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RESEARCH ARTICLE

Quantifying Wheat Blast Disease Induced Yield and Production Losses of Wheat: A Quasi-Natural Experiment

Khondoker Abdul Mottaleb[1,2*], David P. Hodson[2], Timothy J. Krupnik[2] and Kai Sonder[2]

[1]Department of Agricultural Economics and Agribusiness, University of Arkansas, Fayetteville, AR 72701, USA and [2]Sustainable Agrifood Systems (SAS) Program, International Maize and Wheat Improvement Center (CIMMYT), Texcoco, Mexico, and Dhaka, Bangladesh
*Corresponding author. Email: mottaleb@uark.edu

Abstract

Applying the difference-in-difference (DID) estimation procedure, this study quantifies the wheat blast (*Magnaporthe oryzae* pathotype Triticum) induced losses in wheat yield, quantity of wheat sold, consumed, or stored, as well as wheat grain value in Bangladesh in 2016 following a disease outbreak that affected over 15,000 ha. Estimates show that the blast-induced yield loss was 540 kg ha^{-1} on average for households in blast-affected districts. Estimated total wheat production loss was approximately 8,205 tons worth USD 2.1 million in during the 2016 outbreak. Based on these insights, we discuss the need for long-term assured investment and concerted research efforts in controlling transboundary diseases such as wheat blast, including the importance of weather forecast driven early warning systems and the dissemination of blast-resistant varieties.

Keywords: diseases; economic valuation; invasion; maintenance breeding; pests; wheat

JEL classifications: O13; Q12; C01

1. Introduction

Crop diseases and pests are a consistent concern for resource-poor farmers, particularly in developing countries, as they can threaten food and income security by undermining yield stability (Anderson et al., 2004; FAO, 2017; Fisher et al., 2012; Fones, Fisher, and Gurr, 2017; Fones et al., 2020; Lidwell-Durnin and Lapthorn, 2020; McDonald and Stukenbrock, 2016; Mitra, 2021; Strange and Scott, 2005). Recent examples of damaging disease outbreaks include the re-emergence and spread of stem rust (*Puccinia graminis* f. sp. *tritici*) of wheat (*Triticum aestivum* L.), in Africa, the Middle East, and Europe (Patpour et al., 2022; Singh et al., 2015), the advent and spread of Maize Lethal Necrosis (MLN) to eastern Africa (Wangai et al., 2012), the incursion of Fall Armyworm (*Spodoptera frugiperda*) to Africa, Asia, and Oceania (Goergen et al., 2016; Piggott et al., 2021; Sharanabasappa Kalleshwaraswamy et al., 2018). The emergence of wheat blast (*Magnaporthe oryzae* pathotype *Triticum* (MoT)) in Asia is an additional concerning example (Islam et al., 2016; Montes, Hussain, and Krupnik, 2022; Mottaleb, Singh, et al., 2018). Quantifying the impacts of pests and diseases on crops is important and has long been a major research area in agriculture, with increasing emphasis now placed on transboundary pests

(De Groote et al., 2016; Donatelli et al., 2017; Esker, Savary, and McRoberts, 2012; Marenya et al., 2018; Oerke, 2006; Savary et al., 2019; Whish et al., 2015).

Pure empirical studies quantifying the impacts of pest and disease outbreaks on crops at national or regional scales are few. This is because, a proper pathological and economic impact assessment of crop loss due to pests and diseases requires accurate datasets on crop production and pre- and post-outbreak incidence and severity measures in a specific country or region. Assessing impacts of crop loss due to pests and diseases by applying a rigorous econometric estimation process with actual datasets may conversely provide important insights as to the severity of pest and disease outbreaks, thereby providing information and insights to aid farmers and agricultural development planners in improved decision-making. Yet as appropriate datasets are limited, impact studies of crop pest and disease outbreaks mostly rely on opinion survey, small-scale agronomic and plot based studies, farmer surveys, or expert solicitations and crop modeling approaches (De Groote et al., 2016; Donatelli et al., 2017; Marenya et al., 2018; Oerke, 2006; Savary et al., 2019; Whish et al., 2015). To our knowledge, there is no single study that applied a rigorous econometric estimation process using reliable datasets, to quantify the economic impacts of crop pest and disease outbreaks in any country or geography. Using nationally representative datasets collected by the Bangladesh Bureau of Statistics (BBS) to address this important research gap, we apply a difference-in-difference (DID) estimation procedure to provide quantitative estimates of wheat blast induced production losses during an outbreak year in Bangladesh.

Wheat blast is caused by the fungus *Magnaporthe oryzae* pathotype *triticum* (MoT) and can result in significant yield losses (Urashima et al., 2009). It is one of the most challenging wheat diseases to control and can exert significant damage by infecting wheat spikes and reducing grain formation. In less than three weeks from infection and as short as a week from showing the first visible symptoms, wheat blast desiccate and deform grain (O'Leary, 2019). In cases of severe outbreaks, applications of fungicides are often ineffective (Urashima et al., 2009). The speed at which yield loss is incurred following visible symptoms means that it is very challenging for smallholder farmers—especially those who may not be able to afford or access fungicides—implement disease control tactics. Wheat blast was first identified in Parana State of Brazil in 1985 (Igarashi, 1986), later spreading to many wheat-producing areas of Brazil (Goulart et al., 2003; Igarashi, 1990). It was reported in Bolivia in 1996, and Paraguay and northeastern Argentina in 2002 (Cruz and Valent, 2017). Further spread was recorded in Argentina and by 2012 the disease was identified in Buenos Aires Province (Perelló, Martinez, and Molina, 2015). In the 2015–16 wheat season, and for the first time outside of Latin America, wheat blast was reported in South Asia and in Bangladesh specifically (Islam et al., 2016). Alarmingly, in 2017–18 season, wheat blast outbreak also confirmed in Africa, specifically in Zambia (Tembo et al., 2020).

In February of 2016, wheat blast affected nearly 15,000 ha of wheats across eight districts of Bangladesh including Barishal, Bhola, Chuadanga, Jashore, Jhenaidah, Kushtia, Meherpur, and Pabna (Islam et al., 2016). The blast-affected wheat area represented approximately 3.4% of Bangladesh's total wheat-producing area in the 2015–16 wheat season of Bangladesh (BBS, 2018). Reported crop yield losses ranged from 5 to 51% (Islam et al., 2016), with incidences of up to 70% of the wheat area in some districts being infected. Varying levels of severity and within-field incidence were reported, with some farmers reporting a near 100% loss, and others with varying levels of reported yield loss (Islam et al., 2016). In subsequent years, wheat blast spread to other districts of Bangladesh; however, incidence and severity of the disease have been limited and repeated outbreaks at the same level of severity as 2016 have not been recorded. Following the 2016 outbreak, the Government of Bangladesh discouraged wheat cultivation in severely blast-affected districts (BBS, 2018; Mottaleb, Singh, Sonder, et al., 2019), an action that may have, to some extend, limited the propagation of MoT spores in the environment, although annual surveillance continues to record airborne MoT spore presence in Bangladesh (CSISA, 2019, 2020, 2021). Following the outbreak of wheat blast and the action of the government, as

Table 1. Wheat cultivation, consumption, and import in Bangladesh

Year	Area ('000 ha)	Production (000, ton)	Yield (tons/ha)	Consumption (yearly/capita/kg)	Share in daily consumption (kcal, %)	Total consumption ('000 tons)	Import ('000, tons)
TE1963	63.0	38.9	0.6	8.8	3.5	465	464
TE1973	124.4	105.9	0.9	21.2	9.2	1,464	1,450
TE1983	548.2	1,051.8	1.9	24.8	10.4	2,162	1,324
TE1993	603.5	1,081.7	1.8	20.1	8.3	2,261	1,372
TE2003	740.5	1,595.2	2.2	20.9	7.7	2,868	2,192
TE2013	382.8	1,074.1	2.8	17.3	6.1	2,673	2,698
TE2018	403.8	1,253.0	3.1	19.0	6.5	3,034	5,724
TE2020	338.0	1048.4	3.1	18.7[a]	6.2[a]	3,011[a]	5,150

[a]TE2019.

Note: TE: triennium average ending.

Source: Authors' calculation from (FAOSTAT, 2021b).

well as due to competition with alternative crops (Mottaleb, Singh, He, et al., 2019), total wheat area in Bangladesh has gradually reduced to 25% (to 332,278 ha) in 2019–20 (BBS, 2020).

Despite the damaging nature and scale of the wheat blast outbreak in Bangladesh, no study quantified the national productivity and profitability impact of wheat blast in Bangladesh. While some studies have assessed wheat yield losses, for example Islam et al. (2016), they tend to be based on less systematic observational data and reports from farmers. Islam et al. (2016), for example, states that crop yield losses ranged from 5 to 51% across Bangladesh but did not include fully representative sampling. Reportedly, up to 70% of the wheat area in some districts was infected by wheat blast, though with varying severity levels. Conversely, the present study provides the first quantitative assessment of wheat production losses using data supplied by the Government of Bangladesh and applying econometric methods that have not yet been applied in the study of disease inflicted yield losses.

2. State of Wheat Production and Consumption in Bangladesh

Bangladesh is a major rice-consuming country; however, wheat consumption has also been increasing due to rising per capita income, rapid urbanization, and associated changes in lifestyles and dietary preferences (Hossain and Teixeira da Silva, 2013; Mottaleb, Rahut, et al. 2018a, 2018b, 2018c). In the triennium ending (TE) 1963, the average yearly per capita wheat consumption in East Pakistan (now Bangladesh) was nearly 9 kg, providing 3.5% of the daily per capita average total calorie intake (Table 1). In TE 2019, the average yearly per capita wheat consumption had increased to 18.7 kg, providing 6.2% of the daily per capita average total calorie intake (Table 1).

