Spatial difference of climate change effects on wheat protein concentration in China

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Abstract

Climate change effects on global food security are not only limited to its effects on the yield of cereals but also their nutritional quality. However, climate change effects on crop nutritional quality, particularly grain protein concentration (PC) on a large geographical scale have not yet been quantified in China. For this purpose, we assessed the effects of three key climatic factors (temperature, precipitation, and solar radiation) on wheat PC in ten wheat-growing areas of China using a series of statistical models on a county-level PC dataset. The results demonstrated that the average PC in China from 2006 to 2018 ranged from 12.01% to 14.50% across the ten areas, with an obvious spatial difference pattern showing an increase in PC from south to north and from west to east. The sensitivity analysis indicated that PC showed a positive response to variation in the increasing temperature, and the PC of wheat grown in the Huanghuai area was less affected than the PC of wheat grown in other areas. Conversely, solar radiation posed negative effects on the PC in the southwestern area, whereas precipitation had intricate effects on the PC in all areas. Besides, the highest explanation of climate variability during five growth periods contributed 26.0%–47.6% of the PC variability in the northeastern area, whereas the lowest explanation of climate variability during five growth periods only accounted for 2.5%–3.7% of PC variability in the Yangtze River area. Our study further demonstrated that the effects of climate change on wheat grain PC in China were spatially heterogeneous with higher effects on PC in spring wheat-growing areas as compared to winter wheat-growing areas. We suggested that the northern and the northeastern area in China could be developed as alternative areas to produce wheat with high grain PC in the face of climate warming.

1. Introduction

Hunger, malnutrition, and food insecurity are emerging as major challenges for sustainable development worldwide. Climate change is prophesied to affect global crop production in terms of quantity and nutritional quality due to climate change-induced intensification of the extremity and occurrence of high temperature and rainfall variability (Myers et al 2014, Lesk et al 2016, Ortiz-Bobea et al 2021). Malnutrition associated with protein deficiency in major cereal crops is leading to increased risks of hypertension, coronary heart disease, and lipid disorders (Wang et al 2019). The impacts of climate change on agriculture in terms of crop yields have been widely investigated (Ray et al 2015, Zampieri et al 2017; Zhao et al 2017), yet little is known regarding the effects of climate change on nutritional quality (Asseng et al 2019, Liu et al 2019).

Wheat (\textit{Triticum aestivum} L.) being a major staple food crop is an important source of protein and energy intake for humans worldwide. Protein concentration (PC), the ratio of grain protein amount to grain yield, is a key indicator of wheat nutritional
quality and its end-use value (Shewry and Halford 2002). Changes in PC are mainly attributed to climate change, crop management, and genetic characteristics (Johansson 2020). The protein nutritional value of wheat grain could be influenced by climate change through its effects on photosynthesis, growth rate, nutrient use efficiency, and sink-to-source translocation of carbon and nitrogen (Soares et al 2019). Temperature, precipitation, and solar radiation through their impacts on crop growth are considered major climatic constraints for grain yield and PC. However, a rise of 1.5 °C in the global average temperature is projected by 2050 (IPCC (Intergovernmental Panel on Climate Change) 2018). Besides, the increasing fluctuations in the extent and intensity of precipitation patterns (Fischer et al 2019), and decreasing solar radiation owing to increasing aerosol concentration and pollutants in the atmosphere (Shuai et al 2013) are becoming major challenges for agricultural production. Consequently, the detailed assessment of climate change effects on wheat PC is imperative for global food and nutritional security.

There have been field studies that assess the effect of climate change on wheat PC, with discrepancies between crop types (Zhang et al 2016), experiment methods (Liu et al 2019), and sites (Asseng et al 2019). Studies conducted in both under growth chambers and in field conditions reported positive relationships between the higher temperature and wheat PC (Dupont et al 2006, Liu et al 2017, Nuttall et al 2018), while others reported a negative association between them (Casagrande et al 2009, Hurkman et al 2009).

