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Possible Impact of Climate Change on the Quality of Apples from the Major Producing Areas of China

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Abstract: Meteorological conditions are important environmental factors affecting apple quality. To understand the possible impact of climate change on the apple quality of the major producing areas in China and assess the quality of major apple species (e.g., Fuji, Ralls, and Golden Delicious), we studied the variation trends and abrupt change characteristics of six major climate factors affecting seven physicochemical indices of apple quality across five apple regions, including the Loess Plateau, Bohai Bay, the Old Course of the Yellow River, Southwest Highlands, and Xinjiang, using statistical methods, meteorological indices, and the ArcGIS analysis tool based on the meteorological observational data from 1961 to 2013. The results show that the spatial and temporal distributions of annual average temperature, annual sunshine duration, average summer temperature, summer diurnal temperature range, and average summer relative humidity all significantly changed (except annual precipitation) and that abrupt changes occurred. The annual temperatures and average summer temperatures in the Loess Plateau apple region and the Liaoning producing region of Bohai Bay increased within optimal ranges. In addition, for high-value regions, the hours of sunshine decreased, helping to improve the fruit shape index, sugar-acid ratio, and vitamin C (VC) content. Relatively high temperatures continued to increase to high values which remained lower than the optimal upper limit; the diurnal temperature range continued to decrease; and the sunshine hours significantly decreased within the optimal range, which might have worsened fruit hardness, soluble sugar, and peel anthocyanin in the producing regions of Southwest Shandong of Bohai Bay, Southeast Hebei of the Old Course of the Yellow River, Northern Anhui, and Jiangsu. In the production regions of the Yun-Gui plateau in the Southwest highlands, increased summer temperature and the diurnal temperature range were both within the optimal ranges, which might have helped to reduce fruit hardness and increase soluble sugar content. However, continuously increased temperature and reduced sunshine might have worsened the apple shape index and fruit coloring. In the Xinjiang apple-producing region, the climate became warmer and more humid with reduced daily sunshine hours, which might have improved the exterior quality of apples and reduced fruit hardness. Thus, the climate changes over the last 50 years have positively affected the seven apple quality physicochemical properties in the Loess Plateau and Xinjiang, whereas the impacts on the different indices of apple quality in the other apple-producing regions are less coherent. In general, climate change has significantly affected the apple quality of the major production regions in China. Corresponding scientific measures are needed to assure high apple quality to increase the income of farmers in the future.

Keywords: climate change; abrupt change; apple; quality; impact

1. Introduction

Quality is an important factor in determining the competitive power of fruit in the market [1]. China is the biggest apple-producing country in the world, and it produces 25% of all apples [2]. Limited by apple quality, the exported amount of Chinese fresh apples is below 3% of its total yield, and the price is approximately 65% of the average exported price of other countries. Thus, the apple production industry in China desires a transition from quantity to quality [3]. The climate partially determines crop yield and quality [4]. The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) proposed that negative impact of climate change on the yield and quality of most global crops is more common than the positive effects; however, variations exist among different crops and regions [5,6]. To assure the high quality of the apples produced in China, it is urgent to find temporal and spatial variations in the major climate factors that determine apple quality in the major producing areas of China. Moreover, research must reveal the potential effects of climate change on apple quality to eventually allow scientific measures to respond to the effects of climate change on apple production.

Numerous previous studies have examined the effects of climate factors on apple quality and its quantitative assessment (e.g., the effects of thermal resources and temperature conditions during different growth periods on the apple quality [7,8], the relationship between precipitation and sunshine condition, and the weight of single apples, their coloring, and soluble solid content [9–11]). In addition, the relationship between the quality of major apple species (e.g., Fuji, Ralls, and Golden Delicious) in China and climate factors has been previously investigated, including effects of climate factors on the different physicochemical indices of apple quality [12,13]; the relationships between climate change and the apple blooming period, growth season length, planting pattern, and production, regional differences [14–17]; as well as the temporal and spatial characteristics of the apple phenological phase and major meteorological hazards [18–20]. However, these studies primarily focused on the relationships between climate factors and apple quality. Only a few studies have stressed the effect of climate change on apple quality, especially with regard to the major apple-producing regions in China.

Based on the meteorological observational data of the major apple-producing regions in China from 1961 to 2013 and the meteorological indices that determine the quality of major apple species (e.g., Fuji, Ralls, and Golden Delicious), this study analyzed the variation trends and abrupt change characteristics of six major climate factors that affect seven physicochemical indices of apple quality in the Loess Plateau, Bohai Bay, the Old Course of the Yellow River, Southwest Highlands, and Xinjiang using statistical methods and the ArcGIS analysis tool. Furthermore, this paper discusses the spatial distribution characteristics of the climate factors before and after these abrupt changes to reveal the potential effects of climate change on apple quality in the major producing regions of China and provide scientific basis to formulate countermeasures for climate change.

2. Data and Methods

2.1. Study Areas

A variety of species of apples is widely planted in China. Based on the apple advantageous region layout plan (2008–2015) and China's rural statistical yearbooks, 16 large-scale Fuji apple-planting provinces (including cities and municipalities) were chosen as the research areas in this study. Based on planning regions and climate characteristics, the producing regions can be divided into the Loess Plateau (including Shaanxi, Gansu, Shanxi, and Ningxia), Bohai Bay (including Shandong, Hebei, Liaoning, Beijing, and Tianjin), the Old Course of the Yellow River (including Henan, Jiangsu, and Anhui), the cold Southwestern Highlands (Yunnan, Sichuan, and Guizhou), and Xinjiang (Figure 1). The total apple yield in the research area is approximately 98% of the total amount in China. The planting species are primarily Fuji, Ralls, and Golden Delicious, which comprise more than 80% of all apples produced. Thus, the chosen research region and apple species are representative.

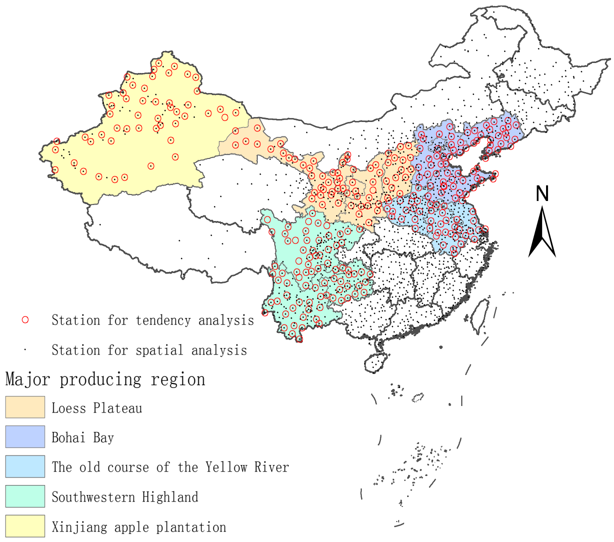

Figure 1. Research areas and the distributions of weather stations and apple plantations in China.

