Food and Energy Security

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ORIGINAL ARTICLE OPEN ACCESS

Prediction of Inflorescence Emergence in 'Yu Her Pau' Litchi Under Climate Change Using an Optimised Model

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Received: 15 July 2024 | **Revised:** 29 November 2024 | **Accepted:** 11 December 2024

Funding: This study was supported by Ministry of Agriculture, Taiwan.

Keywords: flowering | modelling | phenology | subtropical fruit

ABSTRACT

For litchi (*Litchi chinensis*), successful floral induction requires adequate cool temperatures in winter, perceived by mature leaves like many other subtropical fruit species. As a result, rising ambient temperatures due to global climate change has posed a threat to litchi flowering and fruit production. The goal of this research was to assess the potential impacts of climate change on flowering in 'Yu Her Pau' litchi on Taiwan. To better characterise the relationship between temperatures and inflorescence emergence (IE), we built a model by applying the beta-distribution function method with 12 phenological datasets (two orchard blocks for 6 years) recorded from field-grown 'Yu Her Pau' litchi trees. For this predictive model, the minimum, maximum, and optimal temperatures that resulted in successful floral induction were estimated to be 0.0°C, 21.9°C, and 19.8°C, respectively; under these criteria, at least 60.37 units of cumulative cool temperatures are necessary for IE based on the historical data. Subsequently, the IE model was used to evaluate the likelihood of successful flowering in 'Yu Her Pau' litchi at four major producing areas on Taiwan during five decades from 2026 to 2075, respectively, under three separate climate change (emission) scenarios based on three General Circulation Models (GCMs) in. Our results, based on any of the GCMs, suggested that 'Yu Her Pau' litchi grown on Southern Taiwan could face poor flowering due to insufficient cool winter temperatures in the coming decade even in the emission scenario with very stringent mitigation effort, which can lead to serious crop loss in the near future.

1 | Introduction

Climate change has resulted in irregular weather patterns, including increasing temperatures, since the mid-20th century and continues to hinder global fruit production (Lawrence et al. 2022). Based on the upward trajectory of temperature (Arias et al. 2021), threats to the productivity and stability of perennial fruit trees are growing due to warming conditions (Hatfield and Prueger 2015). Rising temperatures are particularly pertinent to subtropical fruit crops as most of them require sufficient cool temperatures in winter for floral induction, including litchi (Wilkie, Sedgley, and Olesen 2008), but the literature on this is limited (Stuble, Bennion, and Kuebbing 2021). In litchi, active vegetative flushing takes place in response to warm temperatures and frequent precipitation during summer, followed by growth cessation and flush maturation (FM) in fall (Wei et al. 2013). Subsequently, mature leaves of litchi trees become capable of perceiving cool ambient temperatures as the environmental cue for initiating floral induction via a transcriptional cascade (Ding et al. 2015; Shen et al. 2016; Zhang et al. 2017). It has been demonstrated that the expression levels of a *FLOWERING LOCUS T1* (*LcFT1*) and *SUPPRESSOR OF OVEREXPRESSION OF CONSTANS1* in leaves were positively correlated to cool-temperature exposure that promoted flowering in litchi (Ding et al. 2015; Shi et al. 2024). Under the field conditions, adequate cool temperatures in winter are necessary

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for floral induction that precedes inflorescence emergence (IE) and fruit production (Menzel and Simpson 1988; Menzel, Rasmussen, and Simpson 1989; Menzel and Simpson 1995) (Figure S1). As a result, a better understanding of the relationship between temperatures and floral induction in a quantitative manner would help predict the impacts of climate change on litchi and inform management decisions under future climate scenarios.

Litchi has been cultivated on Taiwan for around 300 years, and Taiwan has become one of the major producing areas in the world (Huang et al. 2005). Yu Her Pau, one of the top-producing litchi varieties on Taiwan, has a relatively low requirement of cool-temperature exposure for floral induction compared with many other cultivars (Chang 1999). Due to this trait, 'Yu Her Pau' holds its unique geographic distribution and economic importance in the litchi industry on Taiwan for the following two perspectives, making it a suitable model crop and cultivar for indicating potential warming impacts on the subtropical fruit industry. First, 'Yu Her Pau' litchi growing area has expanded to and is mainly located on Southern Taiwan, where the natural mild winter temperatures at present suffice its low cool-temperature requirement but not by a wide margin. Therefore, if the scale of temperature increases because of climate change is similar throughout the island, existing 'Yu Her Pau' litchi production on Southern Taiwan would be more likely to encounter poor flowering and crop loss due to inadequate cool-temperature accumulation compared to other cultivars produced elsewhere on Taiwan (Hwang, Hsu, and Chen 2024). Second, since early flowering in 'Yu Her Pau' litchi, as a result of its low cool-temperature requirement, contributes to early crops with a premium price, litchi growers on Southern Taiwan have relied heavily, if not solely, on this one cultivar as the significant source of income. In other words, the negative impacts of climate change on 'Yu Her Pau' litchi production can cause considerable economic instability in the local farming community.

