



## Article

# Temperature Changes Affected Spring Phenology and Fruit Quality of Apples Grown in High-Latitude Region of South Korea

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**Abstract:** Climate change has had a significant impact on apple phenology and fruit quality worldwide. Similarly, a decline in fruit quality has been observed in major apple-producing areas of Korea. It is predicted that the ideal cultivation areas for apples would need to shift toward higher latitudes due to these changes. Hence, the objective of this study was to assess the influence of climate change on apple cultivated in a higher-latitude region. To achieve this goal, we investigated the flowering and harvest times of apples. Additionally, we measured fruit weight, soluble solid content, and titratable acidity over a period of 20 years in a higher-latitude region in Korea. Subsequently, we examined the relationship between temperature, phenology, and fruit quality through the use of linear regression and correlation analysis methods. The 20-year meteorological data revealed a consistent rise in temperatures. Consistent with this trend, we found a significant advancement in budbreak and flowering dates for the two major apple cultivars grown in a higher latitude in Korea. Furthermore, the increase in temperatures has positively influenced fruit quality, indicating that climate change has an impact not only on phenology, but also on the quality of apples in Korea. Considering the projected gradual increase in temperature, our findings strongly support that higher-latitude regions in Korea have the potential to become optimal locations for apple cultivation.

**Keywords:** climate change; flowering; *Malus domestica*; soluble sugar content**Citation:** Lee, J.-C.; Park, Y.-S.; Jeong, H.-N.; Kim, J.-H.; Heo, J.-Y.Temperature Changes Affected Spring Phenology and Fruit Quality of Apples Grown in High-Latitude Region of South Korea. *Horticulturae* **2023**, *9*, 794. <https://doi.org/10.3390/horticulturae9070794>

Academic Editor: Daniele Bassi

Received: 8 June 2023

Revised: 4 July 2023

Accepted: 10 July 2023

Published: 12 July 2023



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## 1. Introduction

The apple (*Malus domestica* Borkh.) is regarded as one of the most economically important fruit crops globally. It is widely used for fresh consumption as well as a raw material for the production of processed products because it has excellent taste and a rich content of functional substances [1,2]. In Korea, the cultivated area and production of apples as of 2022 are 34,603 hectares and 520,800 tons, respectively. Apples rank as the top fruit crop and play a crucial role in the domestic agricultural industry. According to the Intergovernmental Panel on Climate Change, global temperatures have increased by approximately 1.1 °C since pre-industrial times [3]. The rising trend is expected to continue, with temperature projections ranging from 1.2 °C to 3.0 °C by 2050, depending on different greenhouse gas emission scenarios [4]. Climate change has led to abnormal weather patterns worldwide, including increased mean temperatures and extreme temperature fluctuations, which are also evident in Korea [5,6]. Rising temperatures have been known to induce heat stress in major crop species, affecting crucial growth stages, reducing photosynthesis, and hindering overall plant development [7]. Furthermore, higher temperatures contribute to the proliferation of pests and diseases, leading to decreased crop quality and productivity [8].

In apples, temperature is also a key factor affecting their growth and quality [9]. Numerous studies have examined the effects of climate change on apple production, revealing significant changes in phenology and fruit quality at a global scale. Advancements in

flowering times have been observed in temperate countries like Germany and Japan [10,11], and alterations in essential fruit attributes have been documented in major apple-producing regions [12,13]. Consequently, these findings emphasize the importance of regional adaptation recommendations, particularly for areas with high latitudes or altitudes, in apple cultivation [14,15]. In Korea, it has been reported that problems related to coloration and quality deterioration inhibit the production of high-quality apples in major producing areas due to the frequent occurrence of high temperatures during the growing season, unlike in the past [16]. Accordingly, it is believed that the optimal cultivation area for apples will shift to higher latitudes in Korea [17,18]. However, there has been no comprehensive assessment of the long-term effects of climate change on the phenology and key characteristics of apples in high-latitude regions in Korea. Consequently, there has been no scientific evaluation to determine whether the high latitudes of Korea can serve as optimal cultivation areas for apples. While many studies have focused on either phenology or fruit quality individually, it is crucial to consider these factors simultaneously. Therefore, the objective of this study was to analyze the relationship between temperature, phenology, as well as fruit characteristics based on 20 years of cultivation data from a high-latitude region in Korea. Through this study, we aimed to assess the potential impact of climate change and identify future directions for sustainable apple production on the domestic apple industry.