Similarly, the negative association between the accumulative precipitation during the entire wheat growth period and wheat PC, as well as the positive correlation between total rainfall during the post-anthesis growth period and wheat PC, have also been previously reported (Pan et al 2006, Dalla Marta et al 2011). Generally, the inconsistent association between wheat PC and climatic factors in field-scale studies is mainly attributed to the limited number of years and sites. It has been reported that the same climatic factors did not consistently have the same effect on wheat PC across geographical regions (Nadew 2018). So far, the PC variability in wheat grain on a large geographical scale as a consequence of climate change has remained unclear. Therefore, investigating the relationship between wheat PC and climatic factors on a large geographical scale is imperative.

Statistical models that have the advantage of the uncontrolled experiments conducted by the grower at different locations and years have also been widely used to estimate the effect of climate on crop production on a provincial/state scale (Gammans et al 2017), national scale (Lesk et al 2016), and global scale (Zampieri et al 2017). However, the systematic statistical quantification regarding the effects of climate change on crop nutritional quality (PC) on a large geographical scale is still rarely reported. To fill this void, we quantified the mean sensitivity of wheat PC to the key climatic factors (temperature, precipitation, and solar radiation) in ten wheat-growing geographical areas of China during 2006–2018, based on the linear mixed model and county-level PC data. Furthermore, we explored a range of statistical models to capture linear and non-linear contributions of climatic variation on wheat PC and to identify the dominant climatic factor(s) affecting wheat PC.

2. Data and methods

2.1. Dataset and preprocessing

Wheat PC dataset was obtained from China Wheat Quality Report published by the Ministry of Agriculture and Rural Affairs of China (www.moa.gov.cn). We attempted to preserve as much PC data as possible, and a total of 1457 county-level PC records of 590 counties in China during 2006–2018 were used (figure S1 (available online at stacks.iop.org/ERL/16/124011/mmedia)). PC was measured by multiplying the nitrogen content obtained using the Semi-Micro Kjeldahl method with a nitrogen-to-protein conversion factor of 5.7 (NBSC (National Bureau of Standards of China) 1982). According to PC values, wheat nutritional quality in China can be divided into high nutritional quality (PC not less than 14%); medium nutritional quality (PC lower than 14%, and PC not less than 13%), and low nutritional quality (PC less than 13%) (AQSIQ (State Administration of Quality Supervision, Inspection and Quarantine of China) 1998, Liu et al 2016). The 0.5° × 0.5° monthly gridded temperature and precipitation dataset from the Climate Research Unit of the University of East Anglia (CRU TS 4.03) (Harris et al 2020) and a 0.1° × 0.1° monthly high-resolution dataset for solar radiation from the National Tibetan Plateau Data Center (Tang et al 2019) during 2005–2018 were considered.

Wheat-growing areas in China were divided into ten areas according to the similarity of climatic conditions, initial soil characteristic, as well as wheat nutritional quality (figure S1, table 1) (He et al 2002, MARA (Ministry of Agriculture and Rural Affairs of China, Department of Planting Management) 2016). Each county was classified into the geographical area by area weight. Wheat phenological dates (sowing, heading, and maturity) from 282 winter and 102 spring wheat stations near to the spatial distribution of county-level PC data were collected from China Central Meteorological Agency (figure S1) for each geographical area to determine five growth periods: sowing to heading, heading to maturity, maturity, and sowing to maturity. These critical windows aimed to capture the climatic conditions during the vegetative growth period, heading, reproductive growth period, maturity, and entire growth period. The month of each phenological event in each geographical area was determined by the mean of each phenological date across the stations in the area.
Table 1. Basic information for ten geographical areas in China.

