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DIFFERENTIAL EFFECTS OF PRECIPITATION AND TEMPERATURE ON SEED PHENOLOGY AND SEED PRODUCTION IN *AGATHIS MACROPHYLLA* IN FIJI

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Agathis macrophylla (Araucariaceae) is a native tree in Fiji, found in Vanuatu and Solomon Islands, that is of great socio-economic value, ecological significance and cultural importance. Due to the impact of climate change on biodiversity, this bio-geographical study was initiated to analyse a 30-year (1989–2019) data set from the Monasasvu Meteorological station, using descriptive statistics coupled with Mann-Kendall and Sen's Slope test methods. The study detected the trend and impact of precipitation and rainfall on the fruiting phenology, mean fruit weight, total number of seed produced, volume seed count and germinants propagated for *A. macrophylla* from the Nausori Highlands, Ba Province, Western Division of Fiji for the period 2010–2019. The results showed significant deviation in the flowering and fruiting seasons and emergence of fruit cones which were observed between April to May, a five-month delay from the seed phenology calendar. There has also been a significant shift in fruiting and maturity richness and intensity as it occurred in the months when both the precipitation (456–652 mm) and temperature (26.8–28.6 °C) were higher. The phenological response to these climate variables was astounding as the coefficient of variation for the average fruit weight, seed numbers and germination rate ranged between 65–73%. This calls for more concerted conservation action in the identification and mapping of mature seed trees, a moratorium on timber harvesting during its fruiting and maturity seasons, establishing at least two seed stands, and germinating larger numbers of seedlings following mast seed years and holding them in the nursery under specific conditions until required for field planting.

Keywords: *Agathis macrophylla,* precipitation, temperature, Mann-Kendall, seed phenology, Fiji Nausori Highlands

INTRODUCTION

Climate change is having profound impacts on forest dynamics, resulting in changes in species composition and forest cover. Predictions have been made that unprecedented climates will be experienced earlier in the tropics because of their historically more stable climates, and the increase with any of the climate drivers, e.g. precipitation or temperature, has the capability of exceeding historical variability (Mora et al. 2013).

As part of understanding the relationship between climate, climate change and its influence on tree species, there is a need to study the relationship between temperature, precipitation and flowering/fruiting phenology (Rathcke & Lacey 1985, Crimmins et al. 2011).

Many studies have reported seasonally earlier first flowering dates across ecosystems in response to climate change, i.e. increasing temperatures are the most important climatic variable driving such changes (Sparks and Carey 1995, Ahas et al. 2002, Scheifinger et al. 2003, Menzel et al. 2006, Zheng et al. 2006, Primack et al. 2009, Dunnell & Travers 2011). In addition to shifts in first flowering dates, secondary effects include disrupting flowering and fruiting phenology within communities across the entire growing season by altering co-flowering patterns, redistributing floral and fruit abundance across the season, as well increasing the duration of the flowering season (Aldridge et al. 2011, Caradonna et al. 2014).

These phenological changes are likely to have major impacts on Pacific Islands forests and tree species. In addition to their immense scientific and biodiversity importance, these forests and trees also play an integral role in the culture, health and livelihoods of Pacific islanders and are critical for adaptation to climate change, economic stability and resilience to all forms of changes (Collins et al. 1991, Moorhead, 2011).

Agathis macrophylla is a monoecious gymnosperm, famously known as the Pacific Kauri in the South Pacific region, where it occurs in Fiji, Solomon Islands and Vanuatu. In Fiji, *A. macrophylla* is known as 'dakua makadre' and is found to be prevalent in both lowland and lower montane subtropical rainforest on the main islands of Viti Levu, Vanua Levu, Taveuni, Qamea, Ovalau and Kadavu, where it occurs from near sea level to 1150 m, mostly from 600 to 900 m elevation (Thomson 2006, Keppel et al. 2018).

