

Article

Temperature and Precipitation Synergistically Affect Yield, Harvesting Time and Post-Processing Quality of Tropical Macadamia Nuts

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Abstract: In response to climate change challenges and to ensure stable macadamia nut production, this study analyzed empirical data on macadamia nut yield, climate factors, harvesting time, and post-processing quality from 2020 to 2022. Key findings include: (1) During the flowering to fruit growth stage, 2020 had the highest average temperature, followed by 2021, and then 2022. Conversely, 2022 had the highest precipitation, followed by 2021, and then 2020. (2) Lower temperatures and higher precipitation during the flowering to fruit growth stage contributed to a significant increase in macadamia nut yield, which indirectly extended the harvesting time. In 2022, the average yield of the eight macadamia growers was 8.04 t ha^{-1} , significantly higher than the yields of 6.60 t ha^{-1} and 6.16 t ha^{-1} in 2021 and 2020, respectively. Furthermore, the average harvesting time for the eight macadamia growers in 2022 was 8.88 days longer than that in 2021, and 12.50 days longer than that in 2020. (3) Temperature and precipitation had a significant impact on the post-processing quality of macadamia nuts. Lower temperature and higher precipitation during the flowering to fruit growth stage significantly increased the proportion of first-grade fruit, as well as the incidence of mildewed and insect-infested fruits. In conclusion, although a lower temperature and higher precipitation can improve macadamia nut yield, they also lead to delayed harvesting and decreased post-processing quality. Given the observed yield sensitivity to temperature and precipitation, targeted water supplementation strategies during peak heat periods emerge as vital. This approach should be integrated with broader climate resilience planning, including the timing of pest control and disease management, to safeguard macadamia nut production against the multifaceted challenges posed by climate change.

Keywords: macadamia nuts; temperature; precipitation; climate change; yield



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1. Introduction

Macadamia (*Macadamia* spp.) is a perennial evergreen tree characterized by its fruit production capacity. It is classified within the genus *Macadamia*, which belongs to the Proteaceae family. This species is indigenous to subtropical rainforests along the eastern coastline of southern Queensland and northern New South Wales, Australia. Optimal planting conditions are characterized by an average annual temperature ranging from 20°C to 30°C and annual rainfall between 500 and 2000 mm [1–3]. The nutritional and economic importance of macadamia nuts has prompted numerous tropical and subtropical nations to invest significantly in the cultivation of this sought-after crop. Currently, 26 nations, including China, are actively engaged in the cultivation and enhancement of macadamia nut production [3–5]. In China, it is predominantly distributed in the provinces of Yunnan, Guangxi, Guangdong, and Guizhou, at an altitude of 1300 m below the hilly mountainous regions that are not subjected to severe frost or significant wind damage [6]. To date, the majority of macadamia plantations have been established for over a decade,

achieving a fruitful stage with relatively stable production levels. However, recent years have witnessed an instability in production across many macadamia-producing regions, characterized by fluctuations in annual yields. A comprehensive review of the macadamia nut production process revealed a correlation between significant production variances and abnormal climate shifts. Moreover, an expanding body of research has demonstrated that natural conditions, particularly climate, have become a crucial factor influencing crop production, especially in the context of the increasing refinement of controllable variables such as farming operations and management. Consequently, the relationship between meteorological factors and crop yield has emerged as a significant area of inquiry in agricultural research [7–9].

Temperature is one of the basic conditions for crop growth, development, and yield formation, as well as an important factor affecting crop quality [10]. The unique climatic characteristics inherent to the native habitat of the macadamia nut contribute to its relatively narrow range of adaptability. Regions characterized by excessively low winter temperatures or prolonged high-temperature periods are considered unsuitable for the cultivation and production of macadamia nuts. Shigeura [11] demonstrated that regions maintaining minimum winter temperatures between 14 and 17 °C adequately meet the requirements of the majority of macadamia nut varieties. Macadamia nut growth ceases at temperatures below 10 °C or above 35 °C. However, the rate of leaf synthesis in macadamia nuts halts when temperatures reach 38 °C [2]. Furthermore, temperature requirements vary across different developmental stages of macadamia nuts. For instance, Trueman [12] demonstrated that in trees that had already initiated flower bud development, further raceme production occurred at night temperatures of 12 °C, 15 °C, and 18 °C, but was nearly completely inhibited at 21 °C. Elevated daytime temperatures resulted in earlier raceme elongation, uneven flowering, and decreased productivity in macadamia nuts, whereas lower daytime temperatures yielded more favorable outcomes [13]. Nonetheless, subsequent to the rapid expansion of the nut and initiation of oil accumulation, optimal growth, and oil accumulation occurs at temperatures ranging from 25 to 30 °C; however, temperatures exceeding 35 °C lead to a significant reduction in fruit weight [14]. Furthermore, moisture is a pivotal factor that influences crop yield [8]. The growth, flowering, fruiting, and expansion of macadamia nuts are intrinsically dependent on water availability. Observations indicated that macadamia leaves exhibited signs of wilting and sustained damage in young nutritive flushes at leaf water potentials ranging from −2.45 to −3.78 MPa, as well as at water potentials between −4.13 and −5.0 MPa. Mature leaves exhibited visual stress symptoms, characterized by a dull, glossy color that progressively transformed into silvery-grey. Permanent damage was observed at water potentials below −5.0 MPa, where the leaf tissue exhibited contraction beneath the veins and necrotic spots at the leaf tips became apparent [15]. Furthermore, it has been demonstrated that soil water stress exerts a detrimental effect on macadamia nut yield and inhibits trunk growth [16]. However, in practice, it is challenging to consider temperature and precipitation as independent factors as they synergistically affect the entire macadamia nut production process.