| Abbreviation | Area                          | Yield (kg ha\(^{-1}\))\(^{a}\) | Soil organic matter (%)\(^{b}\) | Wheat          | Sowing      | Heading     | Maturity    |
|--------------|-------------------------------|-------------------------------|--------------------------------|---------------|-------------|-------------|-------------|
| A1           | Northern plain area           | 5074                          | 1–2                            | Winter wheat  | October     | May         | June        |
| A2           | Northern Huanghai area        | 4823                          | 0.5–1.5                        | Winter wheat  | October     | May         | June        |
| A3           | Southern Huanghai area        | 5187                          | 1–1.5                          | Winter wheat  | October     | April       | June        |
| A4           | Yangtze River area            | 3166                          | ~1                             | Winter wheat  | October     | April       | May         |
| A5           | Sichuan Basin area            | 3305                          | <1                             | Winter wheat  | November    | March       | May         |
| A6           | Yungui Plateau area           | 2055                          | 1–3                            | Winter wheat  | November    | March       | May         |
| A7           | Northeastern area             | 3200                          | 1–6                            | Spring wheat  | April       | June        | August      |
| A8           | Northern area                 | 2949                          | —                              | Spring wheat  | April       | June        | July        |
| A9           | Northwestern area             | 4843                          | 0.5–1                          | Spring wheat  | March       | June        | July        |
| A10          | Qinghai-Tibet Plateau area    | 4182                          | —                              | Spring wheat  | March       | June        | August      |

\(^{a}\) Average values during 2006–2010 at each geographical area derived from Agricultural Yearbook.

\(^{b}\) Values derived from China Wheat Quality Report.

Thus, the mean temperature, accumulative precipitation and mean solar radiation during sowing to heading, heading to maturity, and sowing to maturity for the counties in each area were determined as the averages (temperature and solar radiation) and sum (precipitation) of monthly data during each growth period. Conversely, the climatic data at heading and maturity were the monthly mean value in the month of heading and maturity.

Each county area was firstly resampled into 0.1° × 0.1° spatial resolution to ensure the inclusion of each county before extracting the monthly mean temperature, accumulative precipitation, and mean solar radiation over five growth periods in each county. A wheat-growing area map in 2010 (IFPRI (International Food Policy Research Institute) 2019) was resampled into the same spatial resolution and subsequently was overlayed with the resampled county map so that climatic data in places where a given crop grows were selected for further analysis. In this way, the climatic data during the five periods for each county were the weighted average values of grid cells in each county (figure S2). The spatial difference of climatic factors during five growth periods across ten areas in China was compared (see section 2 of supplementary materials for further information).

2.2. Methods

2.2.1. Sensitivity analysis

Wheat PC at harvesting and climatic data during five growth periods were fitted with linear mixed models to analyze the mean sensitivity of PC to climatic factors during 2006–2018 at each geographical area using the ‘lmer4’ package (Bates et al 2014) of statistical software R (R Core Team 2019). The linear mixed models were used as they have the potential to analyze datasets even including unbalanced ones as well as to dissect various effect factors using fixed regression terms and random residuals (Bönecke et al 2020). Data in each area were firstly divided into 13 groups based on the year, as the advances in technology and crop management in each area in the different year is hard to ignore. Then, the linear mixed models including random intercepts and slopes were used in each area to calculate the mean sensitivity of PC to climatic factors across the years (Chen et al 2018). The general form of the model was as follows:

\[
PC_{ij} = (\beta_0 + \gamma_{0j}) + (\beta_1 + \gamma_{1j}) \times Cli_{ij} \tag{1}
\]

where \(PC_{ij}\) is the PC at \(i\) county \(j\) group, \(Cli_{ij}\) represents the average temperature, accumulative precipitation, and average solar radiation at \(i\) county \(j\) group, \(\beta_0\) and \(\beta_1\) are the coefficient of the fixed effects, while \(\gamma_{0j}\) and \(\gamma_{1j}\) are the random intercept and the slope of \(j\) group, respectively. The estimated coefficient \(\beta_1\) represents the mean sensitivity of climate variable to PC during 2006–2018. Statistical significance for \(\beta_1\) was tested by likelihood ratio tests using the ‘lmerTest’ package (Luke 2017) of R.
2.2.2. Quantification of PC variability explained by climate variability

