The Spatio-temporal Pattern of Extreme Temperature Events and Its Impact on Rice Yields across Main Rice Planting Areas in China

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Summary: Average air temperature has been popularly and extensively used to assess the effect of temperature on crop yield. However, it would substantially remove the impacts of the extremes on the yield, consequently resulting in a potential bias on the result. Given this fact, we raised firstly the theory of three-interval temperature (TTIT) to characterize the responses of crops to different air temperature conditions: extremely low, normal and extremely high. The respective thresholds during different phonological phases in different areas were secondly set. Then the spatio-temporal patterns of extreme temperature in main rice planting areas were characterized. Finally the impacts of three temperature-related variables on rice yield were assessed in China. The findings showed that: 1) global warming did increase heat stress (0.04and 0.12◦C year^{-1}for the stages of booting and heading-flowering, respectively) and reduce cold stress(−0.03 and −0.21◦C year^{-1}for the stages of booting and heading-flowering, respectively); 2) the total contributions of three kinds of variations had increased rice yield in Northeast China (0.59% yield year^{-1}) and some portions of Yuannan-Guizhou Palteau (0.34% yield year^{-1}), but seriously hindered in Sichuan Basin (-0.29% yield year^{-1}) and southern cultivated areas (-0.17% yield year^{-1}). Therefore, TTIT had a better performance in the assessment of climate change effects on rice yield, and it would provide new insights into related studies focused on other crops in other cultivation areas..

Keywords: Extreme Temperature, Spatio-temporal Pattern, Rice Yield, China

1. Introduction

Rice is the most important staple crop and feeds more than half of the world's population [1-2]. Among climatic variables, temperature is the principal factor that determines rice growth, development and ultimately grain yield [3-5]. However, extreme temperatures occurring during rice reproductive period would have dramatic impacts on final production, even in case of generally favorable weather conditions for the rest of the growing season [6-7].

With mounting evidence that greenhouse gas concentrations are warming the world's climate [8], researches focus increasingly on evaluating the impacts of temperature variations on rice production [9-10]. In most of these studies, however, some potential bias may have arisen due to the popularly used index of T_{mean} (average temperature), which generally removed the marginal yield impacts of the extremes by offsetting higher temperature values with lower ones [11]. The index of growing degree days (GDD), as an alternative, is a typical measure of accumulated heat over a certain period and has been recognized as an improvement over T_{mean} [11]. Given the different effects of normal and extreme temperatures on crop yields, both normal growing-degree-days (NGDD) and killing growing-degree-days (KGDD) were used to study the nonlinear heat effects on African maize and Indian wheat [12-13]. In China, however, few studies have quantified such different effects of temperatures on rice yields. As the world's largest producer and consumer of rice [14-15], China is in urgent need of a reliable impact assessment of temperature variations on rice yields.

Therefore, the main objectives of the study, 1) to provide more scientific theory to assess the impact of climate change on crop yield; 2) to capture the spatio-temporal patterns of temperature variables (including both NGDD and KGDD); 3) to comprehensively assess the contributions of temperature variations to county-level rice yields in China during the historical period (1980–2008).

2. Results

2.1 The three-interval temperature theory

The previous studies have substantiated that an optimum temperature environment shows a positive impact on the crop yield, while a negative impact from a too low or high temperature (Fig.1) (so called three-interval temperature theory, TITT) [3, 16]. According to the theory, three important temperatures are used to characterize crop responses to ambient air temperature, including the optimum temperature, the high low temperature and the low temperature threshold. The range of the thresholds between high and low temperatures can basically meet the needs for rice growth, and is also indicative of higher yield by some means such as enabling more sufficient heat accumulation for grain development [3, 11]. But temperatures beyond this range, either extreme low or high, would have severe consequences on rice yields. In particular, extreme temperatures occurring during rice reproductive period would have dramatic impacts on final production, even in case of generally favorable weather conditions for the rest of the growing season [17-18]. With comparison of many studies focused on only assessing the impact of some average air temperature variables on the final yield of crop, however, relative fewer studies have clearly classified the three intervals to assess the impact from different temperature variables according to TITT [19-20] Theoretically, TITT would characterize the impact of the extremes on the crop yield, which usually has been removed by average temperature method [21].