Dakua makadre produces high quality furniture timber with excellent gluing and peeling properties. Its wood and non wood values have social implications such as improved livelihood, with a shift to agroforestry, and is listed as a key species with multiple uses such as interplanting and shifting gardens, improved fellows , boundary plantings, upper-story wind breaks and woodlots (Thomson 2006, Keppel et al. 2018). Culturally, dakua makadre is revered as a totem in some provinces, and for some, its resin is used for glacing in pottery. This is especially so in the interior of Nadroga/Navosa province where it is not only a source of income but also a key component in the retention of traditional knowledge of this ancient practice. Furthermore, due to its long life span and its traditional importance, its is often planted as a landmark tree in official ceremonies to mark the significance of the event.

Unfortunately, logging and deforestation have been the key causes of the continuing decline in the population of this species in Fiji, and exacerbated by the near total lack of protected areas. This has led to its listing under section seven (7) of Fiji's Endangered and Protected species Act 2002 and classification as endangered in the IUCN Red List of Threatened Species.

In terms of its phenology, dakua makadre has been observed to bear fruits in early January with seed maturing 13–15 months later from February to March (Thomson 2006). However, changes in weather patterns, intensified over the past decade, may invoke different adaptations and coping strategies in different tree species including changes in their phenology, physiology and behaviour, and changes in months and duration of flowering and fruiting (Saulei et al. 2012).

This study seeks to identify the impact of change in weather patterns over the three past decades (1989–2019) on the phenology of dakua makadre and the implications on regeneration, ecology and conservation. The study specifically considered the following queries:

(1) Has there been a change in precipitation and temperature in the Nausori Highlands region between 1989 and 2019?
(2) How does the seed phenology of *A. macrophylla* respond to annual variability in temperature and precipitation?
(3) How does temperature and precipitation affect the fruit weight, dry weight and seed production of *A. macrophylla*?

MATERIALS AND METHODS

Study site

Seed phenology was carried out in the Nadarivatu-Nadala Forest Reserve which is located on one of the jagged dividing ranges of the western side of Viti Levu, Fiji. The centre of the study site is situated at 17° 35' S and 177° 58' E, with elevation ranging from 700–740 meters, and the total study area covering about 7400 ha.

The collection of dakua makadre seeds was carried out in tropical forest remnants along the Nadarivatu and Nausori Highlands range, near the following villages: Nadarivatu, Koro O, Nadala, Navai, Lewa, Nadrau, Nabutautau, Nanoko, Bukuya and Nausori Highlands.

Climate parameters

Data source

Climatic information of the Monasavu Meteorological Station from 1989 to 2019 was obtained from the Nadi Meteorological Office in order to better understand and document the climate of Nausori Highlands range.

The Monasavu Station was chosen because its climate is representative of the environment in the Nausori Highlands Range and importantly, it had the most consistent value of meteorological data set compared to Nadarivatu Metrological Station, for the study timeframe.

In order to determine whether precipitation and temperature in the study area had changed over the 30-year timeframe, monthly data of climatic parameters, temperature (maximum and minimum in °C) and precipitation (mm) were investigated. A climograph was created from the data to depict the trends, and descriptive statistics were used to study changes over time in the mean, standard error, median, standard deviation, sample variance, kurtosis, skewness, range, minimum and maximum (temperature), coefficient of variance and confidence level (95.0%) of temperature and precipitation.

Non-parametric test

The effect of outliers and other forms of non-normality are usually much less affected by Non-parametric statistics and represent a measure of monotonic linear dependence (Davis 1986, Rossi et al. 1992, Lanzante 1996).

Mann-Kendall test

Mann-Kendall test is a statistical test widely used for the analysis of trend in climatologic and hydrologic time series (Yue & Wang 2004, Mavromatis & Stathis 2011). There are two advantages of using this test. First, it is a non-parametric test which can be employed where data is not normally distributed. Second, due to inhomogeneous time series the test has low sensitivity to abrupt breaks (Tabari et al. 2011). Any data reported as non-detects are included by assigning them a common value that is smaller than the smallest measured value in the data set. According to this test, the null hypothesis (H_0) assumes that there is no trend (the data is independent and randomly ordered), and this is tested against the alternative hypothesis (H_1) which assumes that there is a trend (Onoz & Bayazit 2012).