The linear and squared forms of the climatic factors were used to capture the linear and non-linear effects of variability in climatic factors in determining the extent of wheat PC variability in each area (Ray et al. 2015). We limited our analysis to a total of 17 combinations to avoid over-fitting (table S1). Thus, these 17 statistical models were classified into seven categories: (a) separate effect by temperature; (b) separate effect by precipitation; (c) separate effect by solar radiation; (d) combined effects by temperature and precipitation; (e) combined effects by temperature and solar radiation; (f) combined effects by precipitation and solar radiation; and (g) comprehensive effects by three climatic factors. The base form of 17 models is given as follows:

\[ PC_k = f(T_k, P_k, S_k) \]  

where PC\(_k\) is the observed wheat PC in \(k\) area; \(T_k\), \(P_k\), and \(S_k\) are the mean temperature, accumulative precipitation, and mean solar radiation in \(k\) area, respectively. The 17 statistical models were fitted in each area and subsequently tested statistically. Firstly, F-tests at the \(P = 0.05\) level were conducted to determine whether the selected models were significantly superior to the null model. Then we identified which functional form among 17 models fit the data best in each area using Akaike Information Criterion (AIC), which can penalize functions with more terms. Thus, the model with minimum AIC value was the best-fitted model. The models were then categorized and the most dominant climatic factor was identified. Due to the different number of independent variables among models, the adjusted coefficient of determination (adjR\(^2\), explained variance) was used to represent and compare the explanatory power of climate variables of the best-fitted models across ten areas. In this way, a higher adjR\(^2\) indicates that the model containing climatic factors was able to explain variability in PC. Conversely, a low adjR\(^2\) indicates that PC variability was less influenced by climatic factors as compared to other abiotic or biotic stresses, and a large amount of noise was contained in PC.

3. Results

3.1. Spatial difference of PC in China

An obvious spatial difference with an increasing pattern of wheat PC was observed from south to north and west to east in China from 2006 to 2018 (figure 1(a)). The PC of winter wheat grown in Huanghuai areas (A1, A2, and A3) was higher than that grown in southern China (A4, A5, and A6), with the average values ranging from 13.98% to 14.50%. The average PC values of spring wheat were higher in northeastern China (A7 and A8) than that of spring wheat grown in northwestern China (A9 and A10), with average values ranging from 12.01% to 13.98%. The internal variability of PC in winter wheat showed an opposite spatial pattern with smaller and larger internal variability of PC in the Huanghuai area and southern China, respectively (figure 1(b)). Conversely, the internal variability of PC in spring wheat was in accordance with its spatial pattern. Huanghuai areas (A1, A2, and A3) with the production of more than 50% (53%–73%) of high nutritional quality winter wheat were the areas producing the highest nutritional quality wheat in China (figure 1(c)). In contrast, the southwestern areas (A5 and A6) were the regions producing the lowest nutritional quality wheat in China, where more than 50% of winter wheat was low nutritional quality. The Qinghai-Tibet plateau area (A10) was the region mainly producing medium and low nutritional quality wheat, with 57% and 43% of spring wheat grown in A10 being medium and low nutritional quality, respectively. Collectively, the nutritional quality of winter wheat was higher than that of spring wheat in China.

