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Article

How Climate Change Disrupts Mango Phenology and Affects Fruit Production

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Abstract. Climatic elements are limiting factors for plants; therefore, climate change can impact the phenology of plants. This study aims to determine the impact of climate change on the reproductive phenology of four local mango cultivars on Sulawesi Island, Indonesia. Data were collected during 2013 and 2014 by observing and recording the production of vegetative shoots, generative shoots, and fruits from the trees of each mango cultivar weekly. To assess the impact of seasonal change on fruit quality, the weight and sugar level of the ripe fruits in each cultivar were measured. Climate data were obtained from the National Centers for Environmental Prediction and the Indonesian Agency for Meteorology, Climatology, and Geophysics Region IV, Makassar. Results show that from 1979 until 2014, the climate in the study site changed from type D to type C according to the Schmidt-Ferguson Climate Classification method, indicating that the wet season became longer. Following climate change, the reproductive phenology of the four mango cultivars also changed from once to twice annually, whereby the flush of vegetative and reproductive shoots that appeared during the first period in March did not successfully develop into mature fruit but developed following the second period in July. The change of season also impacted the quality of the mangoes, as fruit produced during the longer dry season had higher sugar levels than those produced during the shorter dry season.

Keywords: climate change; season; reproductive phenology

INTRODUCTION

The climate changes over time following changes in other environmental factors. Climate change within limits to which organisms can still adapt, is a natural phenomenon (Hegerl et al., 2019). However, drastic and extreme climate change due to anthropogenic impacts that do not provide opportunities for organisms to adapt, and can even threaten their lives, is an anomaly (Trenberth, 2012). Scientists currently call this global climate change (Hansen et al., 2000; Kaplan & New, 2006).

Ecologically, plants strictly synchronise their physiological cycles to the climatic conditions of their habitats (Luna-Nieves et al., 2017). Solar radiation and water are the most essential climatic factors required by plants in the process of photosynthesis to produce sufficient organic compounds for growing and supporting fruit production (Girardin et al., 2016; Durand et al., 2021). Unlike temperate climates, where solar radiation is determined by the latitudinal position of the sun, in a tropical monsoon, the intensity of solar radiation is related to the presence of clouds. On the one hand, in the middle of the dry season, when the sky is clear, solar radiation is maximally available, but water is limited. On the other hand, in the middle of the wet season, water is abundantly available, but there is less solar radiation because the sky is always cloudy. Therefore, trees that produce sizeable fleshy fruit with recalcitrant seeds tend to start their

reproductive phenology at the onset of the dry season when the soil is still moderately moist and the sun is shining brightly (Bawa et al., 2003; Nanda et al., 2014).

Previous studies assume that climate change forces plants to adapt their phenological cycle patterns to changing seasonal patterns, such as timing the emergence of young leaves, flowering, and fruit ripening periods (Pau et al., 2011; Menzel et al., 2011). However, rapid and chaotic climate change will not provide sufficient opportunity for plants to adapt (Schmidhuber & Tubiello, 2007; Thackeray et al., 2016). As a result, there can be failures in the reproductive phenology process, for instance, flowers failing to develop into fruit when the weather is cloudy and rainy again after the anthesis. If this happens to agricultural crop commodities, it can cause food scarcity (Schmidhuber & Tubiello, 2007).

A more severe impact of disrupting synchronisation between plant phenology and seasonal patterns due to climate change can occur in forest trees (Blanco et al., 2021) because the resources needed by forest plants to grow, especially water and solar radiation, depend entirely on nature's supply. Mango (*Mangifera indica*) is a tree species that produces sizeable fleshy fruits with large recalcitrant seeds. Although mango trees are mainly cultivated, they are not given the same treatment as other crops, particularly the local cultivar. They are not watered or fertilised and are, therefore, well-suited for studying the impacts of climate change on edible fruit-producing forest trees. This study aims to determine the impact of climate change on the reproductive phenology of four local mango cultivars (*Mangifera indica*) on the Indonesian island of Sulawesi.

The timing and intensity of the flowering of mango trees are strongly influenced by favorable growing conditions that determine when and how many fruits are produced during a given season (Davenport, 2007). To produce a large quantity of large fruit, mangoes require numerous organic compounds from photosynthesis. When growing conditions are favorable, mango trees usually produce seasonally abundant fruit (mass production). We predict that climate change will disrupt the synchronisation of mango phenological cycles and chaotic seasonal patterns and may lead to reduced fruit yields or even a failure of the fruiting process. The results of this study are not only important for understanding the impact of climate change on mango fruit production but also for other fleshy fruit-producing trees. In forest ecosystems, the reproductive failure of fleshy fruit-producing trees can threaten the survival of frugivore wildlife.

MATERIAL AND METHODS

Climate Change

This study was conducted between August 2013 and December 2014 in the forested yard of the Hasanuddin University campus in Makassar City, South Sulawesi, Indonesia. The climate anomaly in the form of an extreme El Niño reported by Nicholas (1999) occurred in Indonesia in 1982, and since then, El Niño and La Niña have become more frequent. To analyse climate change patterns in Makassar over the last four decades, we used the 1979-2014 climate data series obtained from the National Centers for Environmental Prediction.

