, we believe simultaneity is not an issue in our research setting because we use the base period WEAI as an explanatory variable in eq. (8). Therefore, the initial status of a woman in a household is exogenous with respect to how much productivity changes after the initial condition. The second endogeneity issue is omitted variable bias. Given that the WEAI indicators considered here are perceived measures of a woman's ability to exercise control over various dimensions of agriculture, there might be unobserved factors determining both the empowerment in

the base year and productivity change. To empirically address the potential endogeneity of WEAI variables, a Wu-Hausman test for exogeneity of these variables was conducted [52]. Following Diiro et al. [11], domestic violence, dependency ratio, and age and education differences between the principal male respondent and principal female respondent in the household were used to instrument for the WEAI variables. As it will be discussed in more detail in the results section, the Wu-Hausman test results support the exogeneity of WEAI variables. However, recognizing that the used instruments are unlikely to respect the exclusion restriction and better instruments could not be found, it is appropriate to exercise caution when it comes to attributing causality. As a consequence, in this article we speak of association (or correlation) rather than causation.

4. Data

The data used in this study is taken from Bangladesh Integrated Household Survey (BIHS). BIHS is a nationally representative survey in Bangladesh with multiple roundsⁱⁱⁱ, of which the 2011/12 and 2015/16 rounds are available at this time (see Ahmed [53] for details). By using a two-stage stratified sampling technique and a sampling frame developed from the community series of the 2001 population census of Bangladesh, BIHS collects detailed data on (1) plot-level agricultural production and practices, (2) dietary intake of individual household members, (3) anthropometric measurements (height and weight) of all household members, and (4) WEAI. BIHS includes 6,500 households in 325 Primary Sampling Units (PSUs) or villages. This study focuses on farms engaged primarily in rice production, and for this purpose, we have selected households^{iv} whose value of total rice production is at least 80% of their total annual farm revenue and participated in both survey rounds. Some variables in the dataset are reported at the plot-level. Other variables,

including rice output, capital assets, and women's empowerment, are reported for each household, which precludes a plot-level analysis. And, fundamentally, our research question is about the association of women's empowerment and household productivity change, so we do not focus on plot productivity nor, in any case, can we know the variation in women's empowerment as it relates to individual plots from these survey data. As a result, plot-level information was aggregated to the household-level. Although the survey asks about plots, we cannot track plots between survey rounds. The final dataset consists of a balanced panel of 1,197 households with a total of 2,394 observations^v.

The data needed to compute the input distance functions in equation (6) and (7) (that are in turn used to calculate the Malmquist productivity index and its components) include one output and four inputs (Table 1). The output variable includes rice that is produced and either sold or used in the household itself, with the total value of these two uses divided by the consumer price index (CPI)-food [54] to find the total volume as an implicit quantity index. The input variables consist of land, labor, capital and equipment, and miscellaneous input expenses. Land is measured as the total area of cultivable/arable plots (owned or otherwise) used by each household. Labor is the total annual hours of hired and family labor. Capital and equipment are defined as the value of farming tools, machinery, and other tools used in the production process, and is readily available at the household level. Finally, miscellaneous expenses include the value of variable expenses such as seed, irrigation, agrochemicals, and other expenses. All monetary inputs (i.e., capital and miscellaneous inputs) were transformed to implicit quantity indices by calculating the ratio of value to the Bangladesh CPI-Food, with base period being that of 2005/06.

Table 1. Summary statistics of the deflated outputs and inputs of the sample households

2011					
Variables	Unit	Mean	Std. Dev	Min	Max
Output	Taka*	26,485	27,803	544	26,7488
Land	Decimal	131	137	4	1,620
Labor	Hours	484	463	30	6,304
Capital and equipment	Taka*	5,287	26,324	5	491,450
Miscellaneous expenses	Taka*	4,798	4,527	207	39,271
2014					
Variables	Unit	Mean	Std. Dev	Min	Max
Output	Taka*	24,436	27,117	227	276,017
Land	Decimal	135	145	3	1,665
Labor	Hours	599	581	15	7,435
Capital and equipment	Taka*	5,988	29,720	9	867,542
Miscellaneous expenses	Taka*	7,526	7,571	56	92,308

Source: Authors' calculations

Note: The asterisk superscript (*) denotes an implicit quantity index measured in constant 2005/06 prices

Concerning the data used in the second stage of our analysis, the z_i vector in equation (8) includes a household-specific women's empowerment measure (e.g., women's empowerment score, gender parity gap, individual empowerment domains, or empowerment indicators), and a set of control variables. The following subsections describe the procedure followed to calculate the different women's empowerment measures for each household and the variables included in the control variables.

4.1. Women's empowerment in agriculture measures

The women's empowerment in agriculture measures used in this study are based on the women's empowerment in agriculture index (WEAI) developed by Alkire et al. [10]. WEAI is a survey-based index that measures empowerment, agency, and inclusion of women in agriculture. WEAI is an aggregate measure with two sub-indices namely five domains of empowerment (5DE) and gender parity index (GPI).

The first index, 5DE (empowerment score thereafter), is an estimation of respondents' empowerment score based on their role in five domains of agricultural decision making (Table 2). An individual-level questionnaire (see Alkire et al. [55] for details) is used as the primary instrument to measure empowerment using weighted domain-specific indicators. For example, group membership indicator, of the leadership domain, is given a weight of 0.10, and this weight relates to questions about membership in economic or social groups. If the respondent reports membership in at least one economic or social group, she scores 0.10 under this indicator. The empowerment score is calculated similarly for the other nine indicators, and a composite empowerment score is then generated by taking the weighted sum of all ten indicators. By construction, the empowerment score ranges from 0 to 1. Alkire et al. [10] judge that a score of 0.80 or more in the composite scale is required to deem a woman as empowered. The second index, GPI, is the relative measure of inequality and estimated using the difference between 5DE scores of each household's primary adult male and female. The gender parity gap (empowerment gap thereafter) takes a value of zero if the primary female decision maker's 5DE score exceeds or is equal to that of primary male decision maker. This measure reflects the relative empowerment of the women compared to the men in decision making. Gender parity is achieved when the empowerment score of the primary female meets or exceeds the empowerment score of the primary male living in the same household.

Table 2. WEAI domains

Domain	Indicator	Description	Weight
Production	Input in productive decisions	Ability to make decisions (sole or joint) about food and cash-crop farming, livestock, and fisheries	1/10
	Autonomy in production	Ability to act according to own value and judgment regarding inputs to buy, types of crops to grow, when to take or who would take crops to market, and livestock production	1/10
Resources	Ownership of assets	Sole or joint ownership of household assets such as land, livestock, consumer durables, agricultural equipment	1/15
	Purchase, sale, or transfer of assets	Decision-making authority over the purchase, sale, or transfer of household assets	1/15
	Access to and decisions about credit	Decision-making authority over obtaining credit and using credit proceeds	1/15
Income	Control over the use of income	Sole or joint control over income and expenditures	1/5
Leadership	Group membership	Active membership in at least one economic or social group	1/10
	Speaking in public	Ability to speak up in public for reasons like to ensure proper payment of wages for public work programs, to protest the misbehavior of authorities or to help decide on infrastructure	1/10
Time	Workload	The productive and domestic workload in a 24-hour framework	1/10
	Leisure	Subjective satisfaction with available leisure time	1/10

Source: Alkire et al. [10]

WEAI operates under predetermined assumptions to capture the power dynamics of the farm household's women. Such dynamics may alter under much wider or restrictive assumptions. For example, under the leisure indicator, a woman is deemed as empowered if she is at least neither satisfied nor dissatisfied with the time available for leisure. One might argue that such a definition of empowerment (related to leisure time) is not the true

depiction of empirical reality because the assumption does not distinguish between satisfaction and dissatisfaction with available leisure time, nor does it reward a reported higher level of satisfaction with a larger scale. Such variation in the subjective assessment of empowerment will result in different estimates of empowerment score. We capitalized on this idea and developed two alternative empowerment scoring approaches by modifying the WEAI assumptions to refocus this variable on our specific requirements (see online supplement S1 for more details). A summary of the alternative measures used to represent women's empowerment in agriculture is given in Table 3.

Table 3. Summary statistics of WEAI and alternative empowerment measures

	<i>WEAI- Based on Alkire et al. [10]</i>				<i>Alternative approach 1</i>				<i>Alternative approach 2</i>			
	Mean	Std. dev	Min	Max	Mean	Std. dev	Min	Max	Mean	Std. dev	Min	Max
Empowerment score	0.60	0.19	0.10	1.00	0.30	0.12	0.03	0.72	0.53	0.16	0.09	0.97
Empowerment gap	0.15	0.17	0.00	0.80	0.10	0.11	0.00	0.62	0.14	0.15	0.00	0.82
Domains												
Production	0.10	0.07	0.00	0.20	0.07	0.06	0.00	0.20	0.11	0.06	0.00	0.20
Resources	0.13	0.06	0.00	0.20	0.03	0.02	0.00	0.11	0.11	0.06	0.00	0.20
Income	0.15	0.08	0.00	0.20	0.05	0.04	0.00	0.20	0.12	0.06	0.00	0.20
Leadership	0.06	0.07	0.00	0.20	0.01	0.02	0.00	0.11	0.04	0.05	0.00	0.20
Time	0.15	0.06	0.00	0.20	0.12	0.06	0.00	0.20	0.15	0.06	0.00	0.20

Source: Authors' calculations

Under the first alternative approach, we developed empowerment scores based on the gradations of women's power rather than binary assessments. The second alternative approach focuses on a woman's engagement and relative input in the activity or decision-making process in which a household participates. For each of these approaches, scores of empowerment, gender parity gap, individual empowerment domains, and indicators were calculated. The objective behind the formulation of alternatives scores is to improve the tests for an association between women's empowerment and the productivity change of

rice farms in Bangladesh. We can affirm our findings as robust and valid only when the underlying effect estimates remain consistent under different subjective ratings of the empowerment concept. We posit that construction of alternative indices using a single standardized framework that solely focus on agency aspect of women's empowerment runs the risk of ignoring indirect indicators such as resources and achievements. However, the design and implementation of indicators of women's empowerment is beyond the scope of this study. Hence, we followed the framework suggested by Alkire et al. [10] and recalculate the index by testing different assumptions regarding the adequacy requirements. Despite the shortcomings, such assumptions allow us to capture different contexts that different households may encounter and measure multidimensional characteristics of women's empowerment at various levels of aggregation.

4.2 Control variables

The selection of control variables included in equation (8) was guided by data availability and previous studies on the determinants of farm productivity [5,18,20]. These variables include sex, age, education, dependency ration, household size, extension visit, rainfed, tenancy, income share from non-agricultural enterprise, rainfall, temperature, and locational dummies.^{vi} Table 4 presents the definition and summary statistics of these variables.