3.2. Sensitivity of PC to climatic factors in China

PC showed positive sensitivities to temperature except for the wheat grown in A1 (figure 2(a)). Winter wheat demonstrated smaller sensitivities to temperature as compared to spring wheat. PC sensitivities towards temperature were significant in three winter wheat-growing areas (A1, A2, and A5), with larger negative sensitivities for winter wheat PC in A1 of the Huanghuai area than the positive sensitivities in A2. Specifically, winter wheat PC decreased by 0.18%–0.21% with every 1 °C rise in temperature during sowing to heading, maturity, and sowing to maturity in A1, while it increased by 0.09%–0.10% with every 1 °C rise in temperature at heading and maturity in A2. Correspondingly, winter wheat PC increased by 0.18% with each 1 °C rise in temperature during heading to maturity, maturity, and sowing to maturity in A5. Sensitivities of winter wheat PC in the aforementioned areas were significant, particularly to temperature during maturity. Significant positive sensitivities of spring wheat PC to temperature were observed in A7 during all the growth periods, except maturity. The sensitivities of PC to temperature during different growth periods in A7 were the largest (0.75% to 1.08% per °C) across the ten areas.

PC showed more diverse responses to precipitation than temperature (figure 2(b)). Winter wheat PC significantly decreased by 0.30%–1.53% and increased by 0.49%–1.13%, responding to each 100 mm precipitation increasing during four growth periods (except for heading) in A3 and A5, respectively. Additionally, winter wheat PC showed the largest sensitivity to precipitation at maturity in the two areas. However, the smallest sensitivity to precipitation was observed from sowing to maturity. Conversely, sensitivities of spring wheat PC to precipitation were non-significant. The sensitivities of PC
to solar radiation were generally negative across the areas (figure 2(c)). Solar radiation posed significantly negative effects on PC in two winter wheat-growing areas (A3 and A5), while solar radiation posed significantly positive effects on PC in the spring wheat-growing area (A9). The larger significant sensitivities of wheat PC to solar radiation were noticed in most areas, particularly from sowing to heading. Briefly, the sensitivities of PC to temperature in spring wheat were generally larger than those in winter wheat and the effects of precipitation and solar radiation on both winter and spring wheat PC were highly heterogeneous.

3.3. Explanation of climate variability to PC variability in China

Explanation of climate variability to the variability of PC across ten geographical areas in China from 2006 to 2018 was examined based on adjR² of the best-fitted models in each area (figure 3), which were selected by the minimum AIC value (data not shown) in the 17 statistical models. Climate variability was significant (P < 0.05) to explain PC variability in China except for A10. Generally, the effect of climatic factors on PC in spring wheat-growing areas was greater than those in winter wheat-growing areas (table S2). The highest explanation of climate variability was detected in A7 and A8, where climate variability during five growth periods accounted for 26.0%–47.6% of the PC variability. Conversely, climate variability in A4 accounted for only 2.5% and 3.7% of PC variability at heading and from sowing to heading, respectively. Besides, climatic variability from sowing to heading has the largest explanation for PC variability in A4 and A5. However, climate variability during different growth periods performed diverse explanations on the variability of PC and accounted for 3.3%–19.3% of PC variability in A1, A2, and A3. Overall, the climatic variability at heading accounted for the maximum explanation for PC variability in three areas (A6, A7, and A9), whereas climatic variability at maturity accounted for the minimum towards PC variability in A5, A6, and A7.

The temperature was the dominant climatic factor affecting PC variability in all growth periods in A7 and A8. The temperature was the dominant factor controlling PC variability in A5 and A6 from heading to maturity, while the temperature was the most
dominant factor governing PC variability in A1 and A2 from sowing to heading and sowing to maturity. In contrast, solar radiation played a decisive role in PC variability in A5, A6, and A9. Solar radiation posed the largest effect on PC variability from sowing to heading particularly for wheat in A6 and A9, whereas solar radiation was the dominant climatic factor at affecting the variability of PC in A5 at heading, heading to maturity, and sowing to maturity. Conversely, precipitation from sowing to heading and at heading controlled the PC variability in A4 and A5. Nevertheless, the explanation of climatic factors to the variability of PC was diverse in the Huanghuai area as the PC variability was co-regulated by all the climatic factors. Collectively, the temperature was the most dominant climatic factor responsible for the variability of PC in most of the wheat-growing areas of China.