In this research, we aimed to predict and evaluate the impacts of rising temperatures on current litchi growing areas on Taiwan in different emission scenarios. First, we established a new model to predict the IE of 'Yu Her Pau' litchi using phenological data of trees and temperature records from two independent fields collected by the long-term ecological research platform over a period of 6 years to improve the existing inflorescence induction model (IIM) proposed by Chen et al. (2016). Second, the optimised model constructed herein was applied to simulate the likelihood of successful flowering in 'Yu Her Pau' litchi in three separate climate scenarios.

2 | Materials and Methods

2.1 | Phenology and Temperature Data Collection

Twelve 28-year-old 'Yu Her Pau' litchi trees located in two field blocks at the Chiayi Agricultural Experiment Branch Station, Chiayi, Taiwan (Lat. 23°29′ N, Long. 120°28′ E, Alt. 70 m) were used in this research for data collection for six flowering seasons from September 2012 to February 2018. Fifteen 1-year-old shoots were randomly selected and labelled on each tree before floral induction in September of every year for tracking phenology. Based on the description by Chang et al. (2014), FM and IE, respectively, on these shoots were recorded three times a week, starting in September until the following February when no more inflorescences were formed.

Only the shoots that exhibited uninterrupted flush development throughout the season were included in the data analysis for this study. For each block every year, we determined the relationship of cumulative FM and IE, respectively, with calendar date using sigmoid curves; dates corresponding to 50% FM or 50% IE were obtained using the SOLVER function in Microsoft Excel software (Microsoft Corporation, Redmond, WA, USA) (Brown 2001) to represent the FM and IE stages. As litchi leaves can perceive floral-inductive cool temperatures only when reaching maturity (Ding et al. 2015), we designated FM and IE as the starting and end points of the floral induction period for 'Yu Her Pau' litchi (Figure S2B). The duration of floral induction (DFI, Figure S2A), coined by Su et al. (2023), was therefore calculated as the interval between the dates of FM and IE stages.

The mean daily temperature, that is, the average of the highest and lowest daily temperatures, was retrieved from the Chiayi Weather Station (Lat. 23°29′ N, Long. 120°25′ E, Alt. 26.9 m) throughout the phenology survey.

2.2 | IE Model

Litchi floral induction requires cool temperatures in an exposure-dependent manner following the FM stage, when the ambient thermal signals can be perceived by mature leaves, leading to IE (Ding et al. 2015; Wei et al. 2013). In this study, we defined the cool temperature requirement (CTR) as the minimal cumulative amount of cool temperatures necessary for IE in 'Yu Her Pau' litchi based on the concept of the chilling requirement for endodormancy release in temperate trees (Weinberger 1950) or growing degree day (or heat unit) requirement for the timing of various biological processes (McMaster and Wilhelm 1997). To further determine the temperatures post FM that can effectively stimulate floral induction, or effective inductive unit (EIU), on a daily basis for CTR, we proposed the following IE model and applied the β-distribution function method (BFM) (Yan and Hunt 1999; Zhou and Wang 2018) with the DFI each year from the phenology dataset:

$$\mathrm{EIU}=\begin{cases}0 & T_m \geq T_c \\ \left[\frac{T_c-T_m}{T_c-T_o}\right]\times\left[\frac{T_m-T_b}{T_o-T_b}\right]^{\frac{T_o-T_b}{T_c-T_o}}\times\left[T_c-T_o\right] & T_b<T_m<T_c \\ 0 & T_m \leq T_b\end{cases}$$

where T_c and T_b are the highest and lowest temperatures, respectively, for triggering floral induction in 'Yu Her Pau'; T_o is the optimal temperature that results in the maximal EIU on floral induction; T_m is the observed mean daily temperature, equal to the mean of daily minimum and maximum temperatures; when cumulative EIU during the DFI is greater than or equal to CTR, IE occurs.