Table 4. Control variables and descriptive statistics

Variables	Description	Mean	Std. dev	Min	Max
Sex	Categorical: one if female else zero	0.02	0.14	0.00	1.00
Age	Primary respondent's age	46.37	12.46	18.00	85.00
Education	Years of education completed by the primary respondent	3.23	3.92	0.00	16.00
Dependency ratio	The ratio of children (0–14 years old) and nonworking-age household members (65 years or older) to working-age household members (15–64 years old)	0.76	0.60	0.00	5.00
Household size	Total members in the household	4.69	1.68	2.00	14.00
Extension visit	Number of visits by an agricultural extension agent to the household or by a household member to an extension service office during the last 12 months	0.35	1.32	0.00	15.00
Rainfed	Categorical: one if rain is the primary source of water for cultivation else zero ^{vii}	0.37	0.48	0.00	1.00
Tenancy	Categorical: one if the land is taken-in through a cash lease or crop-sharing arrangement else zero ^{viii}	0.33	0.47	0.00	1.00
Non-agri. income share	Share of household income from non-agricultural sources	0.22	0.31	0.00	1.00
Rainfall	Difference between the average annual rainfall of crop cultivation years 2014 and 2011 (in millimeters)	-224.99	299.31	-487.00	349.00
Temperature	Difference between the average of minimum and maximum temperature of crop cultivation year 2014 and 2011 (in Celsius)	0.43	0.20	0.20	0.80
Northwest	Categorical: one if northwest divisions else zero	0.20	0.40	0.00	1.00
Southwest	Categorical: one if southwest divisions else zero	0.23	0.42	0.00	1.00
Northeast	Categorical: one if northeast divisions else zero	0.15	0.36	0.00	1.00

Source: Authors' calculations

Note: Rainfall and temperature data are collected from the yearbook of agricultural statistics -2014 (56).

5. Results

The Malmquist productivity index and its decomposition are summarized in Table 5. Before discussing these results, it should be noted that the mixed-period linear programs used to calculate the Malmquist productivity index and its components may give infeasible solutions. A possible remedy to this problem is to exclude the observations with infeasible solutions from the calculation of average productivity change and its components [51]. Briec and Kerstens [57] argue that studies computing productivity indices using non-parametric estimators should report the infeasibilities resulting from the estimation of the mixed-period distance functions. In our case, out of 1,197 observations, only one observation has an infeasible solution for one of the mixed period distance functions. This observation was excluded in the second stage analysis.

Over the estimation period, on average, productivity fell by 24%, technical efficiency grew by 15%, technological change fell by 35%, and scale efficiency grew by 3%. Putting these results in perspective with that of other studies from Bangladesh agriculture, we see that our estimate of productivity decrease is more severe than that of Coelli et al. [21], who reported a 0.23% decline in productivity, and contrasts with increases reported by Hossain et al. [20], at 2.95%, and Rahman and Salim [19], at 0.57%. However, the findings of this study are not directly comparable to those studies due to the difference in the sample. This study uses plot-level data (aggregated to household level), whereas the aforementioned studies used regional level data. Other notable differences include crop type analyzed (e.g., Coelli et al. [21] aggregated food and cash crops) and estimation method employed (e.g., Rahman and Salim [19] used the Färe-Primont index to measure productivity).

Table 5. Average Malmquist productivity index and its components of the sample households for the period 2011-2014

	Productivity change	Efficiency change	Technical change	Scale efficiency change
Mean	0.76	1.15	0.65	1.03
Std. Dev.	0.40	0.57	0.10	0.21
Min	0.12	0.13	0.29	0.62
Max	3.78	4.35	2.10	6.93
95% Conf. Interval				
Lower bound	0.73	1.12	0.64	1.02
Upper bound	0.78	1.18	0.65	1.04

Source: Authors' calculations

Decomposition results indicate that productivity in Bangladesh rice farming fell due entirely to the decline in technical change. Shifts in technical change can be considered to be evidence of innovation [58]. In the simplest analysis, lack of innovation in the current production technology or the adoption of a production technology that is not innovative enough to reflect the needs of the farmers might cause a decline in technical change, which in turn contributes to overall productivity decline. While we are unable to identify the precise reason for such a big drop in technical change, it seems that the increase in miscellaneous expenses, specifically, fourfold increase in rental cost which includes cost of tools, fuels, machinery, and draft Animal, has negatively affected the direction of technical frontier. Another potential cause of technological regress could be declining soil quality, with evidence suggesting that cropping practices reduce soil organic matter with negative impacts on Bangladesh rice production [59–61].

Table 6. Results of the OLS bootstrap regression of the determinants of farm productivity change and its components

Variables	Model 1: Empowerment score based on Alkire et al. [10]				Model 2: Alternative empowerment score based on approach 1				Model 2: Alternative empowerment score based on approach 2			
	Productivity change	Efficiency change	Technical change	Scale efficiency change	Productivity change	Efficiency change	Technical change	Scale efficiency change	Productivity change	Efficiency change	Technical change	Scale efficiency change
Empowerment score	0.169*** (0.060)	0.166* (0.088)	0.038** (0.017)	-0.017 (0.024)	0.438*** (0.111)	0.460*** (0.157)	0.075*** (0.024)	0.041 (0.063)	0.251*** (0.079)	0.292*** (0.112)	0.038** (0.019)	-0.018 (0.027)
Sex	-0.107 (0.070)	-0.096 (0.108)	-0.037* (0.020)	0.019 (0.025)	-0.128* (0.071)	-0.119 (0.112)	-0.039** (0.019)	0.015 (0.026)	-0.124* (0.069)	-0.119 (0.108)	-0.038* (0.020)	0.020 (0.026)
Age	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	0.000 (0.000)	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	0.000 (0.000)	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	0.000 (0.000)
Education	0.001 (0.003)	-0.004 (0.005)	0.001* (0.001)	0.004* (0.002)	0.000 (0.003)	-0.005 (0.005)	0.001* (0.001)	0.004* (0.002)	0.001 (0.003)	-0.005 (0.005)	0.001* (0.001)	0.004* (0.002)
Dependency ratio	-0.047** (0.019)	-0.055** (0.028)	-0.007 (0.005)	-0.006 (0.011)	-0.045** (0.019)	-0.052* (0.028)	-0.007 (0.005)	-0.006 (0.011)	-0.046** (0.019)	-0.054* (0.028)	-0.007 (0.005)	-0.006 (0.011)
Household size	-0.014 (0.009)	-0.019* (0.011)	0.001 (0.002)	-0.005** (0.003)	-0.013 (0.009)	-0.019* (0.012)	0.001 (0.002)	-0.005** (0.002)	-0.013 (0.009)	-0.019* (0.011)	0.001 (0.003)	-0.005** (0.002)
Extension visit	0.013 (0.021)	-0.004 (0.013)	0.007 (0.009)	0.004 (0.004)	0.013 (0.021)	-0.004 (0.013)	0.007 (0.010)	0.004 (0.004)	0.013 (0.021)	-0.004 (0.013)	0.007 (0.010)	0.004 (0.004)
Income share from non ag. enterprise	0.050 (0.037)	0.111** (0.055)	-0.011 (0.009)	-0.010 (0.017)	0.048 (0.036)	0.108* (0.055)	-0.011 (0.009)	-0.011 (0.018)	0.051 (0.037)	0.111** (0.055)	-0.010 (0.009)	-0.010 (0.018)
Rainfed	0.020 (0.025)	0.026 (0.035)	0.001 (0.006)	-0.004 (0.012)	0.027 (0.024)	0.033 (0.035)	0.002 (0.006)	-0.004 (0.011)	0.022 (0.025)	0.028 (0.035)	0.001 (0.006)	-0.004 (0.012)
Tenancy	0.060** (0.026)	0.059 (0.037)	0.012** (0.005)	0.011 (0.017)	0.058** (0.025)	0.057 (0.037)	0.012** (0.005)	0.011 (0.017)	0.059** (0.026)	0.057 (0.037)	0.012** (0.005)	0.011 (0.017)
Rainfall	-0.000* (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000* (0.000)	-0.000 (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000* (0.000)	-0.000* (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000* (0.000)
Temperature	0.261*** (0.091)	0.237* (0.135)	0.073*** (0.024)	-0.010 (0.027)	0.258*** (0.089)	0.236* (0.133)	0.071*** (0.023)	-0.003 (0.025)	0.262*** (0.090)	0.244* (0.134)	0.070*** (0.024)	-0.009 (0.026)
Northwest	0.041 (0.034)	-0.011 (0.047)	0.026*** (0.008)	0.034 (0.024)	0.054 (0.033)	0.004 (0.048)	0.028*** (0.008)	0.037 (0.026)	0.045 (0.034)	-0.004 (0.048)	0.026*** (0.008)	0.034 (0.024)
Southwest	-0.043 (0.038)	0.003 (0.054)	-0.028*** (0.010)	-0.000 (0.010)	-0.025 (0.037)	0.023 (0.054)	-0.025** (0.011)	0.003 (0.011)	-0.039 (0.038)	0.010 (0.053)	-0.028*** (0.011)	-0.000 (0.010)
Northeast	0.171*** (0.059)	0.157* (0.087)	0.054*** (0.015)	-0.025 (0.022)	0.175*** (0.058)	0.162* (0.087)	0.054*** (0.015)	-0.022 (0.022)	0.177*** (0.057)	0.165* (0.088)	0.054*** (0.015)	-0.025 (0.022)
Constant	0.510*** (0.092)	0.977*** (0.136)	0.556*** (0.024)	1.063*** (0.037)	0.480*** (0.089)	0.937*** (0.130)	0.557*** (0.022)	1.037*** (0.032)	0.476*** (0.095)	0.915*** (0.137)	0.559*** (0.024)	1.062*** (0.036)

Source: Authors' calculations

Note: Standard errors in parentheses; *, **, and *** indicate significance based on 90%, 95% and 99% bootstrap confidence level, respectively

In the second stage, we estimated several specifications of equation (8) to analyze the relationship between productivity indices and the different women's empowerment measures. Before presenting the results of the determinants of productivity change and its components, we first discuss the results of the Wu-Hausman test of the exogeneity of the WEAI variables. The results of the exogeneity tests⁹ indicate that the null hypothesis of exogeneity of the WEAI variables cannot be rejected in all specifications. However as noted earlier and given the absence of better instruments in our database, the WEAI results will be interpreted as implying correlation rather than causation.

Columns 2-5 of Table 6 present the bootstrap regression estimates of the impact of women's empowerment (empowerment score based on Alkire et al. [10]) and other control variables on productivity change and its decompositions. The results show that except for scale efficiency change, the relationship between women's empowerment in agriculture and productivity change, efficiency change, and technical change is positive and statistically significant at 1%, 10%, and 5% level, respectively. Columns 6-13 of Table 6 further reinforce this association; alternative specifications of women's empowerment scores are also statistically significant at 1% and 5% level, and positively related to the Bangladesh rice farming productivity change, efficiency change, and technical change. The positive relationship between empowerment scores and productivity change indicates that a 1% increase in women's empowerment score increases farm productivity by 0.17% to 0.44%. We can also imply that farm productivity can be increased by 3% to 22% if the primary female decision maker of the household achieves adequacy in at least 80% of the weighted indicators (threshold level empowerment).¹⁰ The results also indicate that empowering farm household women can move a farm household toward the best practice

frontier. A 1% increase in empowerment score implies 0.17% to 0.46% increase in efficiency change or, alternatively, if the primary female decision maker achieves an adequacy score of 0.80, the efficiency change index improves by 3% to 23%.¹¹ This indicates that women's greater agency over WEAI domains has the potential to help farm households to increase the level of utilization of the potential (maximal capacity) of the production technology. Similarly, findings also indicate that empowering woman shifts farm's production frontier upward by 0.04% to 0.08%. This implies that lifting primary female decision maker's empowerment score up to the threshold level of empowerment could improve the technical change index by 1% to 4%.¹² This indicates that there is scope for the sample households to increase technological levels and innovative capabilities through ensuring farm household women's agency over domains of WEAI.

Table 6 (Columns 2-5) also shows that, among the household-level characteristics, sex, education, dependency ratio, household size, and income share from the non-agricultural enterprise have statistically significant effects on the productivity indices (for a detailed explanation of control variables see online supplement S2).