Domestic wheat production has, however, failed to meet increasing demand. In TE 1963, wheat was cultivated on 63,000 ha of land with a yield of 600 kg ha^{-1}. Total wheat production was estimated at less than 39,000 tons in East Pakistan (Bangladesh was a part of Pakistan before its independence in 1971) (Table 1). Yearly per capita wheat consumption was 8.8 kg, and total wheat consumption was 465,000 tons. To meet domestic demand, 464,000 tons (Table 1) worth USD 34 million had to be imported (FAOSTAT, 2021a). In TE 2018, total land allocation to wheat in Bangladesh had grown dramatically to nearly 404,000 ha, with yields averaging 3,100 kg ha^{-1}, and total wheat production at approximately 1.3 million tons (Table 1). With a yearly per capita consumption of 19 kg, the total wheat consumed was approximately 3 million tons. To fill the gap

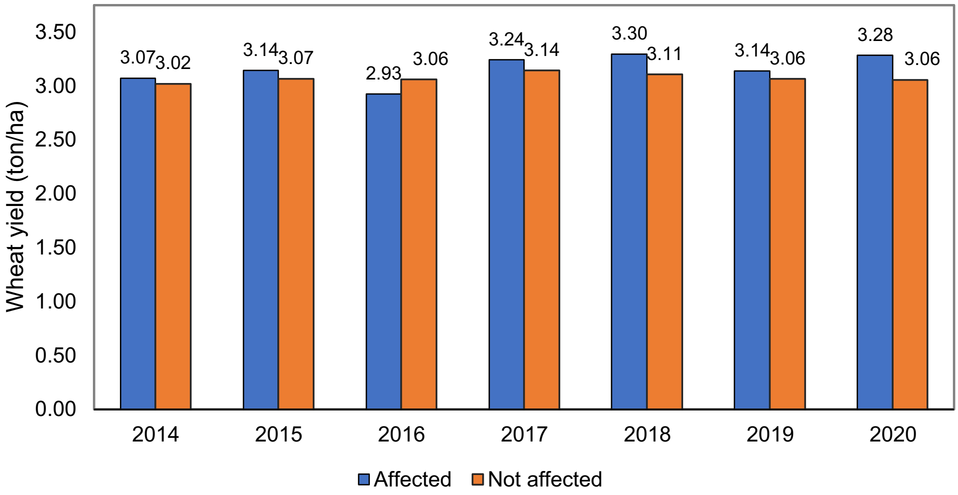

Figure 1. Trends in wheat yield during 2013–14 to 2019–20 seasons by the group of districts whether or affected wheat blast in 2016. Sources: BBS (2016, 2018, 2020); BSS (2020). Note: Barishal, Bhola, Chuadanga, Jashore, Jhenaidah, Kushtia, Meherpur, and Pabna districts were affected by wheat blast in 2016, and all other districts were not affected (Islam et al., 2016).

between domestic supply and demand, Bangladesh imported 5.7 million tons of wheat (Table 1) worth USD 1.2 billion (FAOSTAT, 2021a). In 2020, Bangladesh was the 9th largest wheat importing country in the world with an import of six million tons worth USD 1.4 billion (FAOSTAT, 2021a). Considering the projected population and the per capita GDP growth of Bangladesh and anticipated further changes in lifestyle and diets (including increased consumption of bread, biscuits, pasta, and crackers), it is expected that wheat consumption will increase further in the future (Mottaleb, Hossain, and Hossain, 2020; Mottaleb et al. 2018b, 2018c).

Yet while these figures underscore why there is interest in boosting domestic wheat production in Bangladesh, the outbreak of wheat blast in 2016 severely and negatively affected land area allocated to wheat cultivation. Out of 64 districts, wheat was cultivated in 60 districts in the 2015–16 wheat season (BBS, 2017b). Following initial reports in mid-February of the latter year, wheat blast was subsequently recorded in eight districts including Barishal, Bhola, Chuadanga, Jashore, Jhenaidah, Kushtia, Meherpur, and Pabna (Islam et al., 2016).

The trends of wheat yield from 2013–14 to 2019–20 are presented for the eight affected and 56 unaffected districts in the 2015–16 season (Figure 1). In the 2013–14 and 2014–15 wheat seasons, the average wheat yield in these districts was 3.07 tons ha^{-1} and 3.14 tons ha^{-1}, respectively (Figure 1). In the 2015–16 wheat season, following the blast outbreak, recorded wheat yields were on average 7% lower (2.93 tons ha^{-1}) compared to the 2014–15 season. In contrast, average wheat yield in nonaffected districts remained almost constant in the 2015–16 compared to previous seasons (Figure 1).

As a result of the wheat blast outbreak, and absence of resistant cultivars, farmers responded to governmental directives in the severely blast-affected districts by drastically reducing wheat-cropped areas in the subsequent seasons (Figure 2; BBS, 2018). This severely affected domestic production. In the 2014–15 wheat season, a the ear before the outbreak of wheat blast, total land allocation to wheat was 436,814 ha, with average national yields estimated at 3.08 ton ha (BBS, 2018) and a total wheat production of 1.34 million tons (BBS, 2016). By the 2019–20 wheat season, wheat area had declined to 332,274–ha, that is, 24% less than allocated in 2014–15. Lack of significant blast infections in subsequent years and more favorable growing conditions contributed to a slightly higher average national yield of 3.1 ton ha^{-1} (BBS, 2020). National wheat production

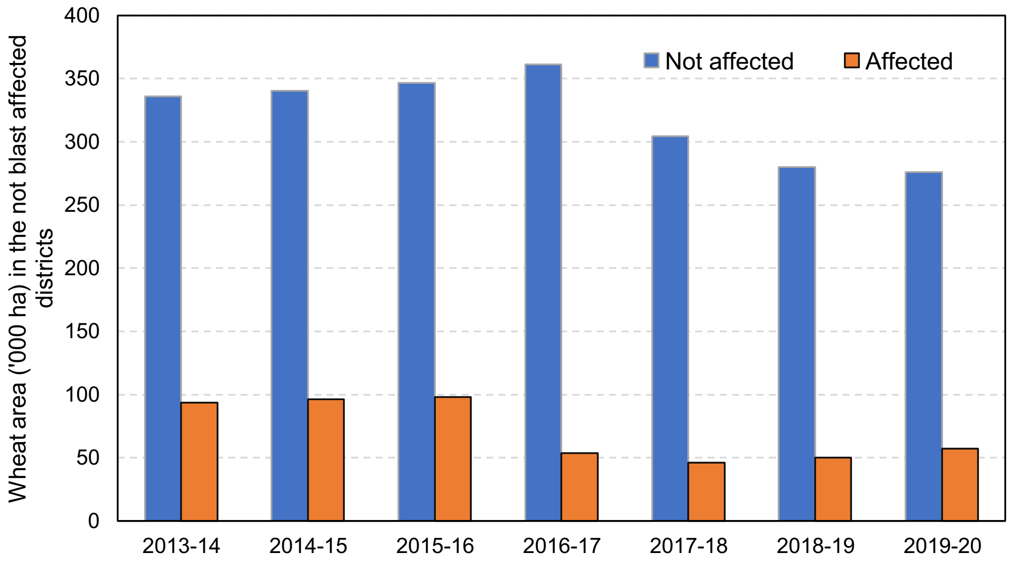

Figure 2. Wheat area during 2013–14 to 2019–20 wheat season in blast-affected and non-affected districts. Source: BBS (2016, 2018, 2020); BSS (2020). Note: Barishal, Bhola, Chuadanga, Jashore, Jhenaidah, Kushtia, Meherpur, and Pabna districts were affected by wheat blast in 2016 (Islam et al., 2016).

nonetheless dropped to 1.02 million tons (BBS, 2020), due in part to the reduction in cropped area (Figure 2).

In 2015–16 wheat season, during which the wheat blast outbreak was experienced, total land allocated to wheat in the initial eight blast-affected districts was 98,000 ha. In the subsequent year, land area allocated to wheat declined by 45% to 54,000 ha. Wheat area also declined in the initially non-blast-affected districts of Bangladesh (Figure 2). In 2016–17, a year after the initial outbreak of wheat blast, the total wheat area in the initially nonaffected districts was 362,000 ha; this declined to 276,000 ha in 2019–20 wheat season (Figure 2). This drastic reduction in wheat area was mainly due to the outbreak of wheat blast and its effects on farmers' willingness to cultivate wheat; this was further compounded because of governmental policy that discouraged wheat production, and that eliminated the supply of seed and subsidized fertilizer for wheat farmers (BBS, 2018). Although wheat blast initially affected eight districts of Bangladesh, in subsequent years wheat blast has spread to several other districts of Bangladesh (Mottaleb, Govindan, Singh, et al., 2019). Further spread of wheat blast is also possible. Using historical climate analogs of the initial blast affected districts, it was initially estimated that 65% of the wheat area of Bangladesh across 45 districts, 21% of the wheat area of India across 138 districts, and nearly 2% of the total wheat area of Pakistan across five districts in the southern region could be vulnerable to wheat blast (Mottaleb, Singh, et al., 2018).

3. Materials and Methods

3.1. Data

To quantify the impacts of wheat blast on yield, wheat marketing, consumption, and income at the household level, Household Income, and Expenditure Survey (HIES) data collected by the BBS were used. Up to 2021, BBS has conducted 16 rounds of surveys since independence in 1971. The HIES data are nationally representative survey data, mainly used for estimating monetary poverty within Bangladesh (BBS, 2017a). To enhance the precision in data collection, a two-stage stratified random sampling process is followed in the data collection process. Firstly, based on the geographic area, the primary sampling units (PSU's) are constructed considering the rural and urban status of the geographic areas. In the second stage, 20 households are randomly selected for a detailed interview from each PSU. In general, the HIES survey of Bangladesh is a multipurpose survey. The questionnaire includes nine sections, from which detailed information on household-level demographics, food consumption, farm, and nonfarm economic activities, and labor allocation information are collected. Details of the data collection process, sampling, questionnaire, and documents related to HIES 2010 and HIES 2016 are available on-line (IHSN, 2018, 2019).

Wheat blast was first detected in Bangladesh during February of 2016 (at the tail end of the 2015–16 wheat season); correspondingly, HIES 2016 data are used as the endline data and HIES 2010 data are used as the baseline data. In the HIES 2010 data, a total of 12,240 households from all 64 districts of Bangladesh were surveyed from February 1, 2010, to January 31, 2011, and in HIES 2016 a total of 46,080 households were surveyed from all 64 districts of Bangladesh during the period April 1, 2016, to March 31, 2017. In this study, we focus on quantification of the impact of the 2016 wheat blast outbreak on wheat yield, marketing, consumption and storage, and income earned from sales of wheat. We therefore considered only the sampled households that cultivated wheat in either 2010 and/or 2016. However, not all districts of Bangladesh are climatically suitable and vulnerable to wheat blast.