To estimate EIU in the model, T_c, T_b and T_o were defined as follows:

$$\begin{cases} T_b: 0 \le T_b \le 13.5 \\ T_b: T_b \le T_o \le T_c \\ T_c: 13.7 \le T_c \le 22.5 \end{cases}$$

The lower limit of T_b was set at 0°C because temperatures lower than this threshold lead to the death of terminal buds and tree mortality of litchi (Groff 1943). The upper limit of T_c was defined at 22.5°C because 'Yu Her Pau' cannot bloom under 25°C/20°C (day/night temperatures) (Chang 1999). The lower limit of T_c (13.7°C) was set below 14°C, the lowest mean daily temperature known to promote litchi flowering (Chang 1999). To estimate T_c, T_b and T_o, we utilised the approach of proof by exhaustion at 0.1°C intervals for the near-optimal solutions until the lowest coefficient of variation (CV) in cumulative EIU in the phenology dataset of 12 samples (i.e., two blocks for 6 years) returned. Finally, we calculated cumulative EIUs for each block in each year using the above IE model with estimated T_c, T_b and T_o and obtained the mean of EIUs, or the CTR for IE in 'Yu Her Pau' litchi.

2.3 | Comparison of Litchi IE Models

The CV of root-mean-square error (CV[RMSE]) was applied to examine the goodness of fit of the IE model derived in this study. The previously reported linear IIM (Chen et al. 2016) was used with the same dataset collected in this research for comparison. Additionally, we calculated the number of days required for 'Yu Her Pau' litchi IE under mean daily temperature of 17.5°C, or 20°C/15°C (day/night), a known floral-inductive condition based on a controlled experiment (Chang 1999), using both the IE model with corresponding T_c, T_b and T_o proposed herein and IIM with the base temperature of 23.42°C according to Chen et al. (2016), respectively.

2.4 | Forecast of IE in 'Yu Her Pau' Litchi Under Different Emission Scenarios

The historical and projected daily average temperature data from 1986 to 2015 and 2026–2075, respectively, on a 5-km grid for Taiwan for each decade based on three General Circulation Models (GCMs) in the three separate climate change (greenhouse gas emission) scenarios were obtained from the Taiwan Climate Change Projection Information and Adaptation Knowledge Platform. Three emission scenarios from the Fifth Assessment Report (AR5) were selected for this study, including a very stringent pathway (RCP 2.6, limiting radiative forcing to 2.6 W/m^2 by 2100); an intermediate emission reduction pathway (RCP 4.5, stabilising radiative forcing at 4.5 W/m^2 after 2100 without overshoot); and a high-emission pathway without reductions (RCP 8.5, leading to radiative forcing of 8.5 W/m^2 by 2100) (van Vuuren et al. 2011; Taylor, Stouffer, and Meehl 2012), for simulation in this study. Three GCMs, namely Model for Interdisciplinary Research on Climate version 5 (MIROC5), Community Earth System Model—Community Atmosphere Model version 5 (CESM1-CAM5), and Community Climate System Model version 4 (CCSM4), were used herein according to the regional suggestions of Lin and Tung (2017). Distribution of litchi growing areas on Taiwan was retrieved from the Soil Resources and Agricultural Land Cover Database (Taiwan Agricultural Research Institute, https://soilsurvey.tari.gov.tw/SOA/index.aspx) for the assessment of potential climate impacts on litchi flowering and fruit production.

The timing of FM dictates whether there is enough time afterwards for EIU to accumulate to satisfy CTR before ambient temperatures start to increase naturally in spring. Therefore, we determined the window (interval of days) during which FM occurs that allows successful IE in the subsequent months in order to assess the risk of failed IE for litchi fruit production. This window was termed competent duration (CD) in this study and determined using the following steps. First, for each growing season (year), we simulated EIU accumulation with FM occurrence on each individual day from October to March using the above IE model with historical temperature records (1986–2015) and projected data (2026–2075) based on three selected GCMs for the three emission scenarios. Second, within each season, the earliest and latest calendar dates on which FM took place followed by cumulative EIU that satisfied the CTR were identified for calculating the interval of days between the two dates, or CD (Figure S2B). Finally, the values of CD were averaged every decade for each GCM in each emission scenario. Mean decade CD of the past (1996–2005) and forecasted scenarios (2026–2075), respectively, overlayed with the four major litchi-producing regions, including Caotun (Caotun Township, Nantou County) and Chuchi (Chuchi Township, Chiayi County) on Central Taiwan and Dashu (Dashu District, Kaohsiung City) and Hengchun (Hengchun Township, Pingtung County) on Southern Taiwan, were visualised by Kriging interpolation methods in ArcGIS 10.8.2 (Environmental Systems Research Institute, Redlands, CA, USA). Additionally, given that maturation of the last vegetative flush (i.e., becoming competent to perceive floral inductive cool temperatures) required about 45 days in 'Yu Her Pau' litchi observed by Chang et al. (2014), we used 45 days as the CD threshold to determine the likelihood of successful flowering in this study.

