



Influence of warming climate and the green revolution on the optimum range of weather parameters of longan yield in Taiwan since 1909

Li-Wei Lai¹

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Abstract

Longans are the fruits of a subtropical evergreen tree (*Dimocarpus longan* Lour.) and are widely distributed in Southern China and Southeast Asia. However, there is a lack of historical records of these fruits. In addition to air temperature, other factors, such as the green revolution effect (GRE), sunshine duration, flower bud differentiation, flowering, and production period, may also be important for longan yield. This study incorporated Duncan's multiple range tests, linear regression models, and multi-regression models, using the forward stepwise method. The results showed that a warming climate was unfavourable to the longan fruits yield (LFY), as the mean negative impact of climate change on LFY was 2489.6 ± 1072.2 kg/ha (mean difference $\pm 95\%$ CI) under GRE. When considering warming climate and GRE, the results showed that, at the time of flower bud differentiation, the optimum ranges of mean air temperature and relative humidity (RH) were 18.0–19.4 °C and 73.9–75.7%, respectively; during flowering, the optimum ranges of cloud cover, sunshine-hour, and rainy days were 6.8–7.3 oktas, 381.3–476.6 h, and 28.9–41.9 days, respectively; during the production period, the optimum ranges of mean diurnal temperature and RH were 6.8–7.4 °C and 75.1–79.4% respectively. A smaller optimum range of weather parameters aids in a greater slope of the accumulated frequency of the LFY. The GRE and small optimum ranges of weather (stable weather conditions) were found to assist in ensuring stable LFY.

1 Introduction

Compared to the period between 1850 and 1900, the global mean surface air temperature over land increased by 1.59 °C (range: 1.34–1.83) between 2011 and 2020 (Gulev et al. 2021), affecting the productivity of tropical and subtropical fruit crops. Climate change can have varying effects on crop productivity in different regions (Shukla et al. 2019). Mathur et al. (2012) reported that the suitable areas for horticultural bananas may decrease and those for horticultural mangoes may increase in tropical and subtropical areas due to climate change. In addition, banana production is limited by high air temperatures and low rainfall. During cold periods, the initiation of flowering in citrus is delayed when the air temperature is below 13 °C. Tender fruitlets were

damaged when the air temperature was higher than 37 °C. Mitra (2018) reported that high air temperatures induce stigma and stamen sterility in papaya, spongy tissue and black tips in mango, and cracking of fruits and granulation in citrus. However, low air temperatures cause flower drops in mango, guava, and litchi in tropical and subtropical regions. Nath et al. (2019) indicated that instead of flowering flushes, an increase of 1–2 °C beyond 25–30 °C can encourage vegetative flushes in citrus, and the number of perfect flowers at air temperatures between 13 and 27 °C was greater than that between 14 and 21 °C in mango.

Longan (*Dimocarpus longan* Lour.) is a fruit in subtropical and tropical regions, with commercial growing areas distributed across China, Thailand, Vietnam, and other countries (Tripathi 2021). In the Ming Dynasty (1368–1644), Li Shi-Zhen described the medical values of longan as both a “stomach-invigorator” and a cure for the deficiency of vital energy in the Compendium of Materia (Medica Bencao Gangmu) (Li 2003). The flowers of longan trees can be used to produce longan honey, and highly nutritious pulp (Wu and Chen 2020). In addition, aqueous extracts of the longan fruit have high radical-scavenging activity (Wang and Smythe

✉ Li-Wei Lai
liweilai@ntub.edu.tw

¹ Centre for General Education, National Taipei University of Business, No. 321, Sec 1, Chi-Nan Rd., Taipei 10051, Taiwan

2003). Li et al. (2020) found that potential areas suitable for growing longans might be affected by the mean temperature of the coldest quarter, minimum temperature of the coldest month, annual mean temperature, and mean temperature of the driest quarter in China, indicating a changing climate.

Currently, there is a lack of understanding regarding the relationship between climate change and longan production, although suitable areas for longan growth are known to have warm, humid summers and cool, dry winters (Dinesh et al. 2012). It is presumed that flowering and maturing happen earlier, and this was due to climate change. For example, weather conditions such as cool and dry winters aid in flower induction (Huang 2005; Wu and Chen 2020). Longan trees begin flowering when the weather becomes warmer, normally from March to May in Taiwan (Council of Agriculture (COA) 2021), which can be potentially influenced by climate change. In addition to the mean and minimum air temperatures (Li et al. 2020), it remains unclear whether other factors in distinct growth stages of longan, such as the diurnal temperature range, sunshine duration, and cloud cover, can affect longan production. Furthermore, it is important to control the effects of the green revolution, such as changes in irrigation methods, fertilisation, and pesticides, as these factors have improved in Asia since 1965 (Hazell 2009). In addition, Yen et al. (2001) found that potassium chlorate could promote longan flowering. This method has been widely applied to longan fruit production (Huang et al. 2021; Matsumoto et al. 2007a), more widely in Northern Thailand (Sutigoolabud et al. 2004, 2005). However, the drawbacks of using potassium chlorate include the risk of combustion, lack of availability, and associated difficulties with transport and storage (Matsumoto et al. 2007b). Its negative effects on the environment include the inhibition of nitrification (Sutigoolabud et al. 2008) and groundwater pollution (Sutigoolabud et al. 2004). This coincided with the period of climate change from 1909 to 2020, during which this study investigated the relationship between climate change and longan yield.

Firstly, this study aims to investigate the relationship between climate change and longan production, including the green revolution effect. Secondly, it aims to identify the factors that contribute to longan yield and their optimum environmental ranges in their distinct main growth stages.

2 Methodology

2.1 Study area

Taiwan was selected as the study area to evaluate the relationship between climate change and longan fruit yield (LFY) for several reasons. Longan is the most important honey plant in Taiwan (Chen 1994), with suitable growing areas distributed throughout the island. In

2020, the corresponding growing area was 10,612 ha (COA 2020). Furthermore, LFY in Taiwan dates back to 1909 (Academia Sinica 2021; COA 2020; Department of Agriculture and Forestry (DAF) 1999). The administrative districts of the harvested areas are shown in Fig. 1a and Table 1.

Longan is an evergreen tree that can reach a height of 12 m (COA 2022). More than 90% of longan cultivars are *Dimocarpus longan* var. Fen Ke in Taiwan (Li et al. 2016; Tripathi 2021). Longans have three major growth periods. The flower bud differentiation period occurs in December, January, and February. In Taiwan, the optimal air temperature for the flower bud differentiation period is between 10 and 14 °C. If air temperature and relative humidity are high, the flower bud morphs into a spring flush. The air temperature from December to January determines the number of flowers on the longan trees (Chen 1994). The flowering period is from March to May, with an optimal air temperature for flowering between 20 and 27 °C (COA 2021). The number of flowers decreases when the air temperature is lower than 13 °C or greater than 30 °C during this period (Chen 1994). The production period is during July and August (COA 2022).