Table 7. Results of the OLS bootstrap regression of the determinants of farm productivity change and its components (Empowerment gap)

Dependent variable	Model 1: Empowerment gap based on Alkire et al. [10]	Model 2: Alternative empowerment gap based on approach 1	Model 3: Alternative empowerment gap based on approach 2
Productivity change	-0.128** (0.063)	-0.182* (0.109)	-0.117 (0.077)
Efficiency change	-0.105 (0.094)	-0.224 (0.157)	-0.123 (0.112)
Technical change	-0.027 (0.018)	-0.016 (0.028)	-0.013 (0.021)
Scale efficiency change	0.002 (0.030)	-0.007 (0.054)	-0.001 (0.033)

Source: Authors' calculations

Note: Standard errors in parentheses; *, **, and *** indicate significance based on 90%, 95% and 99% bootstrap confidence level, respectively

Table 7 reports the effect of empowerment gap on productivity indices, estimated using the approach detailed in section 3.2 (see online supplement S3 for the full set of results). The results (column 2) indicate that the empowerment gap is negatively associated with productivity change and this effect is statistically significant at the 5% level. Empowerment gap calculated based on alternative approach 1 (column 3) also has a significant negative impact on productivity change, further reiterating the findings of column 2. This implies that a 1% reduction in the gap between primary male and female decision maker's 5DE score is associated with an increase in farm household's overall productivity by 0.13% to 0.18%. The results of the control variables (see online supplement S3) are similar to those reported in table 6 in terms of signs and significance, and the magnitudes of the coefficients are also quite similar.

Table 8. Results of the OLS bootstrap regression of the determinants of farm productivity change and its components (WEAI domains)

	Productivity change	Efficiency change	Technical change	Scale efficiency change
Model 1: Empowerment domain score based on Alkire et al. [10]				
Empowerment score: Production	0.483*** (0.168)	0.458* (0.241)	0.115*** (0.041)	0.038 (0.090)
Empowerment score: Resource	0.064 (0.179)	0.091 (0.265)	0.041 (0.042)	-0.067 (0.058)
Empowerment score: Income	-0.010 (0.140)	-0.075 (0.211)	-0.021 (0.034)	0.026 (0.044)
Empowerment score: Leadership	0.096 (0.205)	0.224 (0.275)	0.033 (0.053)	-0.196* (0.103)
Empowerment score: Time	0.196 (0.172)	0.174 (0.258)	0.016 (0.042)	0.083 (0.078)
Model 2: Alternative empowerment domain score based on approach 1				
Empowerment score: Production	0.798*** (0.233)	0.885*** (0.329)	0.121** (0.054)	0.147 (0.179)
Empowerment score: Resource	0.843 (0.593)	0.919 (0.837)	-0.080 (0.142)	0.677 (0.542)
Empowerment score: Income	-0.091 (0.413)	-0.255 (0.583)	0.124 (0.083)	-0.311 (0.247)
Empowerment score: Leadership	0.314 (0.574)	0.576 (0.806)	0.047 (0.118)	-0.472 (0.348)
Empowerment score: Time	0.253 (0.205)	0.293 (0.298)	0.008 (0.049)	0.112 (0.119)
Model 3: Alternative empowerment domain score based on approach 2				
Empowerment score: Production	0.762*** (0.217)	0.838*** (0.314)	0.120** (0.049)	0.132 (0.174)
Empowerment score: Resource	0.412** (0.199)	0.500* (0.303)	0.047 (0.049)	0.014 (0.084)
Empowerment score: Income	-0.101 (0.239)	-0.181 (0.336)	0.014 (0.054)	-0.132 (0.124)
Empowerment score: Leadership	-0.087 (0.249)	0.092 (0.330)	-0.024 (0.064)	-0.217 (0.133)
Empowerment score: Time	0.187 (0.171)	0.167 (0.255)	0.017 (0.042)	0.077 (0.080)

Source: Authors' calculations

Note: Standard errors in parentheses; *, **, and *** indicate significance based on 90%, 95% and 99% bootstrap confidence level, respectively

Table 8 reports the effect of WEAI domains on productivity indices (see supplement S3 for the full set of results). Results indicate that farm household women's agency over production domain is positively associated with productivity change, efficiency change, and technical change. Findings suggest that a 1% increase in women's empowerment in production domain leads to a 0.48% to 0.80% increase in productivity of the sample farms. Results also indicate that a 1% increase in primary female decision makers empowerment in production domain leads to efficiency gains of between 0.46% and 0.89%. Empowerment in the production domain is also positively associated with technical change as the results reveal that it can lead to technological gains of about 0.12%. In the main model (Model 1), the rest of the WEAI domains were not found to have a statistically significant effect on productivity change and its components, except for the leadership domain which is weakly significant only in one out of the three models tested.

Table 9. Results of the OLS bootstrap regression of the determinants of farm productivity change and its components (production domain indicators)

	Productivity change	Efficiency change	Technical change	Scale efficiency change
Model 1: Production domain indicator based on Alkire et al. [10]				
Input in productive decisions	0.045 (0.237)	-0.220 (0.351)	0.087 (0.064)	-0.017 (0.087)
Autonomy in production	0.944*** (0.239)	1.121*** (0.338)	0.133** (0.056)	0.094 (0.130)
Model 2: Alternative production domain indicator based on approach 1				
Input in productive decisions	0.564 (0.712)	-0.102 (0.993)	0.390*** (0.144)	0.040 (0.308)
Autonomy in production	0.896*** (0.240)	1.101*** (0.345)	0.107* (0.057)	0.088 (0.120)
Model 3: Alternative production domain indicator based on approach 2				
Input in productive decisions	0.175 (0.484)	-0.058 (0.713)	0.071 (0.113)	0.093 (0.269)
Autonomy in production	0.945*** (0.230)	1.093*** (0.333)	0.143** (0.056)	0.089 (0.129)

Source: Authors' calculations

Note: Standard errors in parentheses; *, **, and *** indicate significance based on 90%, 95% and 99% bootstrap confidence level, respectively

We also estimate the effect of indicators of production domain on productivity indices. Results indicate that autonomy in production is statistically significant in all three models and positively associated with productivity change, efficiency change, and technical change (Table 9, also see online supplement S3 for the full set of results). This implies that improvements in primary female decision maker's ability to make independent choices regarding agricultural production increases farm household's overall productivity through efficiency and technological gains. Input in production decisions, however, is statistically significant in alternative model (Model 2), and positively associated with only technical change.

6. Conclusions and discussion

This study contributes to the existing literature with an assessment of the association between women's empowerment in agriculture and farm household productivity change and its components. This assessment involves two steps. First, a non-parametric Malmquist approach is used to estimate household-specific productivity change and its decomposition. Next, we employ a non-parametric bootstrap OLS regression method to analyze the link between women's empowerment in agriculture (and a set of control variables) and productivity change and its decomposition. To better understand the relationship between women's empowerment and productivity change, we also analyze the effect of gender parity gap, individual domains and indicators of women's empowerment, and the same measures derived using two alternative scoring procedures. The empirical application focuses on Bangladesh rice farms.

Our first-stage results show that over the sample period, farm household productivity decreased by an average of 24%. The main driver of productivity decline was

technological regress estimated at 35%. Despite the observed negative technical change, we find that the sample households, on average, used the existing production technology more efficiently over time as we record a 15% improvement in efficiency change during the estimation period. In addition, these households achieved adjustments in production scale that allowed them to obtain a 3% growth in productivity over time. Our second stage results indicate that empowering women in agriculture, specifically improving primary female decision makers ability to make independent choices regarding agricultural production, is positively and significantly associated with productivity change, efficiency change, and technical change, while it is not significantly associated with scale efficiency change. We further found that closing the gender parity gap is associated with higher farm productivity. These results hold for alternative measures of empowerment that we test, which validate the inference that might be drawn from this study. We also find that apart from women's empowerment in agriculture, climatic variables, and household characteristics, such as sex, education, household size and location, explain differences in productivity change and its components among households in this study.

Besides the intrinsic value of empowering women involved in farming, our main finding, that women's empowerment in agriculture is associated with higher farm productivity, is even more compelling in view of the fact that population growth, land scarcity, and other resource constraints challenge agricultural regulators and farmers to find innovative ways to use existing farm resources more efficiently. In the case of Bangladesh, women's empowerment in agriculture might not only be valued for contributing towards development goals, but also as a means for increasing agricultural productivity.

Farm household women's contribution to agriculture in Bangladesh are traditionally confined to homestead production (farming carried out around homestead) and post-harvest activities such as drying, sorting, packaging of crops [62,63]. Since the interaction pathway between empowerment and productivity is entirely through the production domain, interventions that increase the primary female decision makers relative autonomy in agricultural productive decisions might help the country boost its agricultural productivity.

This research on the relationship between women's empowerment in agriculture and farm productivity growth focuses on a single developing country. Future research could extend the work in different ways, such as by examining whether similar findings would be observed in different developing countries where cultural and legal (e.g., women's rights) differences can affect women's involvement in agricultural decision-making, different time periods or types of farms, and the role of actual policies to improve women's empowerment where relevant data are available. If sufficient data were available, then the association of women's empowerment and productivity might be decomposed by growing seasons, crop varieties, production technology heterogeneity, market orientation, or at the scale of field or plot. Exploration into these areas could develop further the empirical association of women's empowerment and rice farming household productivity change in Bangladesh.

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End Notes

ⁱ Although Bozoğlu and Ceyhan [7] do not explicitly use the term “women’s empowerment”, their measure of women’s participation in farm decision-making can be considered a measure of women’s empowerment.

ⁱⁱ Technical efficiency is defined as the ability of a decision making unit to produce an output using the lowest possible amount of inputs (input oriented technical efficiency), or to achieve the maximum potential output from a given set of inputs (output oriented technical efficiency) [9].

ⁱⁱⁱ First round (2011/12) and second round (2015/2016) collect data for crop cultivated during December 2010 to November 2011 and December 2013 to November 2014, respectively.

^{iv} There are 33 households in the dataset that have split between rounds. For comparison purpose, we only considered the original household (parent household) in such cases.

^v On average, in both rounds five cultivable/arable plots are available to sample farmers.

^{vi} Location is a set of categorical variables, one for each region, southeast, northeast, southwest, and northeast, with the southeast dummy variable excluded from the regression analysis to avoid perfect collinearity.

^{vii} For household with more than one plot, the rainfed dummy gets the value 1 if rain was the primary irrigation source in the majority of the plots. A similar rule applies for the tenancy status variable. This variable takes the value 1 if the majority of a household’s plots were operated under cash lease or crop-sharing arrangement.

^{viii} We also defined rainfed variable as the ratio of rainfed plots to total plots available to a household. Similarly, for tenancy variable, we estimated the ratio of plots taken-in through a cash lease or crop-sharing arrangement to total plots. We find no significant difference in estimating the empowerment-productivity change relationship when we replace the categorical variables with continuous measures of rainfed and tenancy.

⁹ The results of the exogeneity tests are available from the authors upon request.

¹⁰ Calculated as the estimated parameter times the average gap between the 80% index threshold required to be considered empowered and the average empowerment score, or $(\text{estimate} \times (80\% \text{ of the weighted indicators-mean empowerment scores})) \times 100$.

¹¹ See endnote 10.

¹² See endnote 10.

Supplement S1

Alternative approach 1

The original WEAI has an adequacy requirement for each indicator. For example, for a woman to be empowered under resources domain, it is adequate for her (i) to own any assets provided that it is not just one small asset (a chicken, nonmechanized equipment or small consumer durables), (ii) to participate in at least one type of decision to buy, sell or transfer a major asset that a household owns and (iii) to contribute to at least one decision regarding credit access and use. We modified these assumptions to develop empowerment scores based on the gradations of women's power rather than binary assessments. For example, in the resource domain of the first alternative, we assumed that the more assets a woman owns, the higher the empowerment score, and consequently, we record a higher indicator relating to ownership of assets. Similarly, a woman scores higher under the resource domain if she participates in more decisions regarding purchase, sale, or transfer of assets with more significant input compared to a woman who participates in the decision-making process with low input or does not participate at all. The same assumption is employed for access to and decisions about credit: the more access she has and the higher input she provides in decision making regarding sources of credit and credit proceeds utilization, the higher the empowerment score in this indicator.