3 | Results

3.1 | Improved IE Model for 'Yu Her Pau' Litchi

Phenological data of competent flowering shoots with uninterrupted vegetative growth before IE recorded in two blocks for 6 years indicated that DFI ranged from 49.5 to 89.7 days (Table 1). The near-optimum solutions of T_c, T_b and T_o based on the BFM were 0.0°C, 19.8°C, and 21.9°C, respectively (Figure 1). The CTR for IE in 'Yu Her Pau' litchi was 60.37 EIUs with a CV of about 7.6% in 12 independent repeats (Table S1). Notably, the CV(RMSE) of the BFM (4.7%) generated by the approach proposed in this report was lower than that of the linear method of Chen et al. (2016) when applied to the same dataset, which was 12.7% (Figure 2), suggesting that the BFM is an appropriate approach to predict IE in 'Yu Her Pau' litchi. It has been demonstrated that IE in 'Yu Her Pau' took place after a 40-day

TABLE 1 | Phenological data, including the calendar dates of flush maturation (FM) and inflorescence emergence (IE) and duration of floral induction (DFI, interval between FM and IE) of 'Yu Her Pau' litchi each year from 2012 to 2018.

Year	Block	Competent flowering shoots (number per six trees)	FM date	IE date	DFI (days)
2012–2013	A	33	6 November 2012	15 January 2013	69.1
	B	7	18 December 2012	6 February 2013	49.5
2013–2014	A	16	31 October 2013	5 January 2014	66.2
	B	32	25 October 2013	4 January 2014	71.4
2014–2015	A	48	2 December 2014	23 January 2015	52.0
	B	57	26 November 2014	24 January 2015	58.9
2015–2016	A	54	30 October 2015	15 January 2016	77.4
	B	71	31 October 2015	11 January 2016	72.9
2016–2017	A	51	5 November 2016	3 February 2017	89.7
	B	55	7 November 2016	2 February 2017	87.9
2017–2018	A	29	5 November 2017	9 January 2018	65.0
	B	34	29 October 2017	8 January 2018	70.7

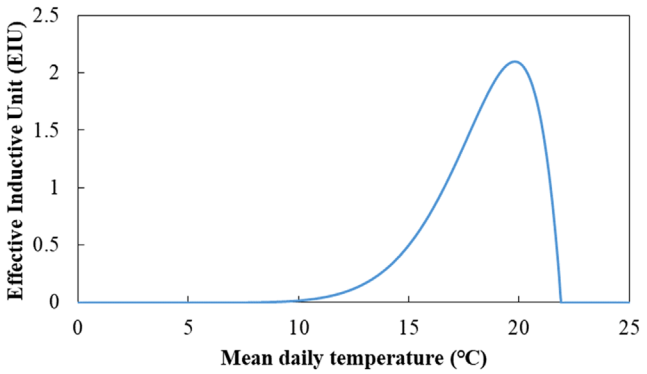


FIGURE 1 | The relationship of mean daily temperature and effective inductive unit (EIU), the quantity of cool temperatures that can effectively stimulate floral induction for inflorescence emergence in 'Yu Her Pau' litchi, calculated by beta-distribution function methods.

exposure to floral inductive temperature of 20°C/15°C (day/night) (Chang 1999). Under this condition, 44.0 days starting at FM were required for inflorescences of 'Yu Her Pau' litchi to emerge according to the IE model proposed in this study, whereas the IIM presented by Chen et al. (2016) estimated 51.9 days (Table S2).

3.2 | Forecast of the Likelihood of Successful Flowering in Existing Litchi-Producing Sites