In a preliminary study, Mottaleb, Singh, et al. (2018) identified that out of 64 districts, only 46 districts are climatically suitable and vulnerable to wheat blast. Subsequently, Montes, Hussain, and Krupnik (2022) applied a continental-scale disease modeling approach and used gridded climate data from 1980 to 2019, with results suggesting that Bangladesh has the highest risk of infection in Asia. In this study, we have considered the wheat-producing agricultural households that are located only in the 46 blast vulnerable districts. This study therefore is based on information of 1,025 wheat-producing agricultural households, of which 310 are from HIES 2010 and 715 are from HIES 2016. Among the sampled households, 454 wheat cultivating agricultural households were sampled in Bhola, Chuadanga, Jashore, Jhenaidah, Kushtia, Meherpur, and Pabna, the districts, which were affected by wheat blast in 2016 (Islam et al., 2016; Malaker et al., 2016). We considered the sampled households in these districts as the households in the experiment group. The rest of the households from other districts are treated as the households in the control group (Figure 3). It is important to mention that Barishal district was affected by wheat blast in 2016; however, in HIES 2010 and 2016, there were no wheat-producing households that were sampled by BBS from this district. We therefore dropped Barishal from our analysis.

In Bangladesh, January and February are the critical months for vegetative growth and March is crucial for the grain filling of wheat. A warmer temperature, with high relative humidity including rainfall, can generate favorable conditions for a blast outbreak. Considering the issue, this study also included weather variables in the estimation to isolate weather impacts on wheat yield, production, wheat marketing, and wheat income. Climate data on daily average maximum and minimum temperature (°C) and daily total precipitation (millimeters) were collected from the Climate Hazards Center of the University of California in Santa Barbara (https://www.chc.ucsb.edu/data). The relative humidity data are derived as a subset from the temperature data. Specifically, the daily average maximum and minimum temperature data are collected from Funk et al. (2019); the daily precipitation data are collected from Funk, Peterson, et al. (2015) and Funk, Verdin, et al. (2015); and the daily relative humidity data (%) are derived as a subset from Funk et al. (2019). The data were downloaded in geotiff format. Using ESRI ArcMap 10.8.1 software, the collected geotiff files data are converted to its native raster format. After that raster calculator functions were used to generate monthly precipitation sums as well as monthly averages for temperature and relative humidity. The zonal statistics function in combination with a polygon file for the district-level administrative boundaries was utilized to calculate average monthly climate values for 64 districts of Bangladesh.

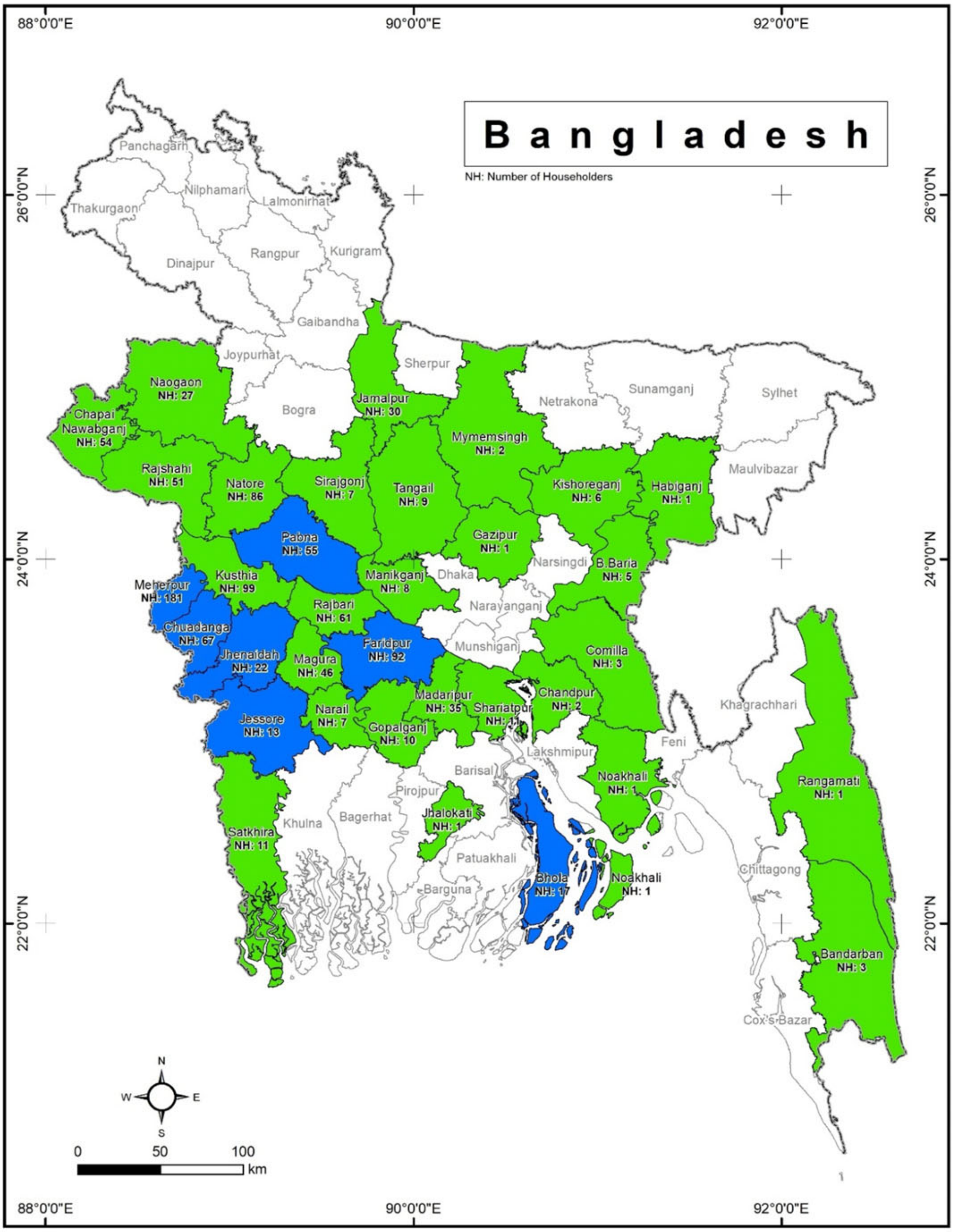

Figure 3. Number of the sampled households by sampled districts. Households located in blue colored districts are in the experiment group – wheat crop affected by blast in 2016, and sampled households located in green colored districts, are in the control group, were not affect by blast in 2016. NH indicates number of households.

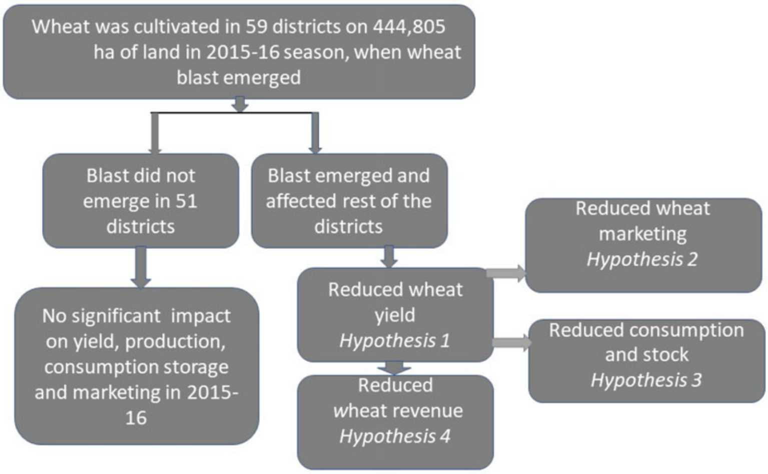

Figure 4. Wheat blast incidence in Bangladesh in 2015–16 and testable hypotheses.

3.2. Research Hypotheses, Model Specification, and Estimation Procedure

3.2.1. Research Hypotheses

In the 2015–16 wheat season, wheat blast affected wheat crops in the sampled Bhola, Chuadanga, Jashore, Jhenaidah, Kushtia, Meherpur, and Pabna districts of Bangladesh, whereas the wheat crop in other districts of Bangladesh was not affected by blast in the 2015–16 wheat season (Islam et al., 2016; Malaker et al., 2016). Based on this natural phenomenon, we developed a conceptual framework and developed four hypotheses (Figure 4).

Four testable hypotheses were developed (Figure 4):

H1: Wheat blast significantly and negative affected wheat yield of households in blast affected districts in 2016 compared to the households in the districts that were not affected in 2016.

H2: Because of significant loss in wheat yield, households in the wheat blast-affected districts sold less wheat compared to others in 2016.

H3: Also because of significant loss in wheat yield, households in the wheat blast-affected districts consumed and stored less wheat compared to others in 2016.

H4: The revenue generated from wheat sales by households in wheat blast-affected districts was also less than other households in 2016.

3.2.2. Model Specification and Estimation Process

To establish and causal relationship, between wheat yield, marketing, consumption and storage, and revenue income from wheat and the wheat blast-affected year (year 2016), we employed the DID estimation procedure (Wooldridge, 2021). To disentangle the impacts of wheat blast from the effects of other factors on wheat yield, wheat marketing, consumption and storage, and revenue income at the wheat household level, the following equation was used:

$$Y_{ikt} = \beta_{0k} + \beta_{1k}(\mathrm{YD}_{2016}) + \beta_{2k}(\mathrm{HAD}_i) + \beta_{3k}(\mathrm{YD}_{2016} \times \mathrm{HAD}_i) + (Z_i)\theta_{ik} + \xi_{itk} \tag{1}$$

In equation (1) $\beta_{0\mathrm{k}}$ are scalar parameters; β_{ik} and θ_{ik} are the parameters to be estimated; i stands for an individual household; t stands for the sampled years ($t = 2010, 2016$); ($k = 1$—4), and ξ_{itk} is the random error term. The variables used in estimating equation (1) are explained in Table 2.