The Mann-Kendall S statistic is computed as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j}^{n} i + 1 \ \mathrm{Sign}(T_j - T_i) \qquad 1$$

$$\mathrm{Sign}(T_f - T_I = \begin{cases} 1 & \text{if } T_j - T_I > 0 \\ 0 & \text{if } T_j - T_i = 0 \\ -1 & \text{if } T_j - T_i < 0 \end{cases} \qquad 2$$

where Tj and Ti are the annual values in years j and i, j > i, respectively (Motiee & McBean 2009).

The standard test statistic Zs is calculated as follows:

$$Z_s = \begin{cases} \frac{s-1}{\sigma} \text{ for } S > 0 \\ 0 \text{ for } S = 0 \\ \frac{s+1}{\sigma} \text{ for } S < 0 \end{cases} \qquad 3$$

where the test statistic Zs is used as a measure of significance of trend and is used to test the null hypothesis, H_0. If | Zs| is greater than $Z\alpha/2$, where α represents the chosen significance level (e.g. 5% with Z 0.025 = 1.96) then the null hypothesis is invalid implying that the trend is significant.

Sen's slope

To estimate the true slope of an existing trend as change per year, the Sen's method is used where there is an assumption that the trend is linear. Sen's slope is defined as:

$$f(t) = Q(t) + B \qquad 4$$

where Q is the slope and B is a constant.

To get the slope estimate (Q), the slopes of all data pairs were calculated using the following equation:

$$Q1 = \frac{x_j - x_i}{j - k} \qquad 5$$

where j > k

A 1–α confidence interval for Sen's slope can be calculated as (lower, upper):

$$N = C\ (n,2) \qquad k = se.Z_{crt} \qquad 6$$

$$\text{lower} = x_{(n-k/_2)} \qquad \text{upper} = x_{(n+k/_{2+1})} \qquad 7$$

where N = the number of pairs of time series elements (xi, xj) where i < j and se = the standard error for the Mann-Kendall test.

The statistical Mann-Kendall test was performed using the software Addinsoft XLSTAT 2012 (Addinsoft 2012). The null hypothesis was tested at 95% confidence level for both temperature and precipitation data to detect any possible trends in the data over the study period, where positive (+) values indicate an increase over time while negative (-) values indicate a downward trend (Xu et al. 2010).

Species phenology

Once a month, the seed technology team visited the research site to carry out phenological studies on the native trees in the reserve. Close attention was given to ten *A. macrophylla* trees and the summary findings are shown in Table 2. The team was able to draw up the seed phenology calendar for *A. macrophylla* from the observations carried out over 19 years (2000 to 2019).

The criteria for these phenological surveys, as applied to each of the selected trees, are in accordance to the presence or absence of fruits and flowers, and when present, their abundance is graded on a scale from 0–3 (Table 1). Zero is indicative that there is no fruiting and flowering whilst three is indicative that heavy fruiting / flowering was observed. The fruits were also assessed for their maturation state in accordance with the observed fruit colour.

These data were used to develop a seed collection calendar that is tabulated in Table 2.

Seed collection

The fruit of dakua makadre matured over a span of about 13–15 months undergoing a series of colour changes from green to brown which is indicative that fruit is ready for collection.

The fruit collection method involved a team of two collectors. One climbed the dakua tree using spikes while the other stayed on the ground as an anchor. The matured fruits from the ten trees in the reserve area and fruiting trees in the neighbouring villages were dislodged using poles and collected in sacks, which were labelled before transportation back to the seed technology laboratory.

Fruit weight analysis

At the laboratory, the sacks of fruits were weighed individually and recorded as total fruit weight of all trees.

The fruits were then left in a well-ventilated room (at ambient temperature) for a period of 2–3 days to allow the fruits to open naturally. In this process the woody brown scales disintegrated and allowed the brown winged seeds to detach from the cone. The seeds were then collected, weighed and sown onto germination trays.

RESULTS AND DISCUSSION

Precipitation trends

The first objective was to determine whether there has been a change in precipitation and temperature at Monasavu between 1989 and 2019. A climograph for the Monasavu region (Figure 1) depicts the variance in both rainfall and temperature for the study time frame.

