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Examination and Empirical Forecast of Wheat Yield in Northwest India Based on Climate and Socio-Economic Factors

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EXAMINATION AND EMPIRICAL FORECAST OF WHEAT YIELD IN NORTHWEST INDIA BASED ON CLIMATE AND SOCIO-ECONOMIC FACTORS

by

Avik Mukherjee

A dissertation submitted in partial fulfillment
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ABSTRACT

Examination and Empirical Forecast of Wheat Yield in Northwest India Based on

Climate and Socio-Economic Factors

by

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Utah State University, 2020

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This work is focused on the impact of climate and socio-economic factors on wheat yield in northwest India and forecasts of wheat yield for the next 2 years. Wheat is one of the most important crops in India and plays a major role in Indian economy and food security for around 1.35 billion people. The two highest wheat producing states in India, Punjab and Haryana experienced prolonged wheat yield during the 2000s.

In the first chapter, the extent of climate variability and the negative impact on wheat yield have been discussed. Two drought indices OPI and SPEI were used to assess the drought condition. The results indicate that wheat yield loss is associated with increasing number of days having a temperature above 35°C during maturity stage coupled with less water supply. Reduction in monsoon rainfall during several years led to depletion of groundwater and less resources for irrigation during the growing season (November-March).

Second part of dissertation is mainly focused on the assessment of socio-economic factors that affect crop yield in northwest India along with the climate factors. A literature

review of the socio-economic factors indicates the close relation with crop yield variability. Due to limited water resources in the state of Punjab and Haryana, these two states require strong water and irrigation policies which is lagging now. The land usage pattern, technologies and the communication between scientists and farmers must be improved in future for sustainable agriculture.

Lastly, third chapter is focused on the forecasting of wheat yield for the next two years. A simple linear regression model is developed to forecast yearly average wheat yield for Punjab and Haryana during the period 1985-2012, where four climatic variables are also considered as independent variables. Based on model output, forecasting of wheat yield for next the 2 years have an accuracy of 74% which is adequate for a small number of data points that are used here. This study also reveals a unique relationship pattern with climatic variables and wheat yield which indicates high precipitation or how high soil moisture content can make a significant negative impact on wheat yield.

(88 pages)

PUBLIC ABSTRACT

Examination and Empirical Forecast of Wheat Yield in Northwest India Based on Climate and Socio-Economic Factors

Avik Mukherjee

This study summarizes the findings of research organized in two parts. The first part includes the impact of climate and socio-economic factors that affected wheat yield in northwest India during the 2000s. The second part focused on the forecast of average wheat yield for the two highest wheat producing states Punjab and Haryana.

Initial study focused on the impact of climate factors on wheat yield in northwest India. It has been found that above normal temperature coupled with water shortage i.e. irregular irrigation and low soil moisture contributed to the prolonged yield reduction during 2002-2010.

Next, we reviewed the socio-economic factors which might be responsible for the wheat yield reduction along with climate factors. Lastly, an attempt has been made to forecast (2 years) wheat yield for the two states with very limited input. Despite of the limited input, the fitted model worked well and produced around 74% forecast accuracy. This short-term forecast can help crop management planning and other decision planning for the next few years.

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CHAPTER I

INTRODUCTION

India is ranked third in wheat production after European Union (EU) and China, where the major wheat belt lies in the north-west of Indo-Gangetic Plain (IGP) (Kumar et al., 2012). Wheat is the most important cereal crop worldwide and the most staple crop in India along with rice. Prolonged reduction in wheat yield in northwest India during 2002-2010 had a negative impact on national grain yield and economy. Although not extreme in statistical sense, this reduction in wheat yield is an indication of the impact of changing climate in a small scale and could be devastating in future.

Many studies have already predicted an increase in the frequency of extremely hot days along with an increase in average global temperature (IPCC 2007), increasing CO_2 concentration, and variable precipitation, which will have a strong negative impact on crop development and production (Monteith, 1980; Asseng et al., 2011; Knox et al., 2016). Combined effects of elevated temperature, increased drought, and crop-water availability could have a significant impact on wheat yield and production globally (Xiao et al., 2018).

Except climate factors, there are several socio-economic factors which play key role in crop production. These factors have a significant role in strengthening a farmer's daily decision-making related to agricultural activities by enhancing their knowledge regarding new technologies and information (Mittal et al., 2015). These include a number of economic and governmental policies and subsidies for the farmers to encourage them to cultivate particular crops in a particular region. Crop yield prediction is important for

policy making, developing strategies, setting goals and crop planning for the future (Biswas et al., 2014).

The above literatures are a summary of the viewpoints that have led to the overarching goal of this work, that is: to examine climate and other socio-economic factors that reduced wheat yield in northwest India during the 2000s and the extent of its impact on crop production and short-term empirical forecast of wheat yield for the states of northwest India. Through the application of a variety of climate data, climate-crop relationship, statistical techniques and reviewing a number of literatures, the following objectives are addressed to accomplish the main goal.

Objectives

1. Examination of the climate factors that reduced wheat yield in northwest India during the 2000s.
2. Review and assessment of the socio-economic factors associated with wheat production.
3. Short-term empirical forecast of wheat yield for Punjab and Haryana based on climate factors.

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CHAPTER II

EXAMINATION OF THE CLIMATE FACTORS THAT REDUCED WHEAT YIELD IN NORTHWEST INDIA DURING THE 2000S

Abstract

In India, a significant reduction of wheat yield would cause a widespread impact on national food security for 1.35 billion people. The two highest wheat producing states in northern India, Punjab and Haryana, experienced a prolonged period of anomalously low wheat yield during 2002-2010. The extent of climate variability and change in influencing the prolonged reduction in wheat yield was examined herein. Daily air temperature (T_{max} and T_{ave}) was used to calculate the number of days above optimum temperature and growing degree days (GDD) anomaly. Two drought indices, the standard precipitation and evapotranspiration index and radiation-based precipitation index, were used to describe the drought conditions. Groundwater variability was assessed via satellite-based approximation. The analysis results indicate that the wheat yield loss corresponds to the increase in the number of days with temperature above 35°C during maturity stage (March). Reduction in monsoon rainfall led to depletion of groundwater and reduced surface water for irrigation in the wheat growing season (November-March). Higher temperature coupled with water shortage and irregular irrigation appear to impact yield reduction. Meanwhile, improving the agronomic practices to minimize crop water usage could be an adaptation strategy to maintain desired wheat yield in the face of climate-induced drought and precipitation anomaly.

Keywords: Wheat yield; northwest India; precipitation; temperature; groundwater; irrigation

1. Introduction

Globally, India ranks third in wheat production, after the European Union (EU) and China, India's main wheat production lies in the northwest of the Indo-Gangetic Plain (IGP) [1,2]. The highest wheat-producing states in the IGP are Punjab and Haryana. There was a prolonged reduction in wheat yield during 2002–2010 in the states of Punjab and Haryana and this reduction significantly impacted the total Indian wheat yield [3]. In this study, an attempt was made to understand the wheat yield variability in northwest India with a focus on the prolonged reduction during the 2000s.

Wheat is a winter (rabi) crop sown in November–December and harvested in March–April and the crop fully relies on irrigation because of low precipitation during winter. Thunderstorms associated with the so-called Western Disturbances may occasionally occur. Increased rainfall during critical stages (crown root initiation, flowering, and physiological maturity) enhances the yield [4] more than during dry years, while high temperature threatens the yield [5]. Variation of wheat yield in the IGP can also be caused by other factors such as sowing dates [6], soil moisture, and nitrogen application [7]. Among these factors, wheat is most sensitive to high temperatures, especially during the reproductive stage [8,9]. High temperatures increase levels of water stress in plant cells, crop water requirement, and respiration [10]. Heat stress also affects plant photosynthesis [11,12]. The optimum temperature range for the early growth stages of wheat is lower than the threshold for the later growth stages—a temperature range of 12–25 °C is ideal for seed

germination, while the critical temperature for the grain-filling stage is 35.4 °C [13]. In the face of climate change, the projected increase in temperature, along with frequent hot and dry spells, heavy rainfall events, and droughts in semi-arid and tropical regions [14], can negatively impact wheat production. In India, a 1 °C increase in temperature can reduce wheat production by 4–5 mt [15,16].

The objective of this study is to determine the extent to which climate and related factors have played a role in the notable wheat yield reduction in India during 2002–2010 (shown later). The results are expected to help management practices sustain normal wheat production with increased stress from a changing climate. Section 2 describes the method and data used; Section 3 shows the analysis results together with discussions. Finally, Section 4 provides concluding remarks.

2. Materials and Methods

2.1. Study Area

The study was conducted for Punjab and Haryana (28–31 °N and 74–79 °E), located in the northwest part of the IGP (Figure 1). These two states accounted for 34% of total wheat production and 21% of the total cultivated area in India (Directorate of Wheat, India, 2014). The average annual rainfall in Punjab and Haryana is 649 mm and 617 mm (1948–2016), respectively, and 60–70% of annual rainfall is received during the monsoon season (June–September). The average standard deviation of rainfall in Punjab and Haryana is 175.14 mm and 147.71 mm, respectively. This region receives a small amount of rainfall during December–January (vegetative and tillering stage). Therefore, irrigation is required for the overall growing season. The average winter temperature is 11–14 °C, which is good

for spring wheat cultivation. Sowing dates vary from late October to the second week of December and harvesting dates vary from late March–April.

2.2. Data and Methods

2.2.1. Wheat Yield

The national average of wheat yield data for India during 1961–2014 was collected from the Food and Agricultural Organization [17] and the average-yield data at the state level for Punjab and Haryana during 1985–2015, compiled by the Indian Government, was obtained from a private source (this is because official channels of such data are not available). A linear trend was calculated for Indian wheat yield and differenced from the overall timeseries to minimize impacts from non-climate factors (Figure 2-1). Wheat yield anomaly and three-year running mean were constructed for Punjab and Haryana to identify the wheat yield break.

2.2.2. Climate Data Sources

Time period for the climate data varies in this study according to the availability.

(a) Drought:

A number of in-situ and satellite derived observations were used. The outgoing longwave radiation (OLR) Precipitation Index (OPI) and Standardized Precipitation and Evapotranspiration Index (SPEI) were used to investigate seasonal drought (November–March) during 2002–2010. The monthly mean OPI (2.5° × 2.5° resolution), as obtained from National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) [18], and the monthly mean SPEI dataset, based upon Climate Research Unit (CRU) (0.5° × 0.5° resolution), was used for analysis [19]. The area

averaged data for precipitation in Punjab and Haryana was calculated. The timeseries of OPI during 1979–2012 and SPEI during 1961–2012 were normalized and plotted against the three-year running mean (for smoothing and highlighting the decade-long drought).

(b) Growing Degree Days (GDD)

The daily maximum and minimum air temperature (Tmax and Tmin) during 1979–2012 were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim) dataset (0.7° × 0.7° resolution), which assimilates station air temperature observations [20]. Average temperatures for the focus region were used to estimate the GDD following Equation (1) (given below), using 5 °C as the base temperature [21]. Sowing dates in the study area vary by farm location and time, so GDD was computed from 1 November to 31 March to provide total heat units from sowing to harvest.

Equation (1):

$$\mathrm{GDD} = \frac{(\mathrm{Tmax} + \mathrm{Tmin})}{2} - \mathrm{Base\ Temperature\ (5\ ^{o}C)} \tag{1}$$

(c) Frequency of Extreme Temperature:

Daily maximum temperature data at 2.5° × 2.5° resolution was obtained from NCEP-NCAR to cover the regional perspective. ERA-Interim data were not considered due to unavailability. The maximum temperature of the focus region was used to calculate the number of days above the optimal temperature (35 °C). We calculated the areal average maximum temperature in March, because the grain filling and maturity stages (during

March) are the most sensitive to high temperature. The number of days above 35 °C was calculated for the period 1979–2014.

(d) Precipitation:

Monthly averaged precipitation data, for the period 1961–2014 (54 years), was obtained from the PREC/L (Precipitation over Land) and Indian Institute of Tropical Meteorology (IITM) records [22] (available at http://www.tropmet.res.in). The dataset was area weighted and based on a total of 27 stations over the states of Punjab and Haryana. Both the monsoon and winter seasons were analyzed.