The synergistic effect of temperature and precipitation on yield has been observed in numerous crops, including maize, rice, tomatoes, oranges, walnuts, and pistachios [17–19], yet similar detailed studies on macadamia nuts are sparse. Despite the known importance of climate factors on macadamia nut production, there is a lack of targeted research examining the synergistic effects of temperature and precipitation on both the yield and post-processing quality of macadamia nuts, as well as detailed understanding of how specific temperature and precipitation patterns during critical growth stages affect macadamia yield, harvesting time, and post-processing quality remains underexplored. Consequently, this study seeks to fill this crucial gap by providing empirical data on these relationships. The present study monitored the production of eight macadamia nut farmers within the same region over a three-year period, with a specific emphasis on variations in temperature and precipitation during the flowering to fruit growth stage. The primary objective of this study was to investigate the impact of fluctuations in temperature and precipitation during

the flowering to fruit growth stage on the final production of macadamia nuts. Furthermore, the effects of temperature and precipitation on the incidence of mildewed fruit and insect-infested fruit post-processing, as well as the potential extension of harvesting time, were examined. This study aimed to provide practical guidance for the high-yield and high-efficiency cultivation and management of macadamia nuts.

2. Materials and Methods

2.1. Experimental Site and Field Management

The trial sites were selected from areas with a planting history of more than 20 years. The eight trial sites were located in Bana Village, Jingha Township, Jinghong City, and Yunnan Province, China ($100^{\circ}59'16''$ E, $21^{\circ}48'37''$ N), at a distance of approximately 3 km from each other (Figure 1). Jingha Township is situated within the tropical rainforest climate zone, which is characterized by sustained high temperatures and precipitation levels throughout the year. The test site was located in a mountainous region in close proximity to Jingha Township at an altitude of 890–950 m. Notable variations in temperature and precipitation were observed between years, which were attributed to climate change. It was observed that the macadamia nut trees at all trial sites were in a period of stable production.

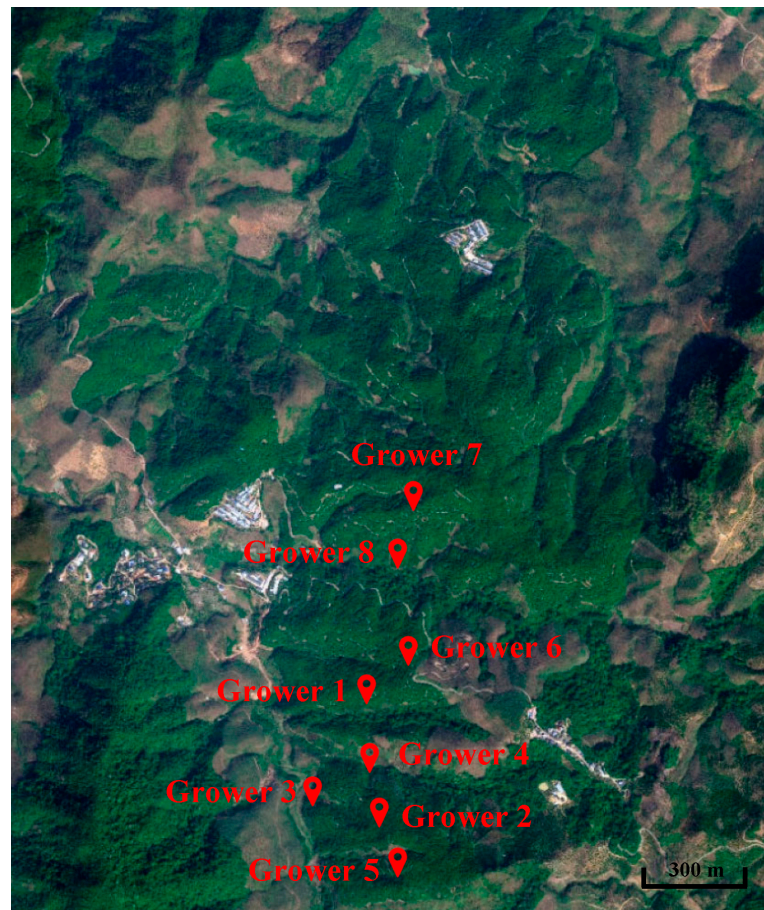


Figure 1. Map of the distribution of the eight growing positions.

The eight growers operate their respective contracted areas as contracted partnerships with ownership of the eight trial sites vested in the same organization. On an annual basis, the organization provides growers with technical guidance, production materials (including pesticides and fertilizers), and farming arrangements. Consequently, the farming practices of all growers remained consistent over the three-year period.

The application of fertilizer was conducted at the same ratio on an annual basis as follows: compound fertilizer was applied four times a year, with a dosage of 500 g per tree

each time. The fertilizer is formulated as follows: The fertilizer regime comprises nitrogen (N), phosphorus (P) and potassium (K) (15:15:15), with the addition of organic fertilizer in winter at a rate of 10 kg per tree per year, and zinc sulfate (100 g), copper sulfate (100 g), magnesium sulfate (200 g), potassium sulfate (300 g), and boric acid (70 g).

2.2. Temperature and Precipitation Observations

Temperature and precipitation data from NASA Prediction of Worldwide Energy Resources (The POWER Project) | Data Access Viewer (DAV) V 2.3.6, which provides solar and meteorological data sets from NASA research for the support of renewable energy, building energy efficiency, and agricultural needs. The data were positioned using a single point (100°59'16" E, 21°48'37" N). Temporal Level: Daily. The parameters are shown in Table 1.

Table 1. Meteorological parameters and its detailed information.

Parameters	Detailed Information
T	The average of the air temperature at a height of 2 m above ground level was defined as the average temperature
T _{Max}	The average of the highest air temperature at a height of 2 m above ground level was defined as the average maximum temperature
T _{Min}	The average of the lowest air temperature at a height of 2 m above ground level was defined as the average minimum temperature
Precipitation	Precipitation corrected

2.3. Division of Macadamia Nut Developmental Stages

Because of the existence of anti-seasonal flowering and batch flowering in macadamia nuts, which can easily lead to inconsistencies in fruit development and maturity, the present study used the approximate period to indicate concentrated fruit development. According to a study by Dong Qianqian et al. [20] and the macadamia development observed in the experimental site, the growth and development stages of macadamia nuts were roughly divided into the flowering stage (January–March), the fruit growth stage (April–June), and the harvesting stage (July–September), as shown in Figure 2.