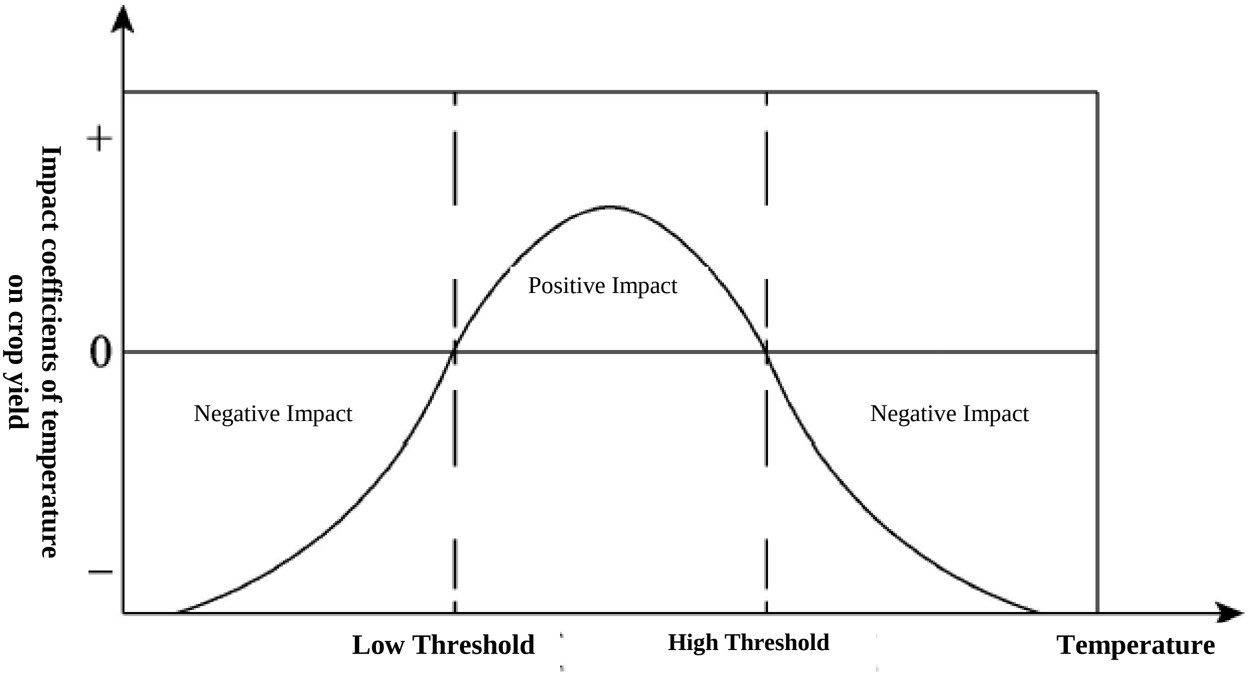

Fig.1 Theoretical diagram of Three-interval Temperature Theory

2.2 The main rice planting area

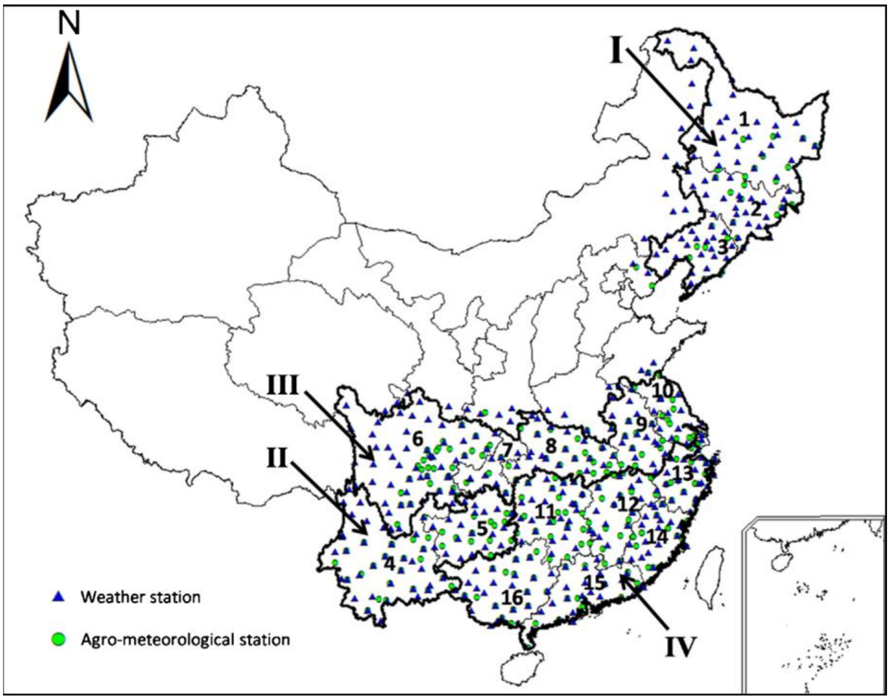

Fig.2 Spatial distribution of rice cultivation in mainland China: (I) single rice in Northeast China; (II) single rice in the Yunnan-Guizhou Plateau; (III) single rice in the Yangtze River basin; (IV) double rice in southern China.

2.3 Temporal trends of temporal variables during the historical period (1980-2008)

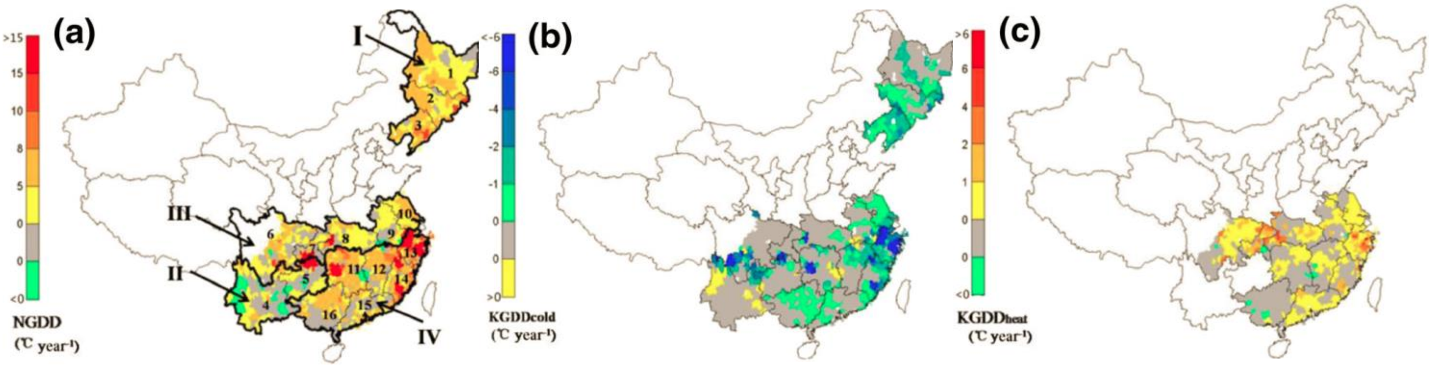

Fig. 3 Temporal trends (°C year^{-1}) of NGDD (a), KGDDcold (b) and KGDDheat (c) during 1980–2008

During rice growing season, NGDD (normal growing- degree-days) generally increased across the major cultivation areas, with particularly large trends of more than 20 °C year^{-1} detected in some portions of eastern China (Fig.3-a). During rice reproductive period, most of Region I and eastern China have witnessed a decreasing trend of $KGDD_{cold}$ (killing growing-degree-days of cold) (Fig.3-b), while Region III and IV were dominated by the increasing trends of $KGDD_{heat}$ (killing growing-degree-days of heat) (Fig.3-c).