2.2. Data Source

The relationships between the physicochemical indices used to assess the apple quality and climate factors are complicated, and large variations exist among different species [1]. According to previous studies, we chose the average annual temperature, annual precipitation, annual sunshine duration, average summer temperature, diurnal temperature range, and relative humidity as the major climate factors that affect apple quality, and we identified apple quality indices and corresponding optimal ranges (Table 1) to study the relationships between the qualities of major apple species (Fuji, Ralls, and Golden Delicious) in the research region, the climate factors, and the seven physicochemical indices (including the apple shape index, apple hardness, soluble sugar content, titratable acid content, sugar-acid ratio, peel anthocyanin, and vitamin C (VC) content).

Table 1. Major climate factors affecting apple quality and the optimal indices.

Climate Factors	Major Affecting Indices	Optimal Range	Literature Source
Average annual temperature (T °C)	Fruit shape index, titratable acid content, vitamin C (VC), peel anthocyanin	8–13°C	[13,21–27]
Annual precipitation (P mm)	Fruit shape index, hardness, soluble sugar, peel anthocyanin	500–800 mm	[13,21–24]
Annual sunshine durations (S h)	Fruit shape index, peel anthocyanin, sugar-acid ratio	2200–2600 h	[21,22,25]
Average summer temperature (Ts °C)	Titratable acid content, hardness, peel anthocyanin, sugar-acid ratio	18–22°C	[21,25–30]
Average summer diurnal temperature variation (SRT °C)	Hardness, soluble sugar, sugar-acid ratio	10–12°C	[22,23,25–29]
Average summer relative humidity (RHs %)	VC, hardness, soluble sugar, peel anthocyanin	60%–75%	[13,22,24–26,28,29]

In the hierarchical evaluation criteria for fresh apples, the physicochemical indicators of high-quality apples are necessary to be within a reasonable range. Therefore, the meteorological indicators influencing the formation of apples' quality generally have reasonable range limits. The impacts of the meteorological indicators on the physicochemical indicators of apples are nonlinear. In the appropriate range, the higher the annual average temperature, the lower the titratable acid content will be, and the higher the fruit shape index, titratable acidity, anthocyanin and VC content will be. Generally, the higher the annual precipitation in an appropriate range, the more conducive it will be to improve fruit shape index and anthocyanin, make the fruit hardness degree and soluble sugar content remain in the appropriate range, which is good for the formation of quality. The higher the annual sunshine-hours in an appropriate range, the more conducive it will be to improve the quality indicators, such as fruit shape index and anthocyanin and sugar-acid ratio. The lower the summer temperature within a reasonable range, the more conducive it will be to improve the fruit hardness degree, anthocyanin and titratable acidity content, but not favorable sugar-acid ratio. The diurnal range in summer is positively correlated with fruit hardness degree, soluble sugar content and sugar-acid ratio, and larger variation of the daily rate is conducive to improve the quality. The average relative humidity in summer is negatively correlated with VC content, fruit hardness degree, soluble sugar, and anthocyanin.

The meteorological data used in this study originated from the National Meteorological Information Center. By testing the continuity and completeness of the data [31], we extracted daily temperature, precipitation, sunshine hours, and relative humidity at 1,722 meteorological stations from 1961 to 2013 as the background data. A total of 307 uniformly distributed stations within the research areas were chosen as representative to study the variation trends of climate factor in the major producing regions and the characteristics of abrupt changes. All of the stations were used to interpolate the spatial variation characteristics. The distribution of these stations is shown in Figure 1.

2.3. Research Methods

2.3.1. Temporal Change and Abrupt Change Test

We calculated the average annual temperature, annual precipitation, annual sunshine duration, average summer temperature, diurnal temperature range, and relative humidity in each apple-producing region from 1961 to 2013. On the one hand, linear regression and a five-year trend-smoothing method were used to analyze the variation trend and trend rate of climatic factors quantitatively. On the other hand, in order to analyze the change features of spatial distribution before and after abrupt change for each climatic factor in the most appropriate range, the years of abrupt change for each climatic factor were determined using the Mann-Kendall nonparametric test and sliding t-test. The detailed calculation method was provided in previous studies [32]. Tests were carried out for the normal distribution of climatic factors before the analysis of linear trend, and it was found that five out of six climatic factors showed obvious normal distribution, except the annual sunshine duration.

2.3.2. Analysis of Spatial Variation

We set the abrupt change years of the different climate factors in all of the producing regions as nodes and calculated the average values of all of the climate factors at the 1722 stations before and after the abrupt changes. Using the ArcGIS software and DEM data of China, the temperature and sunshine hour data were interpolated using a multivariate regression interpolation method [33], and the precipitation and relative humidity factors were interpolated using the spline function interpolation method [34] to 10 km × 10 km grids. Using the ArcGIS crop tool to extract the data in the research areas, we obtained a spatial distribution map of the climate factors that affect apple quality before and after the abrupt changes in the major producing regions. Using the grid calculation tool, we calculated the differences before and after the abrupt changes at each grid point to create characteristic plots to analyze the variation in the spatial distribution of each factor before and after the abrupt change.

3. Results and Analysis

3.1. Annual Variations and Trends of the Major Climate Factors Affecting Apple Quality

Figure 2 shows the annual variations in the six major climate factors that may affect apple quality. The multi-year averages of the six climate factors were all within the optimal ranges for high apple quality. Among the annual variation trends of all of the factors, average annual temperature and average summer temperature were both significantly increased; annual sunshine duration was significantly decreased; the summer diurnal temperature range and summer air relative humidity were both decreased, but these variations were flat. In particular, the average annual temperature and average summer temperature were significantly increased after the 1990s, and the corresponding temporal trend reached 0.25 °C/10a^{-1} and 0.17 °C/10a^{-1}, whereas the variation in the annual sunshine duration was significantly reduced after the 1980s, reaching 43 h/10a^{-1}. The variation in the summer diurnal temperature range was reduced after the 1980s with a rate of −0.16 °C/10a^{-1}. Moreover, the inter-annual variation of precipitation included large magnitudes, but the decreasing trend was not significant with a temporal trend of only −5.5 mm/10a^{-1}. In addition, the summer air humidity varied with precipitation and started to slightly decrease around the 2000s.