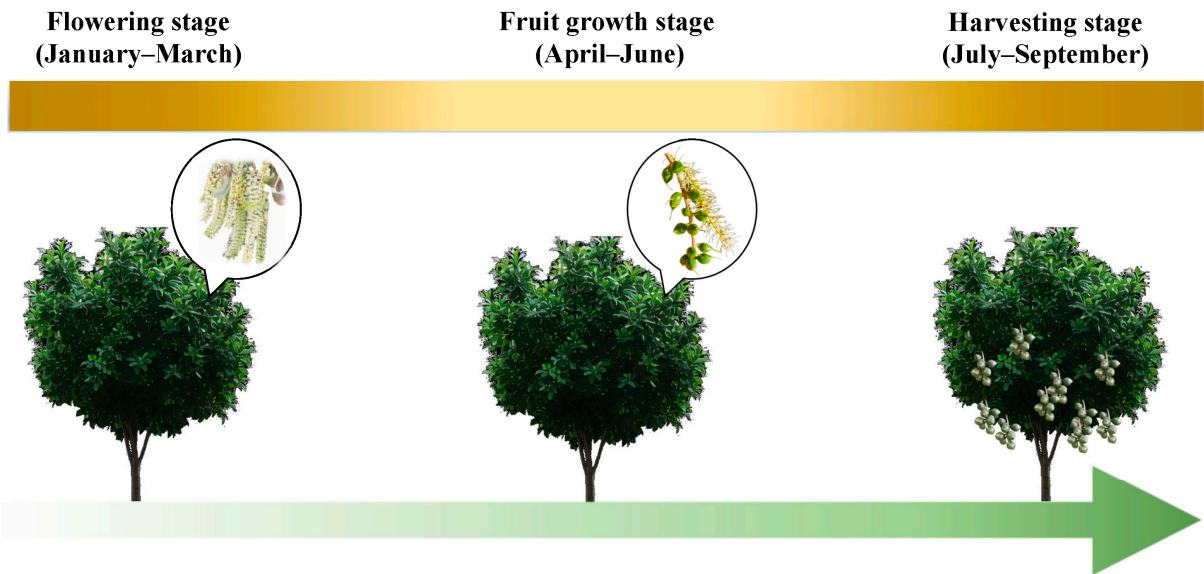


Figure 2. Schematic diagram of fruit development stages.

2.4. Harvesting and Yield Determination of Macadamia Nuts

The growers started to collect macadamia nuts on the ground around 10th July every year and started to harvest the macadamia nuts on the trees at the end of August. Each grower is a husband and wife who share the task of harvesting. The harvested fruit is sent to the base processing plant for weighing and recording in a timely manner, with the sum of the recorded outputs each time being the total output harvested by the grower in that year. Additionally, the time at which the macadamia nuts are harvested by growers must be recorded daily. If the harvesting process spans multiple hours, the total number of hours must be recorded as a single day (8 h recorded as a day).

Following the harvesting of the fruits, a series of processing steps were undertaken, including peeling, washing, removing impurities, and drying. Subsequently, samples were taken in batches to observe the mildew and insect-infested situation of the kernels in the primary processed nut-in-shell, and the rates of mildewed fruit and insect-infested fruit of macadamia nuts were determined respectively for each sample, and the specific formulas were as follows:

$$\text{The rate of mildewed fruit (\%)} = \frac{\text{The weight of mildewed fruit in the sample (g)}}{\text{Total weight of samples (g)}} \times 100\% \quad (1)$$

$$\text{The rate of insect-infested fruit (\%)} = \frac{\text{The weight of insect-infested fruit in the sample (g)}}{\text{Total weight of samples (g)}} \times 100\% \quad (2)$$

The dried samples were graded and screened by rolling automatic grading equipment; 25 mm and above were classified as first-grade fruit, 22 mm–25 mm were classified as second-grade fruit, and 18 mm–22 mm were classified as third-grade fruit. After grading and screening, the proportions of first-grade, second-grade, and third-grade fruit were calculated, respectively, and the specific formulas were as follows:

$$\text{The proportion of first-grade fruit (\%)} = \frac{\text{Total weight of first-grade fruit}}{\text{Total weight}} \times 100\% \quad (3)$$

$$\text{The proportion of second-grade fruit (\%)} = \frac{\text{Total weight of second-grade fruit}}{\text{Total weight}} \times 100\% \quad (4)$$

$$\text{The proportion of third-grade fruit (\%)} = \frac{\text{Total weight of third-grade fruit}}{\text{Total weight}} \times 100\% \quad (5)$$

2.5. Statistical Analysis

The data were recorded and subjected to preliminary analysis using Microsoft Excel 2019. The data were subjected to linear fitting and graphing using Origin 2021b.

3. Results and Discussion

3.1. Temperature and Precipitation

There were significant differences in the temperature and precipitation distributions among years (Figure 3). Specifically, T , T_{Max} , and T_{Min} in 2020 were higher than those in 2021 and 2022 at the flowering stage and fruit growth stages, while T , T_{Max} , and T_{Min} in 2021 were lower than those in 2022 at the flowering stage, conversely, T , T_{Max} , and T_{Min} in 2021 were higher than those in 2022 at the fruit growth stage (Table 2). In terms of precipitation, at the flowering stage, 2022 has the highest precipitation, followed by 2021 and 2020. At the fruit growth stage, the precipitation in 2022 was greater than that in 2020 and 2021. Conversely, at the harvesting stage, the highest precipitation occurred in 2020, followed by 2021 and 2022 (Figure 4). However, as the temperature and precipitation at the harvesting stage exerted minimal influence on fruit growth and development, as well as the differences in temperature changes at the harvesting stage were insignificant across different years, this

study primarily focused on temperature and precipitation alterations during the flowering to fruit growth stage. The temperature changes during the flowering to fruit growth stage indicated that 2020 exhibited the highest temperature, followed by 2021 and then 2022. In contrast, the precipitation changes showed that 2022 exhibited the highest precipitation, followed by 2021 and then 2020. Notably, the precipitation performance was in opposition to the temperature trend.