Taiwan forms part of the East and Southeast Asia island arc, with the Ryukyu Islands to the northeast and the Philippines to the south. It is located between Eurasia and the Pacific Ocean, the largest terrain and ocean on the planet respectively (Fig. 1b). As a result, the East Asian continental cold pressure system and Northwest subtropical Pacific high-pressure system directly affect the variation in weather patterns on the island (Central Weather Bureau (CWB) 2022). The Tropic of Cancer crosses Taiwan, which has a subtropical and tropical climate (Fig. 1c). The mean annual air temperature in Taiwan is 23.63 °C with a mean annual rainfall of 2207 mm based on climate records from 1981 to 2010 (CWB 2020).

Six major meteorological monitoring stations were selected due to their homogeneous distribution across Taiwan (Fig. 1c and Supplementary Table 1) and long period of sufficient historical records, thus providing the climatic characteristics of the whole area in Taiwan. The harvested areas of longan are distributed across 89% of the island's political regions. Therefore, it was assumed that the selected weather stations were aligned with the longan production areas. The harvested area in Kinmen County was less than 0.02% of the total harvested area in Taiwan. Although Kinmen County consists of islands in the Taiwan Strait and not on the main island of Taiwan, its LFY was included in the annual yield record.

2.2 Data sources and site information

Data from 1880 to 2020 of global land anomalies with respect to the 1901–2000 base period average were

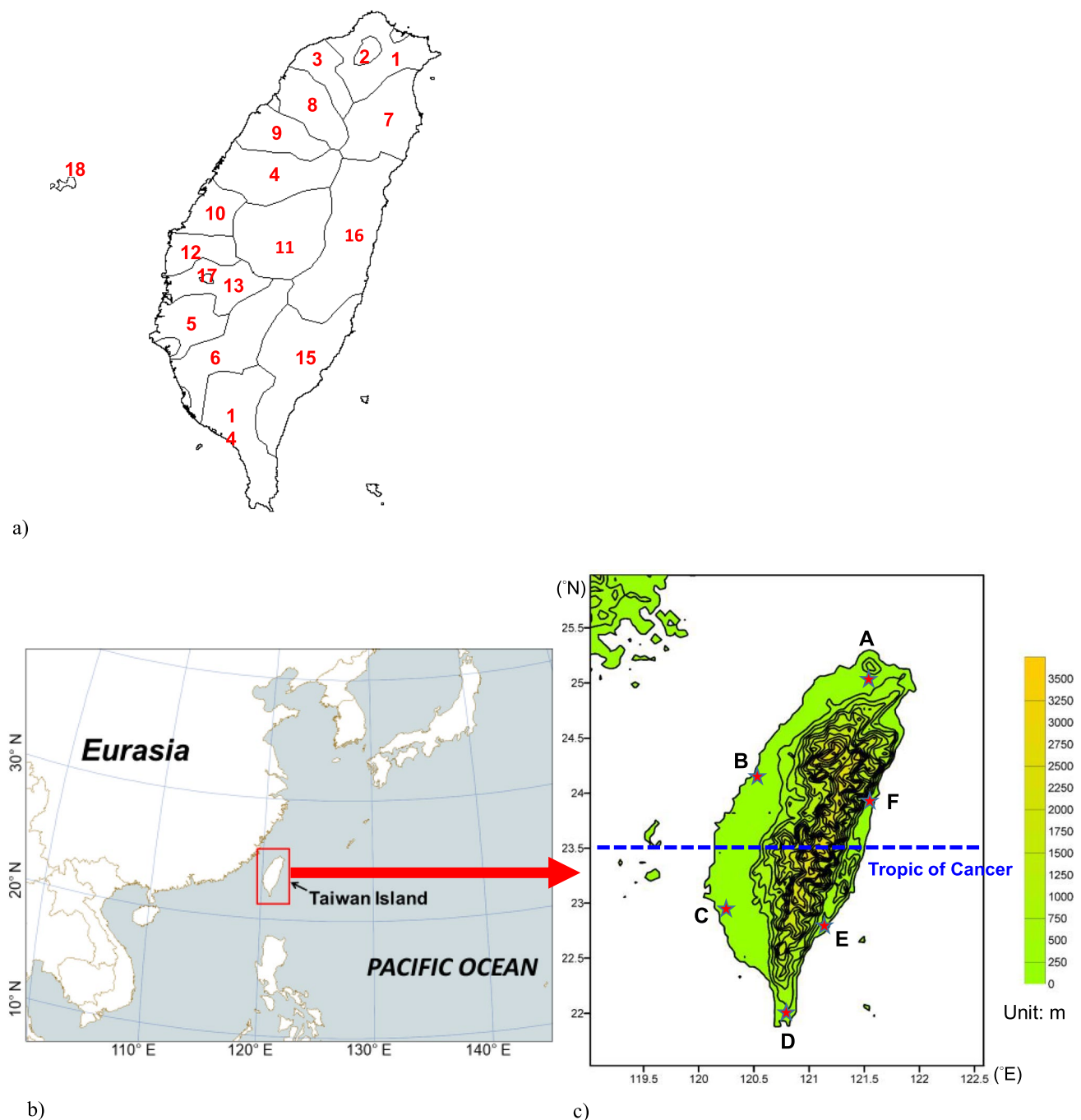


Fig. 1 Geographical information on Taiwan. (a) Administrative districts of the longan harvest area. (b) Location of Taiwan. (c) Location of meteorological monitoring stations in Taiwan Island. A: Taipei; B: Taichung; C: Tainan; D: Hengchung; E: Taitung; F: Hualien

obtained from the National Centers for Environmental Information (NOAA) (NOAA 2021). The study period was from 1909 until 2020. Daily meteorological data were obtained from the CWB in Taiwan. These included the mean air temperature (T_m ; °C), maximum air temperature (T_{max} ; °C), minimum air temperature (T_{min} ; °C), diurnal air temperature range (T_{DTR} ; °C), rainfall amount (RA; mm),

cloud cover (CC; oktas), relative humidity RH (%), rainy days RD (d), and sunshine hours SH (h).