2.2.3. Hydrological Factors

(a) Water Balance Components:

We analyzed parameters in the water balance equation (without considering irrigation) to isolate the impact from natural causes. Monsoon precipitation is implied as a source of groundwater storage for the subsequent wheat growing season. Thus, we investigated the water balance parameters both in the monsoon and wheat growing season, based on:

$$\text{Precipitation} = \text{Runoff} + \text{Evapotranspiration} + \text{Changes in soil water} \quad (2)$$

Potential evaporation (PET) was used instead of evapotranspiration (ET) due to the unavailability of ET data. The increased evaporation can cause underestimation of the water demand due to the exclusion of plant transpiration but given that ET is a function of crop-coefficient and PET [23], our result for PET is still valid in depicting the described relationship. Precipitation reconstruction over land, runoff from NCEP-NCAR reanalysis, PET, and soil water storage were obtained from the National Oceanic and Atmospheric Administration (NOAA) website (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). This data were

acquired for computing the water balance equation. All of the relevant variables were area averaged for the Punjab and Haryana region from 1961–2014 (monsoon and wheat growing season).

(b) Groundwater Proxy:

Well data were sparse and difficult to obtain from northern India. Thus, changes in monsoon-season and winter groundwater were analyzed by using monthly data from NASA's Gravity Recovery and Climate Experiment (GRACE), to calculate a dataset of the liquid terrestrial water storage anomalies (TWSA) for 2002–2011 (https://grace.jpl.nasa.gov/data/). This is not the exact measurement of groundwater, but an approximation or accumulation of all forms of liquid water at and under the land surface assumed to exist above the bedrock. The aquifers in the area are mainly the unconfined type. That is why a lower precipitation rate played an important role in the vanishing groundwater of the region. This dataset measures changes on the local pull of gravity as water shifts around the Earth due to changing seasons, weather, and climate. Obviously, the satellite data/GRACE is not an accurate measurement to any local aquifer but is an indicator of the water storage in recent years. We had to use GRACE since local well data were not available.

All the climate parameters and the drought indices were area averaged (1985–2015) over the Punjab Haryana region.

2.2.4. Other Factors:

Non-hydrological factors such as cropping intensity change in areas net irrigated by canals and tube wells, and changes in the number of overexploited and safe blocks are the supportive factors that could contribute to the wheat yield variability. These datasets were

obtained from http://www.punjabstat.com. Cropping intensity is defined as the number of crops in the same field during one agricultural year and is derived from Equation (3):

$$\textbf{Cropping Intensity} = \frac{\textbf{Gross cropped area}}{\textbf{Net sown area}} \textbf{ X 100} \tag{3}$$

3. Results and Discussion

3.1. Wheat Yield Variation

Wheat yield across the entire Indian region has increased almost consecutively from 1961–2014, as show in Figure 2-1a, due to improvements in crop production technologies.

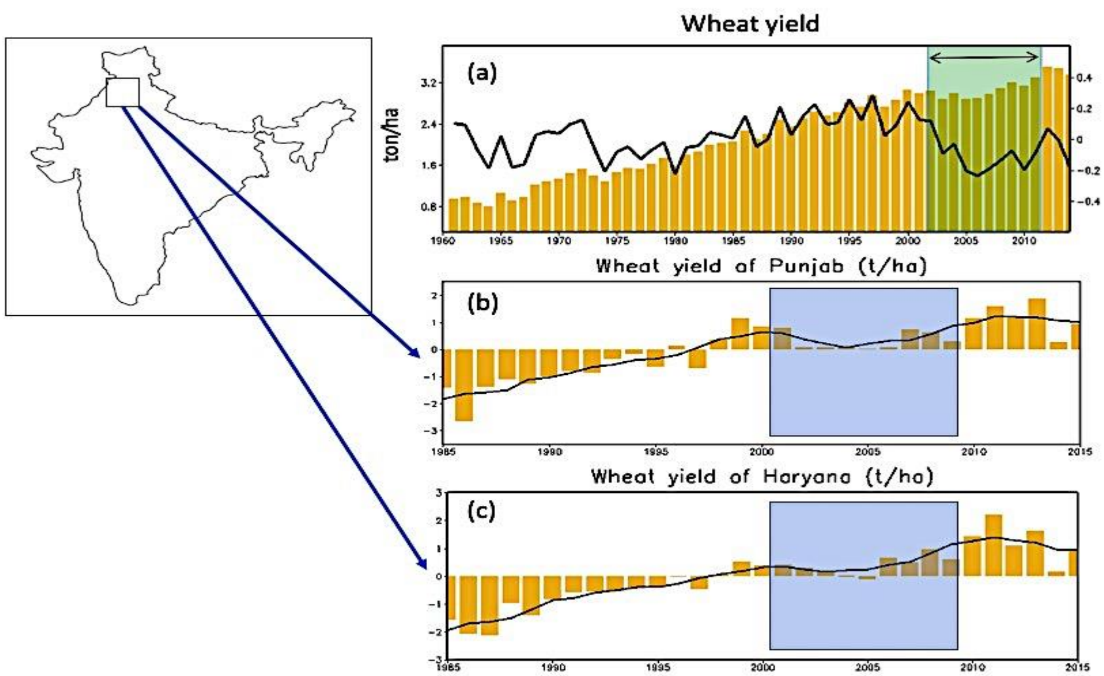

Figure 2-1. Study area (the box in India map): (**a**) total Indian wheat yield (tonnes/ha) (1961–2014), (**b**) normalized wheat yield of Punjab (1985–2015), (**c**) wheat yield of Haryana (1985–2015)—the black lines represent detrended wheat yield (a) and three-year running mean (c,d). The period of 2002–2010 is shaded.

However, there appears to be an inter-decadal variability embedded in this long-term increase. By removing the linear trend of wheat yield, the detrended pattern shows a marked decline followed by a prolonged pause during 2002–2011, as demonstrated by the black line in Figure 2-1a. This decline in wheat yield reflects a reduction of about 0.2–0.4 t/ha. Indian wheat is produced dominantly in the provinces of Punjab and Haryana, see Figure 2-1 map, and their respective wheat yields since 1985, as shown in Figures 2-1b,c, also show a corresponding reduction during the same time period. Since little to no drastic change in management practices or cultivation techniques could last for this long period (almost ten years), environmental factors such as climate variability could play a role in producing such a negative impact on wheat yield.

3.2. Climate Impacts on Wheat Yield

3.2.1. Drought Indices

Two drought indices, OPI and SPEI (see Section 2.2.2a), were used to examine the extent of possible water shortage conditions during 2002–2010. SPEI is a multi-temporal scale drought index based on the balance between precipitation and ET with respect to their climatology. Normalized seasonal OPI and SPEI during the wheat growing season (November–March) are shown in Figures 2-2a, b. Positive OPI values indicate surplus rainfall compared to regional climatology, whereas negative values indicate a deficit in rainfall compared to regional climatology. The OPI clearly shows a below normal condition during 2000–2012, corresponding to the wheat yield reduction. The seasonal SPEI also indicates strong drought with negative anomalies after 2004 (Figure 2-2b), which corresponds to the period of wheat yield reduction.

3.2.2. Temperature

Direct impacts of temperature on wheat yield can be depicted by GDD and the frequency of extreme temperatures above 35 °C during the growing season.

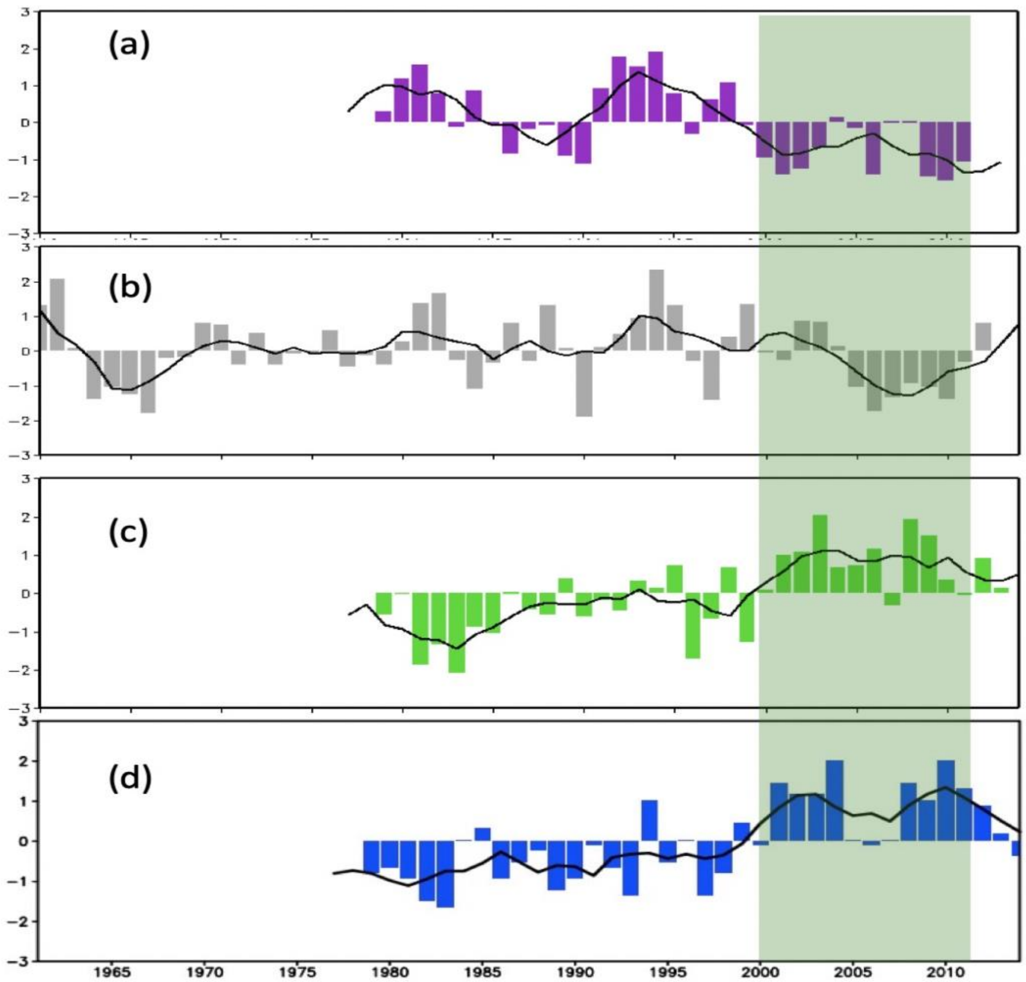

Figure 2-2. Normalized seasonal means (November–March) of (**a**) OLR Precipitation Index (OPI), (**b**) Standard Precipitation and Evapotranspiration Index (SPEI), (**c**) growing degree days (GDD), and (**d**) number of days above 35 °C (during maturity)—the black line in each figure indicates the three-year running mean, and the period of 2002–2011 is shaded.

Figure 2-2c shows normalized GDD timeseries and indicates a general high-GDD period during 2002–2010. A high-GDD environment can either shorten wheat maturity

[24] or directly harm crop growth when the temperature exceeds the critical threshold. Additionally, a high GDD leads to early maturity which affects growth and yield. High temperature conditions also contribute to an overall negative effect on grain filling and physiological maturity.

Wheat crop exposed to temperatures above 34 °C after the anthesis stage has a significantly low yield due to accelerated senescence, decreased rate and duration of grain filling [25,26], and reduction in grain weight [27]. By quantifying the number of days with temperatures above 35 °C in March, which are critical for the grain filling and maturity, we found that the frequency of extreme temperature was relatively high during 2000–2010 (Figure 2-2d). Long periods (continuous days) of heat stress (above 35 °C) conditions during crown root initiation, flowering, and grain filling stages can cause significant yield reduction [28,29] and may lead to total crop damage. Additionally, continuous days with high temperatures can shorten wheat maturity. However, we noted a three-year “gap” in the anomalously high temperature years (2005–2007) and this could imply impacts from other factors (e.g., water resources) not related to heat in the atmosphere.

