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Climatic variability and thermal stress in Pakistan's rice and wheat systems: A stochastic frontier and quantile regression analysis of economic efficiency

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ABSTRACT

South Asia is the world's most poverty-dense region, where climate change and climate variability are expected to result in increased heat stress and erratic precipitation patterns that affect agricultural productivity. Considerable evidence has been generated on the effects of these stresses on crop yield, though previous research has not yet examined their influence on the economic efficiency of cereal producers. Surveying 240 farmers across eight of Pakistan's twelve agro-ecological zones, we examined the impact of temperature and precipitation anomalies – as indicators of climatic variability – and the number of days when temperature exceeds crop specific heat stress thresholds on the economic efficiency of rice and wheat production. To this end, we employed first-stage stochastic production frontier (SPF) models and second-stage ordinary least square (OLS) and quantile regression models. Both OLS and quantile regressions indicated that terminal heat > 34 °C has a significant negative impact on wheat production economic efficiency. Small positive deviation (0.54 °C ± 0.16 SD) of the wheat season's mean temperature from the medium-term historical mean also significantly and negatively affected economic efficiency across all regression models. Heat stress > 35.5 °C during rice flowering in the monsoon also had a significant and negative impact. A slight positive deviation in temperature averaging 0.38 °C (± 0.11 SD) above the medium-term mean also had significant negative effects across all regressions. Cumulative precipitation conversely had significant yet contrary effects, by offsetting farmers' investment in supplementary irrigation and increasing economic efficiency. Our results highlight the fact that indicators of climatic variability and heat stress negatively affect the economic efficiency of both rice and wheat producing farmers. Farmers' education and access to financial and extension services were however both positively associated with economic efficiency. Our findings point to the importance of developing interlinked agronomic, economic and socio-ecological policy strategies to adapt and increase the resilience of Pakistan's cereal systems to climatic variability.

1. Introduction

Ensuring food and livelihood security for an increasing global population in the face of climate change is one of the 21st century's most crucial humanitarian and scientific challenges. The global population is predicted to grow from 6.9 billion to 9.1 billion by 2050, with a potential increase in demand for food of up to 70% by 2050 (Godfray et al., 2010; Alexandratos and Bruinsma, 2012). Climate change is among the greatest challenges to achieve food and income security for the world's growing population (Wheeler and Von Braun, 2013; United Nations, 2012 United Nations, 2012). The potentially negative impacts of climate change on crop yield and farmers' livelihoods are predicted to increase the number of hungry people globally by 20% by 2050 (Carty and Magrath, 2013). A recent report by the World Bank states that over 100 million globally are at risk of falling into extreme poverty as a result of climate change over the next 15 years (Hallegatte et al., 2015).

The obstacles to achieving the goals of sustainable food and income

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security, are perhaps most prominent in the densely populated developing nations of the global south, where the majority of the world's food insecure people currently live (FAO, 2016). In the Asia-Pacific region alone, half a billion rural poor are subsistence farmers who are vulnerable to the effects of climate change and who are expected to experience negative impacts to their livelihoods (FAO, 2015). One third of global crop yield instability can be explained by climatic variability (Ray et al., 2015). Extreme weather events associated with climatic variability are also projected to increase with climate change, negatively affecting agricultural productivity in much of the tropics and subtropics (Rosenzweig et al., 2014). The globe's major cereals – rice (*Oryza sativa*), wheat (*Triticum aestivum*), and maize (*Zea mays*) – are all expected to experience general yield losses in these latitudes as a result of increasing temperatures, drought, flooding, and other extreme weather events (Bebber et al., 2013; FAO, 2016). When combined with poor governance, under developed markets, and limited civil and agricultural support services in many developing nations (Feder et al., 1985; Lee, 2005), climate-change induced crop losses could further worsen the food and income security status of many smallholder farming households (Schmidhuber and Tubiello, 2007).

These issues are particularly acute in South Asia, where approximately 30% of the globe's malnourished live (Lobell et al., 2008). As two of the region's most important crops, over 74 M ha in India, 12 M ha in Pakistan, 12 M ha in Bangladesh, and 2 M ha in Nepal are cropped to rice and wheat (FAOSTAT, 2017). In Pakistan, the productivity of the rice-wheat cropping sequence paramount to national food security. Rice and wheat, for example, contribute 5–10% and 50–60%, respectively, of average daily per capita calorific intake (WFP, 2010). Both crops are however susceptible to productivity declines under climate change. The food insecurity level in Pakistan is acute, with 82.6 million people – nearly half the country's population – suffering from hunger. Poorer households usually spend over 60% of their income on food and 36% of Pakistanis live below the poverty line (WFP, 2010).