Alternative approach 2

The second alternative approach focuses on a woman's engagement and relative input in the activity or decision-making process in which a household participates. For example, under the input in productive decision indicator, a woman is asked about her input in productive decisions around activities such as food crop farming, cash farming, livestock

raising, non-farm economic activities, wage and salary employment, and fishing or fish culture. The answer scale ranges from 1= “no input” to 5= “input in all decisions.” Under the assumptions of original WEAI, a woman is deemed as empowered if she participates in at least two activities in which she has at least “some input.” The fundamental idea behind the second alternative approach is recognizing that a woman might belong to a household that is engaged in only a specific activity, such as cash crop farming. Alternatively, the household might be engaged in all the activities, but the primary female decision-maker has a varying degree of engagement in those activities. Our idea is to develop a scoring system that does not reduce the empowerment of a woman for not contributing to an activity where a household does not participate and not to exaggerate the empowerment a woman who contributes some input in decision making in a minority of several household pursuits compared to a woman who provides more input into a range of agricultural production decisions.

Assumptions of original WEAI, first and second alternative approach are discussed in detail in Table 1.

Supplement S1 Table 1. Empowerment assumptions

Domains\Index	Indicator	Weight	Survey question	WEAI	Alternative approach 1	Alternative approach 2
88	Agricultural Production	0.10	How much input did you have in making decisions about food crop farming, cash crop farming, livestock raising, and fish culture? To what extent do you feel you can make your own personal decisions regarding these aspects of household life if you want(ed) to: agriculture production, which inputs to buy, which types of crops to grow for agricultural production, when to take or who should take crops to market, and livestock raising?	Achievement in two activities. Inadequate if the individual participates but does not/has not at least some input in decisions or does not make decisions nor feels he or she could.	No minimum requirement of activities. Both actual inputs and intent are considered. Inputs and extent account for 60% and 40% of the weight, respectively. Weights are assigned based on the answer scale. Adequacy is calculated as the weighted average of every activity and intent.	No minimum requirement of activities. Considers only those activities or intents in which responses have been recorded. The score is calculated as the weighted average of the degree of the inputs OR intent (cut off is small extent) of activities, whichever is greater.
	<i>Autonomy in production</i>	0.10	My actions in [domain] are partly because I will get in trouble with someone if I act differently. Regarding [domain] I do what I do so others don't think poorly of me. Regarding [domain] I do what I do because I personally think it is the right thing to do. Agricultural production, inputs to buy, crops to grow, take to market, livestock.	Achievement in any. Inadequate if Relative Autonomy Indicator (RAI) is less than 1.	Achievement in any. Inadequate if RAI is less than 1.	Achievement in any. Inadequate if RAI is less than 1.
	Access to and Control of Productive Resources	0.07	Who would you say can use the [item] most of the time? Agricultural land, large livestock, small livestock, chickens and so on; fishpond/equipment; farm equipment (nonmechanized); farm equipment (mechanized); nonfarm business equipment, house; large durables; small durables; cell phone; nonagricultural land (any); transport.	Achievement in any if not only one small asset (chickens, nonmechanized equipment and no small consumer durables). Inadequate if the household does not own any asset or if the household owns the type of asset but she or he does not own most of it alone.	Adequacy is calculated as the weighted average of ALL large and small assets owned by self or jointly.	No adequacy requirement. The score is calculated as the weighted average of the assets owned by self or jointly; large assets get twice the weight of small assets.
	<i>Decisions regarding the purchase, sale, or transfer of land and assets</i>	0.07	Who would you say can decide whether to sell, give away, rent/mortgage [item] most of the time? Who contributes most to decisions regarding a new purchase of [item]? Agricultural land, large livestock, small livestock, chickens and so on, fishpond, farm equipment (nonmechanized), farm equipment (mechanized).	Achievement in any if not only chickens and nonmechanized farming equipment. Inadequate if a household does not own any asset or household owns the type of asset but he or she does not participate in decisions (exchange or buy) about it.	Adequacy is calculated as the weighted average of ALL the decisions associated with ALL the assets owned by self or jointly.	Adequacy is calculated as the weighted average of the decisions associated with large and small assets owned by self or jointly; 80% of the weight is assigned to large assets and participating in at least one decision regarding large asset is required.
	<i>Access to and decisions about credit</i>	0.07	Who made the decision to borrow/what to do with money/item borrowed from [source]? Nongovernmental organization, informal lender, formal lender (bank), friends or relatives, rotating savings and credit associations (savings/credit group).	Achievement in any. Inadequate if the household has no credit or used a source of credit but she or he did not participate in any decisions about it.	Adequacy is calculated as the weighted average of all the decisions (to borrow and use) regarding all the sources of credit.	At least one source of credit is required. Adequacy is calculated as the weighted average of all the decisions regarding a source in which she participated.

Domains\Index	Indicator	Weight	Survey question	WEAI	Alternative approach 1	Alternative approach 2
Income	<i>Control over use of income</i>	0.20	How much input did you have in decisions about the use of income generated from food crop, cash crop, livestock, nonfarm activities, wages and salary, and fish culture? To what extent do you feel you can make your own personal decisions regarding these aspects of household life if you want(ed) to: your own wage or salary employment? Minor household expenditures?	Achievement in any if not only minor household expenditures. Inadequate if the individual participates in the activity but has no input or little input in decisions about the income generated.	Adequacy is calculated as the weighted average of the degree of inputs and the extent the respondent feels she can make decisions. Inputs and extent account for 90% and 10% of the weight respectively.	Adequacy is calculated as the weighted average of the degree of inputs or extent the respondent feels she can make decisions, whichever is greater. Input in only minor household expenditures is not enough.
	Leadership					
	<i>Group membership</i>	0.10	Are you a member of any agricultural/livestock/fisheries producer/market group; water, forest users', credit, or microfinance group; mutual help or insurance group (including burial societies); trade and business association; civic/charitable group; local government; religious group; other women's group; other group?	Achievement in any. Inadequate if not part of at least one group.	Adequacy is calculated as the weighted average of ALL THE MEMBERSHIP OPTIONS (active/inactive) in all eleven groups.	Achievement in any. Inadequate if not part of at least one group.
	<i>Speaking in public</i>	0.10	Do you feel comfortable speaking up in public to help decide on infrastructure (like small wells, roads) to be built, to ensure proper payment of wages for public work or other similar programs, or to protest the misbehavior of authorities or elected officials?	Achievement in any. Inadequate if not comfortable speaking in public.	Adequacy is calculated as the weighted average of the levels of comfort associated with all three public speaking contexts.	Adequacy is calculated as the weighted average of the levels of comfort associated with the context in which she participates.
	Time					
	<i>Workload</i>	0.10	Worked more than 10.5 hours in the previous 24 hours.	Inadequate if individual works more than 10.5 hours per day.	Inadequate if individual works more than 10.5 hours per day.	Inadequate if individual works more than 10.5 hours per day.
	<i>Leisure</i>	0.10	How would you rate your satisfaction with your time available for leisure activities such as visiting neighbors, watching TV, listening to the radio, seeing movies, or doing sports?	Inadequate if not satisfied (<5); 5 being neither satisfied not dissatisfied.	Adequacy is calculated as the weighted average of the levels of satisfaction.	Inadequate if not satisfied (<5); 5 being neither satisfied not dissatisfied.

Source: Alkire et al. [1] & authors

Supplement S2

This section discusses the control variable results of table 6 of the main text. Sex of the primary decision maker is negatively associated with technical change indicating female-headed households make, on average, less technological investments in their farm operations than male headed households. This could be due to the fact that women have relatively poor access to productive resources, inputs and services [2,3]. Education positively affects both the technical change and scale change index. A reason could be that education reduces barriers to adoption and implementation of new agricultural technologies that can not only help farm households to shift their production frontier upward but also bring them closer to the optimal scale. Results also indicate that the dependency ratio negatively affects productivity change and efficiency change. One possible explanation is that a higher dependency ratio replaces unpaid family labor with paid hired labor, which essentially lowers farms' economic performance as overall production cost rises due to reduced economics of scale. Household size is negatively associated with efficiency change and scale change implying that with the increase in the size of the household, a household's ability to use inputs more efficiently and expand the scale of the farm operations diminishes. It might be the case that households with more people spend more resources for their increased consumption needs and save less, limiting their ability to increase productivity at intensive (yield growth through efficient input mix) and extensive (production growth through land expansion) margins. On the other hand, an increase in the share of household income from non-agricultural sources induces a positive shift in efficiency change. This may be due to the fact that an increase in off-farm income increases a household's liquidity or access to credit, facilitating farm investment, including

in better inputs (e.g., purchasing quality seeds, fertilizer), which helps farms to use better technology. The coefficient on irrigation (rainfed) does not have a statistically significant effect. This result differs from expectations based on at least some past studies [4,5], although comparisons are complicated because some past studies focus on a different measure of productivity such as yield. Moving to the tenancy variables, we found a statistically significant, positive effect on productivity change and technical change index. Results indicate that overall productivity increases when the plot(s) is taken-in through a cash lease or crop-sharing arrangement. The positive relationship between tenancy and technical change implies that technological improvement differs depending on the operational status of the arable land. On average, technological improvement is higher in the lands operated under cash lease or crop-sharing arrangement compared to the lands operated under different tenure systems such as owner-operated, group leasing, or joint operation. Both weather variables have a statistically significant impact on productivity indices. The rainfall change variable negatively affects the productivity change and technical change index, but the effect is positive for scale efficiency change. The temperature change variable has a positive effect on productivity, efficiency, and technical change index. Among the locational dummies, households located in northwestern, northeastern, and southwestern districts were found to exhibit technological progress and regress, respectively, compared to households located in the southeastern districts of the country. Households situated in the northeastern districts were also found to experience productivity growth and efficiency gains compared to those in the southeastern districts of the country.