2.4 Sensitivity of rice yield to temperature variations

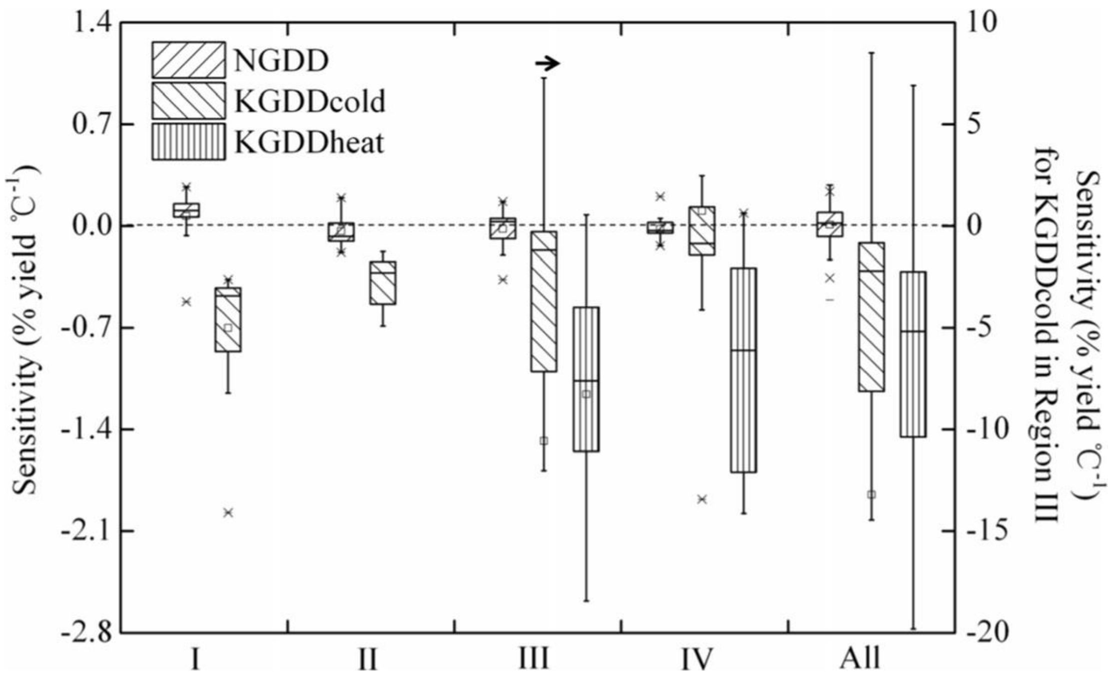

Fig.4 Box plot of the sensitivities of rice yield to temperature variables in different regions. The upper and lower hinges of the box indicate the 75th percentile and 25th percentile of the data set, respectively. The line in the box indicates the median value of the data, and the open square represents the mean of the data. Note: an axis on the right was only prepared for KGDDcold in Region III (marked by the little right arrow), due to its larger range of variation.

Based on the median estimates for each region in Fig.4: Region I would benefit from NGDD increases (0.12 % yield°C^{-1}) but suffer from $KGDD_{cold}$ increases (−0.45 % yield°C^{-1}); Region II would witness a decrease in rice yields from the increases of NGDD (−0.09 % yield°C^{-1}) and $KGDD_{cold}$ (−0.30 % yield°C^{-1}); Region III responded positively to NGDD (0.04 % yield°C^{-1}) but negatively to KGDD (−1.16 % yield°C^{-1} for $KGDD_{cold}$ and −1.04 % yield°C^{-1} for $KGDD_{heat}$); the response patterns in Region IV were −0.06, −0.14 and −0.84 % yield°C^{-1} for NGDD, $KGDD_{cold}$ and $KGDD_{heat}$, respectively. Across China, adverse impacts were dominant for KGDD (−0.30 % yield °C−1 for $KGDD_{cold}$ and −0.71 % yield°C^{-1} for $KGDD_{heat}$), whereas no dominant direction for NGDD impacts was detected (Fig.4).