Table 2. Description of variables included in DID model estimation

	Description	Measuring unit
Dependent variables		
Y_{i1t}	Wheat yield	Kilogram/ha
Y_{i2t}	Wheat revenue = Market price × wheat production	US dollar/ha
Y_{i3t}	Wheat sold in the market	Kilogram/ha
Y_{i4t}	Wheat consumed and stored	Kilogram
Independent variables		
YD_{2016}	Year dummy for year 2016 when wheat affected for the first time in Bangladesh	1 = yes, 0 for year 2010
HAD_i	Dummy for the treatment households: reside in the wheat blast-affected districts	1 = yes, 0 otherwise
$\mathrm{YD}_{2016} \times \mathrm{HAD}_i$	Year 2016 dummy × treatment households	
z_1	Formal years of schooling, head	Years
z_2	Formal years of schooling, spouse	Years
z_3	Age of the household head	Years
z_4	Age of the spouse	Years
z_5	Total number of members in the household	Number
z_6	A dummy for the rural household	1 = rural household, 0 otherwise
z_7	Sex dummy: Female-headed household	1 = headed by a female, 0 otherwise
z_8	Size of wheat land	ha
$z_6 \times \mathrm{YD}_{2016}$	Rural household dummy × Year 2016 dummy	Yes = 1, 0 otherwise
$z_6 \times \mathrm{YD}_{2016} \times \mathrm{HAD}$	Rural household dummy × Year 2016 dummy × Dummy for the treatment households	Yes = 1, 0 otherwise
$z_7 \times \mathrm{YD}_{2016}$	Female-headed household × Year 2016 dummy	Yes = 1, 0 otherwise
$z_7 \times \mathrm{YD}_{2016} \times \mathrm{HAD}$	Female-headed household × Year 2016 dummy × Dummy for the treatment households	Yes = 1, 0 otherwise
Weather variables		
z_9	Relative humidity in January 2010	%
z_{10}	Relative humidity in February 2010	%
z_{11}	Relative humidity in March 2010	%
z_{12}	Relative humidity in January 2016	%
z_{13}	Relative humidity in February 2016	%
z_{14}	Relative humidity in March 2016	%
z_{15}	Total rainfall in January 2010	Millimeter
z_{16}	Total rainfall in February 2010	Millimeter
z_{17}	Total rainfall in March 2010	Millimeter
z_{18}	Total rainfall in January 2016	Millimeter
z_{19}	Total rainfall in February 2016	Millimeter

(*Continued*)

Table 2. (*Continued*)

	Description	Measuring unit
z_{20}	Total rainfall in March 2016	Millimeter
z_{21}	Monthly average maximum temperature in January 2010	Celsius degrees (°C)
z_{22}	Monthly average maximum temperature in February 2010	Celsius degrees (°C)
z_{23}	Monthly average maximum temperature in March 2010	Celsius degrees (°C)
z_{24}	Monthly average maximum temperature in January 2016	Celsius degrees (°C)
z_{25}	Monthly average maximum temperature in February 2016	Celsius degrees (°C)
z_{26}	Monthly average maximum temperature in March 2016	Celsius degrees (°C)

Source: Authors'.

Note that in the equation specification, the reference year, year 2010. From equation (1):

$$Y_{A=0,2010} = \beta_0 + \theta Z_i + \xi \tag{2}$$

$$Y_{A=1,2010} = \beta_0 + \beta_2 + \theta Z_i + \xi \tag{3}$$

$$Y_{A=0,2016} = \beta_0 + \beta_1 + \theta Z_i + \xi \tag{4}$$

$$Y_{A=1,2016} = \beta_0 + \beta_1 + \beta_2 + \beta_3 + \theta Z_i + \xi \tag{5}$$

Essentially, the coefficient $\beta_3 = (Y_{A\,=\,0,\,2010} - Y_{A\,=\,1,\,2010}) - (Y_{A\,=\,2016} - Y_{A\,=\,1,\,2016})$ is the DID estimator which presents a causal relationship. In equation (1), some other variables are included just to enhance the prevision of the DID estimator.

Importantly, HIES datasets are repeated cross-sectional in nature. Therefore, the application of the conventional panel data estimation procedure by applying a fixed-effect or random-effect estimation procedure is not possible. In estimating equation (1), we therefore applied the ordinary least square (OLS) estimation procedure, using the robust-clustered standard error approach in which standard errors are clustered at the household level.

Although the DID estimator β_3 already captures any external impacts on the variables of interest, to enhance the precision in the estimation process, in an alternative specification (Model 2), we have included the district level maximum temperature (°C), total rainfall (mm), and relative humidity (%) in January, February, and March in 2010 and 2016 in our estimation process. In addition, wheat blast can affect different subgroups heterogeneously. To capture the heterogeneous impacts (if any) of wheat blast on male- versus female-headed households and rural versus urban households, in another specification, we have included four multiplicative dummies to isolate heterogeneous impacts of wheat blast (Table 2).

4. Results and Discussion

Out of the total 1,025 sampled households, 310 sampled households are from HIES 2010 and 715 are from HIES 2016 (Table 3). A total of 571 sampled households are in the control group, from districts that were not affected by wheat blast in 2016 (Table 3). In contrast, a total of 454 sampled households are in the experiment group, from districts affected by wheat blast in 2016 (Table 3).

The background information of the sampled households is presented as group averages and by years sampled. It shows that the sampled households from HIES 2010 were mostly headed by a male; on average, a household head was nearly 47 years old, and with nearly three years of formal schooling. On average, more than 82% of the sampled households are from rural areas, consist of a spouse aged 38 years and nearly five family members (Table 3). Similarly, the sampled households

Table 3. Background information of the sampled households by their location in the initial blast affected eight districts or not affected districts

	All households	Households from non-affected districts (a)	Households from affected districts (b)	Difference (a–b)
Year 2010				
No. of households	310	212	98	
Years of schooling, spouse	2.6	2.93	1.9	1.04**
	(3.51)	(3.66)	(3.03)	(2.45)
Years of schooling, head	2.89	3.11	2.41	0.69*
	(4.15)	(4.39)	(3.89)	(1.33)
Age, spouse	38.1	36.9	40.6	−3.66**
	(12.6)	(12.9)	(11.4)	(−2.39)
Age, head	46.8	46.5	47.4	−0.97
	(12.5)	(13.04)	(11.1)	(−0.64)
Household size	4.93	5.09	4.57	0.53**
	(2.03)	(2.13)	(1.74)	(2.14)
%Rural households	82.6	83.5	80.6	2.9
	(38.0)	(37.2)	(39.7)	(0.62)
%Female-headed household	4.2	5.2	2.0	3.1*
	(20.1)	(22.2)	(14.2)	(1.28)
Year 2016				
No. of households	715	359	356	
Years of schooling, spouse	3.41	3.29	3.53	−0.24
	(3.67)	(3.80)	(3.53)	(0.87)
Years of schooling, head	3.4	3.58	3.21	0.36
	(3.94)	(4.13)	(3.73)	(1.23)
Age, spouse	38.2	38.2	38.1	0.15
	(14.0)	(14.1)	(13.9)	(0.14)
Age, head	47.7	48.4	46.9	1.43*
	(12.3)	(12.4)	(12.2)	(1.55)
Household size	4.15	4.43	3.87	0.56***
	(1.39)	(1.44)	(1.28)	(5.46)
%Rural households	89.1	86.9	91.2	−4.4
	(31.2)	(33.8)	(28.2)	(−1.88)
%Female-headed household	2.7	2.5	2.8	−0.30
	(16.1)	(15.6)	(16.5)	(−0.25)

Difference = variable of interest (mean from not blast affected districts) − variable of interest (mean from blast-affected districts). H0: Diff = 0, Ha: Diff ≠ 0. Numbers in parentheses are *t*-statistics. ***, **, and * indicate 1%, 5%, and 10% levels of significance, respectively.

from HIES 2016 were mostly headed by a male (97%); on average, a household head was nearly 48 years old, and with more than three years of formal schooling. On average, nearly 90% of the sampled households are from rural areas. These households consist of a spouse aged 38 years and with four family members.

In Table 3, we also have presented the statistical differences of the mean of the variables based on whether or not they are from the control or experiment group and by years sampled. It shows that the average years of schooling of the household head and spouse, the size of the household, and the percentage of female-headed households, in the control group in HIES 2010, are statistically significantly higher than the treatment group in the same year (Table 3). In contrast, the average age of the spouse of the households in the control group was statistically significantly lower than the average age of the spouse of the experiment group in HIES 2010. In the case of the sampled households from HIES 2016, the average household size and age of the household heads are statistically significantly higher for the control group than the treatment group. In our empirical estimation method, the age, and years of schooling of the household head and spouse and the household size measured by the number of family members are included to examine their impacts on wheat yield and income in Bangladesh.

Information on the total cultivated land, wheat land, wheat yield, production, and the product value of wheat are presented in Table 4. All monetary values are converted into US dollar using the reported exchange rate between Bangladesh Taka (BDT) and US dollar as 1 USD = BDT 69.6 in 2010 and 1 USD = BDT 78.5 in 2016 (World Bank, 2022).

The yearly average total crop income per household in HIES 2010 was USD 1336 (Table 4). Average wheat yield was 2,414 kg ha^{-1} equivalent, and average wheat production per household was nearly 367 kg with a value of USD 92 (Table 4). In general, the households in the experiment group (from the blast-affected districts) have significantly higher total crop income. They sold more and consumed less wheat compared to the households in the 2010 HEIS control group. Importantly, wheat yield per ha was statistically indifferent among the households in the experiment (2,340 kg ha^{-1}) and the control groups (2,448 K kg ha^{-1}) in HIES 2010.

In 2016, wheat blast affected the wheat fields of the sampled seven districts. HIES 2016 data indicate that households in the experiment group (from the seven blasts affected districts) allocated significantly less land to wheat, and wheat yield was significantly lower (1,667 kg ha^{-1}) compared to the control group (2,272 kg ha^{-1}) (Table 3). In addition, total wheat produced, wheat product value (total production × price), wheat sold per hectare equivalent production, and wheat stocked at the household level were all statistically significantly lower for the households in the experimental group compared to the control group households in HIES 2016 (Table 4).

Results in Table 4 indicate the severity of wheat blast on wheat yield, wheat marketing, and stock. However, these are simple descriptive metrics that do not account for the influence of additional variables, such as characteristics of the wheat-producing households. To ensure more refined impacts of wheat blast on yield, marketing, consumption, and stock, we estimated equation (1).