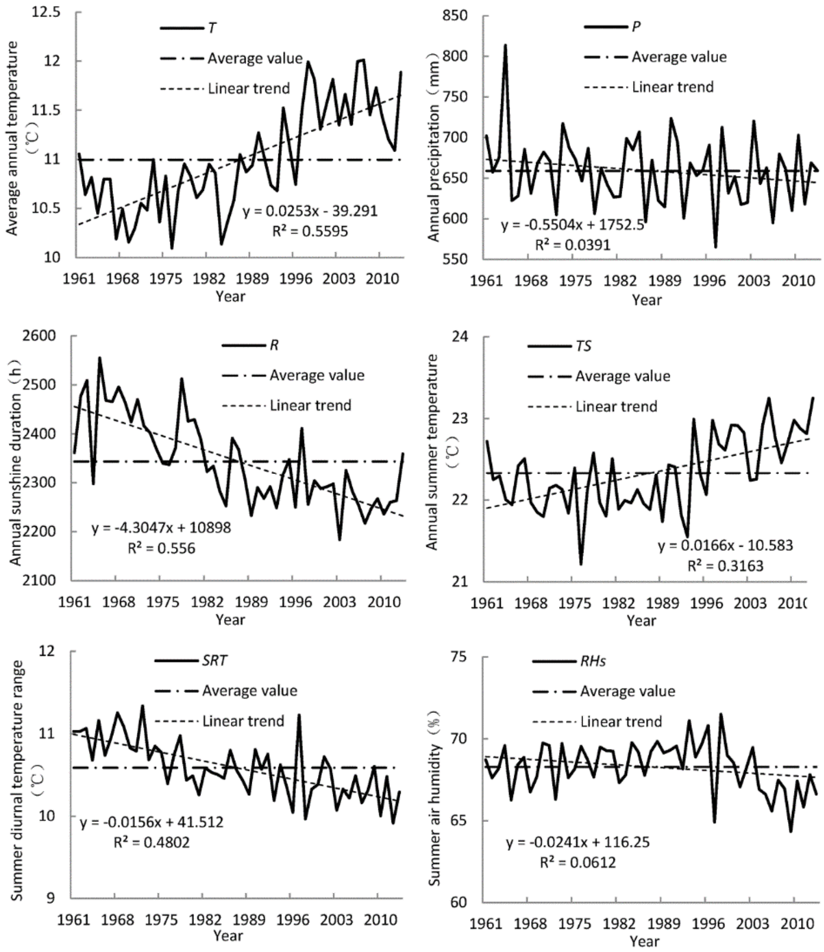

Figure 2. Annual variations of the major climate factors affecting apple quality in the main apple-producing regions of China.

The annual variations in the entire major production regions of China show that all of the average summer temperatures after the 1990s exceeded the upper limit of the optimal range for producing high-quality apples because of the effect of climate change. After the 2000s, however, the sunshine hours of some years were even lower than the lower limit of the optimal range. Thus, increased summer temperatures and reduced sunshine hours on the country scale might have affected the physicochemical indices including the fruit shape index, hardness, titratable acid content, sugar-acid ratio, and peel anthocyanin.

Table 2 and Figure 3 show the distributions of the average values, change trend ratios, and annual variations of the six climate factors within the optimal index ranges in the apple-producing sub-regions. Temperature was the most important environmental factor in determining apple quality, and it was therefore significantly correlated with fruit hardness, soluble sugar content, and fruit coloring [12].

In regions with relatively high annual average temperatures, the sugar-acid ratio was usually high, but the fruit hardness was low. Therefore, these fruits could not be stored for a long time. In contrast, in regions with low annual average temperatures, the titratable acid content was too high, which may affect fruit taste. The average annual temperatures in the different producing regions differ: The average annual temperature in the old course of the Yellow River was the highest, whereas that in Xinjiang was the lowest at 14.8 °C and 7.3 °C, respectively. Moreover, the average annual temperatures in Bohai Bay and the Loess Plateau were both within the optimal index range for good apple quality. The average annual temperatures in the old course of the Yellow River and Southwest Highlands were higher than the upper limit of the optimal range, whereas the titratable acid content, fruit hardness, VC content, and peel anthocyanin were lower than those of the other apple-producing regions. The average annual temperatures in all of the producing regions were increased. In particular, the temperature variation in the Loess Plateau was the most significant, 0.32 $°C/10a^{-1}$, and that in the Southwest Highlands was the smallest, only 0.18 $°C/10a^{-1}$. As Figure 3 shows, the increasing temperature trend had likely positive effects in the Loess Plateau. Since the late 1980s, the average annual temperature has always been within the optimal range. In contrast, the increased temperatures might negatively affected apple quality in the old course of the Yellow River and the Southwest Highlands, which had already exceeded the upper limit of the optimal range, especially with regard to the fruit shape index, titratable acid content, VC content, and peel anthocyanin.

Table 2. Average values and change trend ratios of the major climate factors affecting apple quality in China.

		All Producing Regions	Loess Plateau	Bohai Bay	Old Course of the Yellow River	Southwest Highland	Xinjiang
T	Average value (°C)	11.0	8.5	10.5	14.8	13.9	7.3
	Trend ($°C/10a^{-1}$)	0.25 ***	0.32 ***	0.25 ***	0.22 ***	0.18 ***	0.31 ***
P	Average value (mm)	659	404	641	971	1050	137
	Trend ($mm/10a^{-1}$)	−5.5	7.4	−9.7	2.7	−14.7 ***	8.7 ***
S	Average value (h)	2344	2604	2575	2058	1737	2891
	Trend ($h/10a^{-1}$)	−43 ***	−28 **	−69 ***	−86 ***	−26 ***	−18 **
Ts	Average value (°C)	22.3	20.8	23.7	26.1	20.8	21.8
	Trend ($°C/10a^{-1}$)	0.17 *	0.24 ***	0.15 **	0.05	0.15 *	0.22
SRT	Average value (°C)	10.6	12.3	9.3	8.6	9.1	14.1
	Trend ($°C/10a^{-1}$)	−0.16 ***	−0.14 **	−0.17 ***	−0.24 ***	−0.06	−0.23 ***
RHs	Average value (%)	68.3	62.1	74.7	77.4	78.3	44.5
	Trend ($\%/10a^{-1}$)	−0.24 *	−0.24 **	−0.2 **	−0.15	−0.66 ***	0.23 **

***: $P < 0.01$, **: $P < 0.05$, *: $P < 0.1$.

Except for Xinjiang and the Loess Plateau, the percentages of irrigation in the apple-producing regions were low. Thus, the apple shape index, hardness, soluble sugar, and peel anthocyanin relied strongly on precipitation [28]. Of the five apple-producing regions, annual precipitation was the most abundant in the Southwest Highlands, followed by the Old Course of the Yellow River, whereas precipitation in Bohai Bay was most suitable. Moreover, precipitation in the Loess Plateau was slightly insufficient, and the natural precipitation in Xinjiang did not satisfy the normal growth of apples. The variation in precipitation does not clearly show regional differentiation characteristics. Precipitations in the Southwest highlands and Bohai Bay were slightly decreased but showed significant increases in other locations (except for Xinjiang); however, the precipitation variations in the other regions were not significant. Overall, the precipitation in all of the apple-producing regions tended to shift toward the optimal range (Figure 3) for growing high-quality apples.