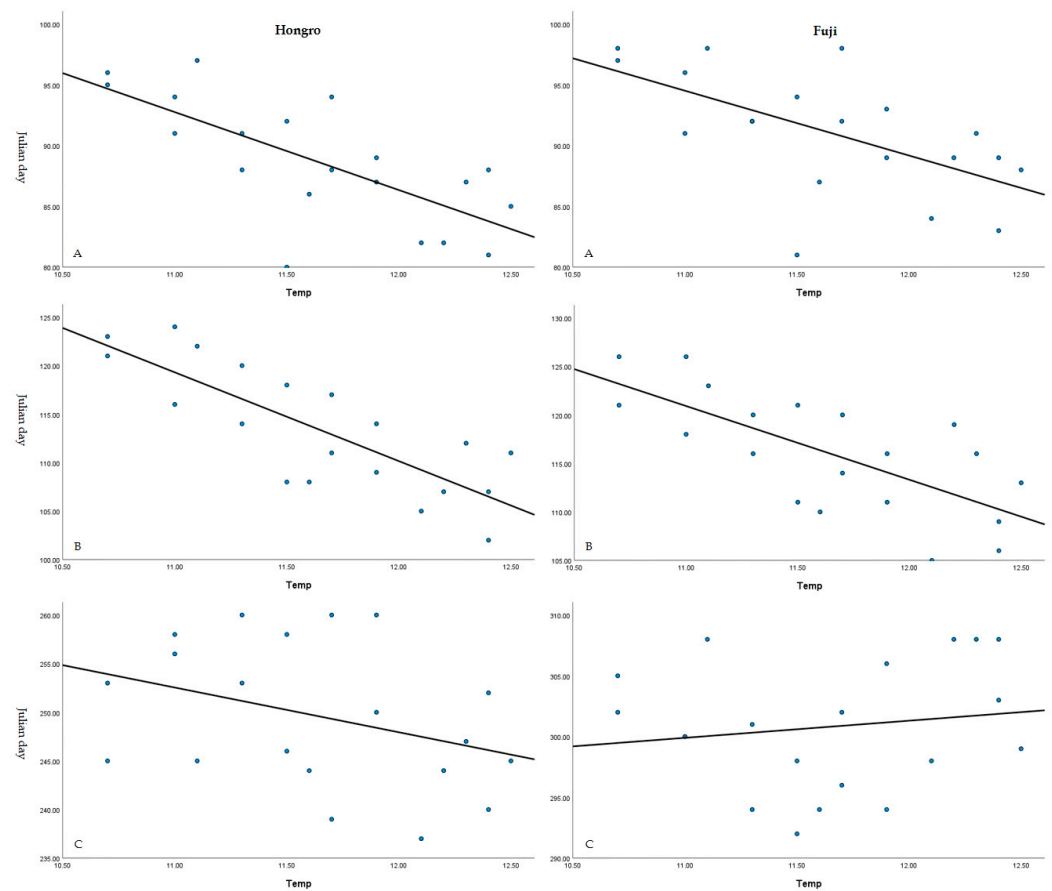
## 2. Materials and Methods

### 2.1. Plant Materials

This experiment was conducted at the orchard (37°94'73.80 N, 127°75'44.30 E) of Gangwon State Agricultural Research and Extension Service (GARES) in Chuncheon, a high-latitude region of South Korea, from 2003 to 2022 (Figure 1). Two apple cultivars, 'Fuji' (late-maturing) and the 'Hongro' (mid-maturing), were selected as plant materials. In Korea, 'Fuji' and 'Hongro' account for 61.5% and 13.9% of apple production, respectively, and are considered the most important apple cultivars in the country. Three plants per cultivar were chosen for this study. They were grafted with M.9 rootstock and planted using the slender-spindle system. At the beginning of the experiment, the plants were 4 years old. The objective was to achieve approximately 80 fruits per plant each year, and consistent management practices, including fertilization, thinning, disease control, and pest control, were implemented throughout the experimental period.