3.2.3. Water Balance

Precipitation levels during the monsoon (June–September) and wheat growing season (November–March) are displayed in Figure 2-3 for (a) Punjab and (b) Haryana. Both monsoon and winter precipitation fluctuated year-to-year, but they appeared to reach relatively low levels during the 2002–2010 period, particularly in Punjab, and the decline persisted through 2015. The decreases of monsoon and winter precipitation during this period, compared to their long-term (1948–2016) means, were 27.6% and 8% for Punjab and 16.5% and 33% for Haryana, respectively. The mean winter precipitation was less than

300 mm, which is not enough for wheat cultivation. Hence monsoon precipitation plays a vital role in recharging the groundwater that is consequently used for wheat irrigation, mostly from tube wells.

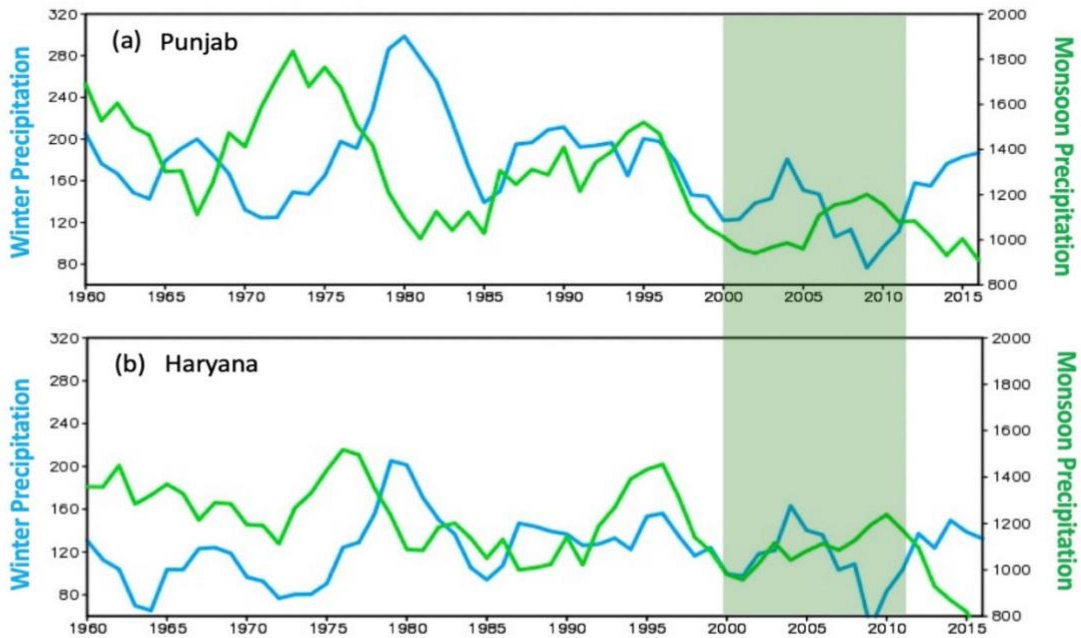

Figure 2-3. Timeseries of winter (indigo line) and monsoon precipitation (green line) (mm, 1961–2015) of (**a**) Punjab and (**b**) Haryana; the period of 2002–2011 is shaded.

The PREC/L data shows similar precipitation variations, as shown in Figure 2-4a, as the IITM precipitation, characterized with a marked decadal-scale variability that was previously documented for both summer monsoon and winter seasons [29], suggesting natural variability in terms of the weather pattern change. However, the predominant reduction in precipitation during 2002–2010 suggests inadequate hydrologic input for recharging the groundwater supply.

The increasing trend of potential evaporation during 2002–2010 in both seasons, as shown in Figure 2-4b, suggests a higher amount of water loss from the soil surface when

precipitation started to decline. The seasonal run-offs in Figure 4c also show below-normal conditions, corresponding to the combined change in precipitation and PET. Soil water storage (Figure 2-4d) during the 2002–2010 period exhibited a clear reduction in both seasons, but the reduction was particularly pronounced during the wheat growing season. This reduction in soil water storage negatively impacted the critical stages of wheat growth, since low soil water storage can be harmful to crop growth through low water supply and unsuitable growth conditions.

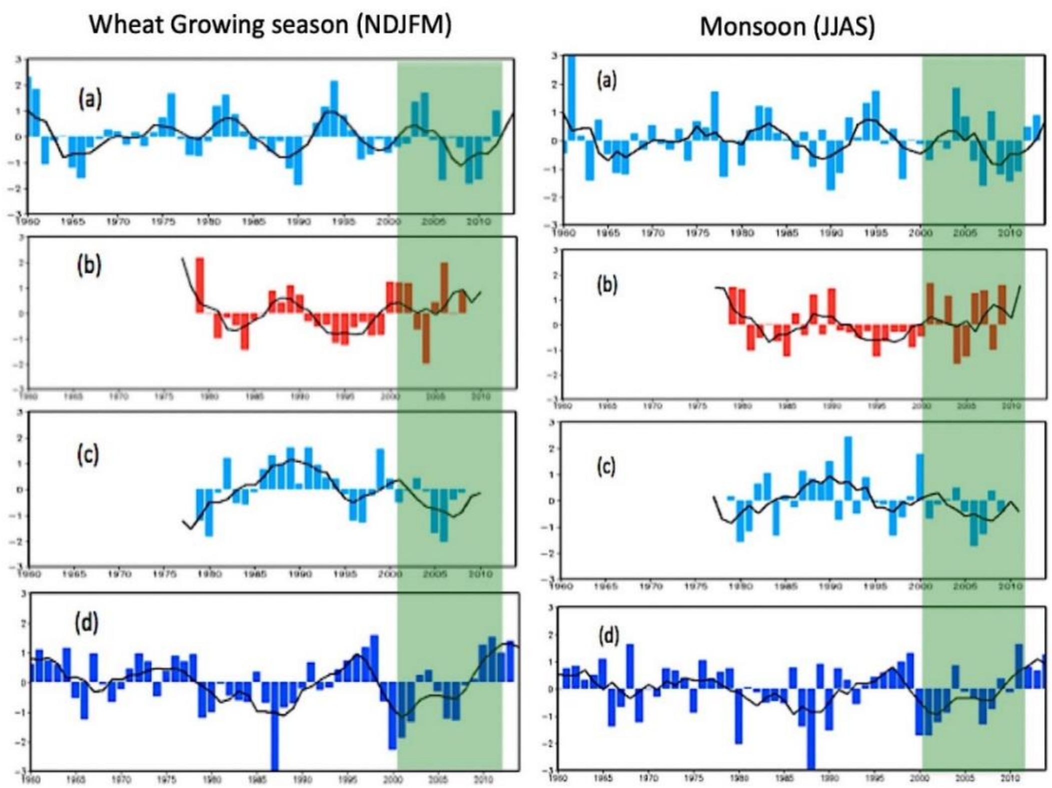

Figure 2-4. Seasonal (winter and monsoon) anomaly of (**a**) precipitation (1961–2012), (**b**) potential evaporation (1979–2010), (**c**) run-off (1979–2010), and (**d**) soil water storage (1961–2012)—the black line in each figure indicates the three-year running mean. The 2002–2011 period is shaded.

During dry season, soil becomes hard to penetrate for the root system to absorb water and nutrients, especially during juvenile stages. Low soil water storage is a balance between a low amount of precipitation, high PET, and low run-off, which can impact groundwater and thereby irrigation.

Next, we present the changes in groundwater estimation during monsoon and wheat growing seasons in Figures 2-5a,b in terms of the spatial distribution of long-term trend in the GRACE TWSA.

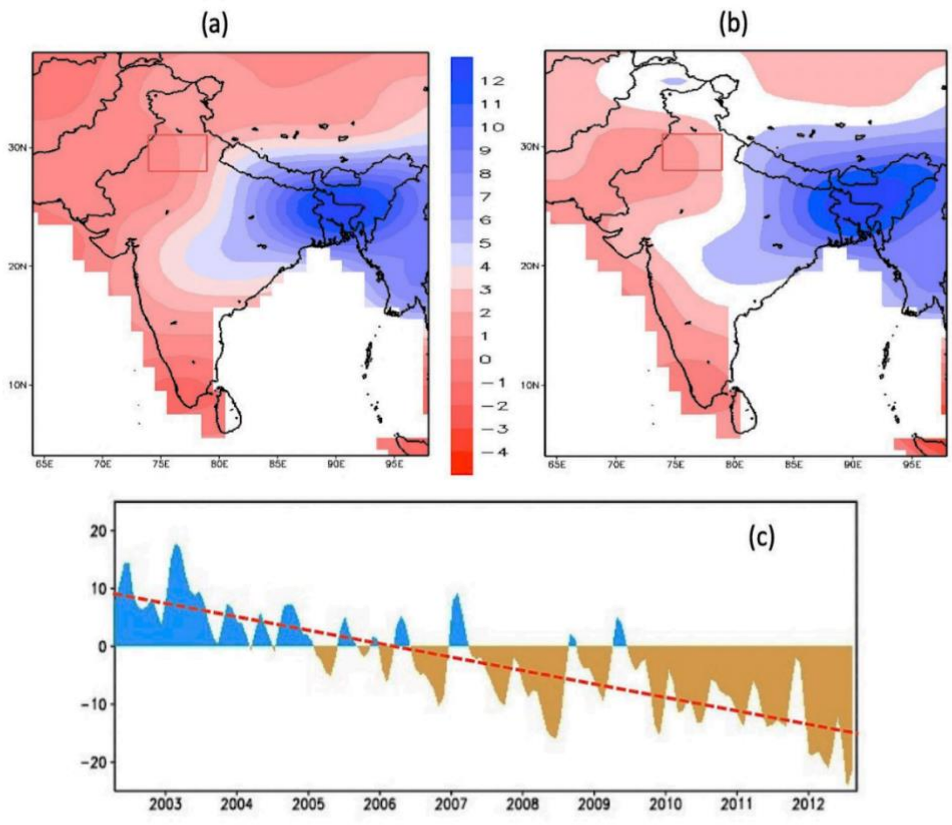

Figure 2-5. Changes in estimated ground water depth (mm) during 2002–2013 in (**a**) monsoon season (June–September) and (**b**) wheat growing season (November–March), (**c**) anomaly in estimated groundwater level (2002–2013)—the red-dotted line is the trendline.

The northwestern part of India is characterized by a decade-long reduction in TWSA, suggesting groundwater depletion. By plotting the normalized timeseries of TWSA averaged over Punjab and Haryana (Figure 2-5c), the decline shows the reduction of the groundwater level (estimated) to be 2–3 cm during 2002–2011—this could mean a significant impact on crop irrigation. Similar results of the drastic depletion in groundwater level in northern India have been reported [30,31], for example, a groundwater decrease may be compounded by the overexploitation of groundwater for crop irrigation.

3.2.4. Correlation between Climate Factors and Wheat Yield

Climate factors are always present when it comes to crop production, especially for wheat, which is very sensitive to heat and moisture stress. In Table 2-1, we list the major climate factors' correlation with the average wheat yields of Punjab and Haryana. Winter and monsoon precipitation did not a show significant correlation at the 95% significance level, which indicates an indirect relationship of precipitation with wheat yield in those two states. Air temperature had an inverse relationship, which indicates that higher temperatures during the growing season lead to a lower wheat yield. PET showed a non-significant linear relationship with wheat yield. Soil moisture storage can help the yield, though not significant at 95% significance level, which indicates that a higher soil moisture level can help to enhance the yield.

From this correlation table, it can be concluded that not a single factor has a significant negative impact on wheat yield; rather, there is a combined effect from all these climate factors. While the drought indices showed a significant correlation with the wheat yield, this analysis shows and supports the combined impact of climate factors on reduced wheat yield during the early 2000s.

Table 2-1. Correlation co-efficient table with different climate factors, drought indices, and wheat yield at the 95% significance level.