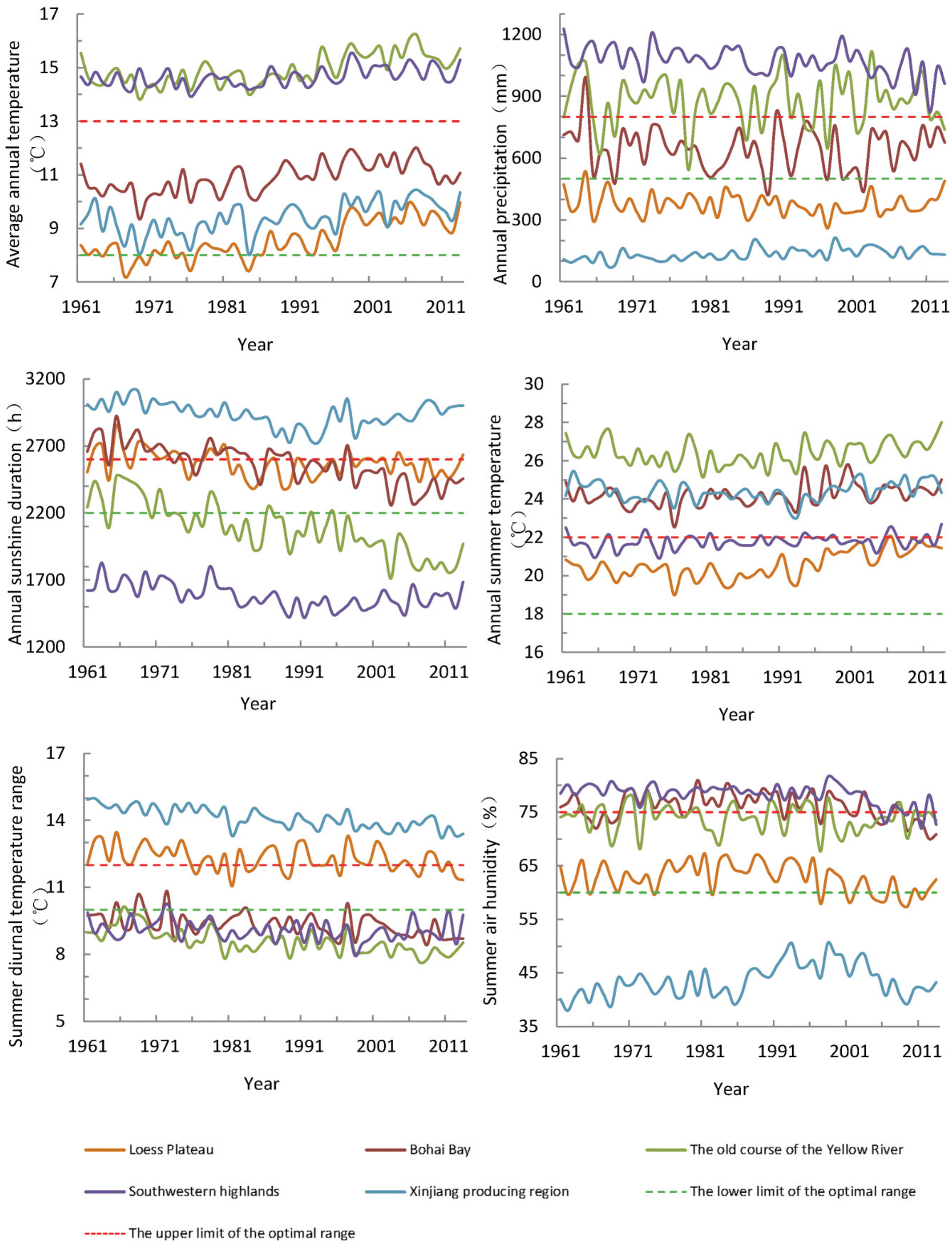

Figure 3. Annual variations of the major climate factors affecting apple quality in the different apple-producing regions of China.

A sufficient number of sunshine hours is important to assure high-quality apples with regard to the apple shape index, peel anthocyanin, and sugar-acid ratio [10]. Insufficient sunshine hours may affect fruit coloring and sugar accumulation; however, extensive sunshine hours can decrease the fruit shape index [22]. Of the five fruit-producing regions, the sunshine in Xinjiang was the highest, whereas that in the Loess Plateau and Bohai Bay did not assure good apple quality. In contrast, the sunshine conditions in the Old Course of the Yellow River and Southwest highlands were slightly worse, especially in the case of the latter, which had fewer than 1,800 sunshine hours. The sunshine hours in all of the apple-producing regions were consistently decreased but with significant variations. In particular, the decrease in sunshine hours was most significant for the Old Course of the Yellow

River, which already had insufficient sunshine hours. The decreasing rate reached –86 h/10a^{-1}. As Figure 3 shows, sunshine hours have gradually decreasing since the 1990s to a level below the lower limit of the optimal range, and the decreasing rate of the sunshine hours in the Southwest highlands (which had the fewest sunshine hours) also reached –26 h/10a^{-1}, which inhibited good apple quality. Although the sunshine hours in Bohai Bay were significantly decreased, the effect on its apple quality was not large. Overall, the decreasing sunshine trends in the Old Course of the Yellow River and Southwest Highlands might negatively affected apple quality.

Summer is a key stage for fruit to grow and convert sugars. Therefore, the average summer temperature is significantly correlated with the titratable acid content, fruit hardness, peel anthocyanin, and sugar-acid ratio [30]. Temperatures exceeding the optimal range can result in a quick decrease in apple hardness and inhibit fruit coloring [25]. The average summer temperatures in both Bohai Bay and the Old Course of the Yellow River were higher than those in the other apple-producing regions, which were also higher than the optimal temperature, especially in the case of the Old Course of the Yellow River with temperature of 26 °C. The temperatures in the other apple-producing regions were all within the optimal range. All of the average summer temperatures in the five apple-producing regions were increased, and the increases in the Loess Plateau and Xinjiang were most significant. Figure 3 shows that the average summer temperature in the Southwest Highlands gradually increased to a level above the upper limit of the optimal index since the 2000s. In sum, the increased summer temperatures might have negligibly affected the Loess Plateau but might have threatened other producing regions.

The optimal summer diurnal temperature range plays an important role in determining apple hardness, soluble sugar level, and the sugar-acid ratio [22]. Within the optimal range, a large diurnal temperature range can significantly increase peel anthocyanin; if the temperature is too high, however, then it can hamper sugar accumulation and affect the conversion of peel anthocyanin, leading to decreased quality [22]. The diurnal temperature ranges in the Loess Plateau and Bohai Bay were generally close to the optimal range, whereas those in the Old Course of the Yellow River and Southwest Highlands were below the lower limit of the optimal range. In addition, the diurnal temperature range in Xinjiang was above the optimal range. The summer diurnal temperature range in all of the regions tended to decrease, and these decreases might positively have affected the apple quality of the Loess Plateau and Xinjiang producing regions. Figure 3 shows that the average diurnal temperature range has gradually decreased since the 2000s to the optimal range in the Loess Plateau, whereas the diurnal temperature range in Bohai Bay, the old course of the Yellow River, and the Southwestern Highlands significantly decreased, which might have negatively affected apple quality.

Summer relative humidity is of great importance to the VC content, hardness, soluble sugar, and peel anthocyanin; furthermore, it is closely related to the occurrence index of orchard pest hazards [21]. The relative humidity in the Loess Plateau and Bohai Bay were within the optimal range, whereas excessive precipitation resulted in relative humidity that exceeded the upper limit of the optimal range in the Old Course of the Yellow River and Southwest Highlands. The relative humidity in Xinjiang was clearly the lowest. Figure 3 shows that the relative humidity had slightly increased in Xinjiang since the 2000s, whereas the relative humidity tended to decrease in the other producing regions; these levels were suitable to grow high-quality apples in the Old Course of the Yellow River and Southwest Highlands.