The DID estimators of impacts of wheat blast on wheat yield (kg ha^{-1}), wheat sold (kg ha^{-1}), wheat consumed and stocked (kg), and wheat product value (USD ha^{-1}) are presented in Table 5 for three different specifications (Models 1–3). In the first specification (Model 1), we included the DID estimator and additional primary control variables. However, one might argue that the impact of blast on yield, consumption and storage, the market share sold, and wheat product value might be overestimated as we were unable to include the implications of weather variability in our model. To isolate the impacts of weather variables, in the second specification (Model 2), we have included the district-level maximum temperature (°C), total rainfall (mm), and relative humidity in January, February, and March in 2010 and 2016 in our estimation process. In the third specification (Model 3), four additional multiplicative dummies are included including the original control variables used in estimating Model 1. These additional multiplicative dummies are included to

Table 4. Balancing test: wheat cultivation, production, and consumption-related information by the location of the households in the initial blast-affected eight districts or other districts

	All households	Households from non-affected districts (a)	Households from affected districts (b)	Difference (a–b)
Year 2010				
Total wheat land (ha)	0.15	0.16	0.15	0.003
	(0.14)	(0.15)	(0.12)	(0.23)
Total land cultivated (ha)	1.15	1.09	1.24	−0.15
	(1.05)	(1.04)	(1.06)	(-1.17)
Total crop income (US$)	1336.2	1233.3	1558.8	−325.4**
	(1330.9)	(1212.9)	(1539.5)	(-2.01)
Wheat yield (kg/ha)	2413.6	2447.6	2340.1	107.5
	(1561.4)	(1787.5)	(899.4)	(0.56)
Total wheat produced (kg)	368.7	383.3	336.9	46.4
	(436.4)	(492.0)	(280.4)	(0.87)
Wheat product value (US$)	91.5	95.1	83.6	11.5
	(108.3)	(122.1)	(69.6)	(0.87)
Wheat sold (kg)	163.2	144.9	202.7	−57.7*
	(270.2)	(284.6)	(23.5)	(-1.75)
Wheat sold per ha (kg)	962.7	818.3	1275.1	−456.8***
	(1044.3)	(1022.7)	(1027.1)	(-3.65)
Wheat consumed (kg)	115.1	137.5	66.4	71.1***
	(234.3)	(278.2)	(55.2)	(2.51)
Wheat under stock (kg)	56.7	56.5	57.2	−0.69
	(172.9)	(181.4)	(153.8)	(-0.03)
Year 2016				
Total wheat land (ha)	0.43	0.59	0.26	0.34*
	(3.45)	(0.25)	(0.08)	(1.30)
Total land cultivated (ha)	1.71	2.33	1.09	1.24**
	(8.44)	(0.56)	(0.28)	(1.97)
Total crop income (US$)	1781.6	1310.3	2256.9	−946.6
	(18,222.3)	(1654.8)	(25,780.5)	(-0.69)
Wheat yield (kg/ha)	1970.9	2272.0	1667.2	604.8***
	(1699.4)	(1785.6)	(1552.1)	(4.83)
Total wheat produced (kg)	314.0	398.6	228.7	169.8***
	(589.9)	(713.2)	(415.2)	(3.89)
Wheat product value (US$)	78.2	99.3	57.0	42.3***
	(147.0)	(177.7)	(103.5)	(3.89)
Wheat sold (kg)	60.7	60.8	60.5	0.30
	(230)	(143.5)	(292.6)	(0.02)

(*Continued*)

Table 4. (*Continued*)

	All households	Households from non-affected districts (a)	Households from affected districts (b)	Difference (a–b)
Wheat sold per ha (kg)	329.0	376.4	281.2	95.3*
	(902.2)	(841.7)	(958.2)	(1.41)
Wheat consumed (kg)	44.1	50.4	37.7	12.7
	(254.6)	(265.5)	(243.3)	(0.66)
Wheat under stock (kg)	28.0	38.09	17.7	20.4***
	(101.9)	(134.2)	(50.3)	(2.68)

Difference = variable of interest (mean from not blast-affected districts) − variable of interest (mean from blast-affected districts). H0: Diff = 0, Ha: Diff ≠ 0. Numbers in parentheses are *t*-statistics. ***, **, and * indicate 1%, 5%, and 10% levels of significance, respectively.

capture the heterogeneous impacts of wheat blast based on the sex of the household head and rural–urban affiliation of the households.

The year dummy for the year 2016, where the base is the year 2010, represents the general trends in 2016 (Table 5). It shows that in general, there was no statistically significant yield difference between the years 2010 and 2016 after controlling for other variables. However, in 2016, sampled households sold 400–500 kg ha^{-1} less and consumed 100–11 kg less wheat compared to the year 2010 (Table 5). On average, there was no statistically significant difference in wheat yield between the households in the blast-affected treatment districts and non-affected control districts (control), as indicated by the dummy for the households in blast-affected districts (HAD) (Table 5). The households in the treatment group, however, on average sold more wheat per ha and consumed and stocked a significantly lower amount of wheat than the households in the control group.

Our DID estimator ($YD_{2016} \times HAD$) shows that in the year 2016, the average wheat yield of households in blast-affected districts was statistically significantly lower by 500 kg ha^{-1} (Model 2) to 540 kg ha^{-1} to (Model 1). Wheat sold by households was around 410 kg ha^{-1} (Model 2) to 630 kg ha^{-1} lower (Table 5). Finally, wheat product value per ha was USD 124 (Model 2) to 135 ha^{-1} lower compared to households in the control group (Table 5).

In 2016, an estimated 15,000 ha of wheat across eight districts was affected by wheat blast (Islam et al., 2016). Although the severity of infection was not assessed by Islam et al, 2016, we can still conservatively apply average wheat blast-associated yield loss (540 kg ha^{-1}, Model 1). Extrapolating these data, aggregate average production loss would be around 8,205 tons with an estimated value of USD 2.1 million based on the 2016 wheat price of USD 254.7 ton^{-1} (FAOSTAT, 2022). Furthermore, our models suggest that the wheat blast-induced wheat product value loss per hectare was on average around USD 135 (Table 5). Using these results, it can be calculated that in 2016, the monetary value of wheat blast-induced wheat production loss was equivalent to USD 2.02 million (USD 135 × 15,000). These data therefore suggest that the wheat blast outbreak in Bangladesh in 2016 caused a wheat yield loss of 540 kg ha^{-1}, with an economic monetary loss among farmers of USD 2.02–2.1 million (Table 5). These result support to the hypotheses that the impact of wheat blast was significant and economically damaging for affected households in terms yield loss, wheat marketing, and revenue generated from wheat sales.

Interestingly, the DID estimator in Table 5 demonstrates that there were no significant differences in consumption and wheat stock between the households in the experiment and control groups in 2016, even though the wheat yield of the households in the experiment group was significantly lower in 2016. The finding falsifies our fourth hypothesis. In Bangladesh, wheat is largely produced for self-consumption by the households. In the face of negative yield shock,

Table 5. Functions estimated applying ordinary least square (OLS) estimation procedure explaining yield (kg/ha), wheat sold, wheat consumed and stored, and wheat product value (USD ha^{-1})

	Model 1				Model 2				Model 3			
	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US $/ha)	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US$/ha)	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US $/ha)
Dependent variables												
Year 2016 (YD_{2016}) dummy (yes = 1)	−166.5	−438.8***	−110.6***	−38.9	−65.2	−504.0***	−111.7***	−13.7	−371.4	−403.4**	−101.0*	−90.2
	(152.68)	(80.82)	(27.70)	(37.95)	(164.28)	(88.03)	(31.16)	(40.84)	(259.74)	(174.28)	(52.96)	(64.53)
Households in blast affected district dummy (yes = 1) (HAD)	−88.3	459.0***	−72.5**	−21.9	293.6	536.4**	−42.5	73.5	−78.8	469.9***	−74.2**	−19.5
	(154.73)	(125.51)	(29.32)	(38.40)	(529.94)	(228.24)	(72.12)	(131.62)	(151.99)	(124.11)	(29.20)	(37.72)
YD_{2016} × HAD	−539.6***	−564.6***	52.6	−134.6***	−498.6**	−409.7***	42.8	−124.3**	−259.9	−630.2***	22.1	−64.9
	(196.67)	(142.24)	(34.04)	(48.88)	(220.48)	(154.23)	(39.80)	(54.82)	(284.12)	(152.23)	(55.59)	(70.71)
Years of schooling, spouse	18.2	−3.96	−3.76	4.54	24.5	−1.21	−2.76	6.12	18.6	−3.97	−3.89	4.65
	(20.90)	(13.14)	(2.68)	(5.20)	(21.07)	(12.53)	(2.64)	(5.24)	(20.56)	(12.83)	(2.66)	(5.12)
Years of schooling, head	17.3	4.16	2.87	4.30	14.6	4.09	2.74	3.62	17.2	4.63	2.91	4.26
	(16.01)	(10.41)	(2.33)	(3.98)	(15.73)	(10.26)	(2.25)	(3.91)	(16.05)	(10.38)	(2.36)	(3.99)
Age, spouse	10.6**	3.60	0.80	2.65**	15.1***	5.26	0.69	3.76***	9.88**	3.35	0.92	2.46**
	(4.98)	(3.45)	(0.66)	(1.24)	(5.17)	(3.48)	(0.82)	(1.29)	(5.00)	(3.42)	(0.69)	(1.24)
Age, head	−4.85	−0.84	−0.45	−1.21	−8.92*	−2.32	−0.24	−2.22*	−4.20	−0.81	−0.57	−1.05
	(5.59)	(3.53)	(0.58)	(1.39)	(5.39)	(3.55)	(0.71)	(1.34)	(5.31)	(3.35)	(0.59)	(1.32)
No. of family members	19.7	−3.32	5.31	4.91	4.93	−15.6	5.66	1.24	18.4	−2.52	5.27	4.58
	(28.54)	(20.59)	(5.55)	(7.10)	(29.69)	(21.64)	(5.83)	(7.38)	(29.11)	(20.80)	(5.40)	(7.24)
Rural household dummy (yes = 1)	306.9**	156.2**	−43.7*	76.4**	342.0**	129.2	−50.9*	85.2**	229.1	149.1	−44.3	56.9
	(128.75)	(78.89)	(23.58)	(32.01)	(151.14)	(88.89)	(27.36)	(37.57)	(252.79)	(176.48)	(37.05)	(62.73)

(*Continued*)

Table 5. (*Continued*)