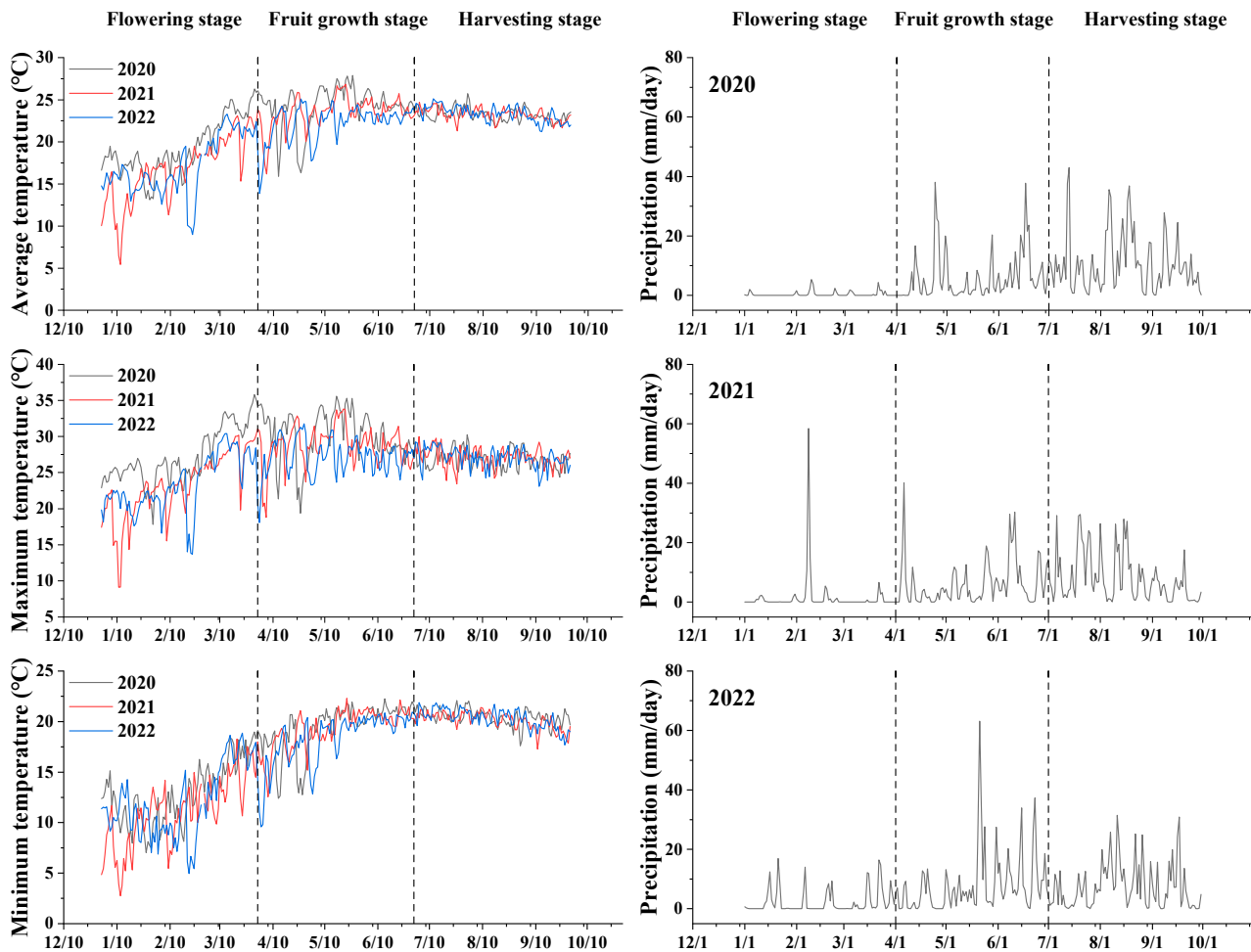


Figure 3. Temperature and precipitation trends at the flowering, fruit growth, and harvesting stages of macadamia nuts from 2020 to 2022. Note: The dotted lines in the figure are used to distinguish the different growth stages of macadamia nuts.

Table 2. Temperature performance at the flowering, fruit growth, and harvesting stages of macadamia nuts from 2020 to 2022.

Year.	Flowering (January–March)			Fruit Growth (April–June)			Harvesting (July–September)			Flowering to Fruit Growth (January–June)		
	T	T _{Max}	T _{Min}	T	T _{Max}	T _{Min}	T	T _{Max}	T _{Min}	T	T _{Max}	T _{Min}
2020	19.34	27.13	12.86	24.24	30.25	19.44	23.21	26.84	20.44	21.79	28.69	16.15
2021	16.71	23.12	11.10	23.52	28.85	19.29	23.23	27.12	20.12	20.12	25.99	15.20
2022	17.15	23.41	12.01	22.25	27.16	18.28	23.35	27.09	20.34	19.70	25.29	15.15

Note: The values of T, T_{Max}, and T_{Min} indicate the average temperature values for the specified stage.

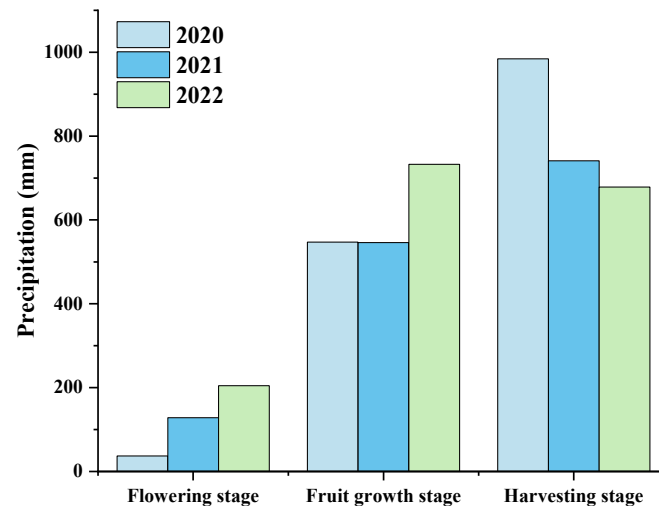


Figure 4. Differences in precipitation at the flowering, fruit growth, and harvesting stages of macadamia nuts from 2020 to 2022.