3.2. Abrupt Change Characteristics of the Major Climate Factors Affecting Apple Quality

The evolution of climate is not always gradual. Sometimes, it might change from a relatively stable phase to another stable phase within a relatively brief period of time (i.e., an abrupt change of a climate system). Such an abrupt change might occur on different timescales. The Mann-Kendall test was used to analyze the abrupt changes of the six climate factors that affect apple quality in the apple-producing regions and sub-regions. The results are listed in Table 3. The average annual temperature, annual sunshine duration, and average summer temperature all abruptly changed throughout all of the producing regions. Except for Bohai Bay, abrupt changes were detected in the average summer diurnal temperature range in all producing regions; the average summer relative humidity in the Loess Plateau and Southwest Highlands also abruptly changed. Moreover, the annual precipitation in Xinjiang was significantly increased and abruptly changed around 1986. Based on the collected data of all of the major producing regions, abrupt changes occurred with regard to all of the factors except annual precipitation. Abrupt changes occurred in the average annual temperature, annual sunshine duration, average summer temperature, average summer diurnal temperature variation, and relative humid in 1991, 1982, 1997, 1979, and 2001, respectively. The abrupt changes in these climate factors might have significantly affected apple quality.

Table 3. The abrupt change analyses of the major climate factors affecting apple quality in China using the Mann-Kendall method (α = 0.01).

Production Areas	*T*	*P*	*S*	*Ts*	*SRT*	*RHs*
Major production areas (MA)	1991	-	1982	1997	1979	2001
Loess Plateau (PL)	1992	-	1981	1998	1975	2002
Bohai Bay (BG)	1988	-	1989	1997	-	-
Old Course of the Yellow River (LY)	1996	-	1981	1994	1979	-
Southwest Highlands (SW)	1996	-	1982	1997	1979	2003
Xinjiang (XJ)	1992	1986	1978	1997	1981	-

3.3. Spatial Distribution Characteristics of the Major Climate Factors Affecting Apple Quality

Based on variations of the average climate factor values in the producing sub-regions, we compared the regional differences of the major climate factors affecting apple quality. Thus, 10 km × 10 km grids of five out of six climate factors showing abrupt changes affecting apple quality were calculated before and after the corresponding abrupt changes (Figures 4–8). Significant spatial variations occurred before and after the abrupt changes for the climate factors that affect apple quality.

The average annual temperatures of all of the producing regions were significantly increased (Figure 4), especially in the Northwest Xinjiang, Northwest Loess Plateau, and Southern Jiangsu regions with the increasing magnitudes exceeding 1 °C after the abrupt change. Overall, the optimal temperature distribution region for good apple quality was shifted toward the north. This result is because the variation in the average annual temperature may positively affect the Northern Loess Plateau producing region; in contrast, it may negatively affect Southwestern Bohai Bay and the Old Course of the Yellow River because very high temperatures lower fruit hardness, reduce acid content, and affect fruit coloring.

Figure 4 shows that after the abrupt climate change, the annual sunshine duration in the major producing regions was greatly reduced, with decreases in Bohai Bay and the Old Course of the Yellow River being the greatest, >150 h. Decreases in Gansu within the Loess Plateau and Southwest Highlands were relatively lower but approximately 50 h. The decreased sunshine hours resulted in less than 2000 sunshine hours in the Old Course of the Yellow River and Shandong within the Bohai producing region and less than 2200 h in Southern Hebei. The decreased sunshine hours in the above regions might have resulted in lower fruit sugar-acid ratios and more fruit coloring problems.

Comparisons of the variations in the spatial distribution of the average summer temperature during abrupt climate changes show that the average summer temperature was also significantly increased (Figure 5). The spatial distribution characteristics of summer temperature before and after the abrupt change are similar to those of average annual temperature. The spatial distribution of the optimal regions with increased summer temperature show that the effect on the Bohai producing region was the most significant, resulting in an increase in summer temperatures above 25 °C in Liaoning, which is within the Bohai and Old Course of the Yellow River producing regions. This increased temperature greatly and negatively affected apple quality.

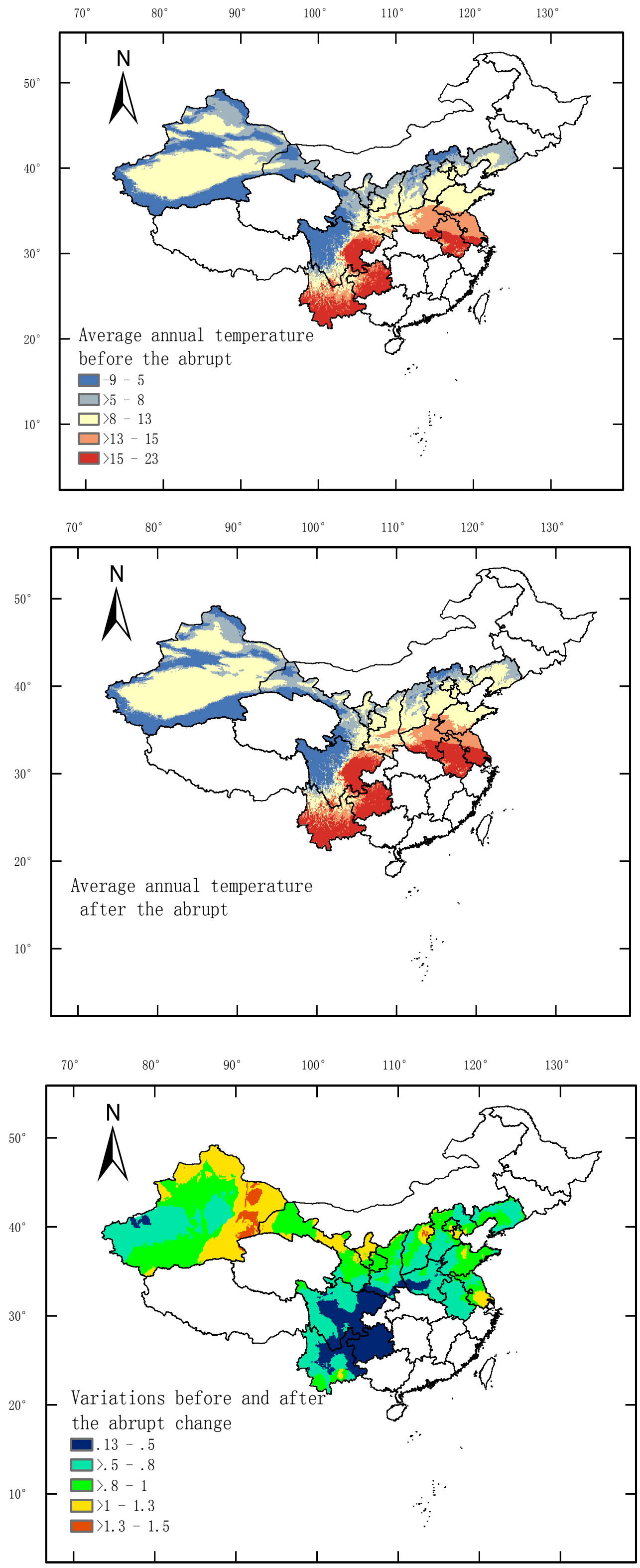

Figure 4. The changes in spatial distribution of the major apple-producing regions in China before and after the abrupt change of annual average temperature, wherein the yellow area represents the optimal range of annual average temperature for high-quality apple growing.