### 2.2. Observation of Phenology and Fruit Quality

The phenology observations were recorded by research experts working at GARES. The recorded seasonal biological events included budburst, flowering, and harvest dates. The budburst and flowering dates were visually determined when 50 percent of the buds and flowers across the tree had opened for the examined cultivars. The harvest date was determined based on the visual monitoring of fruit coloration. When 80 percent of the apple peel in the produced fruits at the middle part of the tree exhibited a red coloration, it defined the harvest time. To assess the impact of temperature change on major fruit characteristics, measurements were taken for fruit weight, soluble sugar content, and titratable acidity from the same trees used for the phenology observations. Twelve fruits were harvested from the middle part of each tree per cultivar at the designated harvest time, and the major fruit characteristics were directly investigated. The fruit weight was determined using a digital weight balance and expressed in grams (g). Soluble sugar content and titratable acidity were measured using apple juice extracted from 10 g of pulp, which was then filtered through cheesecloth at room temperature. Soluble sugar content was measured using a hand refractometer (PR-101, Tokyo, Japan) and expressed as °Brix. Titratable acidity was measured using an automatic titrator (Schott Titro-line alpha, Mainz, Germany). The juice was titrated to an endpoint of pH 8.2 using 0.1 N sodium hydrogen phthalate.



**Figure 1.** Relationship between budburst (A), flowering (B), harvest date (C), and mean air temperature.

### 2.3. Collection of Meteorological Data

Meteorological data from 2003 to 2022 were collected from the nearest meteorological station of the Korean Meteorological Institute, located in Chuncheon, Korea ( $37^{\circ}94'73.80$  N,  $127^{\circ}75'44.30$  E). The meteorological station is in close proximity to the experimental site, with a distance of only 3 km. The collected data include daily observations of mean temperature, total solar radiation, and total precipitation.

### 2.4. Data Analysis

To identify the climate factor that consistently changed over the 20-year period, a correlation analysis was performed between the years and the three meteorological variables using SPSS statistics 27 (IBM, Armonk, NY, USA). The results indicated that only the annual temperature showed a significant correlation with the progress of the year (Table 1). Since average temperatures are commonly used in this type of analysis, linear regression techniques were further employed to establish the relationship between the apple variables and the year and temperature variables using SPSS statistics 27 (IBM, Armonk, NY, USA). A stepwise methodology was used to select the most significant temperature predictors. The final regression models primarily included predictors that have been frequently used by other researchers in similar analyses. Additionally, a correlation analysis method was applied to explore the potential impact of long-term meteorological patterns on the observed tree characteristics.

**Table 1.** Meteorological data obtained from Chuncheon in Korea.

Parameter	Minimum Value	Maximum Value	Mean Value	Standard Deviation	b	R-Squared	p Value
Temperature (°C)	10.70	12.50	11.64	0.568	<b>0.052</b>	0.293	<b>0.014</b>
Total precipitation (mm)	674.40	2029.30	1391.58	348.01	−19.01	0.104	0.165
Total solar radiation	4534.76	5162.29	4909.20	186.70	4.053	0.016	0.589

Trends through year progress are summarized in the final three columns from regressions of the variable. b = Slope of regression coefficient. Significant results are represented in bold ( $p < 0.05$ ).

### 3. Results and Discussion

#### 3.1. Effect of Temperature Change on Phenology in Apples Grown at High-Latitude Region of Korea

The annual and monthly mean temperatures for 20 years are presented in Tables 1 and 2. The average annual temperature over the last 20 years was 11.64 °C, with the lowest value recorded in 2011 (10.70 °C) and the highest value in 2015 (12.50 °C). When dividing the temperatures over the past 20 years into two quarters, the average temperature from 2003 to 2012 was 11.26 °C, while the average temperature from 2013 to 2022 was recorded as 12.02 °C, indicating that the average temperature in the past 10 years has risen compared to the previous decade. Statistically, a clear increasing trend in the annual average temperature has been observed for the last 20 years. Additionally, it was estimated that among the 12 monthly temperatures, the temperatures in March, June, and July have had significant influence on the increase in the annual average temperature (Table 3).