4. Discussion

The increasing spatial pattern of wheat PC from south to north and from west to east (figure 1) was consistent with a previous study characterizing the spatial pattern of PC during 2009–2011 in China (Liu et al. 2016). Interestingly, PC of winter wheat was higher in the high yield areas (A1, A2, and A3) than other winter wheat-growing areas. In contrast, PC of spring wheat was lower in high yield area (A9) than low to medium yield spring wheat-growing areas. The simultaneous increase of grain yield and PC could be explained to higher nutrient availability under optimal to supra optimal soil N supply, while the increase of only grain yield under sub-optimal soil N supply is attributed to dilution effect (Jones and Kathrin 2012). Therefore, N fertilizer application may boost yield and PC in areas with high soil organic matter contents (A1, A2, and A3). However, N fertilizer application in areas with low soil organic matter (A9) only results in a high grain yield (table 1).

The spatial difference of PC was also attributed to climatic conditions. The positive responses of PC to temperature in different wheat-growing areas of China as demonstrated by sensitivity analysis (figure 2) were consistent with previous findings.

Figure 2. Sensitivities of PC to (a) mean temperature, (b) accumulative precipitation, and (c) mean solar radiation in China. ** represents $P < 0.001$, * represents $P < 0.01$, and * represents $P < 0.05$. $S_{\text{tem}}$ represents mean sensitivity of PC to mean temperature; $S_{\text{pre}}$ represents mean sensitivity of PC to accumulative precipitation, and $S_{\text{sun}}$ represents mean sensitivity of PC to mean solar radiation during the corresponding growth periods.
Figure 3. PC variability explained due to climate variability and the dominant climatic factors impacting PC variability during 2006–2018 in China.

(Cosentino et al. 2019). The reduction in photosynthesis rate, increased respiration, accelerated leaf senescence, and enhanced evapotranspiration due to higher temperature can lead to a decreased accumulation of nitrogen and carbohydrates in wheat grain (Reyer et al. 2013). However, the lower reduction of nitrogen accumulation in wheat grain as compared to carbohydrates accumulation under higher temperatures was reported to lead to a higher PC (Gooding et al. 2003). Besides, the positive sensitivity between PC and temperature might potentially be associated with the mineralization and nitrogen uptake associated with higher temperatures (Boczulak et al. 2014). However, PC does not always increase with the increase in temperature under field conditions as shown in A1 and by Wrigley et al. (1994). The mean temperature during the grain filling and development period (heading, heading to maturity, maturity) in A1 was higher than in other areas (figure S3). Consequently, a higher possibility of extremely high temperature beyond the heat tolerance threshold and drought during wheat growth season in A1 might result in low PC due to the low uptake of N from soil.

Additionally, high precipitation generally resulted in an inferior nutritional quality of wheat as a consequence of reduced nitrogen availability for protein synthesis through nitrogen leaching to the subsoil (Rodríguez-Félix et al. 2014), which was confirmed by the significant negative response in A3 (figure 2(b)). Conversely, the positive response of PC to the high precipitation in the low soil nutrient area (A5) might be attributed to the higher rates of reduction of nitrogen availability in grain but lower rates of reduction of carbohydrates. However, the effect of solar radiation on wheat PC depends on the growth period as its negative effects mainly occur during the pre-anthesis growth period followed by post-anthesis, which was confirmed by field studies (Shimoda and Sugikawa 2020). Solar radiation could promote photosynthesis, increase grain weight, and grain yield (Shuai et al. 2013). Consequently, the negative response of PC in A3 and A5 to solar radiation might be attributed to the dilution effect (figure 2(c)). Conversely, the
positive response of PC to solar radiation in the A9 despite lower precipitation during the wheat growth period might be attributed to higher evapotranspiration as a consequence of the simultaneous effect of higher solar radiation and the lower precipitation. The lower water availability due to lower precipitation and higher solar radiation posed a negative impact on the wheat growth and productivity during its growth period, which led to higher PC due to the dilution effect.