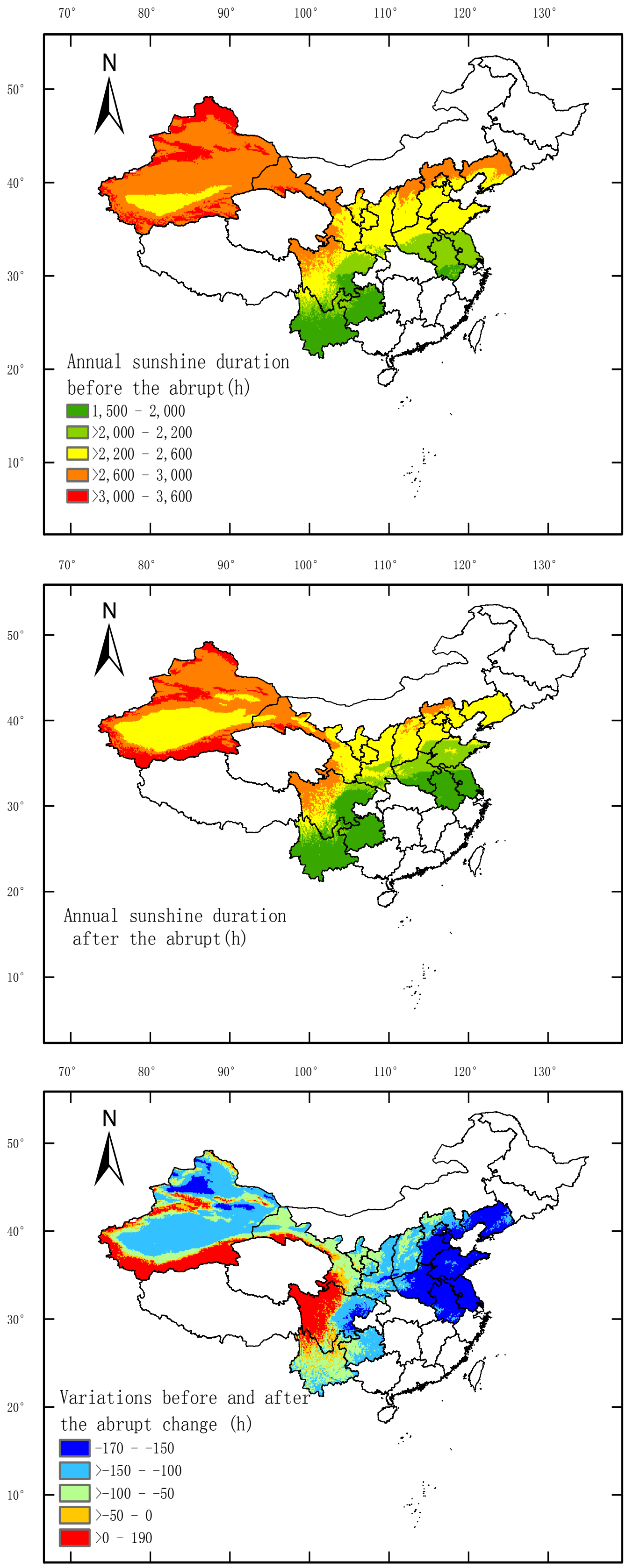

Figure 5. The changes in spatial distribution of the major apple-producing regions in China before and after the abrupt change of annual sunshine, wherein the yellow area represents the optimal range of annual sunshine for high-quality apple growing.

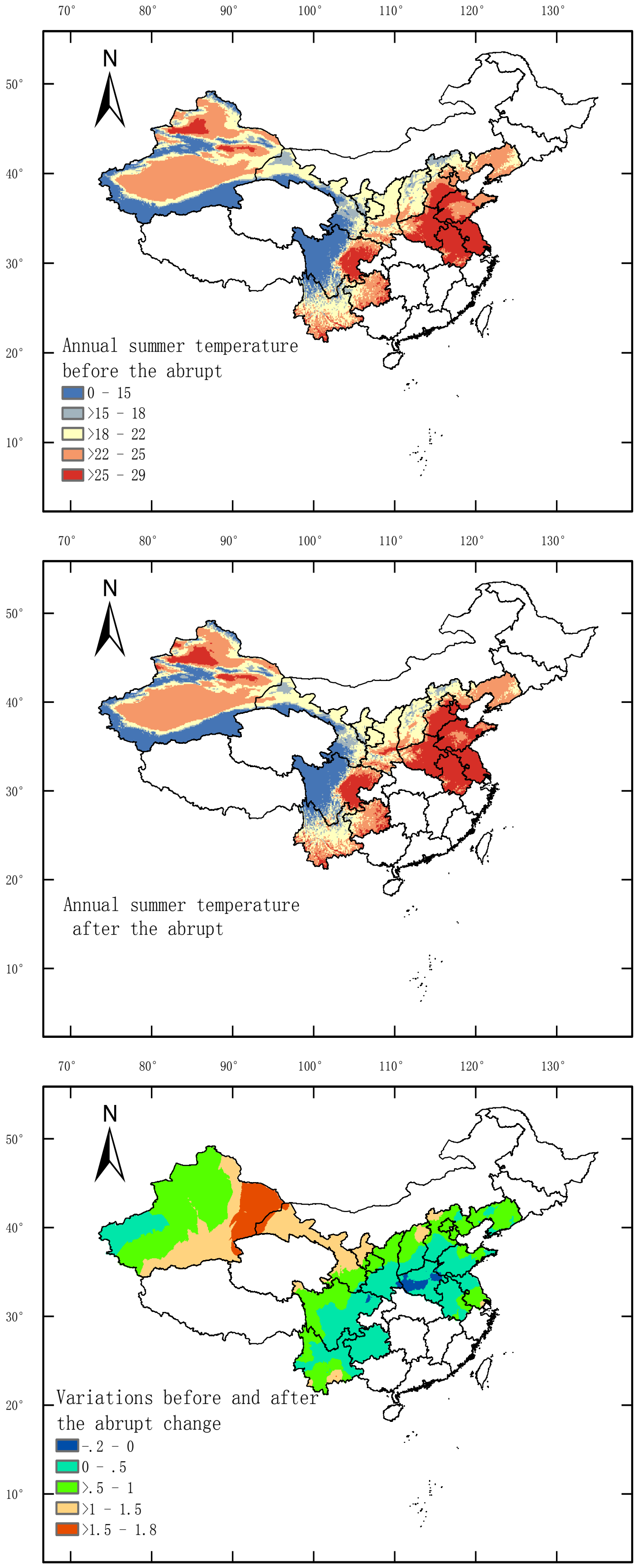

Figure 6. The changes in spatial distribution of the major apple-producing regions in China before and after the abrupt change of average summer temperature, wherein the yellow area represents the optimal range of average summer temperature for high-quality apple growing.