Based on differences in annual rainfall patterns from 1979 to 2014, we analysed whether there was a change in climate type (Q) from two different periods (1979–1989 and 2003–2013) using the climate classification system developed by Schmidt and Ferguson (1951).

$$Q = \frac{\text{Average of dry months}}{\text{Average of wet months}} \text{ X } 100\% \quad (1)$$

Dry months are months with less than 60 mm of rainfall, and wet months have more than 100 mm of rainfall. Based on the Q value, the climate type was divided into eight categories from type A (very wet) to type H (very dry) (Table 1).

Table 1. Climate type classification according to Schmidt and Ferguson (1951)

Climate condition	Climate type	Q value (%)
Very wet	A	0–14.3
Wet	B	14.3–33.3
Somewhat wet	C	33.3–60.0
Moderate	D	60.0–100
Somewhat dry	E	100–160
Dry	F	160–300
Very dry	G	300–700
Extremely dry	H	> 700

We used more detailed short-term climate data (2013–2014) from the Meteorology, Climatology and Geophysics Agency Region IV Makassar to analyse the impact of seasonal dynamics on the reproductive phenology of mangoes.

Mango Phenology

To obtain general information about the reproductive phenological cycle of mangoes before the extreme El Niño in 1982, we interviewed 20 respondents aged over 60. The respondents either owned a mango garden or planted mango trees in their yards. Our questions to the respondents were: (1) in what month do mangoes usually start flowering?; (2) what month are mangoes usually ripe?; (3) do mango trees bear fruit every year?; (4) do all mature mango trees bear fruit every year?; (5) do all the branches bear fruit in the fruiting season?

We observed the reproductive phenology of four cultivars of native mango (*Mangifera indica*): taipa banyak papan, taipa juru', taipa golla-golla, and taipa mu'musang. The four cultivars we observed were mature trees (diameter >50 cm) that grew close together, and each was in an open area so that it received full solar radiation. A phenological assessment of tree samples from each cultivar was carried out every week from August 2013 to December 2014. The parameters that were recorded and measured were the proportion of the crown that produced vegetative shoots, generative shoots (flowering shoots) and fruit (young and ripe) with the following proportional scales: less than 25% when the crown produced vegetative shoots, generative shoots or fruits on less than a quarter of the total crown cover; 26%-50% when the crown produced vegetative shoots, generative shoots or fruits on more than a quarter but less than half of the total crown cover; 51%-75% when the crown produced vegetative shoots, generative shoot or fruits on more than half but less than three-quarters of the crown cover; 76%-100% when the crown produced vegetative shoots, generative shoots or fruits on more than three-quarters of the width of the crown cover (see Riley, 2007).

Fruit Quality

Fruit quality was determined by the size and sugar content of ripe fruits, and these were measured to determine whether seasonal changes affect fruit quality. Ripe fruit was classed as fruit that dropped naturally from the mother tree because it was ripe. Fruit size was presented as the fresh weight measured using an analogue scale, while the sugar level was measured using a hand refractometer (ATAGO N-1). The number of fruit samples varied by cultivar from 50 to 58, taken from one tree sample.

Data Analyses

We presented the climate data in graph form and the phenological cycle data in diagram form. We analysed the association between the climate variables (rainfall, maximum and minimum temperature, solar radiation, and humidity) with the mango phenological cycle between 2013 and 2014 qualitatively by comparing the pattern of the monthly dynamic of each climate variable and the reproductive phenological cycles of each mango cultivar. The differences in the mango fruit quality in each cultivar between 2013 and 2014 were statistically analysed using ANOVA with Tukey's honestly significant difference method. All statistical analyses were performed using the R version 3.6.2 application (RStudio Team, 2020).

RESULTS

Climate Change in Makassar from 1979 to 2014

The annual rainfall intensity fluctuated from 1979 to 2013 (Fig. 1 top). There was a trend of increasing annual total rainfall, and after 1995, years with a rainfall intensity of more than 2,500 mm were more common. In line with this trend, the proportion of wet months in a year also tended to increase annually (Fig. 1 bottom). The results of the climate type assessment (according to the climate classification system by Schmidt-Ferguson) based on two periods of 10-year rainfall data (1979-1989 and 2003-2013) showed a change in climate type from type D (moderate) during 1979-1989 to type C (somewhat wet) from 2003-2013. These data indicate that the climate in the study area became wetter.

A change in the seasonal pattern from 1979 to 2013 was also detected. Data on the number of dry, humid, and wet months (Fig. 2) show that from 1979-1994, wet months were mostly concentrated earlier in the year, from January to April, and then started again from November to December. However, since 1999, the total number of wet months increased, with the initial period extending until July and then starting again in November (or even October 1999) to December.