In this study, the annual harvested area (ha) and fruit production (kg) of longan from the last 112 years were analysed. Data on the annual harvested area and longan fruit production from 1909 to 1945 were obtained from the E-Databases of Taiwan Studies (Academia Sinica 2021), data from 1933

Table 1 Administrative districts of longan tree harvest areas in Taiwan in 2020

No. in Fig. 1a	Administrative district	Harvested area (ha)	No. in Fig. 1a	Administrative district	Harvested area (ha)
1	New Taipei City	0.47	10	Changhua County	672
2	Taipei City	2	11	Nantou County	1,323
3	Taoyuan City	4.36	12	Yunlin County	31
4	Taichung City	2,200	13	Chiayi County	993
5	Tainan City	3,788	14	Pingtung County	12
6	Kaohsiung City	1,437	15	Taitung County	18
7	Yilan County	7	16	Hualien County	5
8	Hsinchu County	10	17	Chiayi City	40
9	Miaoli County	64	18	Kinmen County	1.77

Values were estimated using data from the Council of Agriculture, Executive Yuan, Taiwan R.O.C. (COA 2020)

to 1999 were obtained from the Taiwan Agricultural Yearbook (DAF 1999), and data from 2000 to 2020 were obtained from the Agricultural Statistics Yearbook (COA 2020). All the data were compiled in the same manner although they were obtained from different databases. In this study, the longan fruit yield (LFY) was defined as shown in Eq. 1:

$$\text{LFY} = \frac{P}{A} \quad (1)$$

where LFY is the yield (kg/ha) of longan production per harvested area, P is the production of longan fruit, and A is the harvested area. Areas with longans of non-bearing age were excluded (Academia Sinica 2021; COA 2020; DAF 1999).

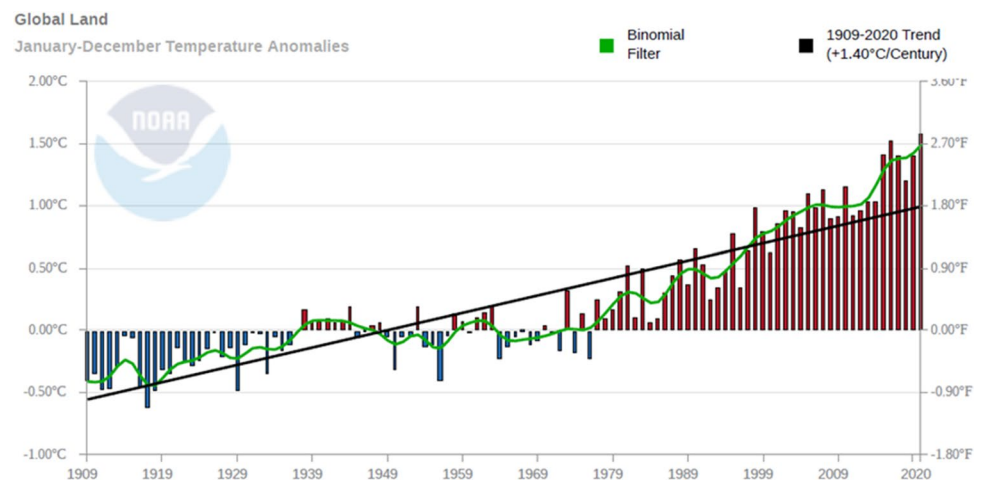
The timing of flower bud differentiation, flowering, and fruit harvesting varies due to the presence of many longan cultivars in different regions. For example, in comparison to other countries, the flowering of longan occurs earlier in Thailand (Tripathi 2021). To clarify the relationship between climate change and LFY, unlike the study by Pham et al. (2015), which included seven main longan

growth stages, the longan growth periods were simplified into three main stages in this study. *Dimocarpus longan* var. Fen Ke is the major longan cultivar in Taiwan (Li et al. 2016; Tripathi 2021). Therefore, the three main growth periods in this study were flower bud differentiation in December, January, and February (DJF); flowering in March, April, and May (MAM); and fruit production in July and August (JA).

2.3 Analysis methods

2.3.1 Definition of the two warming and green revolution effect periods

The time series of global land anomalies from 1880 to 2020 was based on the 1901–2000 base period average (NOAA 2021). Anomalies were observed from 1909 till 2020 and are shown in Fig. 2 to compare the anomalies of Taiwan Island with those of other terrestrial areas. The number of cut-off points and periods of the anomaly series can be determined from the anomaly values.

Fig. 2 Global anomaly air temperature (°C) on land from 1909 to 2020 (NOAA 2021)

In this study, the start of the green revolution in Asia was determined to be 1965 (Hazell 2009), with the period from 1965 to 2020 defined as the green revolution effect interval. Factors associated with the green revolution effect, such as improvement in irrigation methods, rising efficiency of fertilisation, wide use of pesticides, and new cultivars (Hazell 2009), can promote the yield of longan fruits, coinciding with the influence of climate change. The number of longan trees, which may influence yield, is related to management techniques in orchards (Tripathi 2021). Therefore, this was included as a green revolution effect factor.

To test whether climate change affected LFY over the data period and whether the green revolution effect increased LFY, environmental conditions were categorised into four groups. Group A indicated that the warming climate phenomena occurred from 1909 to 1937, and Group B indicated that the climate was stable under normal conditions from 1938 to 1964. Group C indicated that from 1965 to 1976, the green revolution in Asia began in 1965, and the climate was stable under normal conditions. Group D indicated that from 1977 to 2020, warming climate phenomena appeared in 1977, and the green revolution effect lasted between 1977 and 2020.

2.3.2 Time series regression model

The slopes of the weather parameters in DJF, MAM, and JA from 1909 to 2020 are listed in Tables 4, 5, and 6, respectively. The time series regression model was used to estimate the slope of the weather parameters, as follows:

$$y = \beta_1 x + \beta_0 + \varepsilon \quad (2)$$

where β_1 is the regression coefficient/slope; x is the independent variable; y is the dependent variable (weather parameters such as T_m , T_{max} , T_{min} , T_{DTR} , RA, RH, SH, CC, and RD); β_0 is the y -intercept; and ε is the error term that represents the effects of all factors on y (Bowerman et al., 2005).

2.3.3 Percentile ranking

Percentile ranking (PR) was used to represent the relationship between a measurement and the remaining data (relative standing of a measurement) (McClave and Sincich 2003). In this study, PR represents LFY. The annual PR from 1909 to 2020 was then calculated. The following PR groups were selected: very low, $PR < 5$; low, $5 \leq PR < 25$; high, $75 \leq PR < 95$; and very high, $95 \leq PR$. Their frequencies (%) in Groups A, B, C, and D were calculated. Duncan's multiple range comparison (Ronald and Jeffrey 2006) was used to determine whether the weather parameters varied between the three periods:

1909–1937, 1938–1976, and 1977–2020. A one-tailed t -test was used to determine whether the null hypothesis was accepted (McClave and Sincich 2003).

