Europ. J. Agronomy 73 (2016) 55–63

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Identifying the impact of multi-hazards on crop yield—A case for heat stress and dry stress on winter wheat yield in northern China

Yi Chen[a], Zhao Zhang[a,*], Pin Wang[a], Xiao Song[a], Xing Wei[a], Fulu Tao[b]

[a] State Key Laboratory of Earth Surface Processes and Resources Ecology, Academy of Disaster Reduction and Emergency Management, Beijing Normal University, Beijing 100875, China
[b] Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

ARTICLE INFO

Article history:
Received 3 October 2014
Received in revised form 17 October 2015
Accepted 27 October 2015
Available online 17 November 2015

Keywords:
Northern China
Heat stress
Dry stress
Adaptation
Winter wheat

ABSTRACT

Winter wheat production in northern China severely suffered from high temperatures and low relative humidity. However, the spatio-temporal pattern of heat stress and dry stress and the impacts of these multi-hazards on winter wheat yield have rarely been investigated. Using historical climate data, phenology data and yield records from 1980 to 2008, an analysis was performed to characterize the spatio-temporal variability of heat stress and dry stress in the post-heading stages of wheat growth in northern China. Additionally, these stresses' impacts on winter wheat yield fluctuations were evaluated. Spatially, the central and northern parts of northern China have seen more serious heat stress, while greater dry stress has been observed in the northwest and north of the research area. Temporally, the heat stress has increased in the western part but decreased in the central and eastern parts of research area. Dry stress has aggravated in the entire northern China during the past decades, indicating the complexity of the exposure to adverse climate conditions. These two hazards (heat stress and dry stress) have contributed significant yield loss (up to 1.28% yield yr^{-1}) in most parts of the research region. The yield in the west was more sensitive to heat stress, and dry stress was the main hazard in the south. Additionally, the opposite spatial pattern between the sensitivity and exposure revealed that the climate is not the only factor controlling the yield fluctuation, the local adaptation measures used to mitigate negative influences of extreme events should not be ignored. In general, this study highlighted a focus on the impacts of multi-hazards on agricultural production, and an equal importance of considering local adaptation ability during the evaluation of agricultural risk in the future. Additionally, paying more attention to higher sensitive areas and to more reasonable and practical adaptive strategies is critical and significant for food supply security.

1. Introduction

Ongoing climate change impacts agricultural production because of the increase of temperature, carbon dioxide concentration and the changes in precipitation patterns (Li et al., 2010). Meanwhile, the increasing incidence and intensity of extreme climate events, such as extreme high-temperatures, droughts and floods have severely threatened crop growth (Decker, 1994; Zhang et al., 2010; Zhang et al., 2014a; IPCC, 2012; Wang et al., 2014). The quantification of extreme events' impacts on agricultural outputs and the uncertainty, variability and error propagation during risk evaluation have drawn more concerns since AR4 (Porter et al., 2014). In many studies, high temperature stress is regarded as the most critical factor impacting the crop yield and quality (Rane and Nagarajan, 2004; Lobell et al., 2011; Asseng et al., 2011; Semenov et al., 2012). Exposure to extreme high temperatures for a few hours could drastically reduce the crop yield (Randall and Moss, 1990; Porter and Gawith, 1999; Tao et al., 2013). Thus, more attentions are now paid to the influence of extreme high temperatures on different types of crops (Stone and Nicolas, 1994; Deryng et al., 2014; Asseng et al., 2015). In addition to extreme temperature stress, other combined climate variables in extreme events, such as extreme low relative humidity (Lobell et al., 2011), also play important roles in restricting crop growth. However, attentions on these variables are insufficient. Most of the studies are oblivious to the impacts of multi-hazards (e.g., dry heat, humid heat) in extreme events. The analyses focusing on a single extreme climate variable may not be convincing enough to characterize the entire impact of

* Corresponding author. Tel.: +86 10 58805461.
E-mail address: zhangzhao@bnu.edu.cn (Z. Zhang).

http://dx.doi.org/10.1016/j.eja.2015.10.009
1161-0301/

extreme events, and influence our understanding of comprehensive risk of extreme events for food supply security.

As one of the major food crops in China, wheat accounted for 21.9% of the total sowing area of crops in 2011 (National Bureau of Statistics of China, 2011), which makes China the largest wheat-producing country in the world (FAO, 2012). The sensitive period for wheat growth to extreme climate conditions is the post-heading reproductive stages. It is in these stages that climate conditions drive the grain number per m^2 and average grain weight, which determine the yield (Ugarte et al., 2007). During these stages, the dominant agro-meteorological disaster in northern China is dry-hot wind. As a typical multi-hazards-disaster, this disaster involves the concurrent of two extreme climate variables, including a daily maximum temperature greater than 30 °C and a daily minimum relative humidity less than 30% (Deng et al., 2009). The noticeable effect of the dry-hot wind, which can lead to the crop failure for 5–20% of the annual production, has been concerned for many years, especially after 1988 when the coordination research group of dry-hot wind for wheat in northern China was established. Previous domestic research have characterized the spatio-temporal distribution of dry-hot wind using the disaster records in a limited geographic area (e.g., a single county, or province), or evaluated the responses of winter wheat to the disaster by conducting field experiments (Cao and Dou, 1997; Cheng et al., 2011; Yang et al., 2013; Zhang et al., 2014b). These studies have clearly stated that temperature is the pivotal variable controlling the winter wheat growth, and the effects of humidity are also significant in that low humidity would further aggravate the impacts of heat stress (Liu et al., 2008; Gourdji et al., 2013). However, few studies have quantified the impacts of both climatic variables (heat and dry) on winter wheat production using long-term historical climate and yield records. Therefore, it is still difficult to diagnose the comprehensive risk from extreme climate conditions on winter wheat growth in northern China.