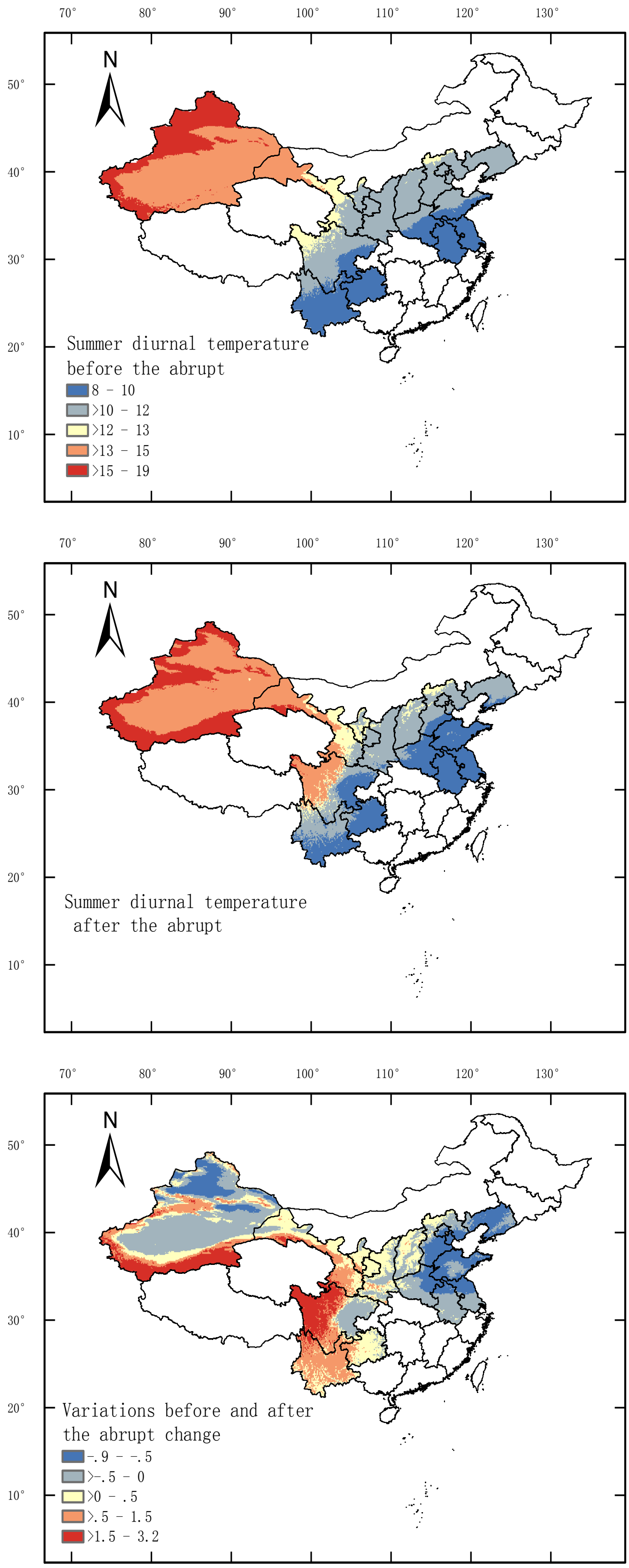

Figure 7. The changes in spatial distribution of the major apple-producing regions in China before and after the abrupt change of average summer diurnal temperature, wherein the yellow area represents the optimal range of average summer diurnal temperature for high-quality apple growing.

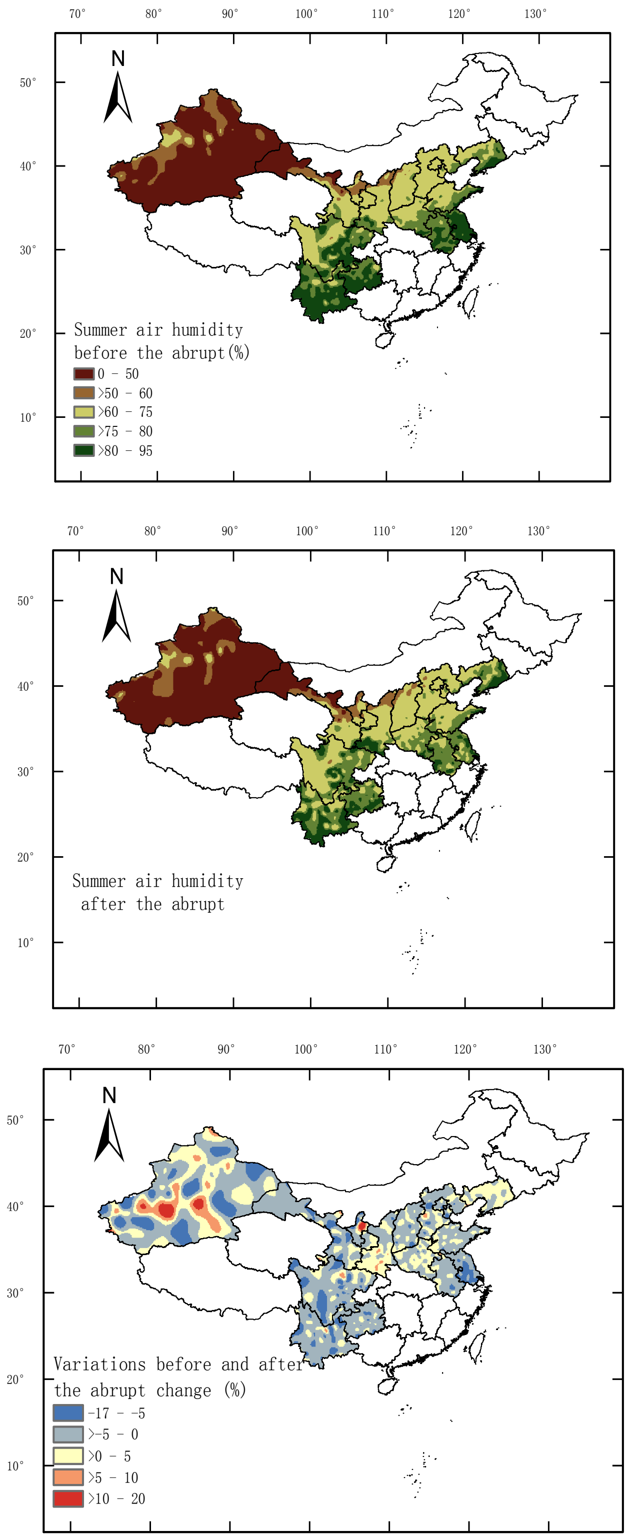

Figure 8. The changes in spatial distribution of the major apple-producing regions in China before and after the abrupt change of average relative humidity, wherein the yellow area represents the optimal range of average relative humidity for high-quality apple growing.