The optimal thermal range for rice growth is approximately 27–32 °C (Shah et al., 2011). Temperatures above 32 °C approximately a week prior to or during anthesis can however result in decreased pollen viability and pollination. Embryo abortion and increased spikelet sterility can result, thereby lowering yields (Reynolds et al., 2016; Shah et al., 2011). The effects of terminal heat stress on the productivity of wheat in South Asia have been widely documented (Pfeiffer et al., 2005; Mondal et al., 2013; Krupnik et al., 2015a; Krupnik et al., 2015b). When temperatures exceed 30 °C, wheat photosynthesis can be disrupted, triggering the early onset of senescence and resulting in reduced grain filling and lower yields (Asseng et al., 2011; Reynolds et al., 1994; Lobell et al., 2012). Temperatures in excess of 32 °C during rice flowering can be more damaging, as reduced pollination, grain formation and filling can result (Farooq et al., 2011; Lobell et al., 2012; Reynolds et al., 2016; Shah et al., 2011). High temperatures also frequently coincide with drought stress, which is typically most severe if experienced in excess of 14 days during heading and early flowering. In both cases, decreased grain weight results (Reynolds et al., 2016).

As demonstrated by the above literature, most studies on the effects of climatic variability in South Asia focus on crop yields. In addition to providing the caloric basis for food security (WFP, 2010), wheat and rice are also important income generators for smallholder farmers in Pakistan, a country in which agriculture contributed 21% of GDP in 2015–16 (Govt. of Pakistan, 2016). Crop production in Pakistan generates roughly 43.5% of rural households' expendable income (Govt. of Pakistan, 2016). Wheat is Pakistan's most widely grown field crop, with over 25 million tons produced in 2014–15 (FAOSTAT, 2016), contributing 10% to agricultural value addition (Govt. of Pakistan, 2016). Rice is conversely Pakistan's second most prominent field crop, although mean yields have declined by 1.3 t ha^{-1} since 2009, resulting in a 30% loss in national production (FAOSTAT, 2016). The reasons for such decline appear to be related to rising temperatures, recurrent heat waves, flood events and consequent crop losses, in addition to high production costs which then affect farm income and farmers' livelihoods (Zahid and Rasul, 2012; Govt. of Pakistan, 2016).

This situation can have significant income implications in Pakistan, with potentially important ramifications for rural farm households' expenditures on health and child education, as well as in entrepreneurial investments, all of which affect development trajectories (Amjath-Babu et al., 2016; Govt. of Pakistan, 2016). Quantification of the effect of climatic variability on the economic efficiency of rice and wheat production is therefore warranted. This study responds to these issues and contributes to the literature on the effect of indicators of climatic variability and heat stress on crop productivity by analyzing how temperature and cumulative precipitation anomalies from medium-term climatic history and the number of days when temperature exceeds crop specific thresholds affect *ceteris paribus* the economic efficiency of wheat and rice farmers in Pakistan. In doing so, this paper breaks from more conventional analytical frameworks that treat indicators of climatic variability and heat stress as "given conditions" and that are inadequately represented as factors influencing farm efficiency performance. Employing a sample of 240 rice and wheat farmers across eight of Pakistan's leading cereal producing agro-ecological zones, our objectives were two-fold. We first sought to quantify the economic efficiency of both rice and wheat. In addition, we assessed if economic efficiency could be better explained through the inclusion of indicators of climatic variability and heat stress as independent variables in regression models.

2. Materials and methods

2.1. Primary data collection

Farm household surveys were conducted across eight of Pakistan's twelve rice and wheat producing agro-ecological zones (AEZs) as defined by PARC (2015) (Fig. 1). These AEZs were selected for study because they constitute some of the country's most important rice and wheat producing zones. In the next step, a disproportionate stratified random sampling technique was employed for primary data collection. Considering each AEZ as one stratum (cf. Arshad et al., 2015), surveys were conducted in eight districts randomly selected from within each of the eight AEZs studied. Two administrative units (referred to as *tehsils*) were then randomly selected from within each district. One village from within each *tehsil* was subsequently chosen at random, and from each village, 15 farm households were randomly selected for interviews. This resulted in 240 farm households. Surveys focussed on the prevailing socio-economic and farm characteristics of the sampled households, rice and wheat crop management information with emphasis on input use, resource access, and yield. Farmers' reports of rice and wheat sowing, flowering, and maturity date ranges were also recorded.

2.2. Secondary data collection, processing and threshold setting

We collected thirty-two years of temperature and precipitation data spanning the rice-wheat production seasons from November 1980 to October 2011 from the Pakistan Meteorological Department. Plotting mean seasonal temperature across station observations for the *kharif* and *rabi* seasons against the medium-term (1980–2011) seasonal mean revealed a general trend towards positive temperature anomaly after 2001 for both seasons, indicative of a gradually warming climate (Fig. 2). We further segregated all data into the *kharif* rice and *rabi* wheat production seasons, corresponding to early July to mid-October and November to early April to calculate the indicators of medium-term climatic variability, that is, the deviations of rice and wheat seasons' mean temperature and cumulative precipitation from historical data (Siddiqui et al., 2012).

We calculated cumulative precipitation received during each crop's growing season (sowing to maturity) and the number of days when