Climate Parameters		Correlation Co-efficient
Winter Precipitation (Nov-March)		0.19
Air Temperature (Nov-March)		0.12
Monsoon Precipitation (June-September)	Wheat Yield	-0.33
Potential Evaporation (PET) (Nov-March)		0.29
Soil Moisture Storage (Nov-March)		0.31
Standard Precipitation and Evapotranspiration Index (SPEI) (Nov-March)		0.42
Outgoing Longwave Radiation Precipitation Index (OLR) (Nov-March)		0.47

3.3. Contribution from Other Factors

Cropping intensity and the irrigation situation were considered as well, since these variables are related to water availability and wheat yield reduction. As shown in Figure 2-6, the cropping intensity in Punjab and Haryana is 40–50% higher than that in all of India, suggesting a higher water demand for agricultural production in the two states. Because of the low rainfall during winter, overexploitation of groundwater and low water access can intensify. The decreasing monsoon rainfall [32] also reduces surface water and results in dry canals, which are the main sources of irrigation in these two states.

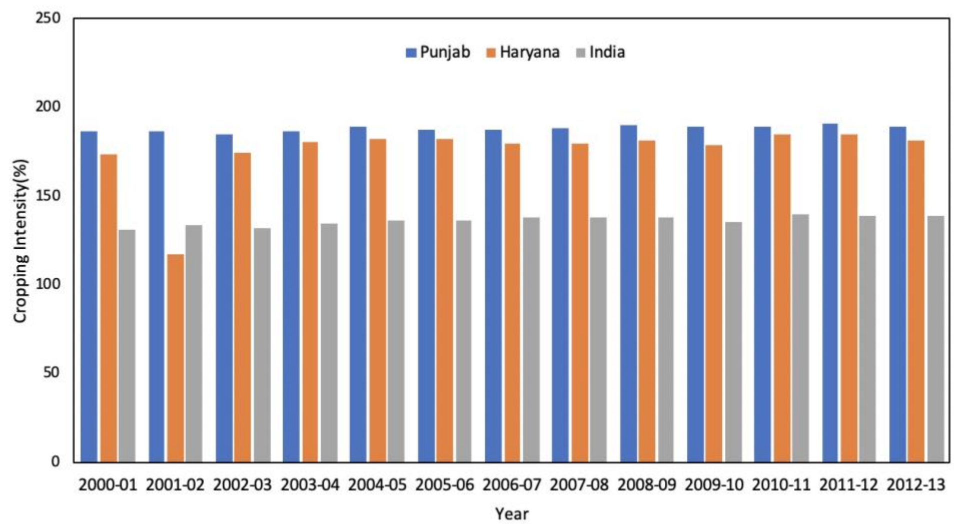

Figure 2-6. Cropping intensity (during one agricultural year, i.e., July–June) of Punjab, Haryana, and India (2001–2013).

As shown in Figure 2-7a, the area net irrigated by canals reduced after the 1990s in both Punjab and Haryana, whereas the area net irrigated by tube wells (Figure 2-7b) has increased over the years. Decreased surface water availability and increased cost of groundwater due to high demand may limit affordable irrigation for poor or middle-class farmers. The situation of groundwater consumption in Punjab is under consideration, but extensive in situ data will be needed.

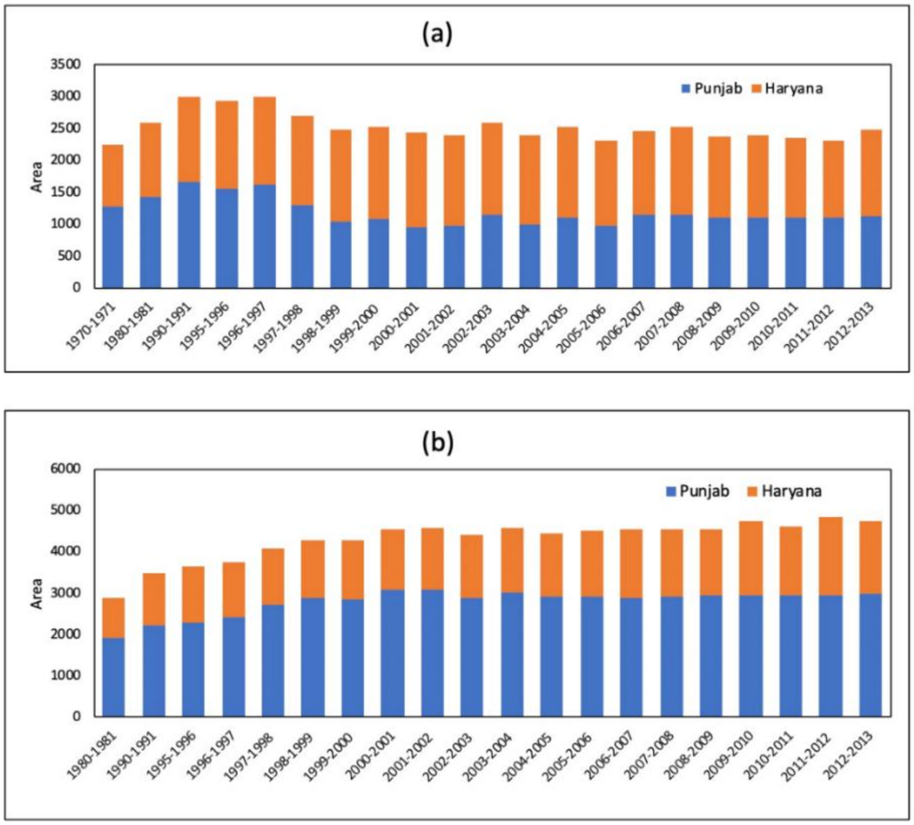

Figure 2-7. Net irrigated areas (thousand hectares) by (**a**) canals and (**b**) tube wells for Punjab and Haryana (1980–1981 to 2012–2013).

Meanwhile, the number of overexploited blocks is increasing, whereas the number of safe blocks is decreasing, as shown in Figure 2-8. This trend indicates the overexploited condition of groundwater, which has gone below a sustainable level. The opposite trend, a decreased number of overexploited blocks and an increased number of safe blocks, would have suggested a well-maintained groundwater level and limited usage of groundwater.

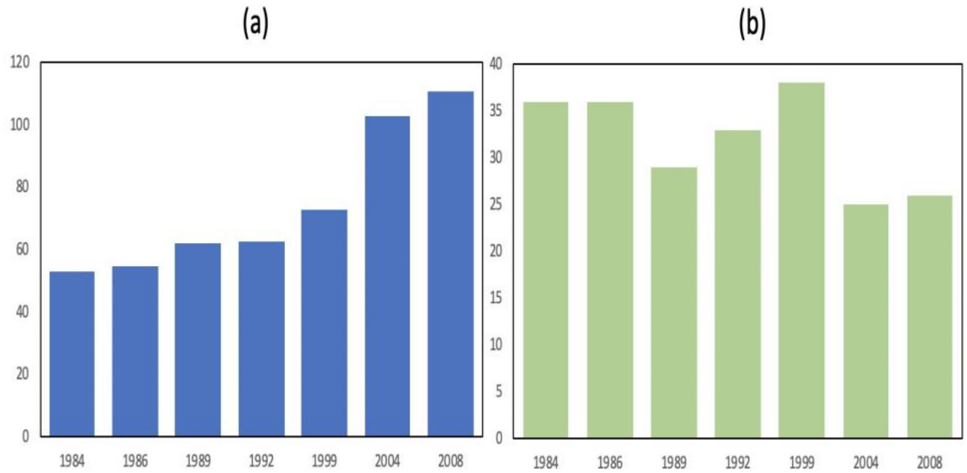

Figure 2-8. Number of blocks with (**a**) overexploited and (**b**) safe water resources in Punjab out of 143 total blocks.

For future research, we shall consider the other factors such as pests and diseases. We note that obtaining official reports of crop loss from pests and diseases during the 2002–2010 period has proven difficult. Moreover, economic and governmental policies regulating input support (e.g., variety, seeds, fertilizers, and pesticides) might be additional factors affecting wheat production. Exploration of these non-climatic elements on wheat yield is an important next step but is outside the scope of this study.

4. Conclusions

The climatological and hydrological factors associated with the pronounced wheat yield reduction during 2002–2010 over northwest India were examined in this study. By focusing on the two wheat growing states, Punjab and Haryana, our analysis indicates that the yield loss is linked to climate variability and change. Decreased trends of monsoon rainfall, winter rainfall, and the increment of average winter temperature were found during the 2002–2010 period. These variations combined contributed to an adverse effect on

wheat yield (both directly and indirectly). Multi-year drought conditions during this period related to the low rainfall, estimated groundwater level, and soil water storage, as observed from multiple sources of data, appeared to have contributed to the prolonged wheat yield reduction. Low water availability tends to limit irrigation requirements for wheat cultivation and can result in growth and yield decrease. Additionally, the increased frequency of days with extreme temperatures above 35 °C during the maturity stage is a significant factor affecting grain sterility and seed weight.

In the face of the projected increases in extreme temperatures in the IGP-wheat region, the decrease in wheat yield could become more dramatic. Alternative management practices may be adapted to maintain wheat yield under climate change in the IGP-wheat region, such as zero tillage (has a positive environmental aspect), water harvesting (a strategic tool for drought mitigation), Variable Rate Technology (VRT) to reduce excess water usage, precision farming, and the usage of drought-resistant varieties or high-yield varieties.

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CHAPTER III

ASSESSMENT OF THE SOCIO-ECONOMIC FACTORS THAT INFLUENCE WHEAT YIELD IN NORTHWEST INDIA

Abstract

This study analyzes the socio-economic factors that affect decision making, crop planning and adoption of different agriculture-related information sources by farmers. A theoretical understanding of existing factors that are related to crop production have been found in this literature. In northwest India, governmental policies and subsidies play an important role in crop yield variability. As most of the farmers are small and marginal farmers, their low education level, age and behavior make a great impact on their decision making and crop season planning. Being financially shorthanded, they lack confidence to adopt new farming techniques and strategies. Similarly, different political, religious and other social factors affect crop production. Comprehensive subsidies and policies can help the farmers improve their livelihood. Proper guidance from agricultural scientists can assist them in adopting new techniques, new machineries and management practices which are also inexpensive and environment friendly.

Keywords: crop production, crop-planning, farmers, policies and subsidies

1. Introduction

Being an agriculture-based economy, more than 60% of India’s population relies on agriculture for their livelihood. Being the second-largest populated country in the world, population pressure on agriculture is enormous in India. It needs an increasing production of food grains to cope up with the increasing population. Variability in crop yield or production creates a significant impact on food security as well as the economy of the country. Hence assessing the variability of crop production and the identification of probable responsible factors is essential.

In addition to environmental factors and natural resources, several socio-economic factors are strongly connected to crop production. However, getting data of these socio-economic factors is a challenging task. Unlike data gathering for climate factors and irrigation (i.e., previous chapter), socio-economic data are entirely based on field visits and surveys, which re territorial and impossible to obtain remotely. Based on their substantial impact on crop production, this chapter took a review approach to assess such socio-economic factors. We want to focus on the factors which may be responsible for the decreased wheat yield in northwest India during the early 2000s.

Crop production includes several management practices and socio-economic factors that contribute to the final yield, but there is no recorded data of these factors. In India, farming is mainly dominated by small and marginal farmers, operating under a wide range of soil, climate, and socio-economic conditions (Ramakrishnan 1992). These small farming systems play a crucial role in crop production. These smallholder systems are strongly constrained by the limited availability of significant resources like land, capital, and labor (Giller et al., 2008). Typically, these constrain the efficiency of the small farming systems.

Stoorvogel et al., (2004) also reported the various constraints like unavailable production technologies, biophysical or geophysical constraints, labor and market constraints, social norms, and policy constraints. Every stage of crop production requires many specific actions or decisions by the farmers (Mittal et al., 2010; Norman et al., 2004). Agricultural practices are becoming more capital and technology-based than labor-intensive during the last couple of decades, which is empowered by new varieties, synthetic inputs, and advanced irrigation techniques (Chavas 2001; Paul et al., 2004; Dimitri et al., 2005; Hoppe et al., 2007).