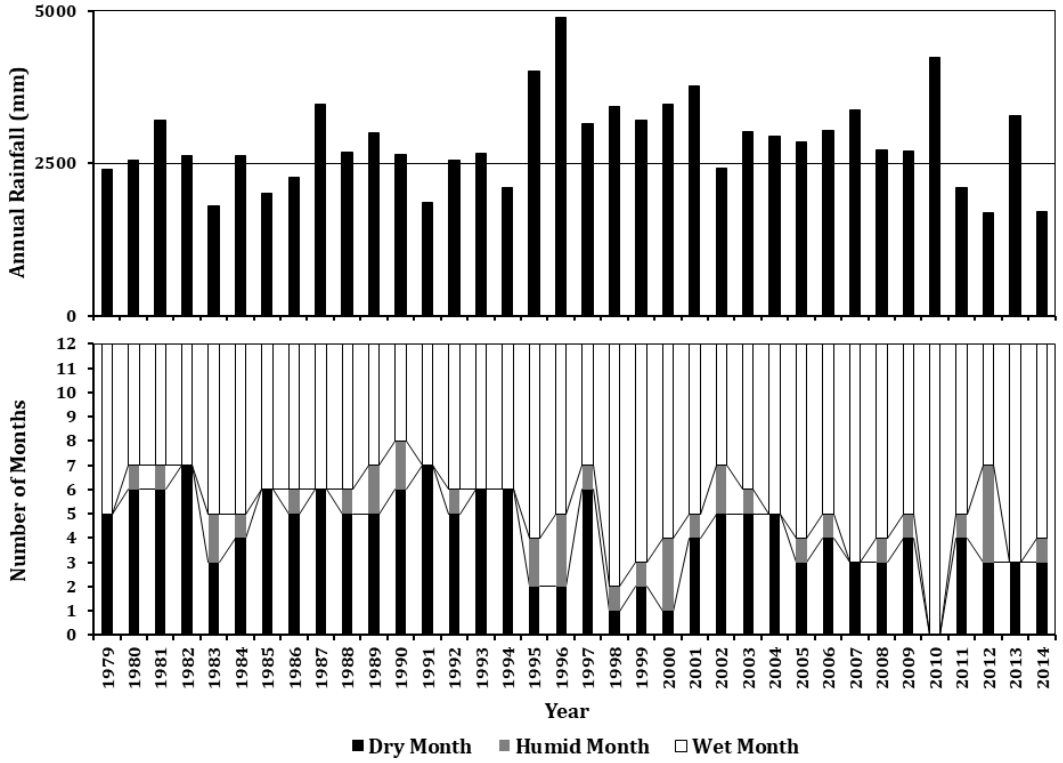

Figure 1. Annual rainfall from 1979 to 2014 (top); the number of annual dry months, humid months, and wet months from 1979–2014 (bottom)

Monthly Dynamics of Climate Variables During the Study Period

The dry season, when total monthly rainfall fell below 60 mm, was shorter in 2013 than in 2014 (Fig. 3 top). In 2013, three dry months occurred in May, August, and September, but in 2014, the dry season was more pronounced for five consecutive months from June to October. The minimum temperature also decreased with a decrease in monthly rainfall and was lowest in the middle of the dry season (Fig. 3 top). During the two years of observation, the lowest minimum temperature in 2014 (19.5 °C in September) was lower than in 2013 (21.3 °C in August). The opposite occurred for the maximum temperature, which increased with the decrease in monthly rainfall and reached its peak at the end of the dry season. The highest maximum temperature in 2014 (35.6 °C in October) was higher than in 2013 (34.2 °C in October). These data indicate that when the dry season is longer and more severe, the maximum temperature increases and the minimum temperature decreases.