According to the historical temperature data, the mean CD of major litchi-producing regions of interest, including Caotun, Chuchi, Dashu, and Hengchun, from 1986 to 1995, 1996–2005, and 2006–2015 were 73.4–104.9, 60.3–96.8, and 47.1–92.0 days, respectively (Table S3), all being > 45 days (visualised in orange-pink gradient in Figure 3). Based on the temperatures predicted by any of the three climate models, there was an overall reduction in CD over time in litchi-producing areas located on Southern Taiwan in all three emission scenarios (Figures 4–6). For Hengchun, the most southern litchi growing site on Taiwan, mean CD was 60.3 days during the decade of 1996–2005; however, predicted CD using MICRO5, CESM1-CAM5, and CCSM4 began to fall below 45 days in 2036, 2026, and 2046, respectively, even in the emission scenario of very stringent pathway, or RCP 2.6 (Table 2). As expected, CD at this location estimated using any of the GCM was shorter in the RCP 8.5 scenario than in the RCP 2.6 scenario after 2055. The results demonstrated a similar reducing trend of predicted CD of Dashu, which is north of Hengchun but still on Southern Taiwan, with CD being < 45 days during the decade of 2045–2055 using MIROC5 or 2056–2065 using CESM1-CAM5 and CCSM4 in the RCP 8.5 scenario. On the other hand, CD of Caotun and Chuchi, two sites located on Central Taiwan, did not drop to < 45 days or exhibit a declining trend over the coming decades using any GCMs and in any emission scenarios. The results herein indicated that IE is less likely to be affected by climate change for litchi production on Central Taiwan than Southern Taiwan.

4 | Discussion

As temperature is an important factor affecting development and phenology in plants, the upward trajectory of ambient temperatures as a result of global climate change presents a threat to crop production. In this study, we assessed the potential impacts of climate change on 'Yu Her Pau' litchi production at four major growing areas on Taiwan by first constructing a temperature-based predictive model for IE with improved accuracy, followed by predicting the probability of successful flowering using three separate climate models in three individual emission scenarios.

The previously reported IIM proposed by Chen et al. (2016) based on the linear regressions estimated that from leaf maturation to

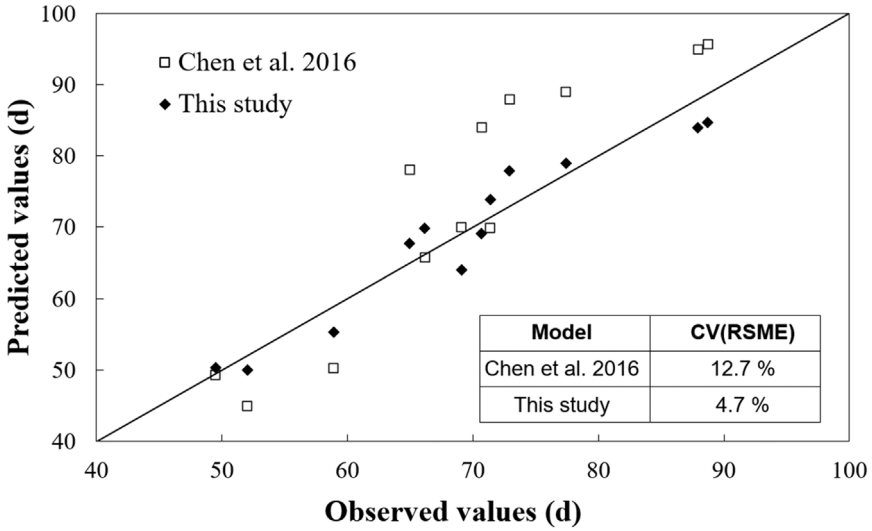


FIGURE 2 | Goodness of fit of the inflorescence emergence in 'Yu Her Pau' litchi using the inflorescence emergence model based on the beta-distribution function method presented in this study and the inflorescence induction model reported by Chen et al. (2016) with coefficients of variation of the root-mean-squared error (CV[RMSE]).

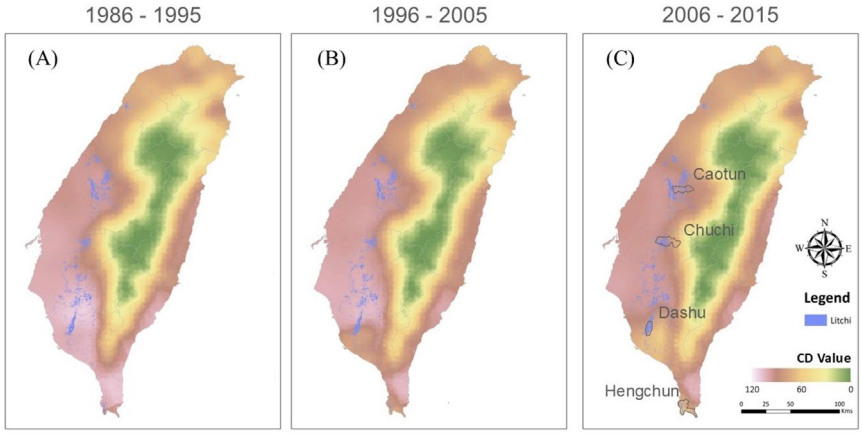


FIGURE 3 | Competent duration (CD), interval of time during which maturation of last flush occurs that allows successful inflorescence emergence in the subsequent months, for 'Yu Her Pau' litchi based on historical temperature data from 1986 to 1995 (A), 1996–2005 (B), and 2006–2015 (C) overlaid with litchi growing areas indicated in blue; the four major litchi-producing locations on Taiwan, including Caotun, Chuchi, Dashu, and Hengchun, were outlined and labelled in (B).