2.3.4 Multi-regression model

This study used a forward stepwise method as a screening procedure to evaluate the important parameters of the multi-regression model (Bowerman et al. 2005) that may potentially influence LFY. A multi-regression model (Eq. 3) was used to select important predictor variables. To compare the contributions of the independent variables (T_m , T_{max} , T_{min} , and others at distinct growth stages) in different units to LFY, the variables of the regression model were transformed to z -scores.

$$cZ_y = \alpha_0 + \alpha_1 Z_1 + \alpha_2 Z_2 + \alpha_3 Z_3 + \dots + \alpha_k D_k + \varepsilon$$

$$D_k = \begin{cases} 1 & \text{green revolution effect} \\ 0 & \text{non-green revolution effect} \end{cases} \quad (3)$$

where $\alpha_1, \alpha_2, \dots, \alpha_k$ are the regression coefficients; Z_1, Z_2, \dots, D_k are independent variables (T_m , T_{max} , T_{min} , and others at distinct growth stages) of the regression; α_0 is the Z_y -intercept; Z_y is LFY; ε is the error term that represents the effects of all factors on Z_y . D_k is a dummy variable that represents the green revolution effect.

2.3.5 Optimum range of weather parameters

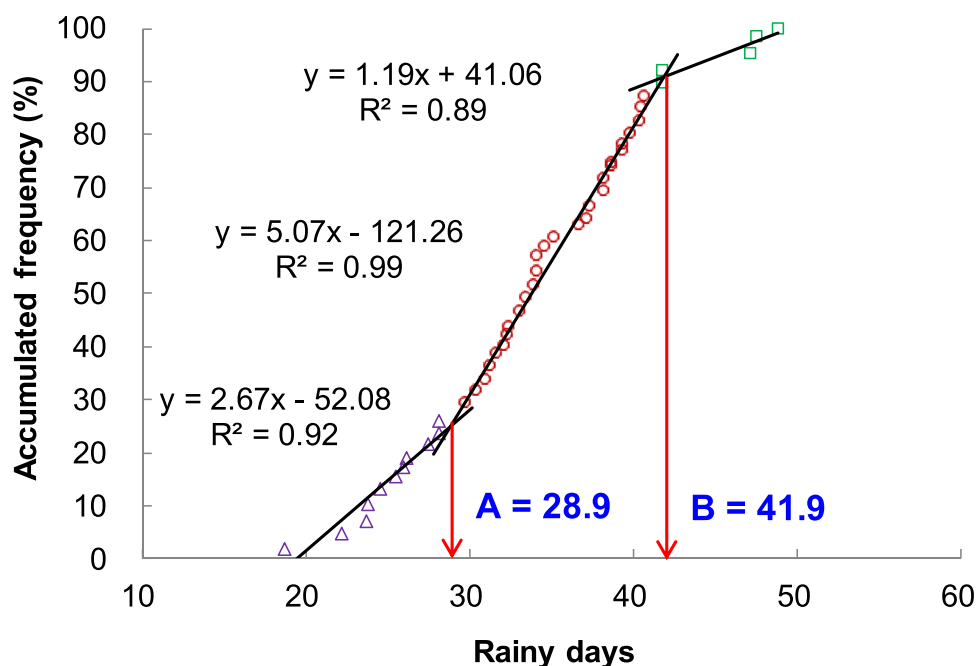
The accumulated frequency (%) of LFY is calculated as follows:

$$\text{Accumulated frequency of LFY}_k(\%) = \frac{\sum_{i=1}^k \text{LFY}_i}{\sum_{i=1}^n \text{LFY}_i} \times 100 \quad (4)$$

where the new LFY dataset is sorted based on the size of the weather parameter values from small to large. The numerator is the k^{th} accumulated frequency of LFY (%), and the denominator is the summation of LFY from 1 to n , where n is 12 (from 1965 to 1976) in Group C and 44 (from 1977 to 2020) in Group D.

The results of the final linear multi-regression models highlight the key parameters that contribute to LFY. The relationship between the accumulated frequency of LFY and weather parameters was evaluated. For example, the relationship between the accumulated frequency of LFY and RD is shown in Fig. 3, where it can be observed that the accumulated frequency of LFY has two major turning points, A and B. These two optimum weather parameter points were determined using the intercepts of three straight-line regression models (Eq. 5).

Fig. 3 Relationship between the accumulated frequency of longan production (%) and rainy days (days) during the flowering time of longan from 1977 to 2020. The red circles indicate linear regression with the highest R^2 value. Letters A and B denote the optimum points at which the three linear regression lines intercept



$$\hat{y} = \hat{\gamma}_1 x + \hat{\gamma}_0 \quad (5)$$

where $\hat{\gamma}_1$ is the slope of the fitted regression line, x is the independent variable (weather parameters, i.e., RD), where \hat{y} is the estimated accumulated frequency (%) of LFY, and $\hat{\gamma}_0$ is the y-intercept of the fitted regression line (Kleinbaum et al. 1988).

The horizontal distance between the two optimum points is denoted as the optimum range. In this study, the x -axis of the points with the maximum slope and r -square of the linear regression model were chosen as the optimum range. This range implies that most LFYs were obtained under normal weather conditions. Fruit yield during extreme weather events was not within this range. The slope of the curve changes when the weather parameter value is not within the optimum range. This implies that LFY is unstable under abnormal weather conditions.

3 Results and discussion

3.1 Climate change

The mean global air temperature on land increased by 0.14°C per decade between 1909 and 2020 (Fig. 2) (NOAA 2021). Figure 2 shows that this anomaly can be divided into three periods: 1909–1937, 1938–1976, and 1977–2020. All anomalies were less than zero before 1938, and greater than zero after 1977. In addition, there were two warming periods, 1909–1937 and 1977–2020. The mean anomalous air temperatures in the three periods were significantly different

and were highest in the third period ($p < 0.05$) (Table 2). The slope of T_m in Taiwan Island was $0.13 \pm 0.02^\circ\text{C/decade}$ between 1909 and 2020, indicative of climate change in Taiwan ($p < 0.05$). By comparing the mean air temperatures during the three periods, the results showed that the mean T_m in Taiwan was also significantly different between the three periods, with the mean T_m in the third period being the highest.

3.2 Climate change and the green revolution effect related to fruit yield

To test whether climate change and the green revolution influenced LFY, environmental conditions were categorised into four groups. The PR of LFY represents the relative magnitude of longan production. The results showed that

Table 2 Estimation of mean surface air temperature anomalies ($^\circ\text{C}$) from 1909 to 2020

	1909–1937 ($n = 29$)	1938–1976 ($n = 39$)	1977–2020 ($n = 44$)
Global land anomaly mean air temperature ($^\circ\text{C}$) *	-0.25 ± 0.17^a	-0.01 ± 0.15^b	0.74 ± 0.42^c
Taiwan anomaly mean air temperature ($^\circ\text{C}$) **	-0.44 ± 0.33^a	0.08 ± 0.30^b	0.70 ± 0.44^c

Values \pm standard errors with the same letters indicate non-significant differences. *The base period was 1901–2000. **The base period was 1909–2000. Statistical significance was set at $p < 0.05$

the frequencies (%) of low and very low LFY were high in Group A, which was the first warming period (Fig. 4). The frequencies of high and very high LFY increased in Groups C and D, which were influenced by the green revolution effect. However, the frequency of very high LFY was higher in Group C than in Group D. This suggests that a warmer climate can reduce longan fruit yield.