2.5 Historical contribution of temperature variations to rice yield (1980–2008)

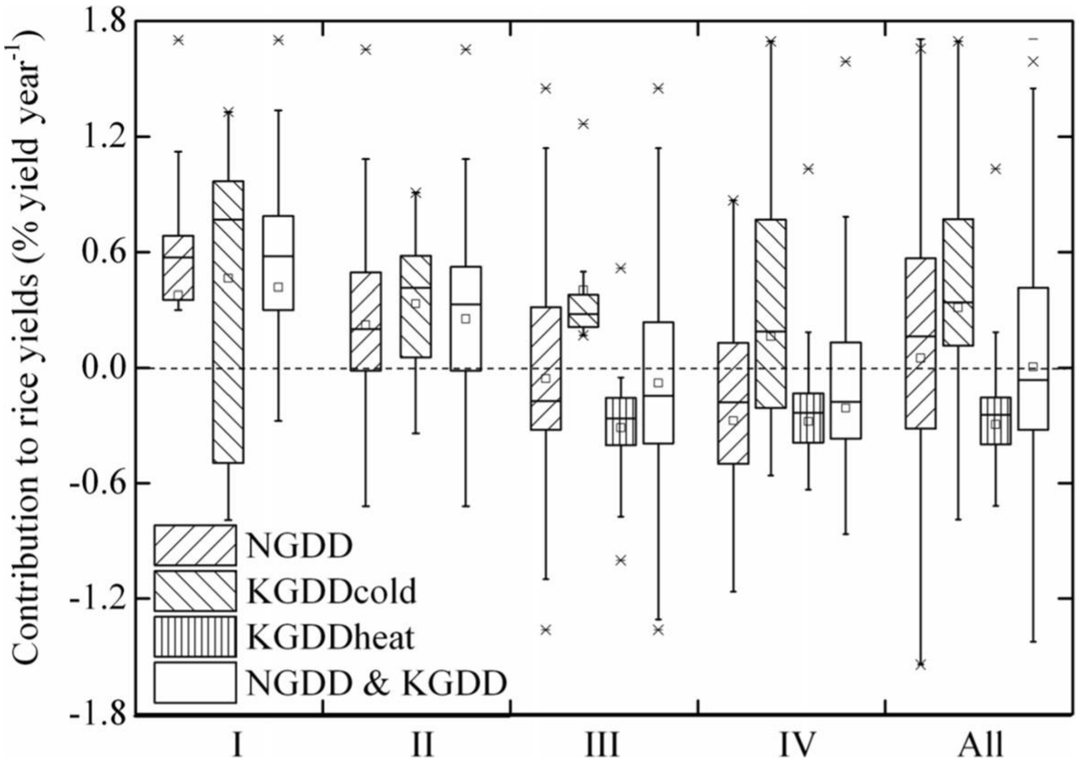

Fig.5 Box plot of the contributions of temperature variables to rice yields in different regions. The upper and lower hinges of the box indicate the 75th percentile and 25th percentile of the data set, respectively. The line in the box indicates the median value of the data, and the open square represents the mean of the data

On the basic of the median estimates of contributions in each region (Fig.5), it was found that: in Region I both the trends of NGDD and $KGDD_{cold}$ had contributed much to the improved yields, resulting in an overall contribution of 0.59 % yield $year^{-1}$; such pattern was also found in Region II, showing 0.21 % yield $year^{-1}$ for NGDD, 0.42 % yield $year^{-1}$ for $KGDD_{cold}$ and 0.34 % yield $year^{-1}$ for overall temperature variations. In Region III and IV, the results showed that: for NGDD, only 40 % of the contribution values were positive in these two regions; the trends of $KGDD_{cold}$ had accelerated the yield growth but that of $KGDD_{heat}$ had hampered the increasing trend of rice yield; overall temperature variations imposed negative impacts on rice yields, with −0.14 % yield $year^{-1}$ for Region III and −0.17 % yield $year^{-1}$ for Region IV. Across China, most areas had witnessed positive contributions of NGDD and $KGDD_{cold}$ but negative contributions of $KGDD_{heat}$ overall temperature variations had contributed positively to rice yields in half of the studied areas (a median of 0.42%yield $year^{-1}$) and negatively in the other half (a median of −0.31 % yield $year^{-1}$), resulting in an average of 0.01 % yield $year^{-1}$ (Fig.5).

3. Conclusion

Based on TITT, the study provided a unique opportunity to quantify historical contributions of temperature variations (1980–2008), including normal and extreme temperatures, to county-level rice yields in the major rice planting areas across China. We found that, historical temperature variations had contributed much to the increased rice yields in Region I and II, but severely hindered the improvement of rice yields in SB and Region IV. For the entire country, a balance pattern of historical contributions could be found. In case of some negative responses to NGDD in Region III and IV, potential adverse impacts of higher accumulation in normal temperatures should get more attention. In the further study, crop models should be used to help understand the responses of rice yield to temperature variations under the future climate.

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