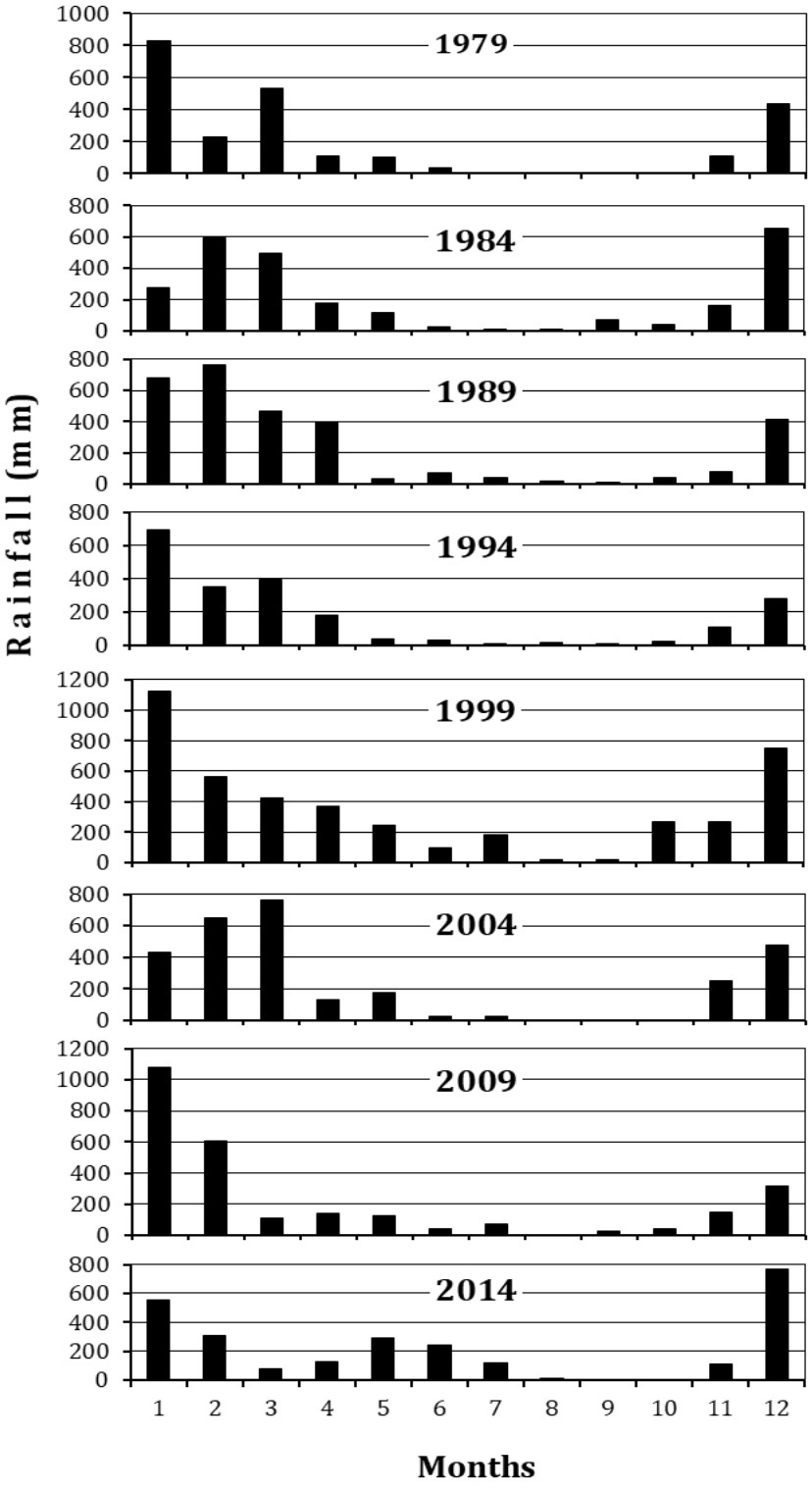

Figure 2. The distribution of dry months, humid months, and wet months in 1979, 1984, 1989, 1994, 1999, 2004, 2009, and 2014

The mean monthly humidity fluctuated following the intensity of rainfall; it decreased when rainfall decreased and increased when rainfall increased (Fig. 3 bottom). The mean monthly percentage of solar radiation also fluctuated sharply from month to month. However, the pattern of fluctuation showed an opposite trend to the fluctuation patterns of monthly rainfall and monthly humidity. In both 2013 and 2014, the average monthly percentage of solar radiation reached its climax during the dry season.

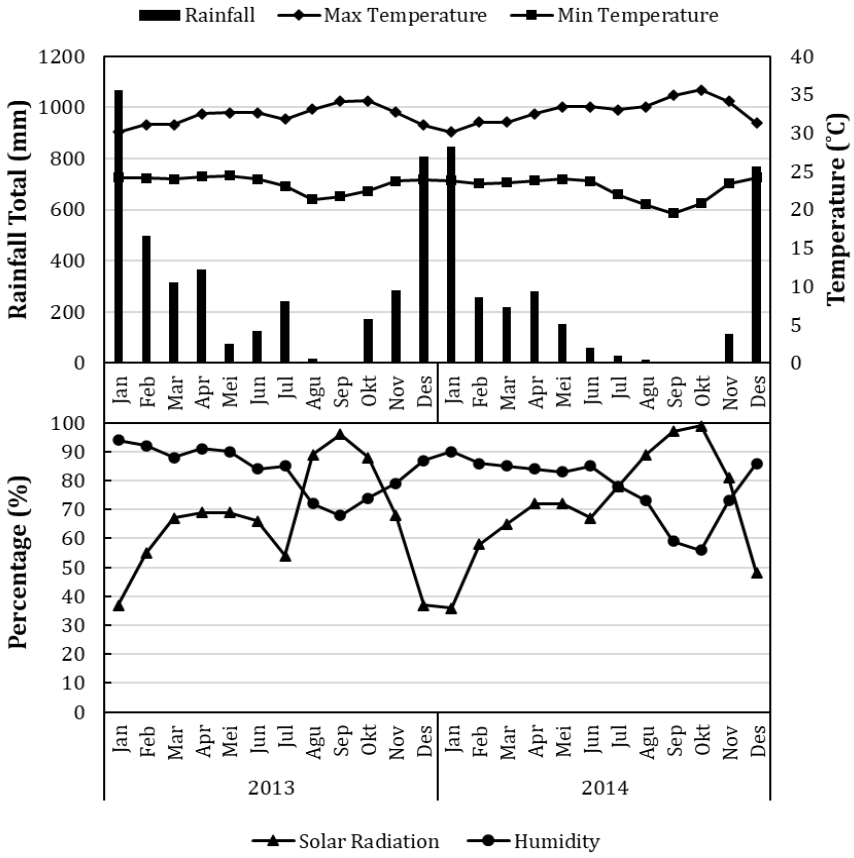

Figure 3. Monthly rainfall, maximum temperature, and minimum temperature from 2013 to 2014 (top); solar radiation and humidity from 2013 to 2014 (bottom)

Mango Phenology Pre- and Post-Climate Change

All 20 interviewees agreed that when they were young (between the 1970s and 1980s), native mango cultivars were more common than hybrid mangoes. They revealed that the mango fruiting season at that time generally occurred simultaneously once a year, starting with the flowering cycle at the beginning of the dry season, around May to June. The fruit ripened from the end of the dry season to the beginning of the wet season (around October to November). Respondents who owned mango plantations also stated that mangoes were mass-produced almost every year. However, there were years when the mango trees produced less fruit.

Our observations from mid-2013 to late 2014 showed that all four mango cultivars periodically exhibited similar phenological patterns (Fig. 4). There were two periods of vegetative shoot flush a year, with the first period occurring around the end of March to early April. Among the four cultivars in 2014, only taipa juru' produced flowers after the first vegetative flush in April, but the flowers failed to develop into fruit. The second vegetative flush occurred from mid-July to early August, about two months after the failure of the first flush. For all cultivars, the second vegetative shoot flush was followed by a generative shoot flush from early to late August. The flowers produced after the second flush of vegetative shoots managed to develop into fruit that began to ripen from late October to early November. The second period of vegetative shoot flush in 2014 occurred approximately one month earlier than the period in 2013. Correspondingly, the fruit ripening period also occurred about a week earlier in 2014 than in 2013.