**Table 2.** Change of monthly temperature observed in Chuncheon in Korea over 20 years.

	Minimum Value	Maximum Value	Mean Value	Standard Deviation	b	R-Squared	p Value
January	−9.50	−0.10	−4.30	2.01	0.052	0.023	0.520
February	−3.80	1.50	−0.77	1.72	−0.011	0.001	0.878
March	3.20	7.80	5.38	1.27	<b>0.138</b>	0.418	<b>0.002</b>
April	9.10	14.00	11.87	1.48	0.071	0.082	0.222
May	16.40	19.10	17.93	0.80	0.043	0.101	0.172
June	20.50	24.20	22.58	0.90	<b>0.070</b>	0.212	<b>0.041</b>
July	23.10	27.30	25.12	1.13	<b>0.123</b>	0.415	<b>0.002</b>
August	23.60	27.30	25.32	1.01	0.074	0.189	0.055
September	18.90	21.30	20.11	0.67	0.042	0.133	0.114
October	10.90	15.10	13.12	1.12	0.022	0.014	0.626
November	3.79	8.20	5.82	1.34	0.007	0.001	0.900
December	−6.20	0.10	−2.45	1.98	−0.024	0.005	0.767

Trends through year progress are summarized in the final three columns from regressions of the variable. b = Slope of regression coefficient. Significant results are represented in bold ( $p < 0.05$ ).

At our experimental site, the average budburst date for ‘Hongro’ and ‘Fuji’ was 29 March and 31 March, respectively, with standard deviations of 4.97 and 4.91 days. The budburst dates for both apple cultivars exhibited a trend of shortening with annual temperature changes, as shown in Figure 1. The mean flowering date for ‘Hongro’ in 2023 was 23 April, while for ‘Fuji’, it was 25 April. Faster flowering was observed in later periods of the record, which also showed a significant relationship with annual temperature. The average harvest date for ‘Hongro’ was 6 September, and it exhibited a high degree of annual variation (7.4 days), but no statistically significant time series changing patterns

were observed. The mean harvest date for ‘Fuji’ was 27 October, ranging from 17 October to 4 November. Unlike the budburst and flowering dates, the harvest dates for both cultivars did not exhibit significant changing patterns.

**Table 3.** Summary of phenology and fruit quality data obtained over 20 years.

Parameter	Cultivar	Mean Value	Standard Deviation	b	R-Squared	p Value
Budburst	Fuji	91.10	4.99	−5.33	0.37	<0.005
	Hongro	88.65	5.09	−6.41	0.51	<0.000
Flowering	Fuji	116.05	6.12	−7.60	0.50	<0.001
	Hongro	113.45	6.47	−9.15	0.65	<0.001
Harvest date	Fuji	300.80	5.23	1.41	0.02	0.519
	Hongro	249.60	7.42	−4.46	0.13	0.127
Fruit weight	Fuji	328.34	45.64	8.97	0.01	0.638
	Hongro	237.26	40.02	<b>31.07</b>	0.20	<b>&lt;0.05</b>
Soluble sugar content	Fuji	14.20	1.15	0.42	0.04	0.378
	Hongro	13.87	1.31	<b>1.65</b>	0.51	<b>&lt;0.000</b>
Titratable acidity	Fuji	0.44	0.30	−0.21	0.16	0.078
	Hongro	0.26	0.08	−0.06	0.16	0.082