3.2. Effect of Temperature and Precipitation on Macadamia Nut Yield

The yield of macadamia nuts exhibited a consistent upward trend during the observation period (Table 3). The average yield of the eight macadamia growers in 2020, 2021, and 2022 was 6.16 t ha^{-1} , 6.60 t ha^{-1} , and 8.04 t ha^{-1} , respectively. The average yield of macadamia nuts in 2021 was 7.16% greater than that in 2020, the average yield of macadamia nuts in 2022 was 22.14% greater than that in 2021, and the average yield of macadamia nuts in 2022 was 30.95% greater than that in 2020.

Table 3. Macadamia nut yield and growth rate over 3 years from eight growers.

Grower No.	Macadamia Nut Yield (t/ha)			2020–2021 Growth Rate (%)	2021–2022 Growth Rate (%)	2020–2022 Growth Rate (%)
	2020	2021	2022			
1	6.95	7.35	8.11	5.73%	10.34%	16.66%
2	5.61	5.94	7.15	5.86%	20.37%	27.43%
3	6.52	6.67	8.08	2.31%	21.19%	23.99%
4	5.67	6.33	8.39	11.52%	32.53%	47.80%
5	5.83	6.25	8.19	7.12%	31.04%	40.38%
6	6.88	7.79	9.22	13.18%	18.40%	34.01%
7	5.59	5.91	7.11	5.66%	20.44%	27.26%
8	6.21	6.58	8.08	5.91%	22.81%	30.06%

The significant increase in yield was observed when all controllable test conditions were maintained at a constant level and indicates that variations in macadamia nut yield across different years are associated with climatic factors, such as temperature and precipitation. Therefore, a linear fit was established between the average temperature and macadamia nut yield during the flowering to fruit growth stage, and between the total precipitation and macadamia nut yield during the same stage. There was a positive correlation (Pearson's $r = 0.8035$) between the total precipitation and macadamia nut yield (Figure 5b). Furthermore, the effects of temperature and precipitation on macadamia nut yield were compared, and it was found that the R^2 value of the linear fit between precipitation and macadamia nut yield was closer to 1, indicating that precipitation has a greater effect on macadamia nut yield. However, the physiological phenomenon of self-incompatibility in macadamia nuts, in conjunction with the observed differences in the proportion of macadamia varieties and cultivars at various trial sites, resulted in notable discrepancies in the impact of temperature and precipitation on yields across different trial sites.

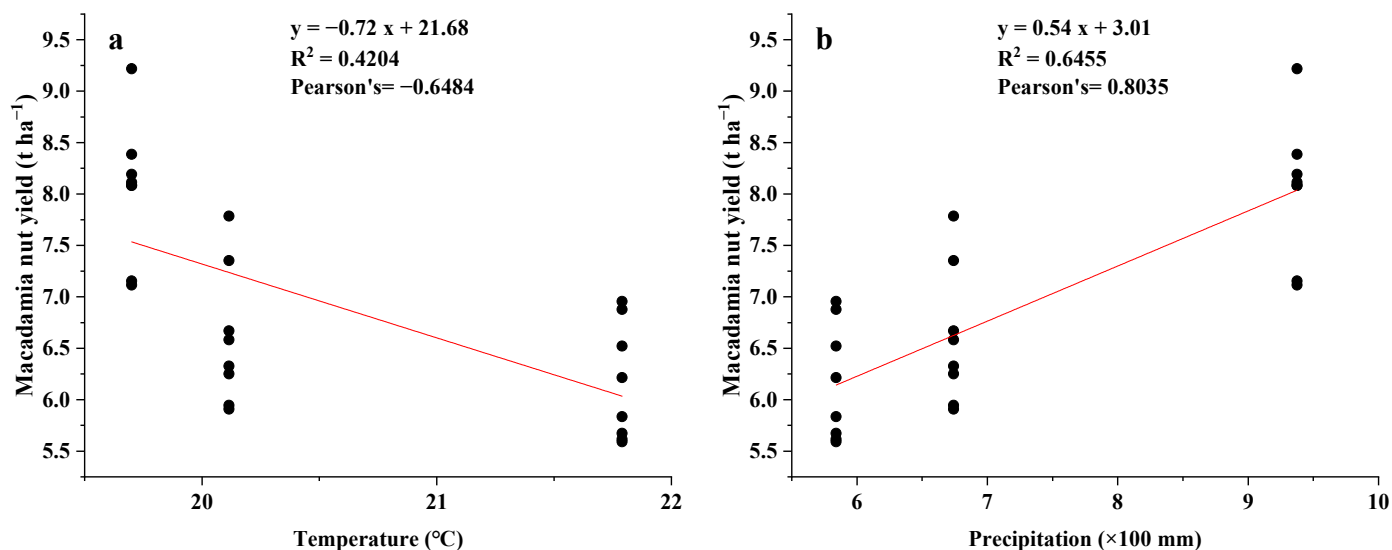


Figure 5. Linear fit of temperature and macadamia nut yield (a) and linear fit of precipitation and macadamia nut yield (b). The temperature represents the average temperature during the flowering to fruit growth stage, whereas the precipitation represents the sum of the precipitation during the flowering to fruit growth stage.

The impact of temperature and precipitation on yield is especially pronounced during the flowering to fruit growth stage. This is due to high temperature and drought conditions being highly detrimental to fruit set and expansion. During the critical period of fruit set and fruit expansion, the demand for water is high, and high temperatures tend to accelerate the overall transpiration rate of the plant. Jifeng et al. [6] found that under the persistent high temperatures and dry weather in summer, some heat-intolerant macadamia nut varieties cultivated in the macadamia nut production areas of Guangdong and Guangxi in China would show the phenomenon of yellowing of new leaves. In serious cases, the leaves would be yellowish-white, with leaf margins scorched, or even dry and fall off, which resulted in a reduction in photosynthesis, and thus affected the yield and quality of macadamia nuts. However, this phenomenon is mainly due to the excess excitation energy caused by high-temperature stress, which induces chloroplasts to produce excessive reactive oxygen species (ROS), contributing to the lipid peroxidation of photosynthetic membranes and the destruction of chloroplast structure, leading to leaf PSII protein damage, chlorophyll degradation, and yellowing [21,22]. In addition, Stephenson and Gallagher [23] discovered that the highest fruit survival rate was found in macadamia nuts under low temperatures, adequate water supply, and high humidity environmental conditions. The fruit survival rate decreased with increasing temperature, while insufficient water supply increased the fruit drop and reduced the fruit survival rate, it was also found that the number of young fruits surviving in the daytime at low temperatures was higher. Furthermore, macadamia nut size is reduced when trees are subjected to water stress in summer and early autumn [24]. Therefore, the higher temperature and lower precipitation in 2020 resulted in a significant reduction in macadamia nut yield. While the macadamia nut yield in 2022 was higher than that in 2021 due to the higher precipitation, which provided a better growing environment for fruit set and expansion.