Additionally, when assessing the influences of climate change on crop yield, adaptation should also be accounted for because of its crucial effect on mitigating the negative impacts of extreme events (Bryan et al., 2009; Reidsma et al., 2010). Evaluation on the exposure of extreme events and the effects of adaptation are both essential for better understanding agricultural risks from climate changes. Thus, we should pay attention to the vulnerability of crop and identify the areas with high risk of yield loss.

In this study, our aims were to: (1) characterize the spatio-temporal distribution of indexes describing heat and dry stress in post-heading stages of winter wheat during the past 30 years in northern China, (2) characterize the changes of detrended yields in research regions, and (3) evaluate the impacts of heat and dry stress and adaptations on the observed winter wheat yield.

2. Data and methods

2.1. Study region and data source

Our study area covered six main winter wheat producing provinces in northern China (National Bureau of Statistics of China, 2011) (Fig. 1a). Observed daily climate datasets were collected from 50 meteorological stations in this region to calculate climate indexes. County-level data of winter wheat yield (kg ha^{-1}) in the region were collected from the Agricultural Yearbook of each county (published annually by the China Agriculture Press in Beijing), and some unpublished records from local county bureau of statistics as mentioned in Tao et al. (2012) from 1980 to 2008. Phenology data from 70 agro-meteorological stations were used to identify the local specific sensitive period for each county (Fig. 1b).

2.2. Yield data detrending

The winter wheat yield data were preprocessed to control the data quality. For time series of yield in each county, the mean and standard deviation were calculated. The outliers were defined as the data points that fell outside the range of mean value ± two times of standard deviation (Zhang et al., 2014). These outliers were then removed.

To assess the influence of climate change on winter wheat yield, the impacts of technological progresses on yields should be removed. Because of the local-specific characteristics of climate conditions, soil, management etc., the technological yield may vary among different counties. In this study, we adopted the method proposed by Ray et al. (2012). For the time series of yield in each county, four regression models, including the intercept-only model, linear model, quadratic model and cubic model, were fitted. The best model was chosen based on the Akaike Information Criterion (Akaike, 1974) and *F*-test. This model can best represent the yield trend and was then used to calculate the technological yield series for this county. Additionally, the ratio of detrended yield was calculated as the difference ratio between technological yield and actual yield relative to the technological yield (Eq. (1)).

$$R = \frac{Y_A - Y_T}{Y_T} \times 100\% \tag{1}$$

where R is the ratio of detrended yield, and Y_A and Y_T are the actual yield and technological yield, respectively.

2.3. Defining climate indexes

This study focused on the sensitive periods of winter wheat to dry heat stress, which was from the heading stage to the maturity stage (post-heading stages). The dates of these two stages from 1980 to 2008 were processed using spatial interpolation in ArcGIS 9.3 to identify the heading date and maturity date at each meteorological station. Climate dataset during the sensitive periods were used to calculate the climate indexes.

Four indexes were developed to characterize the dry heat stress. We defined accumulated heat stress (GDD_{heat}) as the annual accumulated heat degree days when the daily maximum temperature was greater than 30 °C in post-heading stages using Eqs. (2) and (3). The intensity of GDD_{heat} (named as $GDD_{heat}I$) was calculated as the daily average GDD_{heat} for days suffering from heat stress (Eq. (4)).

$$GDD_{heat} = \sum_{dh}^{dm} HS_i \tag{2}$$

$$HS_i = \begin{cases} 0 & T_{maxi} < T \\ T_{maxi} - T & T_{maxi} \geq T \end{cases} \tag{3}$$

$$GDD_{heat}I = \frac{GDD_{heat}}{n} \tag{4}$$

In these equations, the dh and dm are the dates of the heading stage and maturity stage at the meteorological stations, respectively. HS_i is the heat stress for days with a maximum temperature (T_{maxi}) greater than T (threshold of 30 °C), GDD_{heat} is the accumulation of HS_i from the heading stage to the maturity stage, and n is the number of days with a daily maximum temperature greater than 30 °C.

The other two indexes were developed for dry stress. An annual accumulated deficit of humidity (HDD) was calculated as the sum of the differences between the actual relative humidity and a threshold of 30% during heat stress days using Eq. (5). The intensity of HDD