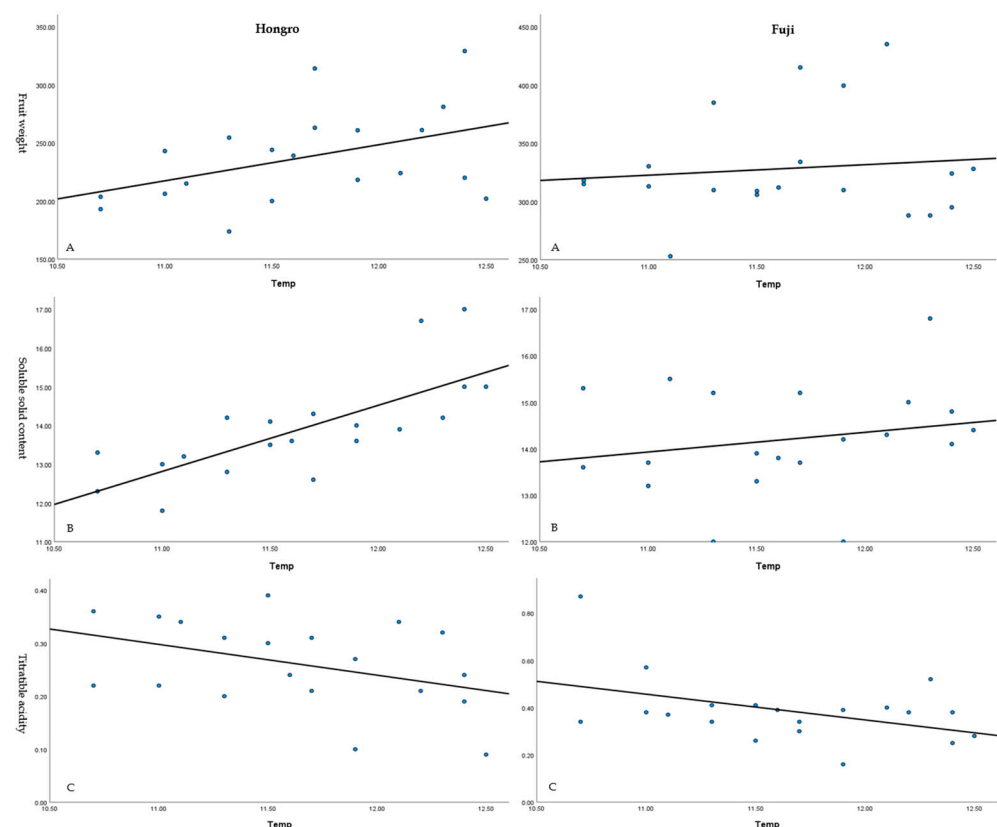
Trends through annual temperature changes are summarized in the final three columns using regressions of the variables. The slope of the regression coefficient (b) indicates the magnitude of the trend. Significant results are highlighted in bold.

Previous studies have reported that spring phenophases in apples are becoming earlier due to temperature increases in different countries [19,20]. Some studies have shown that spring temperatures have a greater influence on the earlier onset of budburst and flowering dates in fruit crops [11,21]. This study also demonstrated that the increase in temperature accelerated spring phenology in the high-latitude region of Korea. Warmer temperatures caused by climate change are assumed to accelerate the accumulation of heat units required for budburst and flowering.

Rising temperatures signal to the dormant buds that favorable conditions for growth and development are present, leading to an earlier initiation of budburst and subsequent flowering. However, the influence of climate change on the harvest date of apple in the high-latitude region differed among cultivars. ‘Hongro’ shows a slightly earlier harvest date, while no significant effect is found in ‘Fuji’. It should be noted that the harvest date proposed in this study is recorded when the fruits exhibit an optimum level of coloration for marketability. Therefore, the earlier harvest date observed in ‘Hongro’ indicates that fruit coloration is completed earlier. Apple coloration is influenced by anthocyanin accumulation [22], and it is suggested that the biosynthesis of anthocyanin in ‘Hongro’ might be more efficiently activated with an increase in temperature. This result suggests that anthocyanin biosynthesis could also be promoted in ‘Fuji’ during a specific growing season. However, the issue with ‘Fuji’, compared to ‘Hongro’, is that it grows in a high-latitude region such as Chuncheon, where low temperatures are frequently experienced from October. It is well-known that low temperatures can rupture cell membranes [23], resulting in a loss of structural integrity and a delay in ripening as ice crystals form within the fruit tissues. Additionally, the enzymatic processes involved in pigment synthesis might slow down or temporarily halt due to excessively low temperatures, leading to reduced levels of anthocyanins and other pigments responsible for color development. Hence, the excessive low temperatures occurring in the late growing season of ‘Fuji’ might delay the maturity of the fruit, requiring a longer time for the apples to reach their optimal coloration.