Our study has identified unique spatial patterns of the effects of the variability in temperature, precipitation, and solar radiation on PC variability and concluded that the effects of climatic factors on PC in China were heterogeneous across wheat-growing areas (figure 3). The simple classification of the prevailing relationships concerning climatic factors and PC enables the detection of variations in specific areas. Precipitation was the most dominant climatic factor for explaining PC variability in southern China where wheat is not irrigated, whereas temperature became the most critical climatic factor for explaining PC in northern China where wheat is irrigated. The northern area (A7) and the northeastern area (A8) could be developed as areas to produce wheat with high grain PC in the face of climate change as PC in these areas had positive sensitivities to temperature. The appropriate crop management strategies could be developed in other areas according to the local conditions due to the slight effects of climate on PC. North Huanghuai area (A1 and A2) owing to the low explanation of climatic factors to PC and high inherent soil fertilizer can be considered as an optimal area to cultivate wheat genotypes with high yield stability and high nutritional quality in China. Conversely, the Yangtze River area (A4) and Sichuan Basin area (A5) can be developed for the long-term cultivation of low nutritional quality wheat due to the low explanation of PC to climatic factors. Yungui Plateau area (A6) had the potential to cultivate medium nutritional quality wheat under future global warming.

The effects of climatic factors during the five growth periods of wheat were closely assessed in this study. Our results confirmed that the climatic factors at heading played a dominant role in the PC variability, which is consistent with Halford et al (2014). We emphasized that the critical crop growth periods should be considered while assessing the effects of climatic factors on wheat PC on a large scale using historical crop data and statistical models. The judicious crop management strategy can be suggested according to the quantified effects of climatic factors during different growth periods in each area. For instance, supplemental N application at heading might be beneficial for improving wheat nutritional quality in the southern Huanghuai area, as PC was less affected by the climatic factors at heading as compared to other stages. However, post-anthesis N application can be recommended in the Yangtze River area (A4) and the northwestern area (A9) due to the non-significant effects of climatic factors on PC in these areas.

In this study, our understanding concerning the spatial difference of the effects of climatic factors on wheat PC in China has advanced through analyzing historical climate and PC datasets. However, there are some limitations. The small PC sample size in A7 and A10 may cause biased estimation. More field data should be collected to reduce uncertainties in estimating the response of regional wheat nutritional quality to climate. Alternatively, a decrease in wheat PC due to the negative effects of elevated atmospheric carbon dioxide ([CO₂]) has been widely reported from field experiments on free-air carbon dioxide enrichment (Taub et al 2008). We did not consider the direct effects of [CO₂] on PC variability, in part due to the limitation of statistical models, and in part due to the slight increase of global annual mean [CO₂] from 381 ppm in 2006 relative to 408 ppm in 2018 (www.esrl.noaa.gov/gmd/ccgg/trends/global.html). Additionally, recent studies based on a single experimental station in China reported that the increase or decrease in temperature beyond a certain threshold (maximum temperature > 30 °C (Osman et al 2020) and minimum temperature < 2 °C (Liu et al 2019)) could significantly affect wheat PC. Therefore, further studies under field conditions in diverse geographical regions are required for assessing the impacts of extreme climatic events on wheat PC on a large scale in China.

5. Conclusion

We estimated the effects of climate change variability on wheat grain PC across ten areas in China during 2006–2018. Overall, variability in climatic factors at heading had the largest explanation for PC variability in most of the wheat-growing areas (Yungui Plateau area, northeastern area, and northwestern area), whereas the climatic variability at maturity had the smallest explanation for PC variability in wheat-growing areas of China (Sichuan Basin area, Yungui Plateau area, and northeastern area). The findings would assist in regional decision-making on appropriate climate change mitigation strategies to facilitate China’s sustainable agriculture and nutritional security.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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