The results of descriptive statistics analysis of the annual precipitation data are presented in Tables 3. In order to ascertain and classify the degree of variability of rainfall in this region, the classification was according to Harew (2003) whereby the value of coefficient of variance (CV) is classified into the following: less (CV < 20), moderate (20 < CV < 30), high (CV > 30), very high (CV > 40%) and extremely high (CV > 70%) indicating inter-annual variability of rainfall. The results showed that all the months had above 30% coefficient of variation which is indicative that the Nadarivatu range had a high variability of precipitation over the 30-year timeframe.

The annual rainfall for the Nausori Highlands range varied from 4000 to 6870 mm (Table 4). Statistical analysis of the data showed that the mean precipitation received on a monthly basis

Table 1 Phenological survey criteria

Stages	Description
0	Not Flowering / fruiting
1	Light flowering/fruiting
2	Moderate flowering/fruiting
3	Heavy fruiting

Note The phenology and abundance of seeds of *A. macrophylla* were tracked for most years between 1999 and 2019 (except for 1999)

Table 2 Phenological calendar of *A. macrophylla*

Species	Appearance of first cones	Fruiting	Maturity and seed storage category
Agathis macrophylla	April–May	July–Oct	December–March Orthodox

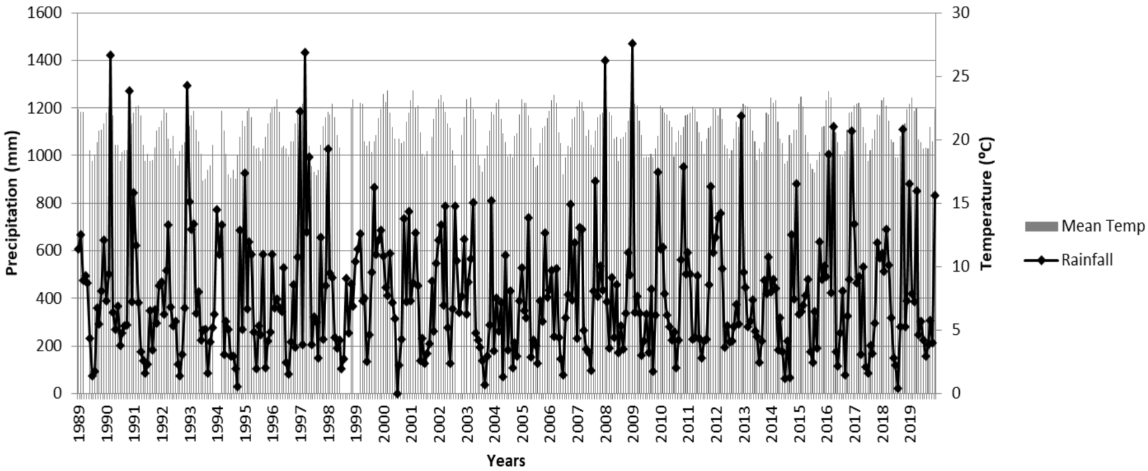

Figure 1 Average precipitation and temperature trend for the Monasavu Region from 1989–2019

Table 3 Descriptive static analysis of precipitation data from the Monasavu Metrological Station from 1989–2019

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Count	30	30	30	30	30	30	30	30	30	30	30	30
Mean	652	503	533	467	307	239	188	249	282	406	456	609
Std Error	56.9	29.3	53.4	43.3	31.6	21.7	16.1	28.4	39.5	43.2	45.8	48.0
Median	587	475	433	401	272	225	189	220	220	346	395	559
SD	312	161	293	237	173	119	88	155	216	236	251	263
SV	97240	25766	85659	56218	29968	14064	7803	24170	46762	55875	62836	69016
Kurtosis	1.10	2.04	4.41	0.41	7.79	2.00	-0.62	3.68	2.25	1.31	2.74	0.63
Skewness	1.09	1.04	1.93	0.84	2.24	1.38	0.05	1.58	1.56	0.94	1.53	1.05
Range	1290	799	1245	957	923	494	357	765	855	1080	1116	1037
Min	180	208	190	164	72	85	0	21	38	31	155	257
Max	1469	1006	1435	1121	995	580	357	786	893	1111	1271	1294
CV	48	32	55	51	56	50	47	62	77	58	55	43
CI(95.0%)	116	60	109	89	65	44	33	58	81	88	94	98

SD:Standard Deviation;Std E: Standard Error,SV: Sample Variance, CI: Coefficient of Interval;CV : Coefficient Variance.