These decisions and actions also determine agricultural land use, cropping patterns, and decision making in agriculture. The importance of socio-economic factors in farming was realized by researchers, and they have studied the importance of its impact on increasing agricultural productivity (Williams and Williams 1971; Dervin 1976; Rogers 1995). Moreover, the farmers face a different kind of risks during their whole crop growing season, such as price risk (i.e., whether they will receive less or higher price than an average year), input risk (i.e., risk of water shortage or labor), yield risk (i.e., risk of pest and disease infestation) and other risks (i.e., sick family members or damaged tractor) (McNamara and Weiss 2005). These small factors combined have a significant impact on crop production. This chapter is aimed at summarizing and discussing how the factors can cause yield variability.

2. Methodology

In this study, the possible factors are listed outside the area of natural resources (e.g., climate, soil), including management factors, organizational factors, economic factors, and

different technological issues farmers face during their crop growing period. These factors also have some significant impact on production and play a crucial role in the economy. It is challenging to obtain data for these factors and impossible to obtain adequate data for the entire north-west India (State of Punjab and Haryana). Thus, several papers have been reviewed to list down all the probable factors that can affect crop production in north-west India.

3. Results and Discussion

3.1. Relationship among socio-economic factors

All socio-economic factors are interconnected to each other. Organizational factors play the primary role and have an impact on economic and technological issues, which affect management factors. Management factors decide the final crop yield at the end of the season. Improved management practices increase the chance of getting higher yield, while poor management practices reduce the chance of higher yield and profit. Economic factors and technological issues determine this condition. Wealthy farmers can use improved techniques to get higher profit while poor farmers rely on traditional techniques, which reduce the chance of getting a good yield. Being small or marginal farmers, it is difficult for them to afford high amount of money for the crop production as the profit margin can be very little or sometimes in negative due to different extreme climate events (e.g., flood, drought, forest fire etc.)

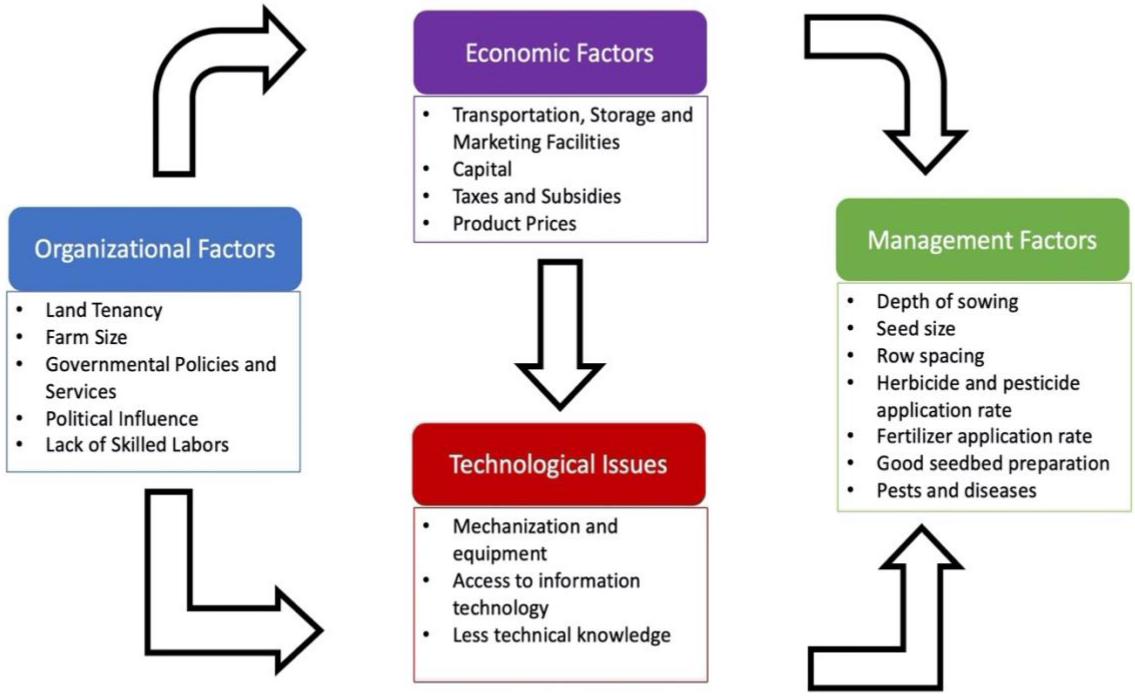

Figure 3.1. Schematic map of the intertwined socio-economic factors that affect wheat yield.

3.2. Organizational Factors

(a) Land tenancy

The pressure of increasing population in India is a major constraint for land availability. Land tenure includes all forms of tenancy and ownership of the lands. The duration of land tenure has a considerable impact on crop production and cropping pattern. According to the duration of land tenure and ownership, cropping pattern or type of crop is decided. Farm management plans are also dependent on the duration of land tenure. For example, in northeast India, the tenure is decided upon the fertility of the land. For Jhum cultivation, the land is tenured for one or two years. Since the independence of India, this tenancy type has been changed, but it still needs improvement for the benefit of the farmers.

(b) Farm Size

Most of the farmers in India are Marginal (who owns or leases ~1-acre land) to small (who have ~5-acre land) farmers. Approximately 36.33% of farmers are marginal, and 30.08% of farmers are small. Hence most of them lease others' land for crop cultivation and production for their livelihood. Despite that, in 2017-18, total food grain production was estimated at 275 million tonnes (MT) though most of the time, they do not get proper facilities and support for the production process. Although in Punjab, the average landholding of farmers is 3.95 ha, which is above the average of India.

(c) Governmental policies and services

Different governmental policies have a crucial role in crop production. Every year small changes in policies make a significant impact on food supply, product prices, influence marketing, irrigation, and trade. Policies also have a high impact on input markets such as seed and fertilizer to produce food. When the government steps in and establishes some policies, which encourage the farmers to adopt new eco-friendly management practices. This approach can improve both farmers and society if appropriately implemented (Just and Antle 1990; Swinton et al., 2006; Smith 2006).

(d) Political influence

A wide range of political factors have a significant impact on agriculture in India. Conflict among different political agendas, approaches, and subsidies to agriculture affect the farmers and producers.

(e) Lack of skilled labors

Young generations are being inclined towards IT and other lucrative jobs now-a-days. Hence the tradition of a farmer's family is changing, and the shortage of skilled young labors results in a negative impact on crop production. On the other hand, farm labors are demanding higher pay, which restricts the small and marginal farmers from improved management practices, which affect the final yield.

The household is both a production and a consumption unit, and inputs differ from one household to another to affect the performance of the farming system (Singh et al., 1986).

3.3. Economic Factors

(a) Transportation, storage and marketing facilities

Due to the lack of timely and reliable transportation and proper storage facilities, a significant amount of crop is destroyed each year. From harvesting to marketing, the whole process plays a significant role in the farmer's economy. Due to poor financial conditions, they cannot afford expensive services for quick transportation and proper storage facilities, which results in degraded grain quality. Especially in hilly areas (Northeast India), lack of proper and quick transportation made life difficult for farmers. Hence most of the small and marginal farmers who do not have access to quick transportation and storage facilities, avoid cultivating the susceptible crop, e.g., vegetable crops.

(b) Capital

The personal capital of each farmer is another critical issue. Most farmers do not have savings to raise crops without loans or mortgages. It is even harder for them to repay these loans as they do not get the desired pricings of their crop and lose interest in cultivation. Crops have higher return needs more capital to input; thus, poor people avoid those crops. The development of quality irrigation systems in the fields and adoption of HYV (High yield varieties) are not possible without good capital. A farmer's income or resource determines his/her ability to obtain credit that will influence the choice of crops, farming systems, and willingness to invest in new crops or technologies (McCann 1997; Knowler and Bradshaw 2007).

(c) Taxes and subsidies

The Indian government has a vital role in agricultural subsidy, which is financial support to the farmers and agribusiness to supplement their income and manage agricultural commodities. Though subsidy on seed, fertilizer, energy, and water for irrigation and low-interest crop loans are being announced, it is execution into action is slow. In 2014, Indian subsides were well below the WTO's cap of 10%. As the net sown area under tube well irrigation increased from 22.33 hundred thousand hectares (58%) to 29.81 hundred thousand hectares (72%) while the area under canal irrigation decreased from 16.60 hundred thousand hectares (43.5%) to 11.60 lakh hectares (28%) during last 30 years (Punjab Govt: www.punjabstat.com). This has increased the cost of tube well installation and electricity consumption. There exists a conflict between the central and state government. Due to the conflict, Punjab does not have any comprehensive agricultural and water policies.

Policies and regulations might impact the profitability and evolution of different agricultural systems by influencing farmers' decisions about what crops to grow or how much land to farm using the policies (Hardie et al., 2004; Goetz and Zilberman 2007). Different policies on labor, immigration, or water do not target agriculture. This has a significant impact on increasing the cost of agricultural production. Subsidies on synthetic pesticides or inefficient irrigation systems should be lowered to limit the usage of these harmful chemicals to crop field and to limit water usage (Lichtenberg 2002).

(d) Product prices

Rapid changes in product prices and increasing living costs are making farmers challenging to rely only on agriculture for their livelihood. Hence, there is a changing trend in India, as many farmers are shifting to other jobs for better livelihood. The crop production prices i.e., minimum support price (MSP) is also a risk factor to the farmers. They are unsure whether they will be in profit or loss after the season. This risk also influences them to choose other options for a job.

3.4. Technological issues

(a) Mechanization and types of equipment

Technological improvements over the years have made a considerable change from hand-drawn bullock tractors to automatic. These changes save the time of the farmers, along with an increased work rate. These changes have not taken place in several rural areas, and people rely on their traditional farming practices, which limits production, cropping patterns, and cropping intensity. Although in Punjab and Haryana, these

technological changes made a good impact, and people are getting huge benefits from these improvements.

(b) Access to information technologies

Rural areas do not have proper access to television, radios, and other services. The lack of communication keeps the farmers uninformed from weather warnings, improved cultivation techniques, new policies, and other relevant information. The communication gap between agricultural universities and farmers should be improved for better information sharing. Governments should take more initiative, i.e., farmers' fair, interactive sessions between farmers and scientists to reduce this communication gap.

(c) Less technical knowledge in Agronomy, genetics, water management

Communication between the farmers and agricultural scientists are not up to mark. Due to this communication gap and low education level of farmers, valuable information and updates on agronomy, genetics, and water management tactics cannot be appropriately shared among the farmers. Lack of knowledge about how to implement new technologies or practices also affect a farmer's propensity to adopt them (Chavas et al., 2010; Chavas and Kim 2010). Sometimes farmers do not want to adopt new technologies because of their old beliefs and family tradition.

3.5. Management factors

Management factors are one of the most important factors along with climate factors. These include the following factors:

- Depth of sowing
- Seed size
- Row spacing
- Herbicide and pesticide application rate
- Fertilizer application rate
- Good seedbed preparation
- Pests and diseases

Those mentioned above are the significant factors that could affect the yield. There was no significant attack of pest or disease reported, which could reduce the yield significantly during the early 2000s. Poor management is the most important among the responsible factors for the lower yield. It lacks in seed rate, fertilization, irrigation, and using patterns of weedicide and pesticides. The other factors are assumed as errorless as these farmers are experienced and ensure the basics of crop production quality. Hence the margin of error is considered as a minimum. Fertilizer application rate may vary from year to year, but it is challenging to acquire that yearly variation data.

3.6. Other factors

(a) Farmer's age and education level

Most farmers are not well educated, which restricts them to a handful use of technologies and improved knowledge on farming. The average age of farmers in India is higher compared to other countries, which is not a good sign for the future improvement of agriculture. Aging people are not very enthusiastic about learning new technologies and management practices. Most of the time, they prefer continuing their own traditional and

primitive methods. Low education level also limits their decision making and adoption of useful timesaving techniques. Farmers' education and knowledge are essential; farmers resist making changes in cropping decisions or adopting new agricultural practices. They might have a very conservative attitude or disregard environmental concern (McCann 1997; Hanson et al., 2004; Serra et al., 2008).