IE in 'Yu Her Pau' requires 7373 h of cumulative cool temperature below the base temperature of 23.42°C. This model also predicted a positive correlation between ambient temperatures and the span of DFI; that is, lower temperatures, as long as they are below the base temperature, following FM would lead to a shorter DFI, or earlier IE, compared to higher temperatures. On the contrary, results of a study conducted in a temperature-controlled environment demonstrated an extended DFI in 'Yu Her Pau' litchi trees under 15°C/13°C (day/night) compared with trees exposed to 20°C/15°C (day/night) (Chang 1999). This suggests that the cool temperature may no longer have the positive effect on litchi floral induction when falling below a certain threshold, which is likely to be 14°C based on the observations by Chang (1999). The discrepancy between the model prediction of Chen et al. (2016) and the empirical results of Chang (1999) indicate that the relationship between temperature and IE is likely non-linear and that other methods, such as BFM (Zhou and Wang 2018), may be more suitable in accounting for the suppression of plant growth and development by temperatures below a threshold. Our results demonstrated that better fitness can be achieved using BFM in the case of IE prediction compared with IIM (Figure 2). In this report, we also compared the two models by simulating the DFI in 'Yu Her Pau' litchi under the 20°C/15°C (day/night) condition, which is known to be around 40 days demonstrated by the results of previous studies (Teng 1988, 1996; Chang 1999). The linear regression-based IIM of Chen et al. (2016) and BFM-based IE model herein predicted 51.9 and 44.0 days, deviating from the observed value reported by Chang (1999) by 11.9 and 4.0 days, respectively, suggesting a higher predictive accuracy of the latter model than that of the former. Relevantly, BFM has also been adapted to vernalisation effectiveness models to predict flowering time in *Arabidopsis thaliana* (Chew et al. 2012), lending further support to the applicability of the IE model proposed in this research for forecasting the influences of progressively increasing fall and winter temperatures on 'Yu Her Pau' litchi flowering.



FIGURE 4 | Forecasted competent duration (CD), interval of time during which maturation of last flush occurs that allows successful 'Yu Her Pau' litchi inflorescence emergence in the subsequent months, of each decade from 2026 to 2027 based on the temperatures predicted by the Model for Interdisciplinary Research on Climate version (MIROC5) in three emission scenarios of the representative concentration pathway (RCP) 2.6, RCP 4.5, and RCP 8.5 overlaid with litchi-producing areas indicated in blue.



FIGURE 5 | Forecasted competent duration (CD), interval of time during which maturation of last flush occurs that allows successful 'Yu Her Pau' litchi inflorescence emergence in the subsequent months of each decade from 2026 to 2027 based on the temperatures predicted by the Community Earth System Model—Community Atmosphere Model version 5 (CESM1-CAM5) in three emission scenarios of the representative concentration pathway (RCP) 2.6, RCP 4.5, and RCP 8.5 overlaid with litchi-producing areas indicated in blue.

Although the basis of estimating cumulative low temperatures for litchi IE in this research is conceptually similar to that for endodormancy release in temperate crops, one significant distinction between the two lies the starting point for calculating temperature accumulation. In most chill models for temperate trees, the temperature is typically tracked starting at a given day in October or November to estimate chilling accumulation (Weinberger 1950; Fernandez, Whitney, and Luedeling 2020). For litchi, however, accumulation of floral-inductive cool temperatures (or EIU in this study) depends on the timing of FM since only when the last vegetative flush reaches maturity in fall does the ambient cool temperature become promotive and additive for floral induction (O'Hare 2002). Evidently, upregulation of *LcFT1*, a key gene in floral regulatory pathways, in



FIGURE 6 | Forecasted competent duration (CD), interval of time during which maturation of last flush occurs that allows successful 'Yu Her Pau' litchi inflorescence emergence in the subsequent months of each decade from 2026 to 2027 based on the temperatures predicted by the Community Climate System Model version 4 (CCSM4) in three emission scenarios of the representative concentration pathway (RCP) 2.6, RCP 4.5, and RCP 8.5 overlaid with litchi-producing areas indicated in blue.