	Model 1				Model 2				Model 3			
	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US $/ha)	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US$/ha)	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US $/ha)
Female-headed household dummy (yes = 1)	114.6	415.3	23.8	28.4	182.1	420.2	15.7	45.2	426.8	716.5	−16.6	106.1
	(414.52)	(290.32)	(34.40)	(102.94)	(398.62)	(262.09)	(36.72)	(99.00)	(810.46)	(546.13)	(52.57)	(201.13)
Wheatland (ha)	−49.9***	−6.59***	24.1***	−12.4***	−48.9***	−4.40	23.0***	−12.2***	−50.0***	−6.66***	24.1***	−12.5***
	(15.07)	(1.92)	(6.79)	(3.75)	(14.39)	(3.56)	(6.63)	(3.59)	(14.88)	(1.97)	(6.80)	(3.71)
Weather variables												
Relative humidity in January 2010 (%)					406.8	−160.1	−37.5	101.4				
					(289.56)	(151.15)	(61.34)	(72.01)				
Relative humidity in February 2010 (%)					−1212.0**	158.6	−66.9	−301.4**				
					(528.41)	(232.64)	(122.06)	(131.47)				
Relative humidity in March 2010 (%)					687.5**	−28.5	88.1	170.9**				
					(295.66)	(112.07)	(66.69)	(73.43)				
Relative humidity in January 2016 (%)					−292.1*	9.38	−6.03	−72.8*				
					(156.62)	(71.77)	(19.92)	(38.92)				
Relative humidity in February 2016 (%)					748.7	17.5	108.0	185.8				
					(557.75)	(180.52)	(155.87)	(138.70)				
Relative humidity in March 2016 (%)					−452.6	−29.9	−109.8	−112.4				
					(393.60)	(125.04)	(103.04)	(97.73)				
Total rainfall (mm) in January 2010					82.7	595.7***	77.5	20.2				
					(442.94)	(155.31)	(71.80)	(110.07)				
Total rainfall (mm) in February 2010					865.6	−618.5*	−65.5	215.5				
					(670.57)	(370.49)	(75.91)	(166.76)				

(Continued)

Table 5. (*Continued*)

	Model 1				Model 2				Model 3			
	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US $/ha)	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US$/ha)	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US $/ha)
Total rainfall (mm) in March 2010					84.0	−4.69	5.28	20.9				
					(71.67)	(32.04)	(13.59)	(17.82)				
Total rainfall (mm) in January 2016					321.4	−273.0***	10.5	80.0				
					(267.13)	(104.51)	(45.70)	(66.41)				
Total rainfall (mm) in February 2016					−160.8	207.0*	26.8	−40.0				
					(237.84)	(121.06)	(30.72)	(59.16)				
Total rainfall (mm) in March 2016					−209.4	−1.95	−19.9	−51.9				
					(156.54)	(63.83)	(28.62)	(38.92)				
Monthly average Maximum Temperature (°C) January 2010					−4181.4	914.2	271.7	−1039.1				
					(6338.47)	(2486.79)	(881.11)	(1575.54)				
Monthly average Maximum Temperature (°C) February 2010					236.8	1455.7	−730.1	61.3				
					(3371.02)	(1859.59)	(841.81)	(838.18)				
Monthly average Maximum Temperature (°C) March 2010					3050.5	752.7	345.1	756.9				
					(4322.16)	(1629.65)	(807.28)	(1074.72)				
Monthly average Maximum Temperature (°C) January 2016					4274.0	−567.6	−1.41	1062.3				
					(5749.22)	(1970.23)	(917.56)	(1429.57)				
Monthly average Maximum Temperature (°C) February 2016					387.1	−815.9	406.4	93.2				
					(3651.76)	(2139.89)	(560.29)	(907.34)				

(*Continued*)

Table 5. (*Continued*)

	Model 1				Model 2				Model 3			
	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US $/ha)	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US$/ha)	Yield (kg/ha)	Wheat sold (kg/ha)	Wheat consumed and stored (kg)	Wheat product value (US $/ha)
Monthly average Maximum Temperature (°C) March 2016					−3395.5	−1439.8	−206.8	−842.5				
					(4458.85)	(1691.61)	(776.83)	(1108.63)				
Rural household dummy ×YD_{2016}									263.2	−25.8	−14.9	65.8
									(309.67)	(199.17)	(59.24)	(76.94)
Female-headed household dummy × YD_{2016}									−564.4	−165.0	92.2	−140.5
									(837.39)	(615.61)	(66.94)	(207.95)
Female-headed household dummy × YD_{2016} × HAD									−17.4	−661.0*	−33.2	−4.30
									(406.66)	(340.88)	(59.03)	(101.33)
Rural household dummy ×YD_{2016} × HAD									−324.4	82.1	36.8	−80.9
									(276.99)	(118.17)	(53.58)	(69.02)
Constant	1817.4***	588.7**	192.1***	450.4***	1188.0	−5432.9	−96.6	301.9	1870.5***	581.3**	196.0***	463.7***
	(317.47)	(231.76)	(40.33)	(78.91)	(55,752.7)	(15,072.6)	(8557.2)	(13,849.6)	(387.49)	(277.39)	(35.22)	(96.25)
No. of observations	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025
F	7.99	14.25	7.08	7.90	7.39	8.79	5.19	7.34	6.74	13.3	5.24	6.67
Prob > *F*	(0.00)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
R^2	0.06	0.11	0.10	0.05	0.12	0.16	0.12	0.11	0.06	0.11	0.10	0.06

Numbers in parentheses are robust standard errors calculated clustering observations at the household level. *Significant at the 10% level. **Significant at the 5% level. ***Significant at the 1% level.
Source: authors' calculation.

households in the treatment group reduced wheat marketing, and by doing so, blast disease affected households in this group appear to have been able to maintain their previous level of wheat consumption. Additionally, although we were unable to estimate wheat purchase rates, households that experienced blast-induced yield loss may have also purchased additional wheat from the market to meet their consumption needs. This finding supports the findings of other studies that agricultural households experiencing market shocks may reduce their product marketing in order to maintain required consumption levels from farm produced foods (Mottaleb and Rahut, 2018; Strauss, 1984). Our results also suggest that in general, there is a reverse relationship between wheat land size and yield, and wheat product value. This supports the findings of Rao and Chotigeat (1981) who observed the inverse relationship between land size and agricultural productivity (Table 5).

The findings from Model 3 demonstrate that the impact of wheat blast is almost uniform for wheat yield, consumption and storage, and wheat revenue across the households in the treatment groups. This appears to be irrespective of sex of the household head and the rural–urban affiliation of the households (Table 5, Model 3). However, the variable wheat marketing is an exception. Our data suggest that, on average, women-headed households that were affected by wheat blast marketed at least 661 kg ha^{-1} of less wheat in 2016, compared to others.

It is important to mention here that the present study is based on pooled data. It provides only district-level average impacts of wheat blast in 2016 in the affected districts of Bangladesh. To calculate household-level impacts, it is necessary to employ household-level panel data collected before and after the blast incidence in Bangladesh.

5. Conclusion and Policy Implications

In the last three decades, the world has witnessed an unprecedented emergence, re-emergence, and globalization of devastating pests and diseases of crops, which have compromised sustainable crop production and food security (Bhattacharya, 2017; Bueno-Sancho et al., 2017; Mehrabi and Ramankutty, 2019; Pennisi, 2010; Singh et al., 2006; Wellings, 2007). To better suggest actions to minimize the impacts of pest and diseases invasions, it is imperative to quantify the impacts of pests and disease invasions at the farm household, national, and regional levels. Yet largely due to the lack of quality datasets, empirical studies on these topics are few and far in-between.

Using wheat blast in Bangladesh as a case study and utilizing the HIES datasets of 2010 and 2016 from the BBS, we quantified the impacts of the 2016 wheat blast outbreak on wheat yield, marketing, consumption, and the value of wheat production. Prior research has suggested that due to wheat blast disease and subsequent governmental campaigns that discouraged wheat cultivation after 2016, Bangladesh's total wheat area declined as farmers either stopped wheat cultivation or allocated less land to wheat. These actions were however taken based on incidence of wheat blast assumptions of the severity risk posed by the disease, and without quantitative estimates of the effect of the disease on yield and household consumption and income associated with wheat. Applying the DID estimation procedure, we quantify blast-induced yield loss and estimate its effect on average at 540 kg ha^{-1}, with a per hectare value income loss from wheat at USD 135. As the initial wheat blast outbreak affected an estimated 15,000 ha of wheat crop area, our data suggest that the total aggregate loss of wheat production due to the 2016 blast outbreak was equivalent to 8,205 tons of wheat worth approximately USD 2.1 million.

These significant crop losses due to wheat blast have important food security implications. Wheat is the second most important staple food for the 163 million inhabitants of Bangladesh, and climate similarity and modeling data suggest that a substantial area in India could be vulnerable to wheat blast. Based on our DID results, we suggest that a range of approaches may be needed to minimize the impacts of wheat blast in South Asia and Bangladesh in particular. Key among these are measures to strengthen research and capacity development on integrated disease management alongside efforts to develop and disseminate wheat blast-resistant wheat cultivars in Bangladesh and neighboring countries. Additional needs include further scaling out of climate information services tools that can provide farmers with early warnings to increase preparedness in the event of a potential disease outbreak. Successful mitigation of wheat blast in Bangladesh is an important steno in restoring farmers' confidence in wheat cultivation in the affected districts. Such efforts could also generate positive externalities by minimizing the possibility of a spread of wheat blast to India, the second-largest wheat-producing country in the world. In Bangladesh, with the help of the International Maize and Wheat Improvement Center (CIMMYT) and national and international research partners, two blast-resistant wheat varieties and a numerical weather forecast-driven blast disease early warning system (e.g., http://beattheblastews.net/) have already been approved and released, with over 6,000 agricultural extension agents trained in how to interpret and communicate advisories to farmers. To obtain the full benefit of these risk-mitigating technologies, it is important to both raise awareness and capacity in the use of decision support tools and to rapidly multiply and disseminate this blast-resistant wheat. International donor agencies can play important role in supporting seed multiplication and dissemination, as well as supporting improvements in early warning systems.

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References

Anderson, P.K., A.A. Cunningham, N.G. Patel, F.J. Morales, P.R. Epstein, and P. Daszak. “Emerging Infectious DIseases of Plants: Pathogen Pollution, Climate Change and Agrotechnology Drivers.” *Trends in Ecology and Evolution* **19**,10(2004):535–44. DOI 10.1016/j.tree.2004.07.021.

BBS. *Yearbook of Agricultural Statistics-2015, 27th Series (27th Serie, Issue July)*, 2016.