Supplement S3

Supplement S3 Table 1. Results of the OLS bootstrap regression of the determinants of farm productivity change and its components (Empowerment gap)

Variables	Model 1: Empowerment gap based on Alkire et al. [10]				Model 2: Alternative empowerment gap based on approach 1				Model 3: Alternative empowerment gap based on approach 2			
	Productivity change	Efficiency change	Technical change	Scale efficiency change	Productivity change	Efficiency change	Technical change	Scale efficiency change	Productivity change	Efficiency change	Technical change	Scale efficiency change
Empowerment gap	-0.128** (0.063)	-0.105 (0.094)	-0.027 (0.018)	0.002 (0.030)	-0.182* (0.109)	-0.224 (0.157)	-0.016 (0.028)	-0.007 (0.054)	-0.117 (0.077)	-0.123 (0.112)	-0.013 (0.021)	-0.001 (0.033)
Sex	-0.097 (0.070)	-0.085 (0.107)	-0.034* (0.020)	0.018 (0.025)	-0.102 (0.071)	-0.093 (0.110)	-0.034* (0.019)	0.018 (0.026)	-0.102 (0.069)	-0.091 (0.107)	-0.034* (0.020)	0.018 (0.026)
Age	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	0.000 (0.000)	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	0.000 (0.000)	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	0.000 (0.000)
Education	0.002 (0.003)	-0.004 (0.005)	0.002* (0.001)	0.004* (0.002)	0.002 (0.003)	-0.003 (0.005)	0.002* (0.001)	0.004 (0.003)	0.002 (0.003)	-0.004 (0.005)	0.002* (0.001)	0.004* (0.002)
Dependency ratio	-0.049** (0.019)	-0.056** (0.028)	-0.008 (0.005)	-0.006 (0.011)	-0.049** (0.019)	-0.057** (0.028)	-0.008 (0.005)	-0.006 (0.012)	-0.049** (0.019)	-0.056** (0.028)	-0.008 (0.005)	-0.006 (0.011)
Household size	-0.014 (0.009)	-0.020* (0.011)	0.001 (0.002)	-0.005** (0.002)	-0.014 (0.009)	-0.020* (0.012)	0.001 (0.003)	-0.005** (0.002)	-0.014 (0.009)	-0.020* (0.011)	0.001 (0.003)	-0.005** (0.002)
Extension visit	0.013 (0.021)	-0.004 (0.013)	0.007 (0.009)	0.004 (0.004)	0.013 (0.021)	-0.004 (0.013)	0.007 (0.010)	0.004 (0.004)	0.013 (0.021)	-0.004 (0.013)	0.007 (0.010)	0.004 (0.004)
Income share from non ag. enterprise	0.052 (0.037)	0.113** (0.055)	-0.010 (0.009)	-0.010 (0.017)	0.054 (0.036)	0.115** (0.055)	-0.010 (0.009)	-0.010 (0.017)	0.053 (0.037)	0.114** (0.055)	-0.010 (0.009)	-0.010 (0.018)
Rainfed	0.023 (0.025)	0.028 (0.035)	0.002 (0.006)	-0.004 (0.012)	0.025 (0.024)	0.031 (0.035)	0.002 (0.006)	-0.004 (0.011)	0.023 (0.025)	0.028 (0.035)	0.001 (0.006)	-0.004 (0.011)
Tenancy	0.061** (0.026)	0.059 (0.037)	0.012** (0.005)	0.011 (0.017)	0.060** (0.026)	0.059 (0.037)	0.012** (0.005)	0.011 (0.018)	0.060** (0.026)	0.059 (0.037)	0.012** (0.005)	0.011 (0.017)
Rainfall	-0.000* (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000* (0.000)	-0.000** (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000* (0.000)	-0.000** (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000* (0.000)
Temperature	0.249*** (0.091)	0.222 (0.135)	0.070*** (0.024)	-0.007 (0.026)	0.251*** (0.091)	0.233* (0.135)	0.067*** (0.023)	-0.005 (0.025)	0.246*** (0.090)	0.224* (0.134)	0.067*** (0.024)	-0.006 (0.026)
Northwest	0.033 (0.034)	-0.019 (0.047)	0.024*** (0.008)	0.035 (0.024)	0.037 (0.034)	-0.014 (0.048)	0.025*** (0.008)	0.035 (0.025)	0.032 (0.034)	-0.019 (0.048)	0.024*** (0.008)	0.035 (0.024)
Southwest	-0.050 (0.038)	-0.004 (0.054)	-0.029*** (0.010)	0.001 (0.010)	-0.048 (0.038)	-0.000 (0.055)	-0.029*** (0.011)	0.001 (0.010)	-0.053 (0.038)	-0.006 (0.053)	-0.030*** (0.011)	0.001 (0.010)
Northeast	0.165*** (0.059)	0.150* (0.087)	0.052*** (0.015)	-0.024 (0.022)	0.166*** (0.058)	0.153* (0.088)	0.052*** (0.014)	-0.023 (0.022)	0.170*** (0.058)	0.156* (0.089)	0.053*** (0.015)	-0.024 (0.022)
Constant	0.635*** (0.083)	1.099*** (0.119)	0.583*** (0.020)	1.051*** (0.036)	0.630*** (0.082)	1.095*** (0.119)	0.582*** (0.021)	1.051*** (0.035)	0.634*** (0.084)	1.098*** (0.120)	0.583*** (0.021)	1.051*** (0.036)

Source: Authors' Calculation; Note: Standard errors in parentheses; *, **, and *** indicate significance based on 90%, 95% and 99% bootstrap confidence level, respectively

Supplement S3 Table 2. Results of the OLS bootstrap regression of the determinants of farm productivity change and its components (WEAI domains)

Variables	Model 1: Empowerment domain score based on Alkire et al. [10]				Model 2: Alternative empowerment domain score based on approach 1				Model 3: Alternative empowerment domain score based on approach 2			
	Productivity change	Efficiency change	Technical change	Scale efficiency change	Productivity change	Efficiency change	Technical change	Scale efficiency change	Productivity change	Efficiency change	Technical change	Scale efficiency change
Empowerment score: Production	0.483*** (0.168)	0.458* (0.241)	0.115*** (0.041)	0.038 (0.090)	0.798*** (0.233)	0.885*** (0.329)	0.121** (0.054)	0.147 (0.179)	0.762*** (0.217)	0.838*** (0.314)	0.120** (0.049)	0.132 (0.174)
Empowerment score: Resource	0.064 (0.179)	0.091 (0.265)	0.041 (0.042)	-0.067 (0.058)	0.843 (0.593)	0.919 (0.837)	-0.080 (0.142)	0.677 (0.542)	0.412** (0.199)	0.500* (0.303)	0.047 (0.049)	0.014 (0.084)
Empowerment score: Income	-0.010 (0.140)	-0.075 (0.211)	-0.021 (0.034)	0.026 (0.044)	-0.091 (0.413)	-0.255 (0.583)	0.124 (0.083)	-0.311 (0.247)	-0.101 (0.239)	-0.181 (0.336)	0.014 (0.054)	-0.132 (0.124)
Empowerment score: Leadership	0.096 (0.205)	0.224 (0.275)	0.033 (0.053)	-0.196* (0.103)	0.314 (0.574)	0.576 (0.806)	0.047 (0.118)	-0.472 (0.348)	-0.087 (0.249)	0.092 (0.330)	-0.024 (0.064)	-0.217 (0.133)
Empowerment score: Time	0.196 (0.172)	0.174 (0.258)	0.016 (0.042)	0.083 (0.078)	0.253 (0.205)	0.293 (0.298)	0.008 (0.049)	0.112 (0.119)	0.187 (0.171)	0.167 (0.255)	0.017 (0.042)	0.077 (0.080)
Sex	-0.113 (0.070)	-0.102 (0.110)	-0.039** (0.020)	0.018 (0.026)	-0.123* (0.073)	-0.110 (0.113)	-0.038** (0.019)	0.012 (0.027)	-0.125* (0.072)	-0.117 (0.112)	-0.039* (0.020)	0.020 (0.026)
Age	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	-0.000 (0.000)	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	0.000 (0.000)	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	0.000 (0.000)
Education	0.001 (0.003)	-0.004 (0.005)	0.001* (0.001)	0.004* (0.002)	0.001 (0.003)	-0.005 (0.005)	0.002* (0.001)	0.004* (0.002)	0.001 (0.003)	-0.005 (0.005)	0.001* (0.001)	0.004* (0.002)
Dependency ratio	-0.046** (0.019)	-0.053* (0.028)	-0.007 (0.005)	-0.007 (0.011)	-0.045** (0.019)	-0.051* (0.029)	-0.008* (0.005)	-0.005 (0.011)	-0.047** (0.019)	-0.053* (0.028)	-0.007 (0.005)	-0.006 (0.011)
Household Size	-0.014 (0.009)	-0.021* (0.012)	0.001 (0.002)	-0.005* (0.002)	-0.014 (0.009)	-0.020* (0.012)	0.001 (0.002)	-0.005* (0.003)	-0.013 (0.009)	-0.019 (0.012)	0.001 (0.003)	-0.005* (0.002)
Extension visit	0.013 (0.021)	-0.005 (0.013)	0.007 (0.010)	0.004 (0.004)	0.012 (0.021)	-0.006 (0.013)	0.007 (0.010)	0.004 (0.004)	0.012 (0.021)	-0.005 (0.013)	0.007 (0.010)	0.004 (0.004)
Income share from non ag. enterprise	0.054 (0.037)	0.114** (0.055)	-0.010 (0.009)	-0.008 (0.017)	0.054 (0.037)	0.115** (0.055)	-0.010 (0.009)	-0.008 (0.017)	0.058 (0.037)	0.118** (0.055)	-0.009 (0.009)	-0.007 (0.017)
Rainfed	-0.018 (0.024)	-0.011 (0.034)	-0.004 (0.006)	-0.009 (0.011)	-0.018 (0.024)	-0.010 (0.034)	-0.003 (0.006)	-0.011 (0.012)	-0.019 (0.024)	-0.012 (0.034)	-0.004 (0.006)	-0.010 (0.012)
Tenancy	0.049* (0.025)	0.030 (0.036)	0.015*** (0.006)	0.016 (0.018)	0.049* (0.025)	0.029 (0.036)	0.015*** (0.005)	0.017 (0.019)	0.050** (0.025)	0.031 (0.036)	0.015*** (0.006)	0.015 (0.018)
Rainfall	-0.000 (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000* (0.000)	-0.000* (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000 (0.000)	-0.000* (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000* (0.000)
Temperature	0.236*** (0.091)	0.214 (0.136)	0.070*** (0.024)	-0.015 (0.027)	0.246*** (0.091)	0.227* (0.137)	0.064*** (0.023)	0.004 (0.025)	0.241*** (0.090)	0.225 (0.137)	0.067*** (0.024)	-0.013 (0.027)
Northwest	0.040 (0.034)	-0.015 (0.047)	0.026*** (0.008)	0.039 (0.027)	0.044 (0.034)	-0.008 (0.048)	0.028*** (0.008)	0.034 (0.024)	0.049 (0.035)	-0.006 (0.048)	0.027*** (0.008)	0.040 (0.029)
Southwest	-0.035 (0.038)	0.008 (0.054)	-0.027** (0.011)	0.007 (0.011)	-0.032 (0.038)	0.013 (0.056)	-0.024** (0.010)	-0.002 (0.010)	-0.031 (0.039)	0.012 (0.054)	-0.026** (0.011)	0.007 (0.012)
Northeast	0.156*** (0.057)	0.142* (0.086)	0.054*** (0.015)	-0.027 (0.022)	0.174*** (0.058)	0.162* (0.087)	0.049*** (0.015)	-0.005 (0.022)	0.174*** (0.057)	0.166* (0.087)	0.054*** (0.015)	-0.023 (0.022)
Constant	0.554*** (0.092)	1.028*** (0.136)	0.563*** (0.025)	1.056*** (0.036)	0.514*** (0.089)	0.971*** (0.130)	0.571*** (0.023)	1.014*** (0.037)	0.490*** (0.092)	0.940*** (0.135)	0.560*** (0.024)	1.050*** (0.035)

Source: Authors' calculations

Note: Standard errors in parentheses; *, **, and *** indicate significance based on 90%, 95% and 99% bootstrap confidence level, respectively

Supplement S3 Table 3. Results of the OLS bootstrap regression of the determinants of farm productivity change and its components (production domain indicators)