### 3.2. Effect of Temperature Change on Fruit Characteristics in Apples Grown at High-Latitude Region of Korea

Soluble sugar content, titratable acidity levels, and fruit weight are important parameters for estimating potential fruit quality in major fruit crops, including apples and grapes [24,25]. In ‘Fuji’, the average soluble sugar content and titratable acidity levels have been 14.15 °Brix and 0.38% malic acid, respectively, while in ‘Hongro’, they have averaged at 13.91 °Brix and 0.26%, respectively (Table 2). The mean titratable acidity level in ‘Fuji’ has consistently been higher than or equal to that of ‘Hongro’, while the average soluble sugar content levels have generally been higher in ‘Fuji’. Over the past 20 years, titratable acidity has shown a downward trend, while soluble sugar content levels have increased in both cultivars (Figure 2). However, statistically significant time series effects were observed only for soluble sugar content. The mean fruit weights of ‘Hongro’ and ‘Fuji’ were 237.25 g and 325.63 g, respectively. Although ‘Fuji’ consistently had higher fruit weights compared to ‘Hongro’ regardless of the year, the increase in fruit weight is greater in ‘Hongro’. In ‘Hongro’, there were significant negative relationships between soluble sugar content and fruit weight with flowering dates, indicating that an earlier phenological timing led to better quality and larger fruits (Table 4). In contrast, no significant correlations were found in ‘Fuji’ between fruit characteristics and spring phenology-related parameters (Table 5). Furthermore, the titratable acidity level was not significantly affected by climate change in either cultivar. The effect of spring phenology changes on fruit characteristics in apple differs among cultivars.



**Figure 2.** Relationship between fruit weight (A), soluble solid content (B), titratable acidity (C), and mean air temperature.

**Table 4.** Pearson's correlation coefficients among studied parameters of 'Hongro' apple cultivar.

	Budburst Date	Flowering Date	Harvest Date	Fruit Weight	Soluble Sugar Content	Titrateable Acidity
Budburst date	1					
Flowering date	0.828 **	1				
Harvest date	0.244	0.481 *	1			
Fruit weight	−0.459 *	−0.379 *	−0.018	1		
Soluble sugar content	−0.746 **	−0.688 **	−0.248	0.520 **	1	
Titrateable acidity	0.182	0.114	−0.079	−0.215	−0.322	1

\* significant at  $p < 0.05$ . \*\* significant at  $p < 0.01$ .

**Table 5.** Pearson's correlation coefficients among studied parameters of 'Fuji' apple cultivar.

	Budburst Date	Flowering Date	Harvest Date	Fruit Weight	Soluble Sugar Content	Titrateable Acidity
Budburst date	1					
Flowering date	0.759 **	1				
Harvest date	0.243	0.196	1			
Fruit weight	−0.069	−0.391 *	−0.224	1		
Soluble sugar content	0.151	−0.041	0.579 **	0.021	1	
Titrateable acidity	0.254	0.336	−0.014	−0.225	0.268	1

\* significant at  $p < 0.05$ . \*\* significant at  $p < 0.01$ .

The fruit characteristics of 'Fuji' and 'Hongro' can vary depending on the growing environment and management conditions, but 'Fuji' is generally known to have a fruit weight of about 300 g, while 'Hongro' has a lower average weight of around 250 g. Hence, 'Fuji' produces larger fruits compared to 'Hongro', and our result is consistent with the previous report [26]. However, both cultivars commonly exhibit soluble sugar contents of 13 °Brix or higher, and our results indicate that there are no significant differences in soluble sugar contents from a genetic standpoint. In our experiment, despite applying the same cultivation environment and management methods, we initially observed a relatively large difference between 'Fuji' and 'Hongro' in terms of fruit weight and soluble sugar content. In particular, 'Hongro' exhibited a lower fruit weight and soluble sugar content than previously reported values, suggesting that the genetic characteristics of 'Hongro' may not have been accurately expressed in high-latitude regions in the past. However, as temperatures rise, both the fruit weight and soluble sugar content of 'Hongro' rapidly increase, indicating that 'Hongro' can also exhibit excellent fruit quality comparable to major production areas in recent times.