A comparative test was conducted to determine whether the alternative hypothesis was accepted (Table 3). The results showed that the mean LFY in Group B (5607.7 ± 2646.5 kg/ha; mean \pm SD) was significantly higher than that in Group A (4243.6 ± 2222.4 kg/ha, $p < 0.05$). This indicates that the longan yield during the warming climate period was lower than that during the stable climate period, implying that a warmer climate tends to reduce LFY. The mean LFY in Group C ($10,948.6 \pm 2566.8$ kg/ha) was significantly higher than that in Group B (5607.7 ± 2646.5 kg/ha, $p < 0.05$). This indicates that LFY during the green revolution period was greater than that during the non-green revolution period, implying that the green revolution effect led to an increase in LFY. The LFY in Group C ($10,948.6 \pm 2566.8$ kg/ha) was significantly greater than that in Group D

(8459.0 ± 2179.2 kg/ha, $p < 0.05$). This demonstrated that LFY during the warming climate period was lower than that during the stable climate period, although both periods were affected by the green revolution effect. This implies that a warmer climate tends to reduce LFY, despite the green revolution effect, under which the mean negative impact of LFY due to climate change was 2489.6 ± 1072.2 kg/ha (mean difference \pm 95% CI).

An analysis was conducted to determine whether the weather parameters during the three periods were similar. The slopes and mean values of the weather parameters for DJF from 1909 to 2020 are listed in Table 4. The slopes of T_m and T_{min} were significantly positive at 0.0133 ± 0.0022 °C/year ($p < 0.05$) and 0.0217 ± 0.0023 °C/year ($p < 0.05$), respectively. During the three time periods, the mean T_m and T_{min} values were considerably higher than the optimal air temperature of 10–14 °C for the flower bud differentiation period (Chen 1994) and were the highest in the third period (1977–2020). For example, the mean T_m values of the three periods A, B, and C were 17.84 ± 0.72 °C, 18.17 ± 0.77 °C, and 18.80 ± 0.77 °C, respectively, and the mean T_{min} values were 14.39 ± 0.80 °C, 14.73 ± 0.81 °C, and 15.93 ± 0.85 °C, respectively. Other weather parameters, including T_{DTR} , RH,

Fig. 4 Frequency of very low (PR < 5), low ($5 \leq \text{PR} < 25$), high ($75 \leq \text{PR} < 95$), and very high (PR ≥ 95) longan fruit yields from 1909 to 2020 in Groups A, B, C, and D. PR, percentile rank

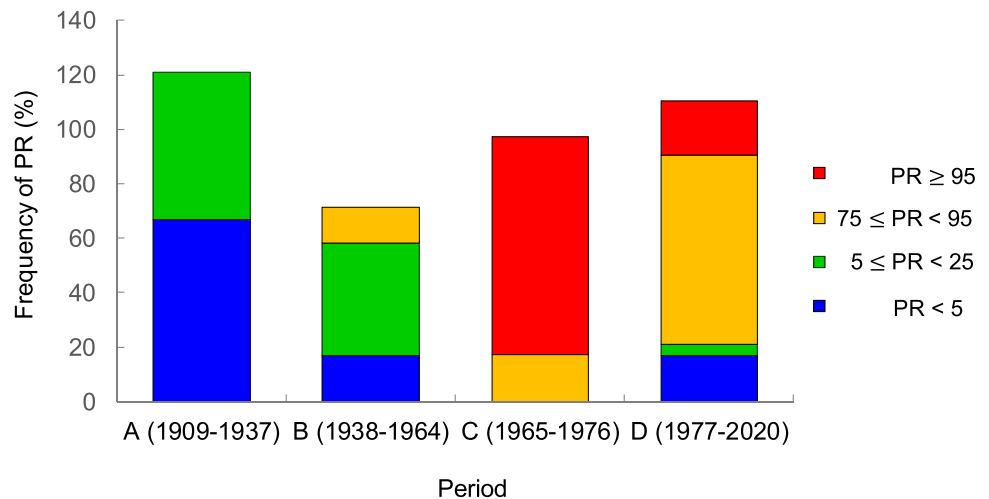


Table 3 Comparison between the null hypothesis and alternative hypothesis in Groups A, B, C, and D

Null hypothesis	Group Longan yield Mean \pm SD (kg/ha)	Group Longan yield Mean \pm SD (kg/ha)	
Warming climate tended to reduce yield	A ($n=29$) 4243.6 ± 2222.4	B ($n=27$) $5607.7 \pm 2646.5^*$	$H_0: A=B, H_1: A < B$
Green revolution effect tended to increase yield	B ($n=27$) 5607.7 ± 2646.5	C ($n=12$) $10,948.6 \pm 2566.8^*$	$H_0: B=C, H_1: B < C$
Warming climate tended to reduce yield although the green revolution effect existed	C ($n=12$) $10,948.6 \pm 2566.8^*$	D ($n=44$) 8459.0 ± 2179.2	$H_0: C=D, H_1: C > D$

Two-sample t -test with one tail at 95% confidence level. * indicates that the alternative hypothesis has been accepted

Table 4 Estimation of slope and mean of weather parameters in December, January, and February (time of flower bud differentiation) in Taiwan using linear regression models (1909–2020)

Weather Parameters	1909–2020 Slope estimate (<i>n</i> = 112)	1909–1937 Mean ± SD (<i>n</i> = 29)	1938–1976 Mean ± SD (<i>n</i> = 39)	1977–2020 Mean ± SD (<i>n</i> = 44)
T_m (°C)	0.0133 ± 0.0022*	17.84 ± 0.72 ^a	18.17 ± 0.77 ^a	18.80 ± 0.77 ^b
T_{max} (°C)	0.0019 ± 0.0023	22.63 ± 0.73 ^a	22.89 ± 0.84 ^a	22.75 ± 0.80 ^a
T_{min} (°C)	0.0217 ± 0.0023*	14.39 ± 0.80 ^a	14.73 ± 0.81 ^a	15.93 ± 0.85 ^b
T_{DTR} (°C)	−0.0194 ± 0.0022*	8.24 ± 0.39 ^a	8.16 ± 0.53 ^a	6.82 ± 0.52 ^b
RA (mm)	0.0867 ± 0.0835	85.12 ± 28.34 ^a	98.24 ± 36.82 ^a	92.82 ± 40.32 ^a
RH (%)	−0.0559 ± 0.0089*	78.61 ± 1.93 ^a	78.72 ± 2.08 ^a	74.37 ± 2.29 ^b
SH (h)	−0.3914 ± 0.1332*	343.95 ± 25.02 ^a	350.51 ± 41.42 ^a	317.81 ± 51.95 ^b
CC (oktas)	−0.0960 ± 0.0162*	5.46 ± 0.30 ^a	5.53 ± 0.41 ^a	5.38 ± 0.42 ^a
RD (days)	−0.0016 ± 0.0015*	33.15 ± 3.8 ^a	30.92 ± 5.79 ^a	26.04 ± 5.76 ^b