3.3. Effect of Temperature and Precipitation on the Harvesting Time of Macadamia Nuts

The harvesting time of macadamia nuts is primarily contingent on the timing of flowering and fruit maturity. The harvesting of macadamia nuts is a lengthy process due to the fact that anti-seasonal and early flowering nuts ripen and drop earlier, and there are significant differences in fruit maturity between different varieties of macadamia nuts. For example, the cultivar 'Keaau' flowers at an early stage, while the variety 'Kakea' tends to

flower a few weeks later [2]. However, in this experiment, the cultivars were consistent, and the flowering time, fruit development, and ripening time of the fruits were almost identical across all three years. Consequently, the length of harvesting time was predominantly contingent upon additional variables, including the number of days devoted to harvesting, and the number of workers involved in the process. Furthermore, the impact of temperature and precipitation on macadamia nut yield is a contributing factor to harvesting time.

As shown in Table 4, the time required to harvest macadamia nuts increased annually. In particular, the average harvesting time in 2021 was 3.63 days longer than that in 2020, whereas the average harvesting time in 2022 was 8.88 days longer than that in 2021. Notably, the average harvesting time in 2022 was 12.50 days longer than that in 2020. The number of workers engaged in harvesting macadamia nuts per grower position per annum is fixed. However, there are variations in the number of workers among the various growers, which give rise to differences in the time required for harvesting by different growers. Additionally, there was little variation in the time required for the collection of fallen fruits and the recollection stages. Therefore, the length of centralized harvesting became the primary factor influencing the harvesting time. Nevertheless, it is reasonable to conclude that the effects of temperature and precipitation on macadamia nut yields increase the risk of growers postponing the harvest, given the considerable impact of temperature and precipitation on macadamia nut yields, and the inherent link between increased yields and the subsequent demand for labor.

Table 4. The harvesting time of macadamia nuts from 2020 to 2022.

Grower No.	Harvesting Time (Days)		
	2020	2021	2022
1	68	74	83
2	52	56	63
3	53	57	63
4	53	57	68
5	60	67	76
6	54	51	69
7	51	53	58
8	56	61	67

3.4. Effect of Temperature and Precipitation on the Post-Processing Quality of Macadamia Nuts

The harvested fruits were classified into three grades (1, 2, and 3) for better marketability, and the proportion of fruits in different grades is a good indicator of the overall development of fruits and the overall quality of the fruits in the year. Figure 6 shows that the proportion of first-grade fruit gradually increased annually, while the proportion of third-grade fruit decreased annually. The proportion of first-grade fruit in 2022 was 21.33% and 75.75% higher than that in 2021 and 2020, respectively. The proportion of third-grade fruit in 2022 was 6.89% and 52.83% lower than that in 2021 and 2020, respectively. This indicates that the development of macadamia nuts in 2022 was significantly better than that in 2021 and 2020. It also demonstrates that the lower temperature and higher precipitation during the flowering to fruit growth stage facilitated greater fruit growth and nutrient accumulation.

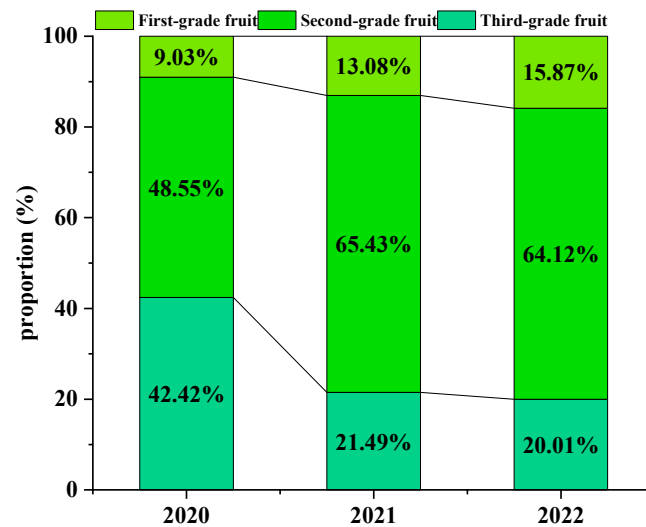


Figure 6. The proportions of first-grade, second-grade, and third-grade fruit from 2020 to 2022.

The incidence of mildewed and insect-infested fruits in macadamia nuts was found to be significantly affected by temperature and precipitation. The rate of mildewed fruit in 2020 was significantly lower than that in 2021 and 2022. The rate of insect-infested fruit showed a significant increase as the year progressed (Figure 7). Specifically, the rate of mildewed fruit in 2020 was 59.00% and 58.49% lower than that in 2021 and 2022, respectively. The rate of insect-infested fruit in 2020 was 54.76% and 67.80% lower than that in 2021 and 2022, respectively.

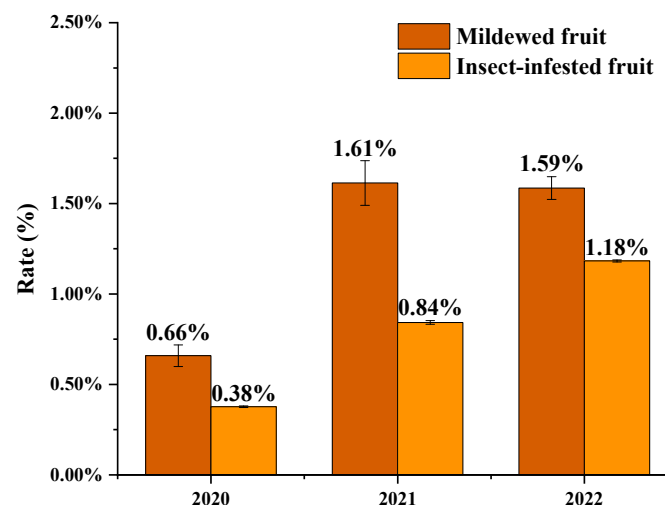


Figure 7. The rates of mildewed and insect-infested fruit from 2020 to 2022.