Although the average summer diurnal temperature range for all of the fruit-producing regions gradually decreased on average, regional differences existed (Figure 6). The distribution of the average summer temperature after the abrupt climate change show that the values in Bohai Bay and the Old

Course of the Yellow River were significantly decreased compared with those before the abrupt change, reaching above 0.5 °C; the values in Shaanxi, Ningxia, and Shanxi, which are within the Loess Plateau and Yun-Gui highland producing regions, were slightly increased. Based on the distribution of the optimal regions after the abrupt change, we conclude that the variations in the diurnal temperature range negatively affected Shandong, Southern Hebei, and Northern Henan but positively affected the major production regions along the boundaries of the Yun-Gui-Chuan provinces.

The spatial variations in summer air relative humidity are complicated. However, the overall variation magnitude was not large. The values in the Southwest Highlands, Old Course of the Yellow River, and Ningxia, which is within the Loess Plateau region, were decreased, whereas those in Liaoning, which is within the Bohai Bay producing region, and Southern Loess Plateau were slightly increased. A large increased magnitude in Southern Xinjiang of >10% was observed. The variation of air relative humidity in the summer may positively have affected the apple quality in the Southwest Highlands and the Old Course of the Yellow River.

4. Discussion and Conclusions

Apples were initially produced in Western Asia and Southern Europe, and this fruit prefers a cold and dry climate [21,35]. With increased climate change, all of the temporal and spatial distributions of the major climate factors that greatly affect apple quality have significantly changed. Moreover, the average phases of all of the climate factors except for annual precipitation abruptly changed, consequently affecting the apple quality of all of the apple-producing regions. Previous studies on the effect of climate change on apple production have primarily focused on the aspects of climate resources, phenological periods, production, and hazard risks [35–38]. Based on the production scale and market percentage of China, the major developing tendency is to control the scale with stable yields while improving quality in the future. An analysis of the comprehensive effects of climate factors on the seven physicochemical indices for assessment (Table 4) demonstrates that these changes positively affected apple quality, especially with regard to the fruit shape index, sugar-acid ratio, and VC content, because the average annual temperature and average summer temperature were both increased within the optimal range, the annual sunshine durations were slightly decreased within the high value regime in the Loess Plateau, and the diurnal temperature range in Gannan was decreased in the upper limit regime within the optimal region. In contrast, the reduced sunshine hours in Guanzhong and Southern Shaanxi regions might have negatively affected the soluble sugar content and fruit coloring. Within the Bohai Bay region, climate change positively affected the Liaoning producing region on average; however, increased temperature, reduced diurnal temperature range, and sunshine hours may have greatly affected the Shandong producing region, especially negatively affecting fruit hardness, soluble sugar levels, and peel anthocyanin. The possible positive effects of climate change on apple quality were more significant than the negative effects on average in the Old Course of the Yellow River. The effects of increased temperature and decreased sunshine hours were most significant in Southeastern Hebei, Northern Anhui, and Northern Jiangsu, and the fruit hardness and soluble sugar content were decreased. The possible impact of climate change in the Southwest Highlands is complicated; both the increased summer temperature and changed diurnal temperature range reached the optimal ranges in the Yun-Gui highland producing region, helping to reduce fruit hardness and increase the soluble sugar content. However, the increased average annual temperature and reduced sunshine hours might have negatively affected the fruit shape index and fruit coloring. The possible impact of climate change in Xinjiang was also positive, especially in the case of increased precipitation and summer air relative humidity, which helped to improve the exterior quality of the apple. In addition, the increased temperature reduced fruit hardness.

Table 4. Possible effects of climate change on apple quality in China.

	Fruit Hardness	Fruit Shape Index	Peel Anthocyanin	VC Content	Soluble sugar	Titratable Acid	Sugar-acid ratio
Loess Plateau (PL)	↓+	↑+	↑+	↑+	↑+	↓+	↑+
Bohai Bay (BG)	↓−	↓−	↓−	↑+	↓−	↑−	↓−
Old Course of the Yellow River (LY)	↓−	↓−	↓−	↑+	↓−	↑−	↓−
Southwest Highland (SW)	↓+	↓−	↓−	↑+	↑+	↓+	↑+
Xinjiang (XJ)	↓+	↑+	↑+	↑+	↓+	↑+	↓+

↑: Increase; ↓: Decrease; +: Positive effect; −: Negative effect.

The survey data of apples quality were collected from three regions (Ningxia, Shaanxi and Shandong), including several indicators, such as hardness, sugar-acid ratio, and coloring degree (redness or anthocyanin). From the comparison analysis, it can be found that the quality of apples in China has been improved overall, due to the improvement of production and management measures. From the comparison among the apples' quality in different regions and different ages, however, it can be seen that the improvement of fruit shape index and sugar-acid ratio of apples in Shaanxi and Ningxia was more significant compared with that in Shandong, but the fruit hardness degree changed little. The fruit shape index in Shandong also increased, although less than that in Shaanxi and Ningxia, and the fruit color of apples in Shandong was relatively poor compared with that in the loess plateau. Although the data is relatively limited, it confirmed the reasonableness of the findings from indirect sources.

Previous studies of the meteorological indices that affect apple quality have primarily considered the sensitivity to the meteorological conditions that affect this quality during the phenomenological period. Some researchers have proposed meteorological indices based on monthly and decadal scales in different regions [22,23,29]. Because of the limited amount of data, we only considered variations in the meteorological factors using annual and seasonal scales to consistently assess the effects across different producing regions. We primarily focused on the effects of the meteorological indices on apple quality during the entire growth and fruit-swelling periods. Moreover, extreme climate events such as freeze injury during the blooming period as well as high temperature and heat during the swelling period can directly affect apple quality [39]. The impacts of spring frost and heat injury during the expansion period on fruit quality were more direct, which only accounted for a limited number for the whole country, but may be more important for some individual regions [40]. The effects of climate hazards on apple quality in apple-producing regions will be analyzed in our future work. In addition, due to a lack of long sequence observation data of apple quality, the conclusions of this paper need to be further verified. The data collection of fruit quality should be carried out so as to further assess the impact of climate change on the apple quality.

Apple quality is closely related to meteorological environmental factors, and it is comprehensively affected by soil, water, and fertilizer as well as the quality of planting and management [41–43]. Since this study has been focused on the impact of apples' quality indicators, in terms of the choice of climatic factors, the key has been the impact of the year's climatic conditions on the quality, and the climatic conditions had a relatively great impact on the quality. Among the selected climatic factors, sunshine duration has a relatively high correlation with the annual precipitation, which has a superimposed effect on the impacts of fruit shape index and anthocyanin. The impacts of average temperature in summer and diurnal range on the quality indicators, such as hardness and anthocyanin, are more complicated, overall consideration should be given in practical application. At present, improved soil organic content, small orchard climate environments, and orchard mulching have been applied in the major producing regions, achieving positive effects [44–46]. The coordinated effects of different factors must be considered when applying our research results. In addition, we suggest that early-, middle- and late-matured species must be arranged and rearranged to improve apple quality and increase financial income, especially in Southern Old Course of the Yellow River and Southwest Shandong, which showed large negative effects. In addition, planting plans should be optimized to positively correspond to climate change.

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