It is known that an increase in temperature in cool regions enhances photosynthesis, leading to an increase in fruit size and quality, as the tree has more energy available for fruit development [27,28]. Additionally, a longer duration of fruit development allows the plant more time to transport and accumulate sugars in the fruit [29]. The longer fruit development period observed in 'Hongro' in this study may have allowed for more carbohydrates to be allocated to the fruit, resulting in an increased soluble sugar content. Medda et al. [30] reported that an extended fruit development time can also impact the ripening process, as it involves the conversion of starches into sugars, contributing to the sweetness of the fruit. Moreover, an increase in temperature generally leads to milder

winters and fewer frosts, reducing stress on the trees that experience harsh winters. In fact, the mean winter temperature from January to February has also decreased over the past 20 years. It is known that decreased abiotic stresses allow plants to allocate more resources toward performance improvement [31,32].

Therefore, the warmer winters observed in this study could potentially result in larger fruits with better quality for 'Hongro'. Although there was a trend of improvement in fruit weight and quality for 'Fuji', no significant relationship was found with temperature rise or spring phenology changes. Overall, our results demonstrate that climate change does not have a negative impact on fruit characteristics of apples grown in high-latitude regions in Korea. However, the obvious positive influence of climate change on fruit characteristics was only found in 'Hongro', a mid-maturing apple cultivar, and not in 'Fuji', a late-maturing apple cultivar. This result suggests that very low temperatures occurring in late autumn may affect this phenomenon and indicates that selecting earlier maturing apple cultivars could be ideal for successful apple production in the high-latitude regions of Korea. In the future, further experiments focusing on these points should be conducted to better understand the relationship between fruit quality improvement and temperature increase in high-latitude regions in Korea.

#### 4. Conclusions

Our study has shown that climate change significantly leads to earlier budbreak and flowering times for 'Hongro' and 'Fuji' apple cultivars grown in the high-latitude region of Korea. Additionally, increased temperatures have resulted in a gradual improvement in fruit quality for both cultivars. These results indicate that climate change affects spring phenology as well as fruit quality in apples, as reported in other countries. There is a question about whether the high latitude region in Korea can be an optimum location for apple cultivation in the future. This is because the study found a gradual improvement pattern in fruit quality grown at high-latitude locations, and a gradual increase in temperature is forecasted. Therefore, we can conclude that high-latitude regions in Korea can become optimal locations for apple cultivation. Interestingly, the harvest date of 'Hongro', a mid-maturing cultivar, was advanced, while the harvest date of 'Fuji', a late-maturing cultivar, remained unchanged and occasionally seemed to be affected by excessive low temperatures around the harvest period. This result suggests that the positive influence of climate change on fruit development is more pronounced in mid-maturing apple cultivars. Hence, efforts to select apple cultivars with superior quality will be needed in the future. Apart from this fact, it is important to note that frost temperatures are frequently observed during the flowering period in high-latitude regions. Frost can pose a significant threat to apple tree flowers as they are highly sensitive to frost temperatures. If frost damage occurs during the critical flowering stage, it can lead to a reduced fruit production or even complete crop loss. As climate change may lead to the further advancement of flowering times in apples, strategies to prevent frost damage during spring will be necessary. Further efforts to address these issues at high-latitude regions will enable successful and sustainable apple cultivation in Korea.

**Author Contributions:** Conceptualization, J.-Y.H.; methodology, J.-C.L. and J.-Y.H.; resource, J.-C.L. and Y.-S.P.; formal analysis, J.-C.L.; investigation, J.-C.L., Y.-S.P., H.-N.J. and J.-H.K.; data curation, J.-C.L. and Y.-S.P.; writing—original draft preparation, J.-C.L.; writing—review and editing, J.-Y.H.; supervision, J.-Y.H.; project administration, J.-C.L.; funding acquisition, J.-C.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the Rural Development Administration of Korea (grant number PJ0124562023).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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