Production of shoots, flowers, and fruits

The number of vegetative shoots (measured by the proportion of newly reddened shoots to total shoots) produced by all cultivars was greater in 2014 than in 2013, with an average of less than 60% in 2013 but more than 60% in 2014 (Fig. 5). The number of generative shoots, which come next, produced by all

cultivars was also greater in 2014 compared to 2013, with an average of less than 40% in 2013 and more than 40% in 2014. However, the proportion of fruit that persisted until ripe varied across the cultivars. The proportion of taipa golla-golla fruit that successfully developed into ripe fruit was lower in 2014 than in 2013. In contrast, the proportion of fruit from the three other cultivars that successfully developed into ripe fruit was higher in 2014 than in 2013.

Fruit quality during the two periods of the fruiting season (i.e. 2013 and 2014) showed that the mean sugar level of taipa juru' and taipa golla-golla fruits in 2014 was significantly higher than in 2013 (P=0.001, df=1, f=17.0792 for taipa juru' and df=1, P=0.001, f=37.1018 for taipa golla-golla) (Fig. 6 top). However, the taipa banyak papan fruit had a significantly lower sugar level in 2014 than in 2013 (df=1, P=0.001, f=1.9136). There was no significant difference in the mean sugar level of taipa mu'musang fruit in 2013 and 2014 (P=0.6195, df=1, f=0.2482). Among the four cultivars, the mean sugar content of the taipa mu'musang fruit was the highest, while the lowest was taipa juru', which corresponds to the name 'juru', which means lime, indicating a sour taste.

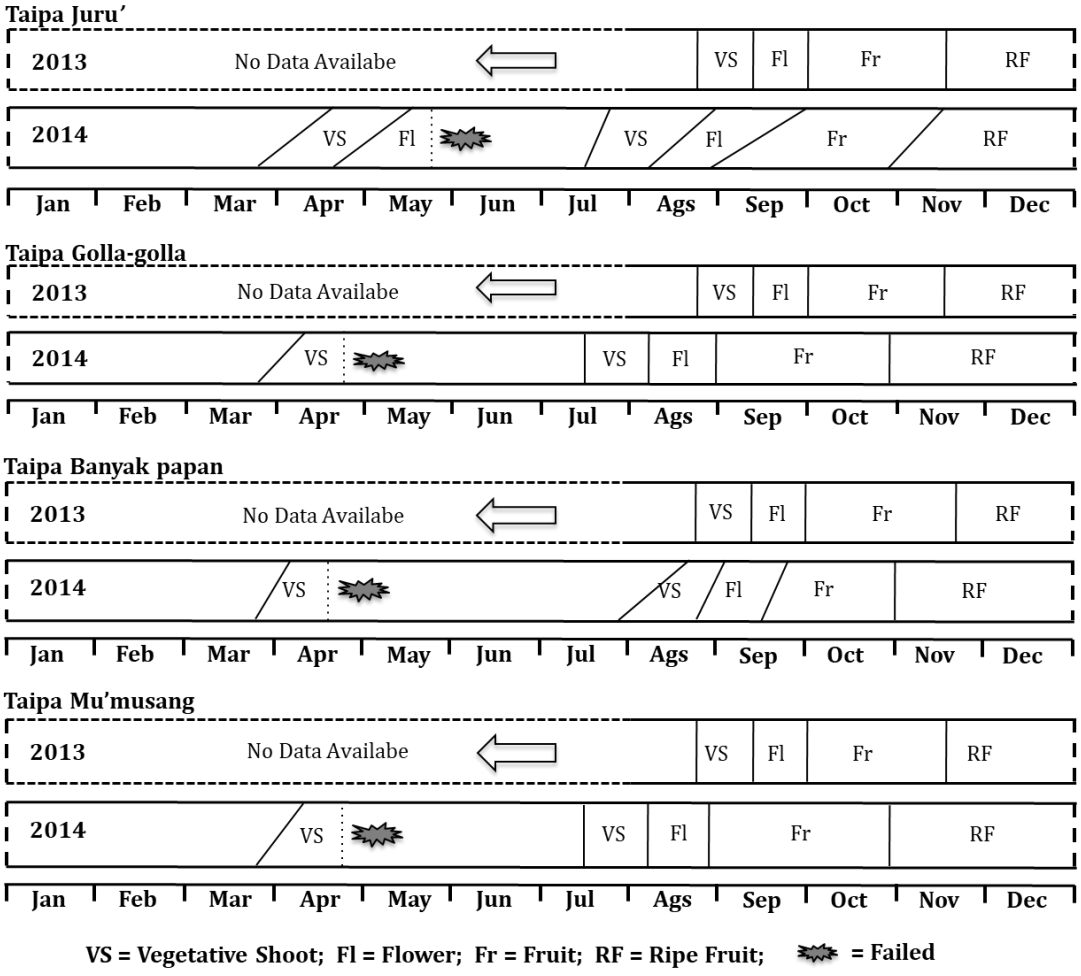

Figure 4. The reproductive phenological cycle of taipa juru', taipa golla-golla, taipa banyak papan, and taipa mu'musang from 2013 to 2014

Another indicator used to determine fruit quality is fruit size, which is indicated by its weight. Among the four cultivars, the mean fruit size of taipa juru' was the largest, followed by taipa banyak papan, taipa golla-golla, and taipa mu'musang. However, the mean fruit size of taipa golla-golla and taipa mu'musang was not significantly different (df=1, f=2.883, P=0.0926). The mean weight of fruits between 2013 and 2014 was not significantly different for the four cultivars (taipa juru': df=1, f=0.258, P=0.6125; taipa golla-golla: df=1, f=2.883, P=0.0928; taipa banyak papan: df=1, f=61.38, P=5.705; taipa mu'musang: df=1, f=0.2482, P=0.6198) (Fig. 6 bottom).