Values ± standard errors with the same letters indicate non-significant differences. *The slope was statistically significant at $p < 0.05$. T_m mean air temperature, T_{max} mean maximum air temperature, T_{min} mean minimum air temperature, T_{DTR} mean diurnal temperature range, RA rainfall amount, RH relative humidity, SH sunshine hours, CC cloud cover, RD rainy days

Table 5 Estimation of slope and mean of weather parameters in March, April, and May (flowering time) in Taiwan using linear regression models (1909–2020)

Weather parameters	1909–2020 Slope estimate (<i>n</i> = 112)	1909–1937 Mean ± SD (<i>n</i> = 29)	1938–1976 Mean ± SD (<i>n</i> = 39)	1977–2020 Mean ± SD (<i>n</i> = 44)
T_m (°C)	0.0150 ± 0.0017*	22.40 ± 0.55 ^a	23.08 ± 0.65 ^b	23.55 ± 0.60 ^c
T_{max} (°C)	0.0065 ± 0.0021*	27.06 ± 0.66 ^a	27.69 ± 0.77 ^b	27.55 ± 0.72 ^b
T_{min} (°C)	0.0224 ± 0.0015*	18.87 ± 0.50 ^a	19.51 ± 0.61 ^b	20.54 ± 0.56 ^c
T_{DTR} (°C)	−0.0154 ± 0.0020*	8.20 ± 0.40 ^a	8.18 ± 0.42 ^a	7.01 ± 0.35 ^b
RA (mm)	−0.3749 ± 0.3067	392.41 ± 139.04 ^a	353.44 ± 134.95 ^a	367.60 ± 123.50 ^a
RH (%)	−0.0555 ± 0.0085*	80.49 ± 1.54 ^a	80.16 ± 1.83 ^a	76.49 ± 2.19 ^b
SH (h)	−0.7790 ± 0.1814*	479.30 ± 63.06 ^a	492.59 ± 53.89 ^a	420.95 ± 54.81 ^b
CC (oktas)	−0.0005 ± 0.0014*	5.58 ± 0.43 ^a	5.75 ± 0.34 ^a	5.67 ± 0.38 ^a
RD (days)	−0.1022 ± 0.0197*	41.27 ± 7.10 ^a	37.47 ± 6.93 ^b	34.01 ± 6.93 ^c

Values ± standard errors with the same letters indicate non-significant differences. *The slope was statistically significant at $p < 0.05$. T_m mean air temperature, T_{max} mean maximum air temperature, T_{min} mean minimum air temperature, T_{DTR} mean diurnal temperature range, RA rainfall amount, RH relative humidity, SH sunshine hours, CC cloud cover, RD rainy days

Table 6 Estimation of slope and mean of original weather parameters in July and August (production period) in Taiwan using linear regression models (1909–2020)

Weather parameters	1909–2020 Slope estimate (<i>n</i> = 112)	1909–1937 Mean ± SD (<i>n</i> = 29)	1938–1976 Mean ± SD (<i>n</i> = 39)	1977–2020 Mean ± SD (<i>n</i> = 44)
T_m (°C)	0.0154 ± 0.0016*	25.97 ± 0.57 ^a	26.43 ± 0.38 ^b	27.15 ± 0.45 ^c
T_{max} (°C)	0.0077 ± 0.0936*	30.62 ± 0.55 ^a	31.04 ± 0.45 ^b	31.21 ± 0.52 ^b
T_{min} (°C)	0.0077 ± 0.0141*	22.29 ± 0.61 ^a	22.77 ± 0.41 ^b	24.05 ± 0.48 ^c
T_{DTR} (°C)	−0.0146 ± 0.0021*	8.33 ± 0.33 ^a	8.27 ± 0.40 ^a	7.16 ± 0.25 ^b
RA (mm)	−0.8409 ± 0.4021*	560.80 ± 155.66 ^a	488.86 ± 144.55 ^a	491.78 ± 116.70 ^a
RH (%)	−0.0470 ± 0.0166*	81.25 ± 1.05 ^a	80.99 ± 1.46 ^a	76.84 ± 1.7 ^b
SH (h)	−0.6692 ± 0.1747*	501.15 ± 37.99 ^a	510.70 ± 45.94 ^a	450.81 ± 33.15 ^b
CC (oktas)	−0.0045 ± 0.0020*	4.96 ± 0.42 ^a	5.12 ± 0.46 ^a	4.96 ± 0.29 ^b
RD (days)	−0.0689 ± 0.0126*	31.16 ± 4.26 ^a	28.35 ± 5.15 ^b	26.09 ± 3.79 ^c

Values ± standard errors with the same letters indicate non-significant differences. *The slope was statistically significant at $p < 0.05$. T_m mean air temperature, T_{max} mean maximum air temperature, T_{min} mean minimum air temperature, T_{DTR} mean diurnal temperature range, RA rainfall amount, RH relative humidity, SH sunshine hours, CC cloud cover, RD rainy days

Table 7 Final multi-regression models of LFY as weather parameters varied during flower bud differentiation, flowering, and production in Taiwan (1909–2020)

Model	Control factor	Final multi-regression model by forward stepwise selection
1	Excluding green revolution effect	$Z_y = -0.32Z_{DIF,m} - 0.08Z_{DIF,SH} + 0.08Z_{MAM,Max} + 0.17Z_{MAM,RA} + 0.20Z_{MAM,RH} + 0.21Z_{MAM,CC} - 0.46Z_{MAM,RD} - 0.37Z_{JA,DTR} - 0.20Z_{JA,RA} + 0.05Z_{JA,CC} - 0.23Z_{JA,SH} - 0.32Z_{JA,RD} + 0.71$ $R^2 = 0.99, AIC = 1602.46, Schwarz's BIC = 1642.83$
2	Including green revolution effect	$Z_y = -0.34Z_{DIF,m} - 0.04Z_{DIF,RH} + 0.04Z_{MAM,CC} - 2471.29Z_{MAM,SH} - 2.22Z_{MAM,RD} - 0.06Z_{JA,DTR} - 0.04Z_{JA,RA} - 0.07Z_{JA,RH} + 0.05Z_{GR} - 197.69$ $R^2 = 1.00, AIC = 1067.40, Schwarz's BIC = 1099.70$

Z_y longan fruit production, Z_{DIF} time of flower bud differentiation, Z_{MAM} flowering time, Z_{JA} production period, Z_m mean air temperature, Z_{RA} mean maximum air temperature, Z_{RH} relative humidity, Z_{DTR} mean diurnal temperature range, Z_{CC} cloud cover, Z_{SH} sunshine hours, Z_{RD} rainy days, AIC Akaike information criterion, BIC Bayesian information criterion. The coefficients of the independent variables in the models are statistically significant ($p < 0.05$)

SH, CC, and RD, decreased from 1909, with significantly lower mean values during the third period (excluding CC). Most weather parameters changed during the third period.