(b) Pressure of population in agriculture

The rapidly growing population in India has extreme pressure on crop production for food security. It is difficult maintaining a balance between production and a population of 1.33 billion. Hence it is crucial to adopt new inventions, technologies, and management practices, which might help steady production even in extreme years.

(c) Rural environment

Rural development plays a vital role in agriculture as well as the economy. Most of the rural areas still lack the necessary facilities which need to improve rapidly. Agriculture plays an essential role in development as it supplies food and money for the local people and foreign currency from cash crops.

(d) Religion

Being the host to several religions (e.g., Hinduism, Islam, Christianism, Jainism, Buddhism) and many other indigenous ethnically bound faiths, India has an incredible unity among people. However, in rural areas, people are still superstitious and firmly believe in their religious values. This belief has a somewhat negative impact on crop production in an indirect way. In some regions, religions still play a crucial role in

determining the cropping pattern. For example, in northwest India, especially in the state of Haryana, the sunflower was being cultivated as a cash crop, which is a short-term crop (between kharif and rabi season) with a large amount of profit. Neelgai (a type of antelope) was abundant in that region and fed on the sunflower plants and increased their number rapidly. Hindus worship neelgai in similar regard to the cow. Rather than controlling neelgai population, sunflower cultivation has been restricted. This habit changed the cropping pattern of the region and restricted them from economic profit.

3.7. Citation map

Based on basic concepts, a citation map is developed to represent a clear relationship among the socio-economic factors through the cited pieces of literature. Organization factors include different policies by the government, which determines resource cost for crop production. Hence these factors determine the economic condition (taxes and subsidies, product prices) for farmers. Based on economic conditions, farmers use technology, and technology determines management factors. Poor management factors result in lower crop yield. Small and marginal farmers cannot invest their capital due to poor economic conditions. That results in inferior technology and resources (i.e., seeds, fertilizers, pesticides) used in management practices. Arrows are used in Figure 2. To show the direct relationship. There is an indirect connection among the factors which are not presented here to avoid complexity in the citation map. Other factors are avoided in the citation map as those factors are independent and hard to connect directly among these

factors by the literature review approach due limited field data and statistics.

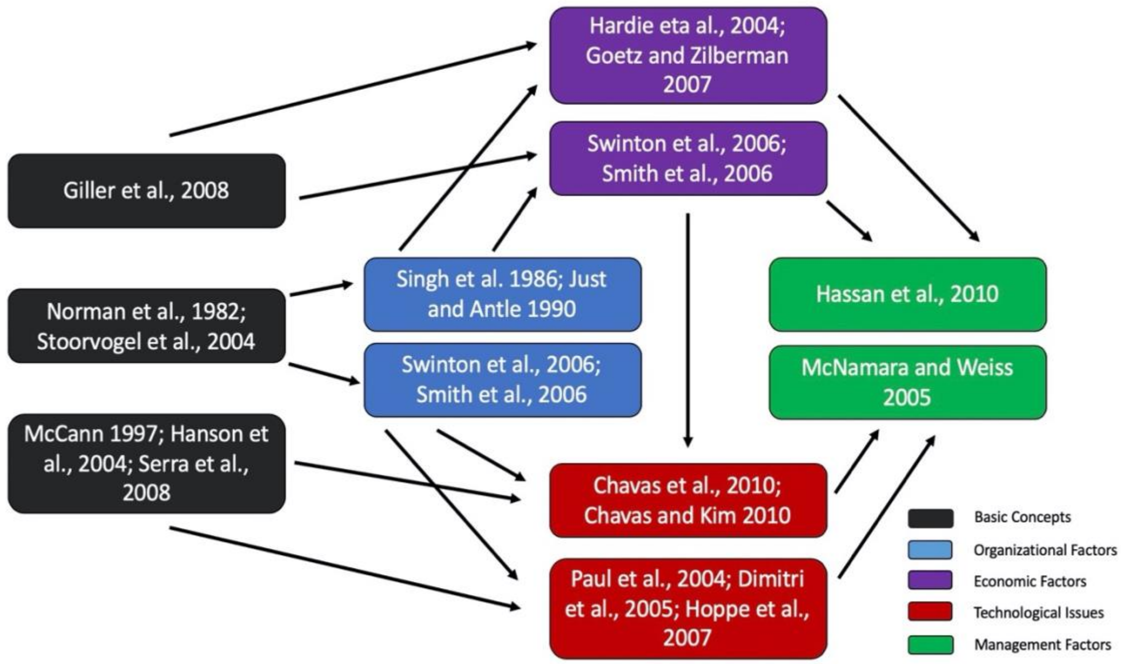

Figure 3.2. Relationship among socio-economic factors based on cited literatures

4. Conclusions

The socio-economic factors that are associated with crop production and responsible for crop production variability, were assessed in this study, along with a literature review and analysis.

In the two major wheat growing states, Punjab and Haryana, the impact of the factors mentioned above is similar to other states. Seeds, fertilizer, pesticide, and irrigation cost makes the majority of the total expenditure for the wheat crop. Somehow organizational factors determine the economic condition of the farmers. Different governmental policies, subsidies, and taxes limit the resources of the farmers and their

economy. Due to poor economic conditions, farmers cannot afford high technology and results in poor management practices.

Despite these uncertainties and risks, the farmers need to learn adaptations like off-farm employment (Ito and Kurosaki 2009), saving or using credit markets, informal borrowing, adopting risk-reducing technologies (i.e., use of improved seed varieties and management practices), ensuring buyers at the end of the season in affixed price (Goodhue and Hoffman 2006). The farmers should adopt these initiatives with the help of government and improved agricultural extension practices (Adhiguru *et al*., 2009). The overall prospect and the economic support for the farmers are being improved and still a long way to go to meet the highest level of production, which requires a complete and restructured policymaking and more support for the small and marginal farmers.

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CHAPTER IV

EMPIRICAL FORECASTING OF WHEAT YIELD IN PUNJAB AND HARYANA USING LINEAR REGRESSION MODEL

Abstract

Wheat is one of the most common agricultural crops in India. For crop planning, forecasting is an important tool for estimating the yield and price of wheat production for upcoming years. Based on the results from prior chapters, this part of the dissertation aims to develop a regression model to predict yearly average wheat yield of Punjab and Haryana using data for the period 1985-2014. Four climatic variables were also considered as independent predictors for the model. Validation of the model was tested by the standard statistical techniques. Based on the model output, forecasting of wheat yield for next 2 years shows an accuracy of 74%. This is not considered high but nonetheless informative, given the small number of data points used. The forecast model suggests a general relationship between the sum of climatic effects and wheat yield highlighting past precipitation or past soil moisture content as the more decisive element.

Keywords: wheat yield, linear regression model, forecasting, climatic variables

Introduction

Wheat yield prediction in northern India is essential for the planning and implementation of different economic policies and management options. In the face of changing climate, it has become increasingly challenging to maintain crop yield every year, due to increased extreme events and uncertainties in monsoon season. In this case, forecasting crop yield can provide insight into possible changes and variations in the future.

Approximately four-tenth of the world's land surface belongs within the arid and semi-arid zones (Meigs 1953). In both these zones, water is the primary factor limiting crop production. Being in a semi-arid zone, Punjab and Haryana face a similar situation, especially for winter crops like wheat. Punjab and Haryana contribute more than 60% of its production to the central pool of wheat. Despite decreasing precipitation, fewer irrigation facilities, and vanishing groundwater, this region is fighting hard to maintain its production growth to feed the nation. The main reason behind the change of crop yield from year to year is climate variability, as any two growing seasons cannot experience the same weather (Lobell et al., 2010). The lack of field data challenges using the crop model (i.e., APSIM) and obtaining satisfactory output. Using climate factors as predictor variables in a regression model could be a good idea to overcome the challenges for forecasting wheat yield and to get a satisfactory result.

The primary objectives of this study were:

- To develop an empirical model to predict yield for the next 2 years.
- To show the general relationship between yield and climate variables.

Methodology

The ARIMA methodology was originally developed by Box and Jenkins (1976) and has been extensively used to describe time-varying processes in nature, economics etc. This model has gained popularity in many areas of research for its power and flexibility (Hoff, 1983; Pankratz, 1983; Vandaele, 1983). AR is also effective in the time series that shows periodity like monsoon in northern India and Nepal (Gillies et al., 2013). The notation AR(p) indicates an autoregressive model of order p. The AR(p) model is defined in equation 1:

$$X_t = c + \sum_{i=1}^{p} \alpha_i \ X_t - i + \ \varepsilon_t \quad (1)$$

Where, variable time t, α_i , ….,α_p are the parameters of the model, c is a constant and ε_t is white noise.

As wheat yield is known to be influenced by weather conditions during its whole growing season, it’s a common method to forecast wheat yield based on weather conditions. Due to lack of field data (i.e. no. of spikes, no. of grains per spikes etc.) in this study, climatic variables identified from chapter II which showed noticeable impacts on wheat yield combinedly. In this study, four variables are taken with specific months i.e. precipitation (JJAS), soil water storage (NDJFM), SPEI (NDJFM) and number of days above 35°C (March) as independent variables. Combination of these four variables were put into a design as no individual variable has significant impact on wheat yield (as of Chapter II). The modified form of the main equation is defined in equation 2:

(2) $$Y_{N+1} = Y_N + V + \varepsilon_t$$

Here Y defines the yield, N refers to the current year and V refers to variable considered at time N.

Next, the average annual yield of Punjab and Haryana for the years 1985-2012 is used to fit an appropriate linear regression model using software R. Fitting a model with limited realizations (i.e. low number of data points) is challenging.

Moreover, linear regression model assumes that the data are stationary and has a limited ability to capture non-stationarities and non-linearities in hydrology and climatic data. For the model, it is assumed that the absence of abnormal climatic conditions, extreme events i.e. flood or drought and effects of pest and disease attacks.

Results and Discussion

Fitting the model

A simple linear regression model is used to forecast future average (2 years) wheat yield (t/ha) for Punjab and Haryana (Table 4-1). This model resulted in an adjusted R^2 value of around 0.74, which refers 74% fit of the model, which is sufficient to forecast the yield of the very next year. Out of four variables, only SPEI has some sort of inverse correlation with wheat yield, still weak at 95% level of significance. Among the four variables, no particular variables have a significant impact on wheat yield, but the combined impact of these four variables has shown a significant impact on wheat yield. The rest of the variables are not correlated with wheat yield significantly.

Normality test

In Fig. 4-1, the quantile-quantile (q-q) plot of the forecast error is given. The overall model fits well, but few points are far from the trendline, which indicates the dataset is rightly skewed, i.e., the mean is higher than the median. Here, the standard residual is defined as the residual divided by its standard deviation. Major data points lie close to the fitted axis though few points are far from the axis on the right-hand side. The q-q plot indicates there is a right tail, but this does not pose a severe violation of normality. However, there is always a chance to improve normality by using a higher number of data points.

Distribution of average yield and climatic variables

In Fig. 4-2, average yield and SPEI show an appropriate normally distributed pattern. The rest of the variables are nowhere near normally distributed, which is not uncommon in climate variables. SPEI has a somewhat inverse correlation (-0.16) with an average yield; hence only the SPEI variable has some normally distributed trend.

Normal distribution frequently occurs in the natural world until there is some external force that makes an impact on it, such as extreme events (O'Brien et al., 2019). The unusual shape of the distribution of the climatic variables hints at the possible influence of external factors on these variables. It is known that highly skewed distributions or distributions with multi-modality always have external causes behind them. Unfortunately, our scope of the study did not allow the collection and study of these external factors due to a lack of field data. In Fig. 4-2., precipitation, and soil moisture have a distorted distribution. These distributions have no left and right tails, respectively, which indicates some substantial impact on them. The number of days above 35°C has three peaks in the distribution, which also indicates the impact of external factors. The number of days

above 35°C is higher than average during the whole period, which indicates above normal temperature throughout the wheat maturing period (March).