response to cool-temperature exposure, followed by successful flowering, was observed in leaves on mature flushes, but not in young leaves on turning (immature) shoots (Ding et al. 2015; Xiao et al. 2019; Chang et al. 2022). In other words, the occurrence of FM in time marks the starting point of EIU calculations and therefore plays a pivotal role in determining the flowering fate. For example, early FM in October allows an extended period for EIU to accumulate in the following months that likely leads to successful IE; however, if FM takes place too late in mid-December, cumulative EIU until the ambient temperatures warm up in March would be insufficient to meet the CTR, resulting in failed IE (Figure S2B). Thus, the timing of FM, in addition to winter cool-temperature accumulation, must be taken into account when assessing the risk of unsuccessful flowering in litchi associated with climate change.

In this study, we used CD, or the interval between the earliest and latest occurrence of FM that allows adequate cool-temperature accumulation using the IE model proposed herein, as a proxy to evaluate the likelihood of successful flowering the following spring. A short CD indicates a narrow window for the last flush to mature and, therefore suggests a greater risk of unsuccessful floral induction in 'Yu Her Pau' litchi compared with an extended CD. It has been documented that FM, from bud break to fully expanded mature leaf, in 'Yu Her Pau' litchi required 45 days (Chang et al. 2014); thus, we used this threshold for successful flowering. Based on the historical temperature records in 1986–2015, the mean decade CD of the four major litchi-producing regions had been > 45 days (Figure 3, Table S3), consistent with relatively stable production of 'Yu Her Pau' litchi in the past. It is noteworthy that in Hengchun, the most southern site of all, the CD of 2006–2015 was only 2.1 days greater than the 45-day threshold (Table S3), suggesting a marked vulnerability to rising temperatures due to climate change. Indeed, with the change in temperatures estimated using the CESM1-CAM5, the CD of this location could drop to 39.2 days as early as 2026 even in RCP 2.6 with very stringent emission mitigation efforts (Table 2). In RCP 8.5, or the worst-case scenario of climate change, the substantial decrease in the likelihood of successful flowering after 2055 (CD ≤ 10 days) based on any GCMs indicated a great risk of crop loss for Hengchun litchi growers in the near future. In the same emission scenario, 'Yu Her Pau' litchi production in Dashu, another litchi growing region on Southern Taiwan, may also be hampered after 2045, predicted by the MIROC5, or after 2055, by both CESM1-CAM5 and CCSM4, due to the high probability of failure in flowering. In contrast, flowering of 'Yu Her Pau' litchi on Central Taiwan is likely to be unaffected in the next five decades as the predicted CD for Coatun and Chuchi predicted using any of the three GCMs will be exceeding the 45-day threshold (> 75 days in all cases) over time in all emission scenarios.

Our results, based on all three GCMs, demonstrated that the potential negative impacts of climate change on 'Yu Her Pau' litchi flowering appear to be limited to Southern Taiwan. Nevertheless, such regional effects can contribute to significant economic losses for Taiwan's litchi industry as a whole since this cultivar is primarily grown in the south and takes up a large market share. To ensure adequate cool-temperature exposure, one strategy is to advance FM (i.e., early start of accumulating floral inductive temperatures by mature flushes). However, common cultural practices that litchi growers have been using to manipulate FM, such as cincturing (girdling) and ethephon applications (Menzel and Paxton 1986; Huang and Chen 2012; Cronje et al. 2022), are not always effective in accelerating fall FM or spring IE because of the variations in growth stages of vegetative flushes within a tree. Litchi growers on Taiwan, like many crop producers globally, typically receive subsidies from

TABLE 2 | The mean decade competent duration (CD), interval of time during which maturation of last flush occurs that allows successful 'Yu Her Pau' litchi inflorescence emergence in the subsequent months, from 2026 to 2075 based on the temperatures predicted by three climate models, Model for Interdisciplinary Research on Climate version 5 (MIROC5), Community Earth System Model-Community Atmosphere Model version 5 (CESM1-CAM5), and Community Climate System Model version 4 (CCSM4) in three emission scenarios of the representative concentration pathway (RCP) 2.6, RCP 4.5, and RCP 8.5 for four major Taiwan litchi-producing areas.