BBS. *Preliminary report on Households Income and Expenditure Survey 2016*. Bangladesh Bureau of Statistics (BBS), Statistics and Informatics Division (SID), Ministry of Planning, 2017a. https://catalog.ihsn.org/index.php/catalog/7399/related-materials

BBS. *Yearbook of Agricultural Statistics-2016, 28th Series (28th Serie)*. Bangladesh Bureau of Statistics (BBS), Statistics and Informatics Division (SID), Ministry of Planning, 2017b. http://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/1b1eb817_9325_4354_a756_3d18412203e2/Yearbook-2016-Final-19-06-2017.pdf

BBS. *Yearbook of Agricultural Statistics-2017, 29th Series (29th Serie)*. Bangladesh Bureau of Statistics (BBS), Statistics and Informatics Division (SID), Ministry of Planning, 2018. http://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/1b1eb817_9325_4354_a756_3d18412203e2/AgriYearbook-2017.pdf

BBS. *Estimated Wheat Crop Production 2019-2020*. Estimate of Major Crops; Bangladesh Bureau of Statistics (BBS), Statistics and Informatics Division, Ministry of Planning, Government of Bangladesh, 2020. http://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/16d38ef2_2163_4252_a28b_e65f60dab8a9/2020-12-15-11-20-1a218eb2ff84a62b6b58532bbc75df8c.pdf

Bhattacharya, S. “Deadly New Wheat DIsease Threatens Europe’s Crops.” *Nature* **542**,7640(2017):145–6. DOI 10.1038/nature.2017.21424.

BSS. *Yearbook of Agricultural Statistics-2019, 31st Series (Issue April)*. Bangladesh Bureau of Statistics (BBS), Statistics and Informatics Division(SID), Ministry of Planning, Government of Bangladesh, 2020.

Bueno-Sancho, V., A. Persoons, A. Hubbard, L.E. Cabrera-Quio, C.M. Lewis, P. Corredor-Moreno, D.C.E. Bunting, et al. “Pathogenomic Analysis of Wheat Yellow Rust Lineages Detects Seasonal Variation and Host Specificity.” *Genome Biology and Evolution* **9**,12(2017):3282–96. DOI 10.1093/gbe/evx241.

Cruz, C.D., and B. Valent. “Wheat Blast DIsease: Danger on the Move.” *Tropical Plant Pathology* **42**,3(2017):210–22. DOI 10.1007/s40858-017-0159-z.

CSISA. *Cereal Systems Initiative for South Asia (CSISA), Phase III. Annual Report (October 2018–September 2019): Building Resilience in South Asia’s Cereal System*. Dhaka and Kathmandu: International Maize and Wheat Improvement Center (CIMMYT), Dhaka, Bangladesh, 2019. https://csisa.org/wp-content/uploads/sites/2/2019/11/Annual-Technical-Report-01Oct18-to-30Sep19-CSISA-III-31Oct19.pdf

CSISA. *Cereal Systems Initiative for South Asia (CSISA), Phase III. Annual Report (October 2019–September 2020): Building Resilience in South Asia’s Cereal System*. Dhaka and Kathmandu: International Maize and Wheat Improvement Center (CIMMYT), Dhaka, Bangladesh, 2020. https://csisa.org/wp-content/uploads/sites/2/2021/09/201102-FINAL-CSISA-PIII-FY-2019-20-ANNUAL-REPORT_BD-NEPAL_web.pdf

CSISA. *Cereal Systems Initiative for South Asia (CSISA): Annual Report (October 2020–September 2021) (Issue October 2020)*. Dhaka and Kathmandu: International Maize and Wheat Improvement Center (CIMMYT), Dhaka, Bangladesh, 2021. https://csisa.org/wp-content/uploads/sites/2/2021/11/211031-CSISA-PIII-APR-Oct20-to-Sept21_web.pdf

De Groote, H., F. Oloo, S. Tongruksawattana, and B. Das. “Community-Survey Based Assessment of the Geographic DIstribution and Impact of Maize Lethal Necrosis (MLN) DIsease in Kenya.” *Crop Protection* **82**(2016):30–5. DOI 10.1016/j.cropro.2015.12.003.

Donatelli, M., R.D. Magarey, S. Bregaglio, L. Willocquet, J.P.M. Whish, and S. Savary. “Modelling the Impacts of Pests and DIseases on Agricultural Systems.” *Agricultural Systems* **155**(2017):213–24. DOI 10.1016/j.agsy.2017.01.019.

Esker, P.D., S. Savary, and N. McRoberts. “Crop Loss Analysis and Global Food Supply: Focusing now on Required Harvests.” *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* **7**,052(2012):1–14. DOI 10.1079/PAVSNNR20127052.

FAO. *The Future of Food and Agriculture: Trends and Challenges (Vol. 4, Issue 4)*. Food and Agriculture Organization of the United Nations (FAO), 2017. http://www.fao.org/3/a-i6583e.pdf

FAOSTAT. *FAOSTAT: Crops and Livestock Products-Trade*. Crops and Livestock Products, 2021a. http://www.fao.org/faostat/en/#data/TP

FAOSTAT. *Food Balance Sheets (Database)*. Food and Agriculture Organization of the United Nations (FAO); Food and Agriculture Organization of the United Nations (FAO), 2021b. http://www.fao.org/faostat/en/#data/FBS

FAOSTAT. *Producer Prices - Annual*. Food and Agriculture Organization of the United Nations (FAO), 2022. https://www.fao.org/faostat/en/#data/PP

Fisher, M.C., D.A. Henk, C.J. Briggs, J.S. Brownstein, L.C. Madoff, S.L. McCraw, and S.J. Gurr. “Emerging Fungal Threats to Animal, Plant and Ecosystem Health.” *Nature* **484**,7393(2012):186–94. DOI 10.1038/nature10947.

Fones, H.N., D.P. Bebber, T.M. Chaloner, W.T. Kay, G. Steinberg, and S.J. Gurr. “Threats to Global Food Security from Emerging Fungal and Oomycete Crop Pathogens.” *Nature Food* **1**,6(2020):332–42. DOI 10.1038/s43016-020-0075-0.

Fones, H.N., M.C. Fisher, and S.J. Gurr. “Emerging Fungal Threats to Plants and Animals Challenge Agriculture and Ecosystem Resilience.” *Microbiol Spectrum* **5**,2(2017):FUNK-0027-2016. DOI 10.1128/microbiolspec.FUNK-0027-2016.

Funk, C., P. Peterson, M. Landsfeld, D. Pedreros, J. Verdin, S. Shukla, G. Husak, et al. “The Climate Hazards Infrared Precipitation with Stations—A New Environmental Record for Monitoring Extremes.” *Scientific Data* **2**,1(2015):150066. DOI 10.1038/sdata.2015.66.

Funk, C., P. Peterson, S. Peterson, S. Shukla, F. Davenport, J. Michaelsen, K.R. Knapp, et al. “A High-Resolution 1983-2016 Tmax Climate Data Record Based on Infrared Temperatures and Stations by the Climate Hazard Center.” *Journal of Climate* **32**,17(2019):5639–58. DOI 10.1175/JCLI-D-18-0698.1.

Funk, C., A. Verdin, J. Michaelsen, P. Peterson, D. Pedreros, and G. Husak. “A Global Satellite-Assisted Precipitation Climatology.” *Earth System Science Data* **7**,2(2015):275–87. DOI 10.5194/essd-7-275-2015.

Goergen, G., P.L. Kumar, S.B. Sankung, A. Togola, and M. Tamò. “First Report of Outbreaks of the Fall Armyworm Spodoptera frugiperda (J E Smith) (Lepidoptera, Noctuidae), a New Alien Invasive Pest in West and Central Africa.” *PLOS ONE* **11**,10(2016):e0165632. DOI 10.1371/journal.pone.0165632.

Goulart, A.P., R.F. Amabili, L.C.B. Nasser, and M.A. Freitas. “Detecção de Pyricularia grisea em sementes de cevada produzidas em sistema irrigado por pivô central no Cerrado Brasileiro.” *Fitopatologia Brasileira* **28**,5(2003):566. DOI 10.1590/S0100-41582003000500019.

Hossain, A., and J.A. Teixeira da Silva. “Wheat Production in Bangladesh: Its Future in the Light of Global Warming.” *AoB Plants* **5**(2013): pls042. DOI 10.1093/aobpla/pls042.

Igarashi, S. “Pyricularia em trigo. 1. Ocorrencia de Pyricularia sp noestado do Parana.” *Fitopatol. Bras* **11**(1986):351–2.

Igarashi, S., *Update on wheat blast (Pyricularia oryzae) in Brazil*. Igarashi, S., ed. CIMMYT, 1990.

IHSN. *Household Income and Expenditure Survey 2016-2017*. International Household Survey Network (IHSN), 2018. https://catalog.ihsn.org/index.php/catalog/7399

IHSN. *Household Income and Expenditure Survey 2010*. International Household Survey Network (IHSN), 2019. https://catalog.ihsn.org/index.php/catalog/2257

Islam, M.T., D. Croll, P. Gladieux, D.M. Soanes, A. Persoons, P. Bhattacharjee, M.S. Hossain, et al. "Emergence of Wheat Blast in Bangladesh Was Caused by a South American Lineage of Magnaporthe oryzae." *BMC Biology* **14**,1(2016):84. DOI 10.1186/s12915-016-0309-7.

Lidwell-Durnin, J., and A. Lapthorn. "The Threat to Global Food Security from Wheat Rust: Ethical and HIstorical Issues in Fighting Crop DIseases and Preserving Genetic Diversity." *Global Food Security* **26**(2020):100446. DOI 10.1016/j.gfs.2020.100446.

Malaker, P.K., N.C.D. Barma, T.P. Tiwari, W.J. Collis, E. Duveiller, P.K. Singh, A.K. Joshi, et al. "First Report of Wheat Blast Caused by Magnaporthe oryzae Pathotype Triticum in Bangladesh." *Plant Disease* **100**,11(2016):2330. DOI 10.1094/PDIS-05-16-0666-PDN.

Marenya, P.P., O. Erenstein, B. Prasanna, D. Makumbi, M. Jumbo, and Y. Beyene. "Maize Lethal Necrosis DIsease: Evaluating Agronomic and Genetic Control Strategies for Ethiopia and Kenya." *Agricultural Systems* **162**(2018):220–8. DOI 10.1016/j.agsy.2018.01.016.