These variables individually might have shown little impact on crop yield, but there is a significant combined effect that is not counted by the model. Even though it might intuitively seem like that these variables have explanatory power to describe yield, by introducing the lagged yield variable, we are, in a way accounting for these effects combinedly. Therefore, regression flags these variables as insignificant, i.e., the lagged yield variable explains considerable variance that there is hardly anything left for these to explain. These results have a clear indication of abnormality in these factors during the growing season. The model might not have shown a clear effect, but a combined effect of all these abnormal factors have a significant impact on forecasting wheat yield.

Average yield vs climatic variable

In figure 4-3, average wheat yield (blue line in fig. 4-3 a,b,c,d) (Punjab and Haryana) and the climate variables i.e. precipitation (June-Sept), SPEI (Nov-March), number of days above 35°C (March) and soil water storage (Nov-March) are plotted. Each variable has a distinct trend over the years (1979-2012). This is a visual presentation of the relationship between yield and climatic variables which might help to assess the relationship between yield and these variables next in Fig. 4-4.

In Fig. 4-4, the trend of yield with the variables are shown. It is observed that precipitation, SPEI, soil moisture, and the number of days above 35°C, all show an overall complicated relationship with wheat yield (blue line). With precipitation, yield trend indicates the increment of return up to 500 mm precipitation; beyond that, increased

precipitation has an inverse effect on yield. This relationship is real for field observation, as wheat is susceptible to a high amount of rainfall.

Some other factors are responsible for the little break during the increasing period. The margin of error (shaded part) also has the same trend and higher uncertainty. With SPEI, the yield has a rising pattern with the increasing value of SPEI. Yield trend is inverse for the number of days above 35°C variable. This might be for the data noise and lack of direct relationship with the number of days above 35°C. However, the relationship with temperature would have been significant if yield can be compared with each growing stage. Since each growing stage of wheat requires a different range of temperatures, it is hard to measure remotely without field data. Yield has also shown variations with soil moisture. Beyond a range of 200 mm soil moisture, the yield has an increasing trend. But for all variables, the margin of error is not significantly affected.

This result indicates a unique aspect of this study that increasing precipitation or SPEI or soil moisture does not help increase yield directly. The long-term yield increase was due to advancements in technology and an increase in cropping intensity and is not climatic. There are only specific ranges that are beneficial to crop growth. In summary, it is observed that wheat crop is susceptible to excess moisture or rainfall, which prevents healthy root growth and causes damaged root. Higher content of soil moisture often damages the root distribution and architecture. Many pathogens and diseases thrive well in high soil moisture or high humid condition. High soil moisture reduces the air content and nutrient mobility in the soil and affects plant root growth. These factors collectively contribute to the reduced yield and yield variability at the end of the growing season. High soil moisture results high above biomass, high harvest index and causes lodging in the later

growth stage, with a negative effect on grain filling. It is reported that high soil moisture content during the grain filling stage may result in lower seed weight, grain yield, and quality of grains (Sheng and Wang, 1985).

One of the other studies (Zhang et al., 1998) reported similar results in China. It has been reported that the remobilization of carbohydrate reserves from the stem and leaf sheath helps to fill the grains. Hence low soil moisture content during grain filling stage leads to better use of the carbon reserves in stems and sheaths (Palta et al., 1994: Ricciardi and Stelluti, 1995), resulting in less yield in higher soil moisture condition than the normal one. A study by Aggarwal et al. (1986) in North India has shown that triticale cultivars have higher water use efficiency (WUE) during dry years compared to wet years. The lower WUE in wet years due to lower specific weight (Passioura et al., 1977), lodging, and high evaporation from the surface.

In this study, shown soil moisture range (in mm) may vary from region to region, soil type, and wheat variety. The soil type in our study area is mainly sandy loam to clayey type (in Punjab) and loamy sand to silty clay (Haryana). Most of the soils are alkaline to sodic soil and have low soil water capacity. More accurate field data, including soil temperature and atmospheric humidity, would have better explained these variabilities. This model could have shown a better and more transparent relationship with the factors mentioned above. Yet, these results may point to some useful avenues of climate and wheat yield relationship for better planning and management in semi-arid regions.

Forecasting the yield

This model delivered an accuracy of about 74% to forecast yield for the next two years (Table 4-2). This percentage is not very high, but a 26% margin of error indicates there should not be any drastic deviation of crop yield outside of this range. Table 4-2 indicates the deviation (%) from the actual yield within the predicted margin of error.

Due to a smaller number of data points and the lack of field data, accuracy is not optimal. Forecasts for the higher number of years could have been conducted, although the accuracy would have been compromised. This study demonstrated forecast ability of wheat yield without field data and created several research aspects which could be important for future examination. On the bright side, these results can be compared with the field experiment in the same region to find out the possible improvements for this model.

Conclusions

The regression model is widely used for forecasting the magnitude of any variable. The strength in this model is that it is suitable for any time series with any change in pattern. However, this model cannot capture the complex characteristics of a time-series. In this study, the wheat yield time-series has an unusual trend of yield (2002-2010) caused by the combined effect of selected climate variables, and the model was unable to capture this trend.

The above analysis showed that climate impact on wheat yield could be severe in the future. However, 74% forecast accuracy is not satisfactory even for the time-series that had a limited number of data points. Adding appropriate variables and field data can get the model to perform much better. The relationship between yield and climate factors reveals a unique aspect of crop production (without field experiment). Increased precipitation or soil moisture does not always help the crop in terms of growth. After a

specific limit, growth, and yield both can be affected due to high moisture that restricts root growth and nutrient availability. It was challenging to find the examples in the literature where all of the climate variables and wheat yield relationships had been estimated simultaneously.

Potentially, this experimental forecasting methodology can be a handy tool for the policymakers, the government, and the farmers. They can plan accordingly for their subsidies, minimum support price, irrigation planning, and the estimation of damage from natural calamities. This study provides an opportunity for further studies with additional field data that could increase the accuracy of the forecast for farmers to plan their management practices and economic precautions. In this case, the non-linear model or crop model can be used to capture the complex behavior of the time-series.

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Table 4-1

List of coefficients for the fitted model

Coefficients:

	Estimate Std.	**Error**	**t value**	**Pr(>|t|)**
(Intercept)	1.09283	0.44566	2.452	0.0226*
y_L1	0.76854	0.09978	7.702	1.1e-07 ***
SPEI	-0.16316	0.10362	-1.575	0.1296

Note: Adjusted R-squared: 0.7374. Y_L1 refers to the previous year's yield.

Table 4-2

Actual Yield and Projected yield for 2013, 2014

Year	**Actual Yield (t/ha)**	**Projected Yield (t/ha)**	**Deviation from actual yield (%)**
2013	5.37	4.91	-8.56
2014	4.56	4.80	+5.26

Figure 4-1

Fit of the model with average wheat yield (t/ha)

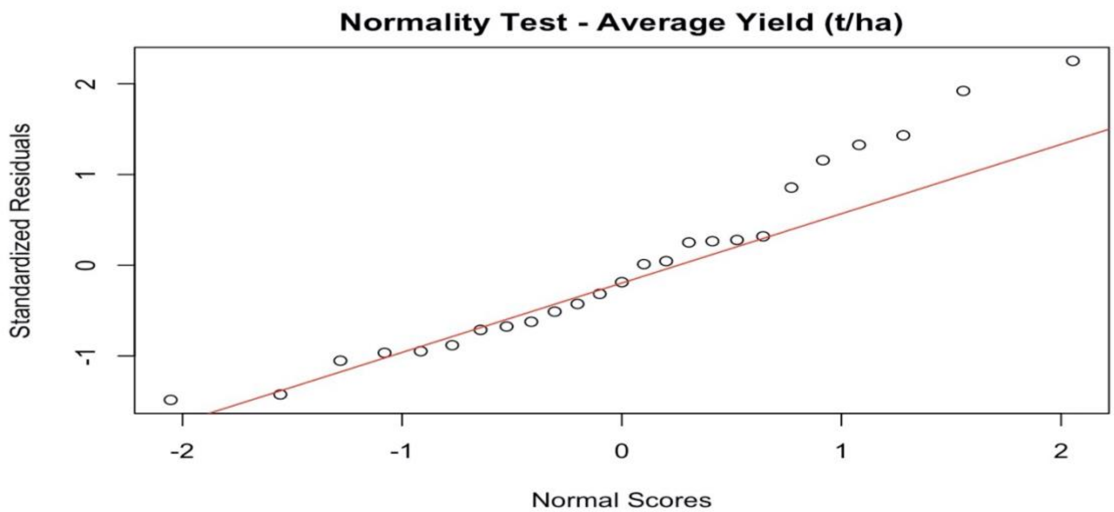


Figure 4-2

Distribution pattern of the (a) average yield, (b) SPEI, (c) Precipitation, (d) number of days above 35°C, (e) Soil moisture

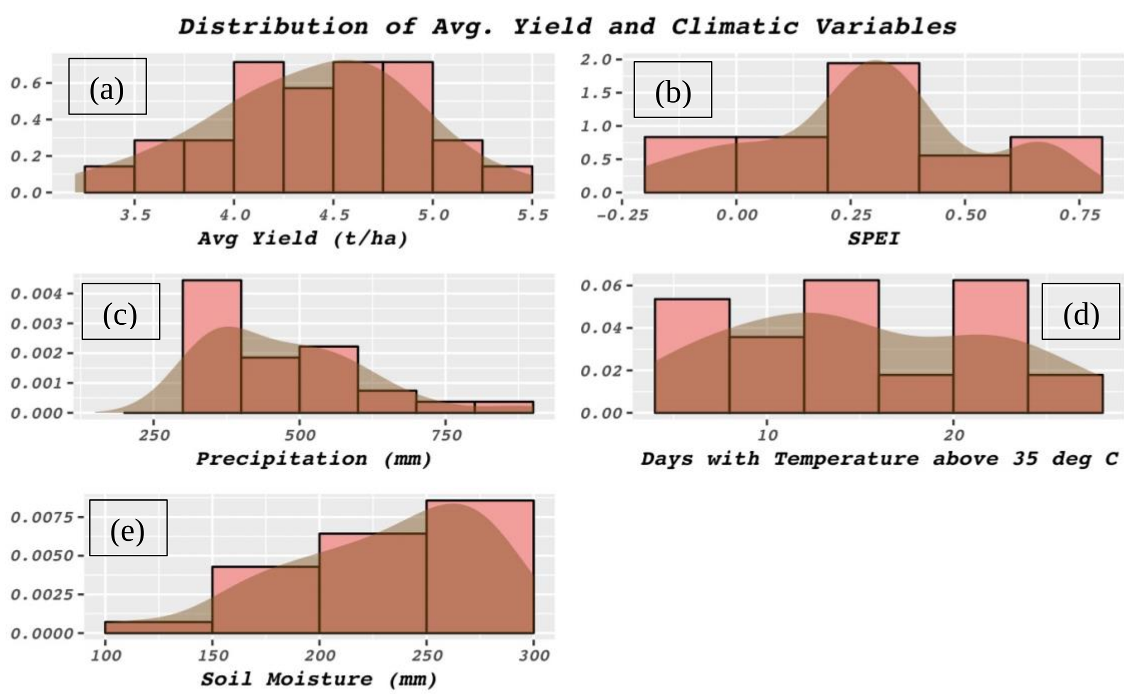


Figure 4-3

Timeseries of average wheat yield (blue line in each diagram) and marked time domain (black box) indicates the yield reduction; (a) precipitation, (b) SPEI, (c) number of days above 35°C and (d) soil moisture storage