The slopes and mean values of the weather parameters in MAM from 1909 to 2020 are listed in Table 5. The slopes of T_m , T_{max} , and T_{min} were significantly positive at 0.0150 ± 0.0017 °C/year ($p < 0.05$), 0.0065 ± 0.0021 °C/year ($p < 0.05$), and 0.0224 ± 0.0015 °C/year ($p < 0.05$), respectively. During flowering, the mean T_m and T_{min} values differed significantly among the three time periods. The highest value was observed in the third period and the lowest value was observed in the first period. Except for T_{min} and T_{max} , the mean T_m values of the three periods were within the optimal air temperature range of 20–27 °C during the flowering period in Taiwan (Chen 1994). The mean T_m , T_{max} , and T_{min} values were no less than 13 °C or greater than 30 °C (Chen 1994), which would negatively impact the number of flowers. Other weather parameters, including T_{DTR} , RA, RH, SH, CC, and RD, decreased from 1909, and, except for CC, their mean values were significantly lower in the third period. Most weather parameters changed during the third period.

The slopes and mean values of the weather parameters for JA from 1909 to 2020 are listed in Table 6. The slopes of T_m , T_{max} , and T_{min} were significantly positive at 0.0154 ± 0.0016 °C/year ($p < 0.05$), 0.0077 ± 0.0936 °C/year ($p < 0.05$), and 0.0077 ± 0.0141 °C/year ($p < 0.05$), respectively. During the production period, T_m and T_{min} were significantly different between the three time periods. For example, the mean T_m values were 25.97 ± 0.57 °C, 26.43 ± 0.38 °C, and 27.15 ± 0.45 °C in the three time periods, respectively, whereas the mean T_{min} values were 22.29 ± 0.61 °C, 22.77 ± 0.41 °C, and 24.05 ± 0.48 °C, respectively. Other weather parameters, including T_{DTR} , RA, RH, SH, CC, and RD, decreased from 1909, and, except for RA, their mean values were significantly lower in the third period.

Most weather parameters during the third period (1977–2020; second warming period) of the main longan fruit growth stage changed significantly. The period for Group D (1977–2020; Table 3) was the same as that of the third period. The results imply that during the warming period (1977–2020), accompanied by a decrease in weather parameters such as T_{DTR} , RH, SH, and RD in the DJF, MAM, and JA periods, the LFY decreased, although the green revolution effect tended to promote LFY. The climatic features of Taiwan from 1977 to 2020 differed from those of areas suitable for longan tree growth, such as areas with humid summers and cool winters (Dinesh et al. 2012).

3.3 Relationship between fruit yield and weather parameters

To estimate the important weather parameters that contributed to the LFY, standardised multi-regression models were

created. One model included the green revolution effect, while another did not (Table 7). The standardised coefficients highlighted the importance of each parameter contributing to LFY, whereby the greater the absolute values, the more important the parameters. Compared with the model excluding the green revolution effect, the final multi-regression model including the green revolution effect was more robust because of its lower Akaike and Schwarz's Bayesian information criterion values. Therefore, this study focuses on the second model to discuss the importance of independent parameters.

During the period of flower bud differentiation (DJF), the results showed that T_m and SH were negatively correlated with LFY. A comparison of the coefficients in Table 7 shows that the total contribution to LFY, such as T_m and SH, is negative, and the negative contribution of T_m is greater than that of SH. Mean air temperature during winter can influence the growth of longan trees (Li et al. 2020; Dinesh et al. 2012). The trend of T_m in DJF was significantly positive from 1909 to 2020. Therefore, it was harmful to flower bud differentiation and reduced the number of flowers (Chen 1994). Flower bud differentiation in unusually warm winters can cause a low flowering rate (Gene Albrigo and Galán Saúco 2004) which is supported by the findings of Chen et al. (2010) where higher air temperatures resulted in a longer period of flower bud differentiation. Cold winters are beneficial to longan blossoms in spring (Yang et al. 2010), which is supported by the results of this study, showing that T_m was negatively correlated with LFY.

These results differed from those of Sritontip et al. (2014), in which climate change was not related to longan yield from 1982 to 2009 in Northern Thailand. The most likely explanation is differences in analysis methods. This study used multi-regression models rather than correlation coefficients to show the relationship between weather parameters and LFY. Correlation coefficients do not represent the true relationship when many other parameters coexist in the environment. Furthermore, the periods of the weather parameters differed: this study recognised DJF as the time of flower bud differentiation, while Sritontip et al. (2014) used November and December to denote the flower induction period. In short, this study considered other factors such as the green revolution effect, flowering time, and production period.

For MAM, which denotes the flowering period, the results showed that CC was positively correlated with LFY. SH and RD were significantly and negatively correlated with LFY, respectively. Comparing the coefficients in Model 2 (Table 7), the findings suggest that the total negative contribution to LFY, such as SH and RD, is greater than the total positive contribution to LFY, such as CC. The largest negative contribution to LFY is from SH. The SH trend in MAM (-0.0555 ± 0.0085 h/year) was significantly negative from 1909 to 2020. If SH maintains this trend in the future,

it would be beneficial for flower generation. Dinesh et al. (2012) suggested that the air temperature influences longan flowering. However, air temperature in the MAM was not a significant parameter in Model 2. Tripathi (2021) reported that during the flowering period of longans, excessive rainfall could increase flower drop and induce deficient pollination by causing a decrease in flower opening and insect activity. The results of this study showed that an increase in rainy days was not beneficial to LFY, which is similar to the findings of Tripathi (2021). Compared with the rainfall amount, the number of rainy days can be a more representative indicator of the impact of rainfall on longan anthesis.

For JA, which denotes the production period, the results showed that T_{DTR} , RA, and RH were negatively correlated with LFY. By comparing the coefficients in Model 2, the findings suggest that the total negative contribution to LFY, such as T_{DTR} , RA, and RH, was -0.17 . The trends in T_{DTR} , RA, and RH in JA were significantly negative from 1909 to 2020. If the trends in T_{DTR} , RA, and RH are maintained in the future, it would be beneficial to LFY. Air temperature is a climatic parameter that influences flowering and fruit sets (Dinesh et al. 2012). The first and second highest numbers of typhoons in Taiwan occurred in August and July, respectively, from 1911 to 2020 (CWB 2021). During typhoons, substantial winds can uproot tropical fruit trees (Chen 2012), break branches (Haque et al. 2020), snap trunks (Marler 2001), and blow fruits from trees (Groff 1943). Furthermore, heavy rain caused by typhoons can increase fruit drop (Gunaratne and Perera 2014) and blemish or bruise fruits (Ferrarezi et al. 2020). These studies on typhoon-related damage demonstrate that LFY is beneficial when there are no typhoons or heavy rainfall in Taiwan during a long production period.