DISCUSSION

This study provides additional evidence supporting the climate change hypothesis. In Makassar city, the climate changed from type D (before 1989) to type C (after 2003) according to the Schmidt-Ferguson climate classification system, which shows that the climate in Makassar is getting wetter. Rainfall or precipitation is one of the climate elements in addition to temperature, humidity, wind, and solar radiation. As climate elements affect each other, changes in rainfall will also indicate changes in other climate elements (Coumou et al., 2014). Each species of plant has a tolerance limit to environmental factors, especially climatic elements (Bertin, 2008; Haggerty & Gallowy, 2011). Therefore, climate change in an area can impact the phenology of plant species, which will determine their regeneration ability in the long term.

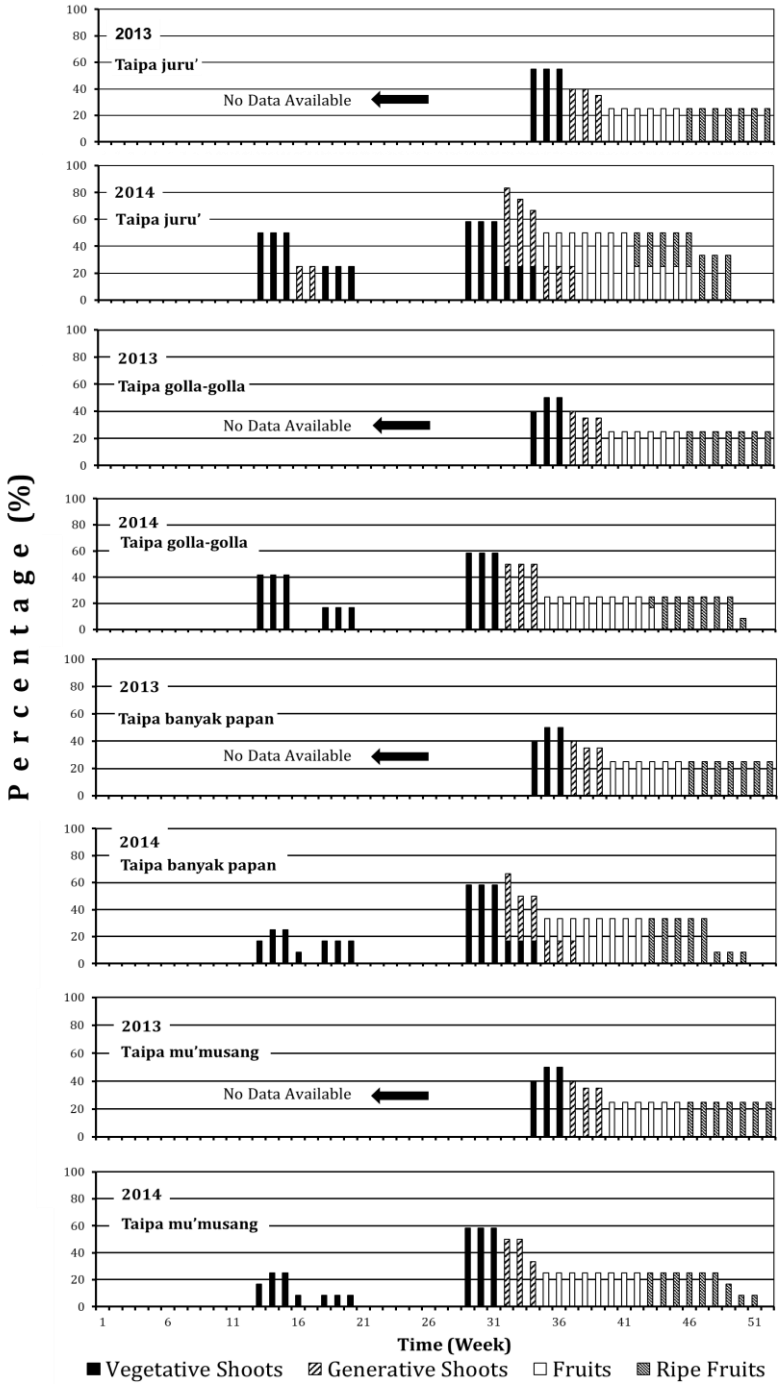

Figure 5. Percentage of the crown covered by vegetative shoots, generative shoots, fruits, and ripe fruits of the four local mango cultivars: taipa juru', taipa golla-golla, taipa banyak papan, and taipa mu'musang

Mango growth is intermittent, not continuous. Vegetative shoots may flush several times per year. However, as uncovered by Davenport (2007), interviews with mango plantation owners revealed that under normal climatic conditions, the typical flushing of reproductive shoots only occurs once a year. The initiation of the flush of vegetative shoots of resting stems is the first event that must occur to produce generative shoots (Davenport & Núñez-Eliséa, 1997; Davenport, 2009). Davenport (2003) revealed that in a subtropical region, the shoot initiation of the mango species may also be stimulated by pruning, defoliation, irrigation during dry conditions, and the application of nitrogen fertilizer in addition to environmental factors. One of the main environmental factors influencing mango flowering in a subtropical region is the shift from cool to warm temperatures (Davenport & Núñez-Eliséa, 1997). However, in the warm tropical region of Guanacaste in Costa Rica, Frankie et al. (1974) reported that vegetative shoot flush followed by the generative shoot flush of forest trees occurred during the onset of the dry season.