		Climate model														
		MIROC5					CESM1-CAM5					CCSM4				
Location	Scenario	2026–2035	2036–2045	2046–2055	2056–2065	2066–2075	2026–2035	2036–2045	2046–2055	2056–2065	2066–2075	2026–2035	2036–2045	2046–2055	2056–2065	2066–2075
Caotun	RCP 2.6	98.8	98.6	96.9	101.2	97.4	104.1	106.0	104.4	97.1	100.2	95.7	98.4	99.3	103.9	96.3
	RCP 4.5	86.7	101.9	98.8	103.4	92.2	99.1	101.8	95.7	103.6	99.0	93.2	98.9	98.7	100.6	102.5
	RCP 8.5	101.2	98.0	81.7	94.8	72.8	97.4	95.0	101.2	95.2	100.6	98.4	97.4	97.3	103.6	98.2
Chuchi	RCP2.6	78.6	84.4	82.7	85.0	82.7	82.7	86.5	83.9	77.8	84.4	77.3	79.8	79.9	82.2	76.4
	RCP4.5	79.1	81.0	81.9	88.4	86.0	78.8	84.8	81.1	89.2	80.5	76.2	80.6	79	83.5	84.6
	RCP8.5	82.2	83.9	75.1	90.9	83.5	82.0	82.0	85.1	87.6	90.5	79.1	81	81.9	88.4	86
Dashu	RCP2.6	93.0	45.3	55.0	51.1	59.5	81.2	70.0	64.3	37.8*	60.7	85.9	82	75.8	74.9	95.4
	RCP4.5	57.0	64.1	60.5	56.9	33.9*	77.3	60.1	66.1	40.0*	59.4	78.4	72.2	75.7	67.2	60.3
	RCP8.5	79.2	57.4	37.5*	29.6*	13.6*	53.7	49.0	48.4	20.6*	22.9*	80.3	61.5	69.1	26.9*	47.4
Hengchun	RCP2.6	69.9	38.7*	26.3*	22.0*	30.4*	39.2*	31.4*	41.0*	11.1*	21.4*	49	72.9	39.7*	45	64.5
	RCP4.5	39.8*	57.3	39.0*	29.0*	25.3*	60.6	41.4*	47.1	17.5*	32.7*	57.3	47.2	46.1	47.7	39.4*
	RCP8.5	64.6	49.8	26.4*	11.1*	2.5*	51.1	37.4*	38.9*	1.6*	3.1*	55.3	37.9*	40.9*	10.9*	30.1*

Note: Competent days (CD) < 45.0days, the minimal required duration for flush maturation, were denoted with asterisks.

crop insurance and/or disaster relief programs for crop damages associated with extreme climate events (Martinez et al. 2022). Nonetheless, evidence-based approaches, including optimisation of predictive models that incorporate environmental variables with plant phenology and physiology and crop improvement (e.g., reduced cool-temperature requirement for flowering), are necessary to provide long-term solutions to sustain fruit production and agricultural prosperity in future scenarios. It should be noted that for other subtropical fruit and nut crops, similar issues are looming ahead as they also rely on cool winter temperatures for floral induction, including mango (*Mangifera indica*), citrus (*Citrus* sp.), avocado (*Persea americana*), and macadamia (*Macadamia integrifolia*) (Wilkie, Sedgley, and Olesen 2008; Nakagawa et al. 2012; Trueman 2013; Ziv et al. 2014; Tang and Lovatt 2019).

5 | Conclusions

In this research, we presented an improved temperature-based model, by leveraging the beta-distribution function, to predict IE in 'Yu Her Pau' litchi, for which floral induction is known to be promoted by cool temperatures following leaf maturation. This inflorescence predictive model was subsequently used to estimate the likelihood of successful flowering for the next few decades in three emission scenarios with separate climate models to assess potential warming impacts as a result of climate change on Taiwan's litchi fruit production. Our results suggested that 'Yu Her Pau' litchi grown on Southern Taiwan, currently of great economic importance, may face poor flowering due to insufficient cool winter temperatures in the coming decade even with very stringent efforts in emission mitigation (RCP 2.6); serious crop loss is impending under the worst-case scenario of climate change pathway (RCP 8.5). Similar negative climate impacts on crop production will likely occur for the subtropical fruit and nut species that share the cool-temperature-dependent floral induction mechanism with litchi and therefore, strategies involving policymaking and/or improvement of resiliency crop traits to mitigate the potential economic effects await to be devised.

Acknowledgements

The research was supported by the Ministry of Agriculture, Taiwan. The authors appreciate Mr. Ming-Yi Fang and Ms. Mei-Li Lin's assistance in field block management data collection, as well as Ms. Yu-Yueh Lin's GIS-based visualisation.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.