Variables	Model 1: Production domain indicator based on Alkire et al. [10]				Model 2: Alternative production domain indicator based on approach 1				Model 3: Alternative production domain indicator based on approach 2			
	Productivity change	Efficiency change	Technical change	Scale efficiency change	Productivity change	Efficiency change	Technical change	Scale efficiency change	Productivity change	Efficiency change	Technical change	Scale efficiency change
Input in productive decisions	0.045 (0.237)	-0.220 (0.351)	0.087 (0.064)	-0.017 (0.087)	0.564 (0.712)	-0.102 (0.993)	0.390*** (0.144)	0.040 (0.308)	0.175 (0.484)	-0.058 (0.713)	0.071 (0.113)	0.093 (0.269)
Autonomy in production	0.944*** (0.239)	1.121*** (0.338)	0.133** (0.056)	0.094 (0.130)	0.896*** (0.240)	1.101*** (0.345)	0.107* (0.057)	0.088 (0.120)	0.945*** (0.230)	1.093*** (0.333)	0.143** (0.056)	0.089 (0.129)
Sex	-0.099 (0.071)	-0.082 (0.112)	-0.036* (0.019)	0.017 (0.025)	-0.103 (0.073)	-0.085 (0.113)	-0.038** (0.019)	0.016 (0.026)	-0.101 (0.070)	-0.085 (0.112)	-0.036* (0.019)	0.015 (0.027)
Age	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	0.000 (0.000)	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	0.000 (0.000)	0.001 (0.001)	0.001 (0.001)	0.000 (0.000)	0.000 (0.000)
Education	0.001 (0.003)	-0.004 (0.005)	0.002* (0.001)	0.004* (0.002)	0.001 (0.003)	-0.005 (0.005)	0.002* (0.001)	0.004* (0.002)	0.001 (0.003)	-0.005 (0.005)	0.002* (0.001)	0.004* (0.002)
Dependency ratio	-0.046** (0.019)	-0.052* (0.028)	-0.007 (0.005)	-0.006 (0.011)	-0.047** (0.019)	-0.053* (0.028)	-0.008* (0.005)	-0.006 (0.011)	-0.046** (0.019)	-0.053* (0.028)	-0.007 (0.005)	-0.006 (0.011)
Household Size	-0.016* (0.009)	-0.022* (0.012)	0.001 (0.002)	-0.006** (0.003)	-0.015* (0.009)	-0.022* (0.012)	0.001 (0.002)	-0.005** (0.003)	-0.016* (0.009)	-0.022* (0.011)	0.001 (0.003)	-0.005** (0.003)
Extension visit	0.012 (0.021)	-0.006 (0.012)	0.007 (0.010)	0.004 (0.004)	0.012 (0.021)	-0.006 (0.013)	0.007 (0.010)	0.004 (0.004)	0.012 (0.021)	-0.006 (0.013)	0.007 (0.010)	0.004 (0.004)
Income share from non ag. enterprise	0.061* (0.037)	0.126** (0.056)	-0.009 (0.009)	-0.010 (0.017)	0.060 (0.037)	0.125** (0.055)	-0.010 (0.009)	-0.010 (0.018)	0.062* (0.037)	0.125** (0.054)	-0.009 (0.009)	-0.010 (0.017)
Rainfed	-0.018 (0.024)	-0.010 (0.034)	-0.004 (0.006)	-0.010 (0.012)	-0.017 (0.024)	-0.010 (0.034)	-0.004 (0.006)	-0.010 (0.011)	-0.018 (0.024)	-0.009 (0.035)	-0.005 (0.006)	-0.010 (0.011)
Tenancy	0.051** (0.025)	0.032 (0.036)	0.015*** (0.006)	0.016 (0.018)	0.051** (0.025)	0.032 (0.036)	0.015*** (0.005)	0.016 (0.018)	0.051** (0.025)	0.032 (0.035)	0.015*** (0.006)	0.016 (0.018)
Rainfall	-0.000* (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000* (0.000)	-0.000 (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000* (0.000)	-0.000* (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000* (0.000)
Temperature	0.204** (0.090)	0.167 (0.133)	0.066*** (0.023)	-0.008 (0.026)	0.205** (0.089)	0.172 (0.134)	0.066*** (0.023)	-0.008 (0.027)	0.204** (0.089)	0.172 (0.134)	0.065*** (0.023)	-0.007 (0.026)
Northwest	0.037 (0.034)	-0.015 (0.047)	0.026*** (0.008)	0.036 (0.025)	0.040 (0.035)	-0.015 (0.048)	0.028*** (0.008)	0.036 (0.026)	0.038 (0.035)	-0.015 (0.048)	0.026*** (0.008)	0.037 (0.026)
Southwest	-0.042 (0.037)	0.001 (0.055)	-0.027*** (0.010)	0.002 (0.010)	-0.036 (0.038)	0.002 (0.054)	-0.024** (0.010)	0.002 (0.011)	-0.041 (0.037)	0.003 (0.054)	-0.027** (0.011)	0.003 (0.011)
Northeast	0.158*** (0.057)	0.144* (0.085)	0.052*** (0.015)	-0.023 (0.021)	0.155*** (0.058)	0.143 (0.089)	0.050*** (0.015)	-0.024 (0.022)	0.158*** (0.057)	0.142 (0.087)	0.053*** (0.015)	-0.024 (0.021)
Constant	0.612*** (0.083)	1.092*** (0.120)	0.572*** (0.021)	1.049*** (0.033)	0.600*** (0.083)	1.082*** (0.123)	0.567*** (0.021)	1.047*** (0.033)	0.603*** (0.086)	1.083*** (0.129)	0.572*** (0.022)	1.042*** (0.029)

Source: Authors' calculations

Note: Standard errors in parentheses; *, **, and *** indicate significance based on 90%, 95% and 99% bootstrap confidence level, respectively

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Essay 3: Climate change-induced shifts in precipitation: response of Missouri corn and soybean basis

Abstract:

We investigate the effect of different precipitation variables, namely local, growing season, and regional as well as their nonlinear interactions with Missouri corn and soybean basis using a large panel dataset for the 2010–2020 period. Our analysis reveals statistically significant linear and nonlinear basis responses for local and growing season precipitation variations. The estimates show that corn and soybean basis differ in terms of the immediate effect of normal or abnormal weekly rainfall captured by local precipitation variable whereas the growing season precipitation capturing the local supply effect exhibits a U-shaped relationship in both models. We also document a statistically significant moderating effect of port distance measure on the curvilinearity of the association between transportation disruptions proxied by regional precipitation and soybean basis. Given the climate projections, there are legitimate concerns regarding precipitation's influence on future navigability of major transportation arteries that link Missouri to export facilities down the Mississippi river. Hence, the information generated in this research has even greater utility when studied in the context of the role barge freight transportation plays in the state's agriculture.

Keywords: Basis; corn; soybean; precipitation; climate change; transportation

1. Introduction

Current literature suggests that factors such as transportation cost, destination basis, ocean shipping spread [1,2], storage cost, local production, and contract maturity [3], ending stock and interest cost [4] affect commodity basis levels. One possible source of systematic variability in commodity basis that has not been considered so far in the literature is the effect of weather anomalies such as extreme or protracted precipitation events that result from climate change. There are growing concern and evidence that due to climate change, the intensity and frequency of weather events such as droughts and floods have increased in the US, and these events are adversely impacting crop growth, yield, and critical agricultural infrastructure [5–7]. Furthermore, some studies [8–10] imply that climate change might increase agricultural commodity prices by impacting yield. All these indicate a potential causal channel through which extreme climate events can influence commodity basis. In this study, we address how climate change, more specifically the risk from flooding and low flows, can affect the local corn and soybean basis levels.

Since agriculture and climate are intertwined, it is important to understand the consequences of changing global climate and how local climate variations might affect agricultural markets and prices. Although there are studies that demonstrate the link between commodity prices and climate variability, we find no attention has been given to the role of climate change in determining local basis levels. One particular reason that warrants the need for analyzing such a link is the extensive use of commodity basis in grain trading as a tool for risk hedging by the market participants. Therefore, understanding the basis and its determinants is crucial as increased basis variability may significantly increase

traders' risk. Another reason is the role commodity basis plays in grain trade and movement. McKenzie [1] stated that commodity basis determines trade and grain flows. This value arises because basis is thought to be more readily predictable than futures or spot prices due to the convergence issue or the movement of the futures price towards the spot price as the contract expiration date approaches [11,12]. Furthermore, the local impact of climate change can be better understood by basis as local supply and demand conditions are more likely to be influenced by local basis than cash prices. All these indicate that basis is an important local pricing and allocation mechanism. Therefore, failure to account for the risk of climate change when explaining changes in basis may lead to a poorer understanding of basis fluctuations and this, in turn, may have negative consequences for market actors that engage in grain trading and even for producers through an income effect.

Climate change is projected to shift the precipitation regime in Missouri by increasing spring rainfall and average precipitation, and intensifying severe rainstorms, which is likely to affect the state's agriculture [5]. In this paper, the effect of climate change arising from changes in precipitation on the intertemporal price relationship between origin point cash price and delivery point futures price is empirically evaluated. More specifically, the effect of local, growing season, and regional precipitation on the Missouri corn and soybean basis levels is examined. We opt to focus on the corn and soybean basis as these commodities are widely distributed across the state and jointly account for more than a quarter of Missouri's agricultural exports [13]. Thus, understanding the implications of different intensities of precipitation patterns on corn and soybean basis has profound economic implications. However, the extrapolation is based on the key *ceteris paribus*

assumption regarding infrastructure and market participants behavior, and we also assume that the historical weather pattern largely prevails.

This study contributes to the existing literature that examines the determinants of commodity basis. The approach employed here differs from that of earlier works in that it uses more detailed data on local price and precipitation. Along with precipitation data collected from elevator-specific local weather stations, growing season and corn belt precipitation data are used, which allows to capture the spatial variation in basis associated with local, growing season, and regional weather. Therefore, our basis modeling is relatively more robust as the empirical findings highlight the effect of marginal changes in specific precipitation patterns on the relationship between local cash and futures price.

The remainder of the paper is as follows. The literature on basis and climate change is reviewed in Section 2. In Section 3, we discuss the conceptual framework, empirical specifications, and data. A discussion on the empirical findings follows in Section 4, followed by the concluding remarks in Section 5.

2. Theoretical background and related literature

2.1. Basis

Basis influences grain marketing and hedging effectiveness [14]. Earlier works by Kaldor [11], Working [12], and Brennan [15] and later by Williams [16] and Fama & French [17,18] explained commodity basis in terms of storage cost. This theory, called the theory of storage, states that the cash price of a commodity should stay below the futures contract by the cost of carrying the commodity from harvest to that specific contract month, and as the storage season progresses, cash prices should increase relative to the futures prices. However, such cash-futures convergence may not always be perfect because of

transaction costs (i.e., demurrage, interest costs) besides storage costs that limit arbitrage [19]. Since the futures market's performance depends on how smoothly this convergence occurs, several studies examined factors that could potentially expand the spread in CBOT grain futures and exacerbate convergence problem. The literature [20–22] that investigated convergence problems suggested that the wedge between the costs of holding delivery instruments and storing physical grain could be the primary source. Aulerich et al. [23] indicated that such non-convergence could also be associated with the fluctuations in the delivery options at expiration.

Empirical studies that focused on analyzing the determinants and volatility on basis behavior are also extensive. For example, Davis & Hill [24] examined the spatial price differentials among Illinois country elevators and reported that seasonal adjustments, local demand and supply conditions, and transportation facilities' availability significantly affect such price relationships. Thompson et al. [25] used corn and soybean cash and futures prices to analyze the price relationship between and among terminal markets and reported that cash and futures price behavior differs between delivery and non-delivery months. Jiang & Hayenga [26] also analyzed corn and soybean basis behavior and found that seasonal patterns, storage, and transportation costs, and production affect basis significantly. O'Brien [27] examined the impact of structural factors such as elevators' organizational form, local and regional supply-demand situations, storage and handling capacity of grain elevators, the geographical proximity of competitive, non-affiliated elevators, and proximity to rail services on Kansas corn and wheat price differentials.