As shown in Model 2, the first three important parameters contributing to LFY were SH in MAM, RD in MAM, and T_m in DJF. The total net contribution of the parameters to LFY was negative during the three main growth stages, although the contribution of the green revolution effect was positive. This supports the finding that the mean yield of longan fruits in Group C was significantly higher than that in Group D (Table 3). The negative contribution of climate change to LFY tends to offset the positive contribution of the green revolution effect.

3.4 Optimum range of weather parameters during growth periods

To determine whether the warming climate influenced the optimum range of LFY, the optimum range of weather parameters was estimated and compared in Groups C and D, both of which were under the green revolution effect (Table 8). Considering the warming climate, the results showed that in DJF, the optimum

Table 8 Slope of the accumulated frequency (%) of longan fruit yield in Taiwan based from 1965 to 2020 on weather parameters selected in the final multi-regression models

Longan growth	The important parameters	Slope (%/year)	Optimum range in normal period	Slope (%/year)	Optimum range in warming period
Time of flower bud differentiation	T_m (°C)	<u>65.6%/year</u>	17.6–18.0	55.5%/year	<u>18.0–19.4</u>
	RH (%)	<u>60.3%/year</u>	79.6–79.7	27.10%/year	<u>73.9–75.7</u>
Flowering time	CC (oktas)	<u>337.7%/year</u>	7.1–7.2	101.9%/year	<u>6.8–7.3</u>
	SH (h)	<u>2.9%/year</u>	454.5–476.5	0.7%/year	<u>381.3–476.6</u>
	RD (days)	<u>18.1%/year</u>	34.3–36.2	5.1%/year	<u>28.9–41.9</u>
Production period	T_{DTR} (°C)	<u>164.5%/year</u>	8.0–8.3	134.7%/year	<u>6.8–7.4</u>
	RA (mm)	0.4%/year	<u>374.6–496.8</u>	<u>0.7%/year</u>	464.3–536.3
	RH (%)	<u>43.2%/year</u>	80.2–81.6	18.5%/year	<u>75.1–79.4</u>

T_{min} mean minimum air temperature; RH relative humidity; T_{DTR} mean diurnal temperature range; SH sunshine-hour; RD rainy days; RA rainfall amount; CC cloud cover; GR green revolution. Underlined values indicate values or ranges that were greater than others

range of T_m was 18.0–19.4 °C and the optimum range of RH was 73.9–75.7%. In MAM, the optimum ranges were 6.8–7.3 oktas, 381.3–476.6 h (4.14–5.18 h/day), 28.9–41.9 days for CC, SH, and RD, respectively. In JA, the optimum ranges were 6.8–7.4 °C, 464.3–536.3 mm, and 75.1–79.4% for T_{DTR} , RA, and RH, respectively. Sritontip et al. (2014) indicated that a rainfall amount of 32–63 mm and sunshine hours of 5.38–6.88 h/day or 6.11–6.93 h/day were beneficial to LFY in November and December (flower induction period), depending on the location in Northern Thailand. In comparison with the findings of Sritontip et al. (2014), sunshine hours per day in MAM and flowering time in the present study were lower. Regarding the climatic requirements of longan, Verheij and Coronel (1992) indicated that the optimum temperature was 20–25 °C and the rainfall was 1500–2000 mm in humid tropical areas. On the other hand, Nath et al. (2019) reported that the optimum temperature was 20–25 °C and the rainfall was 1400–1600 mm in warm subtropical to tropical areas. Unlike the aforementioned studies, the results of this study further estimated the optimum range of other important parameters at the three main growth stages of longan.

In short, for the most important weather parameters, except for rainfall amount, the slopes of the accumulated frequency (%) of LFY under normal conditions were greater than those under a warming climate (Table 8). These results imply that a warming climate is unfavourable for promoting good yields. Furthermore, these results suggest that a large slope for the accumulated frequency of LFY correlates with a smaller optimum range of weather parameters. This implies that stable weather conditions promote stable LFYs and lead to stable fruit prices. These results could encourage longan farmers to adopt more efficient and precise strategies to adapt to climate change.

4 Conclusions

The major contributions of this study are as follows: first, the data were analysed over a 112-year period; second, the green revolution effect was considered to determine the relationship between climate change and LFY; third, the impact of a warming climate on LFY was quantified; fourth, the optimum range of the important parameters was determined for the three main growth stages. The major findings of this study are as follows.

- 1) Most low and very low LFYs (PR < 25) occurred during 1909–1937 because this was the first warming climate period. In contrast, the highest fruit yields (PR > 75) occurred in 1965–2020, owing to the green revolution effect.
- 2) The warming climate during 1977–2020 was unfavourable to LFY, although fruit yield was promoted by the green revolution effect, where the mean negative impact of climate change on LFY was 2489.6 ± 1072.2 kg/ha.
- 3) During the warming period (1977–2020), a decrease in T_{DTR} , RH, SH, and RD during the DJF, MAM, and JA periods was accompanied by a decrease in LFY despite the green revolution effect.
- 4) Regarding changes in weather parameters from 1909 to 2020 in the final multi-regression models of LFY, in addition to the green revolution effect, the total negative contribution to yield was greater than the total positive contribution at the time of flower bud differentiation, flowering, and fruit production.
- 5) A warming climate is unfavourable for promoting good LFY. A larger slope for the accumulated frequency of yield was correlated with a smaller optimum range of weather parameters. Stable weather conditions promoted a good LFY.

The age of longan trees is one of the primary factors that determine a change in production. In addition, for more than 100 years, the phenological period of longan has possibly been altered due to climate change. Therefore, the periods of longan flower bud differentiation, flowering, and fruit production could change because the beginning and end dates of the three main growth stages vary owing to climate change. They have been altered collinearly with an increase in temperature over the past decade when the warming climate was obvious. However, this study could not control these factors because the official records of these longan factors from the Council of Agriculture, Executive Yuan were limited. This is the primary limitation of the present study.

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Author contribution Li-Wei Lai conceived and designed the research; prepared the material; collected, analysed, and interpreted the data. The first draft of the manuscript was written by Li-Wei Lai. The author read, critically revised the article, and approved the final manuscript to be published.

Data availability The data supporting this study's findings are available from the Council of Agriculture, Executive Yuan, Taiwan R.O.C. at <https://agrstat.coa.gov.tw/sdweb/public/book/Book.aspx> and the Data Bank for Atmospheric and Hydrological Research at <https://dbar.pccu.edu.tw/>.

Code availability SYSTA V: 13.

Declarations

Ethics approval Not applicable.

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Consent for publication Not applicable.

Conflict of interest The author declares no competing interests.

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