McDonald, B.A., and E.H. Stukenbrock. "Rapid Emergence of Pathogens in Agro-Ecosystems: Global Threats to Agricultural Sustainability and Food Security." *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**,1709(2016):20160026. DOI 10.1098/rstb.2016.0026.

Mehrabi, Z., and N. Ramankutty. "Synchronized Failure of Global Crop Production." *Nature Ecology & Evolution* **3**,5(2019):780–6. DOI 10.1038/s41559-019-0862-x.

Mitra, D. "Emerging Plant Diseases: Research Status and Challenges." *Emerging Trends in Plant Pathology*. Mitra, D., eds. Singapore: Springer, 2021, pp. 1–17. 10.1007/978-981-15-6275-4_1.

Montes, C., S.G. Hussain, and T.J. Krupnik. "Variable Climate Suitability for Wheat Blast (Magnaporthe oryzae Pathotype Triticum) in Asia: Results from a Continental-Scale Modeling Approach." *International Journal of Biometeorology* **66**,11(2022):2237–2249. DOI 10.1007/s00484-022-02352-9.

Mottaleb, K.A., V. Govindan, P.K. Singh, K. Sonder, X. He, R.P. Singh, A.K. Joshi, N.C.D. Barma, G. Kruseman, O. Erenstein. "Economic Benefits of Blast-Resistant Biofortified Wheat in Bangladesh: The Case of BARI Gom 33." *Crop Protection* **123**(2019):45–58. DOI 10.1016/j.cropro.2019.05.013.

Mottaleb, K.A., A. Hossain, and M.I. Hossain. "Agriculture on the Rise in Bangladesh: The Future Role of Value Chains." *Transforming Agriculture in South Asia: The Role of Value Chains and Contract Farming*. Mottaleb, K.A., A. Hossain, and M.I. Hossain., eds. London: Routledge, 2020, pp. 30–48.

Mottaleb, K.A., and D.B. Rahut. "Cereal Consumption and Marketing Responses by Rural Smallholders Under Rising Cereal Prices." *Journal of Agribusiness in Developing and Emerging Economies* **8**,3(2018):461–79. DOI 10.1108/JADEE-09-2017-0088.

Mottaleb, K.A., D.B. Rahut, G. Kruseman, and O. Erenstein. "Wheat Production and Consumption Dynamics in an Asian Rice Economy: The Bangladesh Case." *The European Journal of Development Research* **30**,2(2018a):252–75. DOI 10.1057/s41287-017-0096-1.

Mottaleb, K.A., D.B. Rahut, G. Kruseman, and O. Erenstein. "Evolving Food Consumption Patterns of Rural and Urban Households in Developing Countries." *British Food Journal* **120**,2(2018b):392–408. DOI 10.1108/BFJ-12-2016-0620.

Mottaleb, K.A., D.B. Rahut, G. Kruseman, and O. Erenstein. "Changing Food Consumption of Households in Developing Countries: A Bangladesh Case." *Journal of International Food & Agribusiness Marketing* **30**,2(2018c):156–74. DOI 10.1080/08974438.2017.1402727.

Mottaleb, K.A., P.K. Singh, X. He, A. Hossain, G. Kruseman, and O. Erenstein. "Alternative Use of Wheat Land to Implement a Potential Wheat Holiday as Wheat Blast Control: In Search of Feasible Crops in Bangladesh." *Land Use Policy* **82**(2019):1–12. DOI 10.1016/j.landusepol.2018.11.046.

Mottaleb, K.A., P.K. Singh, K. Sonder, G. Kruseman, and O. Erenstein. "Averting Wheat Blast by Implementing a Wheat Holiday: In Search of Alternative Crops in West Bengal, India." *PLOS ONE* **14**,2(2019):e0211410. DOI 10.1371/journal.pone.0211410.

Mottaleb, K.A., P.K. Singh, K. Sonder, G. Kruseman, T.P. Tiwari, N.C.D. Barma, P.K. Malaker, H.J. Braun, and O. Erenstein. "Threat of Wheat Blast to South Asia's Food Security: An Ex-Ante Analysis." *PLoS ONE* **13**,5(2018): e0197555. DOI 10.1371/journal.pone.0197555.

O'Leary, M. *What Is Wheat Blast?*. CIMMYT Website: Nutrition, Health and Food Security, 2019. https://www.cimmyt.org/news/what-is-wheat-blast/

Oerke, E.-C. "Crop Losses to Pests." *The Journal of Agricultural Science* **144**,1(2006):31–43. DOI 10.1017/S0021859605005708.

Patpour, M., M.S. Hovmøller, J. Rodriguez-Algaba, B. Randazzo, D. Villegas, V.P. Shamanin, A. Berlin, et al. "Wheat Stem Rust Back in Europe: Diversity, Prevalence and Impact on Host Resistance." *Frontiers in Plant Science* **13**(2022). DOI 10.3389/fpls.2022.882440.

Pennisi, E. "Armed and Dangerous." *Science* **327**,5967(2010):804–5. DOI 10.1126/science.327.5967.804.

Perelló, A., I. Martinez, and M. Molina. "First Report of Virulence and Effects of Magnaporthe oryzae Isolates Causing Wheat Blast in Argentina." *Plant Disease* **99**,8(2015):1177. DOI 10.1094/PDIS-11-14-1182-PDN.

Piggott, M.P., F.P.J. Tadle, S. Patel, K. Cardenas Gomez, and B. Thistleton. "Corn-Strain or Rice-Strain? Detection of Fall Armyworm, Spodoptera frugiperda (JE Smith) (Lepidoptera: Noctuidae), in Northern Australia." *International Journal of Tropical Insect Science* **41**(2021):2607–15. DOI 10.1007/s42690-021-00441-7.

Rao, V., and T. Chotigeat. "The Inverse Relationship between Size of Land Holdings and Agricultural Productivity." *American Journal of Agricultural Economics* **63**,3(1981):571–4. DOI 10.2307/1240551.

Savary, S., L. Willocquet, S.J. Pethybridge, P. Esker, N. McRoberts, and A. Nelson. "The Global Burden of Pathogens and Pests on Major Food Crops." *Nature Ecology & Evolution* **3**,3(2019):430–9. DOI 10.1038/s41559-018-0793-y.

Sharanabasappa Kalleshwaraswamy, C., R. Asokan, H. Mahadeva, M. Maruthi, H. Pavithra, K. Hegde, S. Navi, S. Prabhu, and G. Geoergen. "First Report of the Fall Armyworm, Spodoptera frugiperda (J E Smith) (Lepidoptera: Noctuidae), an Alien Invasive Pest on Maize in India." *Pest Management in Horticultural Ecosystems* **24**,1(2018):23–9.

Singh, R.P., D.P. Hodson, Y. Jin, J. Huerta-Espino, M.G. Kinyua, R. Wanyera, P. Njau, and R.W. Ward. "Current Status, Likely Migration and Strategies to Mitigate the Threat to Wheat Production from Race Ug99 (TTKS) of Stem Rust Pathogen." *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* **1**,54(2006): 1–13. DOI 10.1079/PAVSNNR20061054.

Singh, R.P., D.P. Hodson, Y. Jin, E.S. Lagudah, M.A. Ayliffe, S. Bhavani, M.N. Rouse, et al. "Emergence and Spread of New Races of Wheat Stem Rust Fungus: Continued Threat to Food Security and Prospects of Genetic Control." *Phytopathology®* **105**,7(2015):872–84. DOI 10.1094/PHYTO-01-15-0030-FI.

Strange, R.N., and P.R. Scott. "Plant DIsease: A Threat to Global Food Security." *Annual Review of Phytopathology* **43**(2005):83–116. DOI 10.1146/annurev.phyto.43.113004.133839.

Strauss, J. "Marketed Surpluses of Agricultural Households in Sierra Leone." *American Journal of Agricultural Economics* **66**,3(1984):321–31. DOI 10.2307/1240799.

Tembo, B., R.M. Mulenga, S. Sichilima, K.K. M'siska, M. Mwale, P.C. Chikoti, P.K. Singh, X. He, K.F. Pedley, G.L. Peterson, R.P. Singh, and H.J. Braun. "Detection and Characterization of Fungus (Magnaporthe Oryzae Pathotype Triticum) Causing Wheat Blast Disease on Rain-Fed Grown Wheat (Triticum Aestivum L.) in Zambia." *PLOS ONE* **15**,9(2020):e0238724. DOI 10.1371/journal.pone.0238724.

Urashima, A.S., C.R.F. Grosso, A. Stabili, E.G. Freitas, C.P. Silva, D.C.S. Netto, I. Franco, and J.H.M. Bottan. "Effect of Magnaporthe Grisea on Seed Germination, Yield and Quality of Wheat." *Advances in Genetics, Genomics and Control of Rice Blast Disease*. Urashima, A.S., C.R.F. Grosso, A. Stabili, E.G. Freitas, C.P. Silva, D.C.S. Netto, I. Franco, and J.H.M. Bottan., eds. Dordrecht: Springer, 2009, pp. 267–77. DOI 10.1007/978-1-4020-9500-9_27.

Wangai, A.W., M.G. Redinbaugh, Z.M. Kinyua, D.W. Miano, P.K. Leley, M. Kasina, G. Mahuku, K. Scheets, and D. Jeffers. "First Report of Maize Chlorotic Mottle Virus and Maize Lethal Necrosis in Kenya." *Plant Disease* **96**,10(2012):1582. DOI 10.1094/PDIS-06-12-0576-PDN.

Wellings, C.R. "Puccinia striiformis in Australia: A Review of the Incursion, Evolution, and Adaptation of Stripe Rust in the Period 1979-2006." *Australian Journal of Agricultural Research* **58**,6(2007):567–75. DOI 10.1071/AR07130.

Whish, J.P.M., N.I. Herrmann, N.A. White, A.D. Moore, and D.J. Kriticos. "Integrating Pest Population Models with Biophysical Crop Models to Better Represent the Farming System." *Environmental Modelling and Software* **72**(2015):418–25. DOI 10.1016/j.envsoft.2014.10.010.

Wooldridge, J.M. "Two-Way Fixed Effects, the Two-Way Mundlak Regression, and Difference-in-Differences Estimators." *SSRN Electronic Journal* (2021):1–77. DOI 10.2139/ssrn.3906345.

World Bank. *World Development Indicators: Data Bank*. Data Bank, World Development Indicators, 2022. https://databank.worldbank.org/source/world-development-indicators#

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