Some studies analyzed basis volatility and examined basis forecasting methods. Symeonidis et al. [28] and Gorton et al. [29] investigated the role of inventories in basis

volatility and stated that lower inventory levels are associated with a wider futures basis. Mobarok [30] estimated spatiotemporal basis volatility and reported that temporal basis volatility is predominant in overall variation in North Dakota corn, soybean, and hard red spring wheat basis levels compared to volatility associated with elevator locations. Taylor et al. [31] compared various basis forecasting methods using the data on the deviation of basis from historical average for wheat, soybeans, corn, and grain sorghum in Kansas markets. They reported that the inclusion of such current market information improves post-harvest basis forecasts. Bekkerman et al. [32] evaluated the forecasting capabilities of northern US hard red spring and hard red winter basis models. They found that recent futures price, protein content, and harvest information are more important for accurate basis forecasts than historical basis averages.

Additionally, some studies focused on the implications of ethanol production for commodity basis relationship. Gallagher et al. [33] and McNew & Griffith [34] reported that ethanol plants affect local grain prices. Fausti et al. [35] examined the relationship between ethanol production and corn basis volatility and reported that greater ethanol production strengthens local corn basis and increases basis volatility.

2.2. Climate change- the missing link?

An alternative pathway through which US agriculture could be affected is through the increased variability in origin basis behavior due to altered local supply and demand conditions and disrupted freight transportation and storage caused by aberrant climatic conditions. For example, droughts can affect vessel draft depth resulting in reduced barge loading capacity and impacting the shipping time and amount of grain transported from the upper Mississippi river basin to lower Mississippi river ports. Such disruptions could create

a grain backlog leading to an increase in inventory being held by the local elevators and subsequently weakening local basis by widening the gap between cash and futures price. Volatile and unpredictable basis behavior is likely to worsen the commodity value chain as well as suppress producer income while at the same time raising buyers' costs and consequently increasing food, biofuel, and other related consumer prices. Therefore, it is imperative to analyze the link between climate change and commodity basis.

A significant amount of literature investigated the impact of weather anomalies on agricultural production and prices. Since commodity basis and cash price are closely linked, existing literature might give us clues regarding the relevance of climate extremes in determining commodity basis. Most of these studies indicate a statistically significant relationship between climate change variables and crop supply outcomes, thus reinforcing the significance of climate extremes in determining local cash and related futures price. For example, Mishra & Cherkauer [36] found evidence of a significant correlation between drought index estimated from overserved precipitation and simulated runoff and soil moisture and US Midwest's corn and soybean yields. Miao et al. [37] estimated that, under different climate change scenarios, climate change negatively affects US corn and soybean supply. Haile et al. [38] evaluated the effect of climate change and reported that extreme growing season precipitation has a detrimental effect on global maize, wheat, rice, and soybean production. Vogel et al. [39] studied the impact of climate extremes on crop yields and reported evidence of a correlation between growing season temperature and precipitation extremes with global maize, soybeans, rice, and spring wheat yield anomalies. Climate extremes such as El Niño Southern Oscillation (ENSO) fluctuations have also been used to examine the impact of climate change on agricultural prices and production.

Ubilava [40,41] found statistically significant linkages between climate anomaly associated with El Niño Southern Oscillation (ENSO) and agricultural commodity prices. Nam [42] examined how extreme climate events resulting from ENSO fluctuations affected the global commodity market and reported that climate uncertainty increases global commodity prices. Gutierrez [43] studied the effect of ENSO occurrences on wheat yields, export prices, stocks, and exports and documented a stronger, relatively negative impact of the cold phase of the Southern Oscillation cycle (La Niña) on wheat yield anomalies, exports, and stock-to-use ratios.

Since agricultural commodities acquire place and time utility by transportation, a review of the effect of climate change on transportation is also necessary. Several studies [44–46] indicated that extreme weather events such as precipitation and storm significantly impact the transportation system. Millerd [47] examined the effects of climate change on the Great lakes international shipping and concluded that a fall in lake's water level due to climate change would restrict vessel drafts, reduce vessel cargo, increase the number of trips and cargo moving costs. Caldwell et al. [48] reported that extreme weather events such as hurricanes, snowstorms, ice storms, floods are likely to decrease safety and increase the maintenance cost of the US freight transport system. Peterson et al. [49] stated that heavy precipitation events are increasing in the US and would adversely affect transportation infrastructure.

The literature review suggests that most climate change discussions concerning agricultural commodities tend to focus on long-run impacts on production, supply and demand fluctuations, freight transportation, and prices. There have been little to no discussions on the possible impact of short-term, extreme weather events on the commodity

basis. In this study, we augment and update current literature by capturing the effect of different precipitation variables as well as their nonlinear interactions with Missouri corn and soybean basis.

3. Methods

3.1. Conceptual framework

For the purpose of this study, we consider the temporal component of corn and soybean basis, defined as:

$$b_{it} = p_{it} - f_{it}, \quad (1)$$

where p_{it} is the local price of corn/soybean and f_{it} is the price of nearby Chicago Board of Trade (CBOT) futures delivery contract.

Given the aim of this research, basis is modeled as a function of different precipitation variables, namely, local, growing season, and regional precipitation, while controlling for the effect of barge rate, diesel price, and ethanol intensity measure. Average temperature across Midwestern US has risen [5,50]. However, shifts in precipitation pattern, by contrast, pose most damaging threat to agriculture as most corn and soybean in the midwestern US are grown under rainfed conditions [51,52]. Therefore, we assume that the variation in corn and soybean production- an important determinant of local cash price, is likely to be linked to variation in precipitation during the grain-filling period. We also do not include ENSO phenomenon as there is weak evidence regarding the effect of such weather anomalies on the growing conditions of the US Midwest [53,54].

We use ethanol intensity measure, barge rate, and diesel price to capture the effect of ethanol production, river, and other non-river transportation costs, respectively.

3.2. Empirical framework

The empirical analysis is based on an unbalanced panel dataset with data available at the grain elevator and local weather station level. We consider the following two-way fixed effects model:

$$b_{it} = X_{it}\beta + u_i + r_t + \varepsilon_{it}, \quad i = 1, \dots, N; t = 1, \dots, T, \quad (2)$$

where b_{it} is weekly average commodity basis quoted by elevator i in period t , X_{it} is a vector of time-variant covariates measuring local, growing season, and regional precipitation and their quadratic terms, ethanol intensity measure, St. Louis segment barge rate, weekly average diesel price, and the interaction between port distance and the regional precipitation variables; u_i and r_t are unobserved elevator specific and time-fixed effects, respectively, and ε_{it} is the idiosyncratic error assumed to be independent and identically distributed (i.i.d.).

Local precipitation captures the immediate effect of normal or abnormal weekly rainfall on the local basis. Growing season precipitation is intended to capture the local supply effect. We fix the growing season to months June through August for corn and soybean. We hold the cumulative average of the growing season constant until the start of next year's growing season, assuming little to no additional effect of precipitation on local production after the growing season ends. Regional rainfall is one of the significant sources of flooding on the Mississippi River and its major tributaries [55]. Therefore, regional precipitation, proxied by a 3-month moving average of corn belt precipitation, aims to capture the effect of freight transportation disruptions on the local basis. To allow for the possible nonlinear influence of weather variables on basis levels, following the convention in the literature [37,38,56], we model the climate variables with linear and quadratic terms.

We also allow the interaction between corn belt precipitation variables and distance measures¹ to see whether the effect changes for points father north or south relative to the Mississippi gulf.

The quadratic nature of the precipitation variables could make parameter estimates' interpretation tricky. For straightforward comparison across models and variables, we employ average marginal effect (AME) estimate. AME is more appropriate than marginal effect at means (MEM) as it reflects the full distribution of an independent variable [57]. We calculate the AME by using the actual observed values of the covariates and then averaging the estimated partial effects. Following Bartus [58], AME can be defined as:

$$AME = \beta_i \frac{1}{n} \sum_{m=1}^n f(\beta x^m), \quad (3)$$

where βx^m is the linear combination of parameters and variables for the m^{th} observation.

We are aware of the potential impact that the different intensities of precipitation could have on barge rate. Barge rates are expected to be affected by the demand for downbound shipment of grain from the origin point. Since precipitation can affect the local grain production and demand for grain shipment, barge demand could derive from the good or bad harvest affected by the different intensities of precipitation. Therefore, the barge rate variable may not be exogenous, and a simultaneity bias may occur. To avoid biased and inconsistent estimates, we resort to two-stage fixed effect (FE-2SLS) estimation. We employ such estimation technique only for the model where barge rate is endogenous.

Since barge rate could be endogenous, identification requires finding at least one instrumental variable, which is exogeneous and uncorrelated with the residual term in the

¹ We estimate the straight-line north-south distance (as crow flies) that an elevator is from the port of New Orleans, Louisiana.

basis equation. The instrumental variables selected include S&P 500 index, U.S. merchandise exports, and U.S. Dollar index. The S&P 500 index is used as a proxy for improved general economic conditions that could drive the demand for non-agricultural barge freight transportation; the U.S. Dollar index (trade-weighted average of major currencies) and U.S. merchandise exports are used as demand shifters, which satisfies the exogeneity requirement essential for our case.

3.3.Data

Data for this research are obtained from a variety of disparate sources. Basis and precipitation data are collected from the dedicated server of refinitiv and National Oceanic and Atmospheric Administration (NOAA), using an application programming interface (API). Transportation data (barge rate and diesel price) were obtained from USDA's Agricultural Transportation Open Data Platform. The data spans the range between January 2010 and October 2020.

As can be seen in Figures 1 and 2, corn and soybean production in Missouri is primarily concentrated in the northern half of the state and the boot heel region. This is mainly due to the mountainous terrain of south-central region which makes it unsuitable for agricultural production. The average weekly basis (Figure 3 & 4) is then estimated from the daily corn and soybean basis quoted by 151 elevators situated across Missouri.

Figure 1. Corn elevator locations

Figure 2. Soybean elevator locations

Figure 3. Corn basis map

Figure 4. Soybean basis map

We also estimate average weekly local precipitation (Figure 5 & 6) using the daily precipitation amounts recorded and reported by 1,112 weather stations positioned across the state.

Figure 5. Local precipitation map- weather stations around corn elevators

Figure 6. Local precipitation map- weather stations around soybean elevators

Stations that do not report precipitation consistently through the sample period for the growing season are excluded from the analysis to minimize potential estimation bias. We assume that an elevator will likely receive its grain from a 30-mile radius. Therefore, we filtered out weather stations that are farther than 30 miles from the respective elevator's location.

The summary statistics are provided in Table 1.

Table 1. Descriptive statistics of the study variables

Variable	unit	Corn				Soybean			
		Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Basis	\$/bu	-0.18	0.30	-1.42	1.83	-0.33	0.44	-1.5	2.97
Local precipitation	inches	0.83	1.07	0.00	10.39	0.82	1.07	0.00	10.39
Growing season precipitation	inches	1.11	0.50	0.00	5.36	1.10	0.48	0.00	5.36
Corn belt precipitation	inches	2.97	1.18	1.08	5.78	2.96	1.18	1.08	5.78
Barge rate	\$/ton	12.82	4.97	6.08	41.23	12.85	4.98	6.08	41.23
Diesel price	\$/gallon	3.10	0.61	1.91	4.15	3.11	0.62	1.91	4.15
Ethanol intensity	000 gallons/sq. km	4.02	2.87	0.00	11.32	4.02	0.45	0.00	11.32
Distance to NOLA	100 km	10.17	0.95	7.34	11.75	10.20	0.93	7.34	11.75
US Dollar index	index	90.31	9.37	73.94	108.19	89.96	9.41	73.94	108.19
S&P 500	index	2043.77	644.81	1022.58	3709.41	2067.94	647.19	1022.58	3709.41
US merchandise export	billion dollars	108.86	9.67	77.45	127.40	108.81	9.64	77.45	127.40

Source: Authors' calculation

The weekly mean corn and soybean basis is negative, indicating local cash price lies mostly under the CBOT futures price, and Missouri is a corn and soybean surplus region. Corn basis appears to be less volatile than soybean when compared based on the standard deviation. This implies that stylized facts such as storage, trade, and transportation have a more exacerbating effect on soybean demand and supply. On the other hand, among the weather variables, corn belt precipitation seems most volatile if assessed by the same

criteria. Barge rates have a relatively high standard deviation when compared to diesel price, indicating frequent higher than the normal price for downbound freight originating from St. Louis. Ethanol intensity² is used as a proxy to capture the exogenous effect of local demand for corn on basis levels. It is a kernel density function-based measure that uses the nameplate capacity of ethanol plants located near the elevators in our sample.