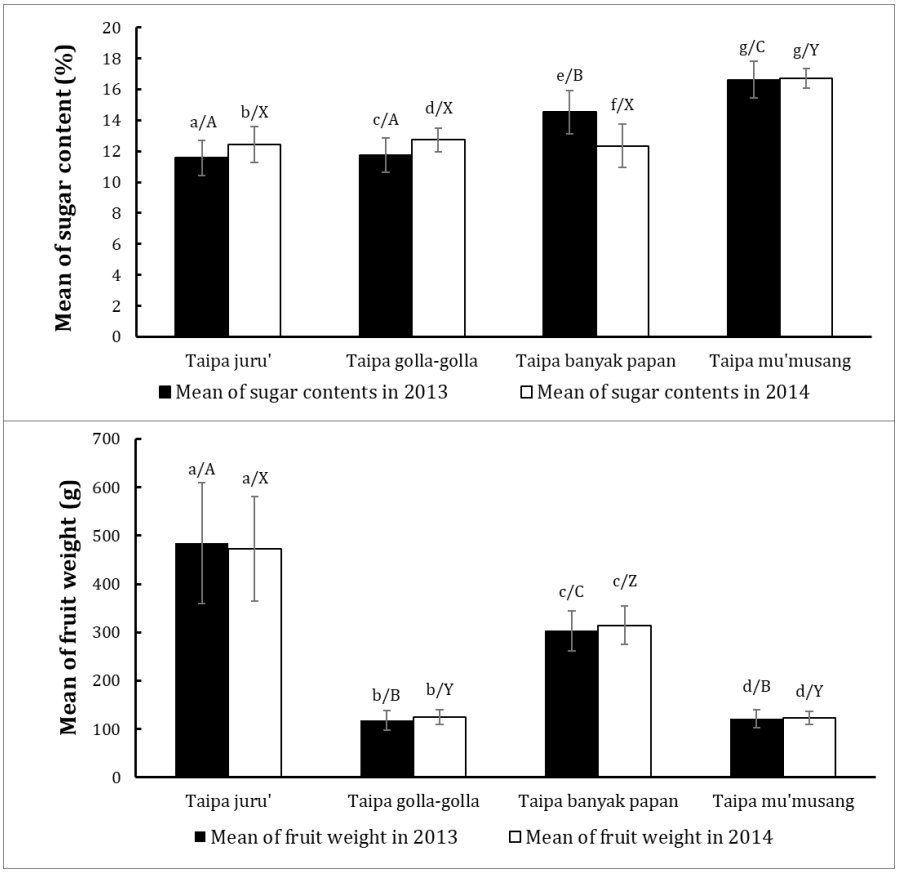

Figure 6. Comparison of mean sugar level (top) and mean fruit weight (bottom) of the four local mango cultivars in 2013 and 2014; different lowercase letters above the bars of each cultivar indicate significant differences between years, and different capital letters indicate significant differences between cultivars in the same year ($P<0.05$)

In this study, mango plantation owners in Makassar revealed that before the 1980s, local mangos typically produced generative shoots from April to May, during the onset of the dry season. The production of generative shoots was usually initiated by a mass flush of vegetative shoots. Fruit development took place during the dry season, and the fruit ripened during the late dry season until the onset of the wet season, which usually occurred from late October until November. Two years of observation in 2013 and 2014 indicate that the vegetative shoot flushing period of local mangoes in Makassar occurred twice a year. During the first period in March, only the taipa juru' successfully produced generative shoots; however, the flowers failed to develop into fruit. During the second period of vegetative shoot flush that occurred from July to August, all four mango cultivars successfully produced shoots that developed into fruit. These data suggest that there has been a shift in the period of generative shoot flush from April to May (before the 1980s) to

July until August, whereas the fruit ripening period has not shifted. The shifting pattern of the generative shoot flushes is exactly aligned with the pattern of a prolonged wet season. The flush of generative shoots that previously occurred during the onset of the dry season in May shifted to late August in 2013 and the middle of July in 2014 as the end of the wet seasons was prolonged.