Climate change may lead to changes in the geographic distribution of agricultural pests, changes in population growth rates, increases in the number of generations, lengthening the developmental season, and increases the risk of invasion by migratory pests [25]. The reproduction of pests is affected by temperature, with optimal conditions falling within the range of 20 °C–25 °C. Temperatures below 15 °C or above 30 °C are detrimental to reproduction, whereas temperatures below this range or above this range can lead to a decrease in pest populations. The proliferation of pests may be increased by drought conditions, whereas higher precipitation can result in the washing away of eggs and larvae, reducing the number of pest populations [26–28]. Muluvhahotho et al. [29] demonstrated that macadamia pests developed faster and their populations increased significantly under elevated temperature conditions compared to those at 18 °C. Bouarakia et al. [30] found that higher precipitation resulted in lower total kernel recovery, increased immaturity, and

increased pest damage in macadamia nuts. The favorable temperature and low precipitation conditions in 2020 were conducive to the proliferation of macadamia nut pests and diseases. However, it is perplexing that the 2020 macadamia nuts exhibited the lowest rates of mildewed and insect-infested fruits. Thus, it is necessary to consider whether other factors contributed to the reduction in pest and disease occurrence. In terms of the life cycle of pests, high temperatures accelerate the transition from eggs to adults [29], which may lead to earlier pest and disease development, coincidentally avoiding critical stages of macadamia nut development [31].

Macadamia nuts left on the orchard floor will develop mildew and rancidity over time [32]. Leverington [33] also discovered that when harvesting is delayed, the kernels may become infected with mildew or germinate, particularly in wet conditions. The extended harvesting time in 2021 and 2022 elevated the probability of mildewed kernels compared to 2020. Moreover, temperature and precipitation were found to exert considerable influence on the occurrence of macadamia nut pathogens. Nagao et al. [2] observed that *Botrytis cinerea* and *Phytophthora capsici* were more prevalent in macadamia nuts in cool and humid weather and were prone to cause raceme rot and fruit pericarp turning blackish-brown or even rotting. Therefore, the damage to the outer epidermis removes a layer of natural protection from the macadamia nut and increases the chances of pathogens invading the nut-in-shell. This led to an increase in the rate of mildewed fruit in 2021 and 2022 due to the lower temperature and higher precipitation compared to 2020.

4. Conclusions

Temperature and precipitation had significant effects on macadamia nut yield, harvesting time, and post-processing quality. A three-year longitudinal trial conducted at eight grower sites revealed that lower temperature and higher precipitation during the flowering to fruit growth stage were conducive to the development of macadamia nuts and subsequent yield increases. However, the increased yield was accompanied by an increased probability of extended harvesting time. Moreover, lower temperatures and higher precipitation during the same stage significantly impacted the post-processing quality of macadamia nuts. The proportion of first-grade fruit was significantly increased, while the proportion of third-grade fruit was significantly decreased, indicating that the overall developmental maturity of macadamia nuts was enhanced. However, the increased incidence of mildewed and insect-infested fruits decreased the quality of macadamia nuts. Therefore, to mitigate the effects of climatic changes on the yield and quality of macadamia nuts, it is essential to provide appropriate water supplementation during the high-temperature period to meet the water demand for fruit expansion. In cases of lower temperature and higher precipitation, it is necessary to strengthen the prevention and control of pests and diseases during the rain-free period. However, although this study underscores the localized climate effects on macadamia nut production, differences in climate types, altitudes, and the response of various macadamia nut varieties to climate change necessitate further research. Additionally, it is crucial to enhance research on the impact of climatic change on the occurrence patterns of macadamia nut pests and diseases. Understanding the nuanced impacts of climate variables on macadamia nut production is not only vital for enhancing yield and quality but also for developing resilient agricultural practices in the face of global climate change.