4. Results

We estimate the FE-2SLS and FE model for corn and soybean, respectively. The model FE-2SLS accounts for the endogeneity of barge rate and minimizes potential simultaneity bias in the estimation procedure. We also estimate the average marginal effect by averaging the partial effect of each observed value of an independent variable. The diagnostics are reported in the lower part of Table 2. First, we test the null hypothesis that barge rate can actually be treated as exogenous. The endogeneity test that we implement here is numerically identical to a Hausman test under the assumption of conditional homoskedasticity [59]. We reject the null in the corn basis model suggesting FE estimates are inconsistent.

On the other hand, in the soybean model, we fail to reject the null, implying the barge rate variable is not endogenous and, consequently, the FE model yields unbiased estimates. Next, for the corn model, we report the Anderson's canonical correlation LM statistic, Cragg–Donald statistic, and Sargan's statistic, which are the results of tests for underidentification, weak identification, and overidentification, respectively. The test results, shown in the lower half of Table 2, indicate that in the corn model, excluded instruments are properly excluded and sufficiently correlated with the barge rate. The test

² This variable is estimated by Vince Breneman (OCE, USDA).

for overidentification, using the Sargan's statistic shows that we cannot reject the joint null hypothesis that instruments are valid and correctly excluded from the estimated equation.

Therefore, the results from the FE-2SLS model are consistent.

Table 2. Effect of precipitation variables on basis

Variables	Corn		Soybean	
	2SLS-FE	Average marginal effect	FE	Average marginal effect
Local precipitation	-0.006** (0.003)	-0.003 (0.002)	0.012*** (0.004)	0.008*** (0.003)
Local precipitation ²	0.002*** (0.001)		-0.002** (0.001)	
Growing season precipitation	-0.190*** (0.007)	-0.111*** (0.003)	-0.289*** (0.028)	-0.082*** (0.011)
Growing season precipitation ²	0.035*** (0.002)		0.094*** (0.011)	
Corn belt precipitation	0.012 (0.067)	0.044*** (0.001)	-0.039 (0.123)	0.062*** (0.003)
Corn belt precipitation ²	0.002 (0.010)		0.012 (0.021)	
Corn belt precipitation*distance	-0.002 (0.007)		-0.022* (0.012)	
Corn belt precipitation ² *distance	0.001 (0.001)		0.004** (0.002)	
Ethanol intensity	0.039*** (0.003)	0.039*** (0.003)	-0.003 (0.017)	0.003 (0.017)
Diesel price (dollars per gallon)	0.306*** (0.005)	0.306*** (0.005)	0.265*** (0.010)	0.265*** (0.010)
Barge rate	-0.047*** (0.001)	-0.047*** (0.001)	-0.025*** (0.001)	-0.025*** (0.001)
Constant	-0.583*** (0.019)		-0.411*** (0.088)	
Endogeneity test of endogenous regressors (P-value)	0.000		0.1159	
Under-identification test (Anderson canon. corr. LM statistic)	2745.739			
Weak identification test (Cragg-Donald Wald F statistic)	988.895			
Overidentification test (p-value of Sargan statistic)	0.140			
Observations	36,794		34,106	
R-squared (overall)	0.234		0.226	

Source: Authors' calculation

Note: Standard errors in parentheses; Delta-method Std. errors are reported for average marginal effect.

*** p<0.01, ** p<0.05, * p<0.1

Results indicate that, the coefficients of local precipitation and squared local precipitation are statistically significant for both corn and soybean model. The findings imply that there exists a U-shaped or convex relationship between local precipitation and corn basis; that is, when local precipitation is lower than the inflection point of 1.5 inch, the increase in local precipitation weakens corn basis, and once it crosses that threshold level, increase in local precipitation strengthens the basis. Response of soybean basis is different from that of corn basis as the effect of local precipitation is positive with a decreasing rate, indicating an inverted U-shaped relationship. This implies that soybean basis strengthens as local precipitation increases and attains the maximum value at 3.25 inch (inflection point). After that, additional average weekly local precipitation accumulation will weaken the soybean basis. The AME estimates for corn basis is statistically insignificant and positive. Conversely, the statistically significant, positive AME estimate in soybean model indicates that a 1% increase in local precipitation will strengthen the soybean basis by 0.90 cents. Our analysis does not lend itself to empirically finding the source of the differences in corn and soybean model in terms of the sign and magnitude of local precipitation variables and AME estimates. However, such contrasts could be due to the variations in evapotranspiration demands during the various growth stages, and difference in market fundamentals such as local supply and demand, stock and storage, and marketing plan.

Growing season precipitation, on the other hand, exhibits U-shaped relationship in both models. The coefficients and associated AME measures are statistically significant at 1%. The estimates show that basis keep weakening up to 2.71 and 1.54 inch of growing season precipitation accumulation for corn, and soybean, respectively, when both basis

levels are at their minimum. The AME estimates suggest that for every 1% increase in growing season precipitation, corn and soybean basis will weaken by 11.1 and 8.1 cents, respectively. Intuitively, we would expect basis to be wider in response to a large local supply caused by a favorable growing season weather and opposite is expected in case of a tighter production situation. This is consistent with the literature that reported higher growing season precipitation improves corn and soybean production, whereas extreme growing season precipitation events have negative impact on production (56,60,61).

The quadratic effect, along with the interaction influence of distance measures make direct interpretation of corn belt precipitation complicated. Hence, for an intuitive understanding, it is better to focus on the AME estimates rather than variable specific discussion. The AME estimates are significant at 1% level and imply that a 1% increase in corn belt precipitation will strengthen corn and soybean basis by 4.4 and 6.3 cents, respectively. This indicates that transportation disruptions are resulting in higher local price compared to futures prices, which is opposite of the findings reported by Hart & Olson [62], who stated that transportation disruptions is associated with widening basis and falling local prices. One possible explanation could be use of alternate trade route (e.g., pacific northwest), transportation mode (e.g., truck, rail), or additional marketing opportunities (e.g., local ethanol production, soybean processing centers, wet corn milling) that absorb displaced barge traffic and bolster local demand- effectively strengthening the basis.

The results also indicate that the relationship between soybean basis and corn belt precipitation is statistically significant when port distance is considered, indicating uninterrupted access to export facilities impact local soybean market through smooth

interregional trade and transportation linkage. One explanation could be, compared to corn, relatively large soybean export volume [13] and share of soybean export from Missouri via Mississippi gulf [63] are exerting influence and allowing soybean basis surface to adjust significantly. The signs of linear and quadratic terms also match the expectations. Negative linear term indicates that under normal weather condition which allows uninterrupted grain shipment along the river, basis would be less negative for southern elevators due to the difference in spatial arbitrage. Positive quadratic term suggests that the soybean basis would be stronger for northern elevators compared to southern elevators when flooding along the Mississippi river disrupts export-bound grain flow. Without any ability to confirm, we presume this could be due the fact that northern elevators have to ship through the south. Therefore, anything that affects the southern elevators for a while would affect the northern elevators as well but not the vice versa.

Among the control variables, the ethanol intensity measure positively affects corn basis, as expected, and is significant at a 5% level. Corn basis strengthens by 3.9 cents with every thousand gallons/per sq. miles increase in ethanol intensity. This could be explained by the increased demand for nearby cash sales of corn due to the expanded ethanol intensity in the area surrounding the local elevator. Concerning the non-river transportation cost proxy, the coefficients for diesel price in both models are positive and statistically significant at 1% level, a finding that is contrary to theoretical expectations. A theoretical explanation of this result could be that the cost paid by the growers for shorter-haul shipment- delivery from farm to elevator location results in a higher local price. Another possible explanation could be that the diesel variable is picking up the effect of cash costs producers incur from using fuel for grain production, but this seems quite unlikely given

the relationship between weekly diesel price and annual production costs as well as the scope for country-wide cost effects rather than locally distinct cost effects. The different barge and diesel price effects are difficult to explain in the end given that both are included to represent costs of transportation from local collection points to markets. The barge rate-basis relationship is statistically significant at a 1% level and has the expected negative sign in both models and consistent with other studies [1,2,64] that reported similar findings.

5. Conclusions

Using an extensive panel dataset for the period from 2010 to 2020 and an empirical framework, we analyze the effect that precipitation variations have on Missouri corn and soybean basis. In particular, we examine the influence of local, growing season, and regional precipitation on corn and soybean basis. We document statistically significant linear and nonlinear basis responses in both corn and soybean models for local and growing season precipitation variations. We also find a statistically significant moderating effect of port distance measure on the curvilinearity of the association between regional precipitation and soybean basis. Correspondingly, we find that transportation disruptions and the interceding effects of port distance are not statistically significant for corn basis. One explanation could be the offsetting effect of local corn demand, boosted by ethanol production and livestock feeding operations, which are muting these impacts on corn basis. The average marginal effect of corn belt precipitation is, however, found to be statistically significant and positive in both corn and soybean model indicating a possible spurring effect of the alternative trade route and grain transportation mode on Missouri corn and soybean basis. It is important to note that we estimated the short-run determinants of basis which might not hold in the long-run as the estimates are sensitive to the future climate

trajectory and any climate change policy framework that can influence market dynamics. Most climate models project that extreme precipitation events such as droughts and floods will increase in the US [5,65–67]. Previous studies have focused on the price and production effect of climate change and overlooked commodity basis. Commodity basis is an important market tool that reflects variability related to local supply and demand. Therefore, estimating the climatic effect on commodity basis and detecting threshold level for significant basis impact could facilitate informed grain marketing and selling decisions. Also, given the climate projections, there are legitimate concerns regarding precipitation's influence on future navigability of major transportation arteries that link Missouri to export facilities down the Mississippi river. Hence, the information generated in this research has even greater utility when studied in the context of the role barge freight transportation plays in the state's agriculture.

Although our models explain significant precipitation-related variation in corn and soybean basis, future research is warranted to predict the effect of alternative future climate change scenarios on the commodity basis. The focus of the current study is on Missouri corn and soybean which may limit the generalization of the findings for locations such as corn belt. Therefore, a more elaborate empirical framework, capable of capturing the regional climate induced basis variation is a likely improvement. However, even with the aforementioned limitations, the findings of this study can still be used to inform policies that aims at limiting adverse impact of climate change on state agriculture by planning and implementing appropriate adaptation strategies.

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Vita

I do not have much to say about me. I am an ordinary man with medium level intellect and very big ambition. I knew that if I can work hard and be honest, I can amount to something in this great country. I was born in a very poor family in Bangladesh. My mother, despite being illiterate, did understand the importance of education and fought courageously against all odds to make sure that her three children get a good education. From the very early age, I wanted to make my parents proud and happy. This terminal degree is my way of honoring my parents for all the sacrifices they made for me and my siblings. I know that this achievement is just the beginning, the night is still young and there are many more to achieve. In the words of Robert Frost- *The woods are lovely, dark and deep/ But I have promises to keep/ And miles to go before I sleep/ And miles to go before I sleep.*