The failure of taipa golla-golla, taipa banyak papan, and taipa mu'musang to produce generative shoots after the emergence of vegetative shoots and the failure of taipa juru' flowers to develop into fruit in April 2014 seem to be closely related to the dynamics of climate elements at the time. Declining rainfall, increasing solar radiation intensity, increasing maximum temperature, and decreasing humidity from February to March 2014 appear to be signals detected by the four mango cultivars as the time to start reproduction. However, increasing rainfall in the subsequent month (April 2014) disrupted these signals. Flowering is the beginning of the reproduction process that includes several steps ranging from anthesis, pollination, fruit development, fruit maturation, and fruit ripening. Normand et al. (2015) suggest that climatic variables can influence processes of agronomical importance for the mango tree, that is, photosynthesis, vegetative and reproductive development, and fruit quality. This study also shows that the ability of a mango tree to produce generative shoots and maintain fruit development until ripening is closely related to the fluctuation pattern of climate elements. The flush of generative shoots occurs during the onset of the dry season when solar radiation and maximum temperature begin to rise, and humidity and minimum temperature begin to decline. During the process of fruit development, solar radiation and maximum temperature continuously rise. The fruit starts to ripen when solar radiation and the maximum temperature decrease and humidity and the minimum temperature begin to rise, signaling that the wet season will soon begin. Thus, the results from this study suggest that climate change affects the cycle of reproductive phenology of the local mango cultivars in Makassar, as each stage in the reproductive phenology cycle is closely related to the dynamics of climate elements.

As climatic elements can influence processes of agronomical importance for the mango tree (Normand et al., 2015), the time between generative shoot flush until the fruit becomes ripe has become shorter due to climate change, which, in turn, probably affects the quantity and quality of the fruit. For two of the four cultivars observed in this study (taipa juru' and taipa golla-golla), the mean sugar levels of the fruit were significantly higher in 2014 than in 2013. In contrast, the mean sugar level of the taipa banyak papan fruit was significantly lower in 2014 than in 2013. Léchaudel & Joas (2007) found that light (solar radiation), temperature, carbon, and water availability are among the main environmental factors influencing fruit development, particularly in mangos. Among these factors, light and temperature have the most important role by directly affecting photosynthetic photon flux on the rate of electron flow (Farquhar et al., 1980). In line with the difference in fruit quality of taipa juru' and taipa golla-golla between 2013 and 2014, data on climate elements indicate that the dry season was longer in 2014 than in 2013. Additionally, the maximum temperature and the percentage of solar radiation in 2014 were also higher than those in 2013. In contrast, the humidity was lower in 2014 than in 2013. Thus, this study clearly shows that to produce better quality fruit, mango trees require a longer dry season when the percentage of solar radiation is greater. For taipa banyak papan, the mean sugar level was lower in 2014 than in 2013, which may be due to the delay in the flushing of generative shoot initiation that year. Field observations found that the taipa banyak papan fruit did not ripen normally and looked like it had been attacked by fungi, as the colour of the fruit flesh was pale.

It is recognised that good-quality fruit is characterised by high levels of carbohydrates (Ferreyra et al., 2006; Prudent et al., 2012; Ara et al., 2014). Carbohydrates are produced by plants through the process of photosynthesis by synthesising CO_2, water, and solar energy. CO_2 is always available as it is abundant in the atmosphere (Leakey et al., 2006). As mango trees are large trees with deep and intensively developed root systems in the aquifer, they will not experience water limitation for photosynthesis, even during the dry season. Thus, light (solar radiation) plays a key role in photosynthesis, as it synthesises water and CO_2 into carbohydrates to develop and ripen the fruit (da Silva et al., 2014). This appears to be the reason the reproductive phenology of the mango occurs during the dry season, and the sugar levels of mangoes are higher when the dry season is longer.

This study explains how climate change has an impact on phenological cycle disruptions and the quality of the fruit produced by the mango tree. This effect is not unique to the mango tree species as it has

been reported for other plant species; for example, McEwan et al. (2011) for *Galanthus* sp. and *Crocus flavus*, Apiratikorn et al. (2012) for *Garcinia mangostana*, Zhao et al. (2013) for five families (Bignoniaceae, Combretaceae, Dipterocarpaceae, Mimosaceae and Papilionaceae) and Dai et al. (2013) for woody plants from 26 families (Aceraceae, Anacardiaceae, Betulaceae, Cornaceae, Ebenaceae, Euphorbiaceae, Ginkgoaceae, Juglandaceae, Leguminosae, Lythraceae, Malvaceae, Meliaceae, Moraceae, Oleaceae, Paeoniaceae, Platanaceae, Punicaceae, Rosaceae, Rutaceae, Salicaceae, Sapindaceae, Simaroubaceae, Sterculiaceae, Taxodiaceae, Ulmaceae and Verbenaceae). Bradley et al. (1999) and Marta et al. (2010) state that when climate change occurs within the limits of tolerance, each tree species will attempt to adapt its phenological cycle to changing weather patterns. However, if climate change is more extreme and surpasses the limits of tolerance of a plant species, the plant species may become extinct from their original habitat due to an inability to successfully reproduce. Further research is needed to detect whether mango seeds produced from shorter fruit development periods will have the same germination rate and whether the seedlings germinated from such seeds will have the same fitness as the seeds and seedlings that result from the longer/normal fruit development period.

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AUTHOR CONTRIBUTIONS

Andi Siady Hamzah: Material preparation, data collection, data analysis, and manuscript writing; Putu Oka Ngakan: research conceptualization, research coordinator, data analysis, data interpretation, manuscript writing; Kaimuddin Kaimuddin: member contributor, research implementer, interpretation; Nasri Nasri: member contributor, research implementer, interpretation, manuscript writing; Putu Supadma Putra: member contributor, manuscript writing; Wardiman Mas'ud: member contributor, manuscript writing.

CONFLICTS OF INTEREST

On behalf of all authors, the corresponding author certifies that we have no competing financial, intellectual properties, or personal relationship interests that could influence the work reported in this paper. The funder had no role in research design, data collection, data analysis and interpretation, writing the manuscript, and the decision to publish the results.

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