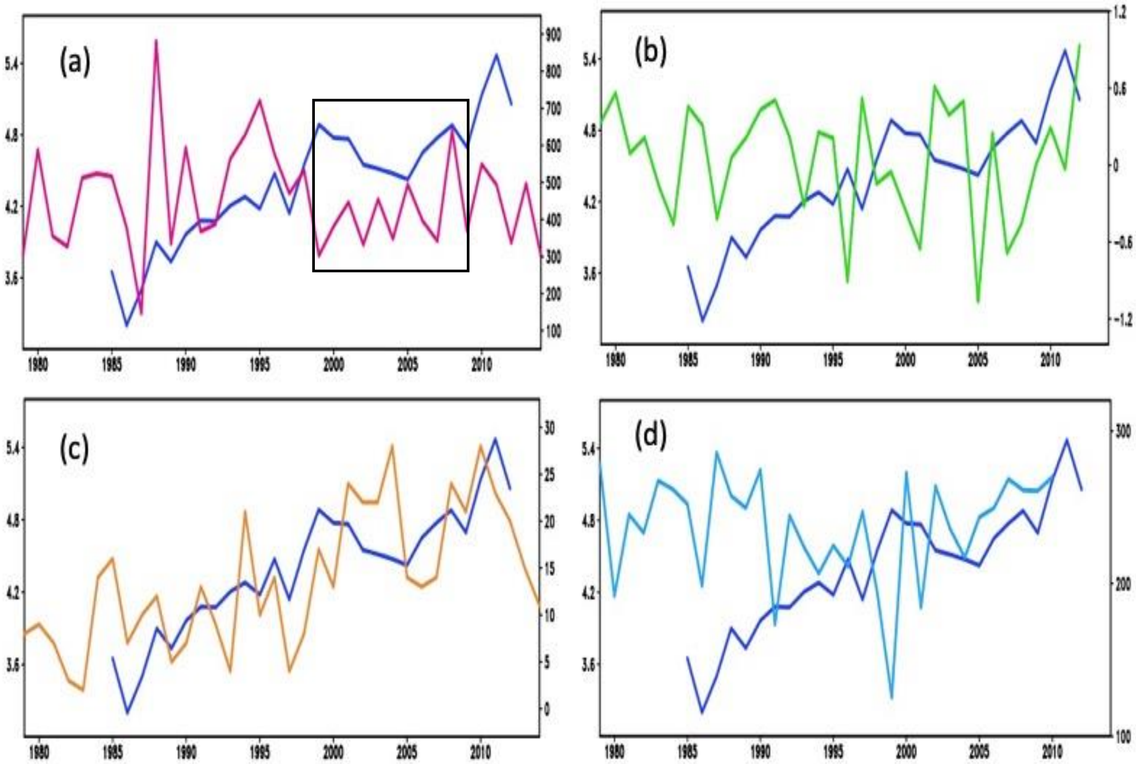
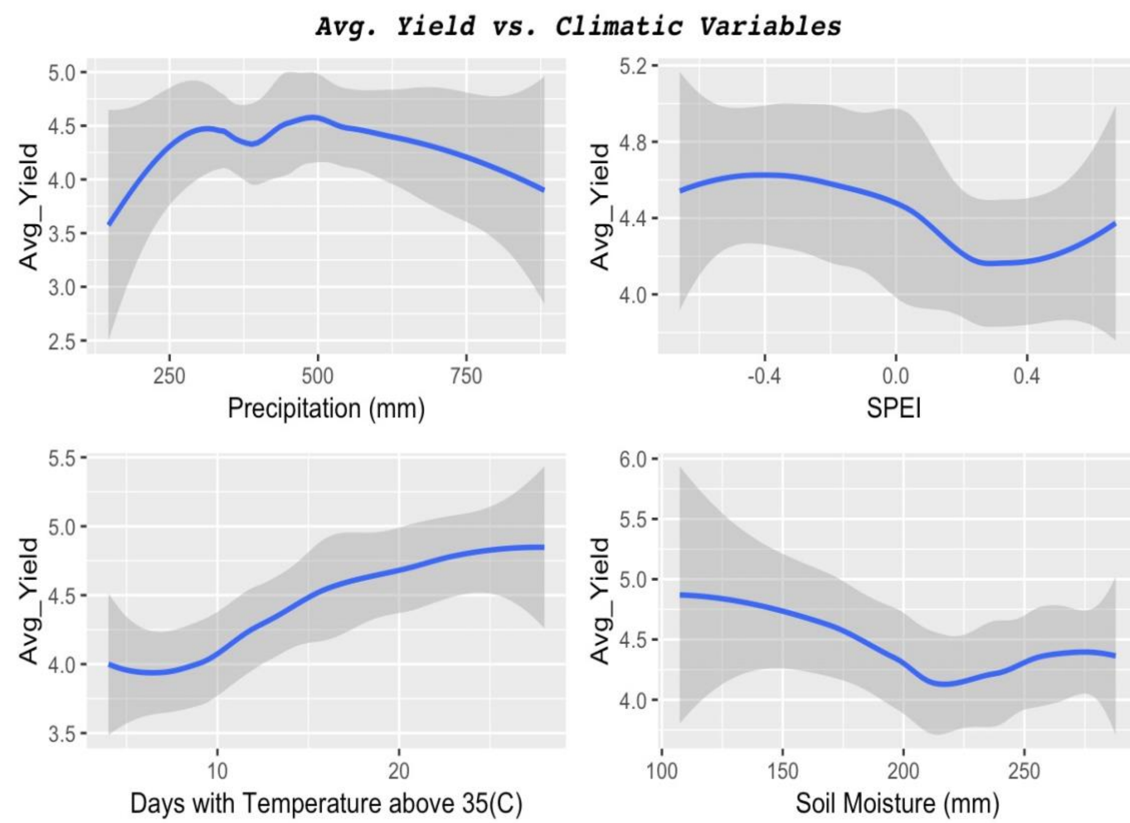


Figure 4-4

Average yield and climatic variables (a) precipitation, (b) SPEI, (c) Days with temperature above 35℃ and (d) soil moisture storage relationship pattern (blue line). Shaded part indicates the margin of error



CHAPTER V

CONCLUSIONS

This work was conducted under the broad research theme of climate effects on crop yield, agronomy, and parts of economics. Empirical methods were developed to assess the climate factors that affect crop yield by using atmospheric reanalysis and satellite data. A statistical model was developed to forecast short-term (2 years) wheat yield. At the core of this dissertation lies the need to improve the understanding of the low-frequency relationship between climate parameters and wheat yield, while improving the wheat yield forecast by using field variables and other atmospheric datasets.

By focusing on the two highest wheat growing states in India, Punjab and Haryana, different climatological and hydrological factors were found to be associated with prolonged wheat yield reduction (during 2002-2010). Decreased trends of monsoon and winter rainfall and the increment of average winter temperatures were observed. The combined effect of these variations contributed to an adverse effect on wheat yield by reducing precipitation and groundwater levels. The lack of water constrained the irrigation system to be dominated by tube well irrigation. Additionally, the increased frequency of days with above 35°C during the maturity stage affected grain sterility, quality, and seed weight. Adoption of an efficient irrigation system, improved management practices, usage of variable rate technology (VRT), water harvesting could be an answer to mitigate such climate change effect.

A literature review of the socio-economic factors that are closely related to crop yield was conducted to outline the non-climatic factors. In northwest India, especially in

Punjab, governmental policies and subsidies are feeble due to prolonged political conflicts between the state and central government. Due to the low level of groundwater, these two states need reliable water and irrigation policies to improve the use and expansion of groundwater for future years. Implementing land usage patterns, technologies, and use of HYV (high yield variety) might take a while, and all the policies should be established based upon the availability of natural and local resources.

In the latter part of this study, a fitted model with wheat yield and climate variables delivers around 74% accuracy in forecasting 2 years of wheat yield. The deviation of forecasted yield from the actual yield is within the margin of error as per the model. In other words, this statistical model demonstrates a broad relationship between yield and climate variables (precipitation, SPEI, and soil water storage found in the diagnostic analysis of chapter II). There is an opportunity to improve this model with additional data points and other variables to achieve higher accuracy. High level of precipitation (above 500 mm) reduced wheat yield, whereas SPEI value above 0 indicated an increase in yield. Similarly, high soil moisture showed a similar trend. Obtaining field data from India is extremely difficult; hence surrogate datasets have been used to achieve the best possible result. Field study could provide not only more information but also a better relationship between yield and these variables.

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CURRICULUM VITAE

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Logan, UT 84321
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CAREER OBJECTIVE

To implement my research experience and knowledge to climate change adaptation, management and drought monitoring projects. Special Areas of Interest: Climate Change, Meteorology, Drought, Water Management, Agriculture.

EDUCATION

2015- 2020 **Ph.D. Climate Science**

Utah State University, Logan, Utah.

Dissertation: "*Examination and empirical forecast of wheat yield in northwest India based on climate and socio-economic factors"*

(**Netaji Subhash International Fellowship** funded by Indian Council of Agricultural Research*).*

2012-2014 **M.S. Agricultural Meteorology**

Punjab Agricultural University, Ludhiana, Punjab, India.

Thesis: "*Quantification of temperature and moisture stress on Wheat Crop (Triticum aestivum L.) using remotely sensed data"* (Funded by Indian Council of Agricultural Research, New Delhi, India).

2008-2012 **B.S. Agriculture (Major: Soil Science and Agricultural Meteorology)**

Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal, India.

WORK EXPERIENCE

May 2015- 2018 Graduate Research Assistant, Plants, Soils and Climate Department, Utah State University, Logan, UT 84321

December 2019- May 2020 GIS Meteorologist, Department of Plants, Soils, and Climate, Utah State University, Logan, UT 84321

RESEARCH EXPERIENCE AND TECHNICAL SKILLS

Ph.D.

- Examination of the climate factors that reduced wheat yield in northwest India during 2000s

	• Assessment of the socio-economic factors that influence wheat yield in northwest India • Empirical forecast of wheat yield in northwest India based on climate factors • Relationship between monsoon variability in northwest India and Climate Indices (e.g. IOD, ENSO 3.4) • Linking low precipitation, depleting groundwater, irrigation shortage and drought monitoring • Tropical cyclone activities over Bay of Bengal
M.S.	• Determination of different vegetative indices under temperature and moisture stress • Development of response functions between stress variables, vegetation indices and yield • Analysis of the micro-meteorological parameters in wheat field • Application of ground-based remote sensing • Management strategies for the management of temperature and moisture stress in wheat
Field Instruments	• Canopy analyzer and Tensiometer • SPAD Chlorophyll meter, Pyranometer • Quantum sensor and Net Radiometer

- Ground truth radiometer
- Eddy covariance system for flux measurements and AWS

Software
- MS Office (Word, Excel PowerPoint), GrADS, NCL, SAS, R, PYTHON

PUBLICATIONS

Zhao L, Wang S Y, Becker E, Yoon J H and **Mukherjee A** (2020) Cyclone Fani: The tug-of-war between regional warming and anthropogenic aerosol effects. *Environmental Research Letter*. DOI:10.1088/1748-9326/ab91e7.

Mukherjee A, Wang S Y, Promchote P (2019) Examination of the climate factors that reduced wheat yield in northwest India during the 2000s, *Water*. https://doi.org/10.3390/w11020343.

AWARDS & ACHIEVEMENTS

2019	**Student Travel Grant:** 3rd Agriculture and Climate Change Conference, Budapest, Hungary, 24-26 March.
2015	**Student Travel Grant:** 48th AGU Fall Meeting, San Francisco, CA, USA.
2015-2018	**Scholarship:** Netaji Subhash International Fellowship (ICAR-IF) by Indian Council of Agricultural Research (ICAR).

2012-2014 **Scholarship:** Junior Research Fellowship (JRF) by Indian Council of Agricultural Research (ICAR).

2008-2012 **Scholarship:** University Merit Scholarship by Bidhan Chandra Krishi Viswavidyalaya, West Bengal, India.

POSTER & ORAL PRESENTATIONS

- Poster presentation on Climate change and crop production in Departmental Showcase, Plants, Soils, and Climate, Utah State University, Logan, UT (2017, 2018 and 2019).
- Impact of climate change on crop production and what we can do (2017) **Guest Speaker** in Congresso de Ingenieria Loyola, Specialized Institution for Higher Education Loyola, San Cristobal, DR.
- The relation between Indian Ocean climate and GDD of wheat crop in North India. (Poster Presented in American Geophysical Union Fall Meeting, 2015)
- Oral Presentation of "Spectral Reflectance Characteristics of Wheat (*Triticum aestivum* L.) under stress and non-stressed conditions" in "New-Dimensions in Agrometeorology for Sustainable Agriculture (NASA-2014)" Organized by Association of Agrometeorologists, Anand, India and GBPUA & T, Pantnagar, India.