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References

1. Mast, A.R.; Willis, C.L.; Jones, E.H.; Downs, K.M.; Weston, P.H. A smaller Macadamia from a more vagile tribe: Inference of phylogenetic relationships, divergence times, and diaspore evolution in Macadamia and relatives (tribe Macadamieae; Proteaceae). *Am. J. Bot.* **2008**, *95*, 843–870. [CrossRef] [PubMed]
2. Nagao, M.A.; Hiraie, H.H.; Stephenson, R.A. Macadamia: Cultivation and physiology. *Crit. Rev. Plant Sci.* **1992**, *10*, 441–470. [CrossRef]
3. Bin, S.; Yanli, N.; Xiyong, H. *High-Yield Cultivation and Management Techniques for Macadamia Nuts*; Yunnan Science and Technology Press: Kunming, China, 2016.
4. INC. Main Producing Countries-Global Statistical Review Crop Progress Report. *Nutfruit Magazine*, July 2023. Available online: <https://inc.nutfruit.org/publications/> (accessed on 15 September 2024).
5. Moncur, M.W.; Stephenson, R.A.; Trochoulis, T. Floral development of Macadamia integrifolia Maiden & Betche under Australian conditions. *Sci. Hortic.* **1985**, *27*, 87–96. [CrossRef]
6. Wan, J.; Zeng, H.; Zou, M.; Song, X.; Yang, Y.; Yang, Q.; Bai, H. Investigation and analysis on heat tolerance of macadamia germplasm resources. *South China Fruits* **2024**, *53*, 80–86+95. (In Chinese with English Abstract)
7. Jägermeyr, J.; Müller, C.; Ruane, A.C.; Elliott, J.; Balkovic, J.; Castillo, O.; Faye, B.; Foster, I.; Folberth, C.; Franke, J.A.; et al. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nat. Food* **2021**, *2*, 873–885. [CrossRef]
8. Fawcett, R.G. Effect of Certain Conditions on Yield of Crop Plants: Plant Density: Soil Water: Yield Relationships. *Nature* **1964**, *204*, 858–859. [CrossRef]
9. Song, L.; Tao, Y.; van Groenigen, K.J.; Chang, S.X.; Peñuelas, J.; Zhang, J.; You, L.; Cai, C.; Wang, S.; Jiang, Y.; et al. Rising atmospheric carbon dioxide concentrations increase gaps of rice yields between low- and middle-to-high-income countries. *Nat. Food* **2024**, *5*, 754–763. [CrossRef]
10. Lesk, C.; Coffel, E.; Winter, J.; Ray, D.; Zscheischler, J.; Seneviratne, S.I.; Horton, R. Stronger temperature–moisture couplings exacerbate the impact of climate warming on global crop yields. *Nat. Food* **2021**, *2*, 683–691. [CrossRef]
11. Shigeura, G. Minimum temperature regime for macadamia: A concept. *Yearb. Calif. Macadamia Soc.* **1981**, *27*, 67–73.
12. Trueman, S.J. The reproductive biology of macadamia. *Sci. Hortic.* **2013**, *150*, 354–359. [CrossRef]
13. Pichakum, A.; Supaibulwattana, K.; Chintakovid, W.; Chanseetis, C. Role of temperature and altitude on flowering performances of macadamia nut. *Acta Hortic.* **2014**, *1024*, 127–132. [CrossRef]
14. Stephenson, R.A.; Gallagher, E.C. Effects of temperature during latter stages of nut development on growth and quality of macadamia nuts. *Sci. Hortic.* **1986**, *30*, 219–225. [CrossRef]
15. Stephenson, R.A.; Ko, H.L.; Gallagher, E.C. Plant-water relations of stressed, non-bearing macadamia trees. *Sci. Hortic.* **1989**, *39*, 41–53. [CrossRef]
16. Awada, M.; Watanabe, Y.; Warner, R.M.; Warner, R.M. *Effects of Soil Moisture Stress on Growth and Yield of Macadamia (Macadamia integrifolia)*; Technical Bulletin No. 69; Hawaii Agricultural Experiment Station, University of Hawaii: Honolulu, HI, USA, 1967; pp. 1–27.
17. Abbas, S.; Mayo, Z.A. Impact of temperature and rainfall on rice production in Punjab, Pakistan. *Environ. Dev. Sustain.* **2021**, *23*, 1706–1728. [CrossRef]
18. Lobell, D.B.; Cahill, K.N.; Field, C.B. Historical effects of temperature and precipitation on California crop yields. *Clim. Change* **2007**, *81*, 187–203. [CrossRef]
19. Maitah, M.; Malec, K.; Maitah, K. Influence of precipitation and temperature on maize production in the Czech Republic from 2002 to 2019. *Sci. Rep.* **2021**, *11*, 10467. [CrossRef] [PubMed]
20. Dong, Q.; Zhao, X.; Ni, S.; He, X.; Shen, J. Nutritional Characteristics and Fertilization Management of Macadamia. *South China Fruits* **2020**, *49*, 149–154. (In Chinese with English Abstract).
21. Yang, W.; Zeng, H.; Wan, J.; Zhang, H.; Lu, C. Preliminary study on physiological characteristics of Macadamia leaf etiolatio under high temperature. *Chin. J. Trop. Crops* **2021**, *42*, 830–838. (In Chinese with English Abstract)
22. Tyystjärvi, E. Chapter Seven—Photoinhibition of Photosystem II*. In *International Review of Cell and Molecular Biology*; Jeon, K.W., Ed.; Academic Press: Cambridge, MA, USA, 2013; Volume 300, pp. 243–303.

23. Stephenson, R.A.; Gallagher, E.C. Effects of temperature, tree water status and relative humidity on premature nut drop from macadamia. *Sci. Hortic.* **1987**, *33*, 113–121. [[CrossRef](#)]
24. Warner, R.M.; Awada, M. Some growth and yield characteristics of Keauhou variety macadamia under different levels of irrigation. *Annu. Rep. North. Nut Grow. Assoc.* **1965**, *55*, 36–41.
25. Porter, J.H.; Parry, M.L.; Carter, T.R. The potential effects of climatic change on agricultural insect pests. *Agric. For. Meteorol.* **1991**, *57*, 221–240. [[CrossRef](#)]
26. de Freitas, F.A.; Zanoncio, T.V.; Zanoncio, J.C.; da Conceição, P.M.; Fialho, M.d.C.Q.; Bernardino, A.S. Effect of plant age, temperature and rainfall on Lepidoptera insect pests collected with light traps in a Eucalyptus grandis plantation in Brazil. *Ann. For. Sci.* **2005**, *62*, 85–90. [[CrossRef](#)]
27. Baltzer, J.L.; Davies, S.J. Rainfall seasonality and pest pressure as determinants of tropical tree species' distributions. *Ecol. Evol.* **2012**, *2*, 2682–2694. [[CrossRef](#)] [[PubMed](#)]
28. Skendžić, S.; Zovko, M.; Živković, I.P.; Lešić, V.; Lemić, D. The Impact of Climate Change on Agricultural Insect Pests. *Insects* **2021**, *12*, 440. [[CrossRef](#)]
29. Muluvhahotho, M.M.; Joubert, E.; Foord, S.H. The Effects of Temperature on the Development and Survival of Bathycoelia distincta (Hemiptera: Pentatomidae), a Significant Pest of Macadamia in South Africa. *Insects* **2024**, *15*, 152. [[CrossRef](#)]
30. Bouarakia, O.; Anders, M.; Linden, V.M.G.; Grass, I.; Westphal, C.; Taylor, P.J.; Foord, S.H. Reduced macadamia nut quality is linked to wetter growing seasons but mitigated at higher elevations. *J. Agric. Food Res.* **2023**, *12*, 100569. [[CrossRef](#)]
31. Drake, V. The influence of weather and climate on agriculturally important insects: An Australian perspective. *Aust. J. Agric. Res.* **1994**, *45*, 487–509. [[CrossRef](#)]
32. Liang, T.; Meng, Q.; Ji, F. Prediction of macadamia nut spoilage for harvest decision making. *J. Agric. Eng. Res.* **1996**, *63*, 237–242. [[CrossRef](#)]
33. Leverington. The macadamia nut industry. *Food Preserv. Q.* **1971**, *31*, 57–65.

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