Table 4 Annual rainfall (mm) at Monasavu from 1989–2019

Year	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Rainfall (mm)	4838	5980	4000	5000	4651	4206	4572	4225	6820	4490	6296
Year		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Rainfall (mm)		4956	4138	6061	4282	3358	4414	4730	5040	5226	5234
Year		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Rainfall (mm)		5084	4801	5710	4257	4327	4437	6003	4441	5001	5035

ranged from 188 mm (July) to 652 mm (January), as shown in Table 3. The highest values of coefficient of Kurtosis were found in May (7.79). From the statistical analysis (Table 3), the results indicated that the data were normally distributed and the average monthly precipitation coefficient of variation ranged from 31–76 %.

In order to determine if this variability had a monotonic upward or downward trend, the precipitation patterns from the Mann-Kendall method showed a degree of variability at 95% confidence level. The month of October had the most pronounced change in precipitation, i.e., it had a Mann-Kendall trend test (MKZ) value of 2 (> 1.96) and a significant increase of 10 mm (Sen's slope value). Furthermore, the trend was higher during the cyclone season and was negative in the non-cyclone season.

Maximum and minimum temperature trends

Maximum temperature analysis

Temperature variation observed within the 30-year timeframe is depicted graphically in Figure 1. From the statistical results tabulated in Tables 5, it can be seen that significant trends were found for the maximum temperature data with a mean temperature range from 24.6–27.8 °C.

The highest value of Kurtosis was in the month of July (27 °C), which also had the lowest value of Skewness (-5.96).

The results from the Mann-Kendall test (Table 7) showed that there was a variance in the trend for maximum temperatures in the area, however, the two months that denoted significant changes (i.e. where MKZ >1.96) were the months of February and July, both of which had an increase of 0.04 °C.

It was interesting to note that despite the fact that the month of February fell within the cyclone season, there was an increase in

Table 5 Statistical summary of monthly maximum temperature for the Monasavu station from 1989–2019

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Count	30	30	30	30	30	30	30	30	30	30	30	30
Mean	27.4	26.8	28.6	27.7	26.3	25.8	24.6	25.5	24.8	27.0	27.4	27.5
Std E	0.96	1.34	0.20	0.15	0.14	0.18	0.86	0.15	1.24	0.22	0.22	0.97
Median	28.4	28.5	28.6	27.6	26.1	25.8	25.5	25.5	26.4	26.9	27.5	28.6
Mode	27.6	28.5	29.0	28.0	26.0	25.5	25.5	25.1	26.3	26.5	27.0	28.0
SD	5.28	7.32	1.10	0.80	0.77	0.99	4.73	0.82	6.79	1.20	1.18	5.30
SV	27.8	53.6	1.2	0.6	0.6	1.0	22.3	0.7	46.1	1.4	1.4	28.1
Kurtosis	27.73	11.90	0.60	1.00	-0.33	1.12	27.87	0.65	11.69	2.06	3.81	27.32
Skewness	-5.18	-3.60	0.71	0.60	0.56	0.40	-5.20	0.36	-3.55	0.33	-1.49	-5.12
Range	30.2	30.5	4.6	3.6	3.0	4.6	26.8	3.7	28.3	6.0	5.7	30.0
Min	0.0	0.0	26.8	26.2	25.0	23.7	0.0	24.0	0.0	24.5	23.5	0.0
Max	30.2	30.5	31.4	29.8	28.0	28.3	26.8	27.7	28.3	30.5	29.2	30.0
CV	19.2	27.3	3.8	2.9	2.9	3.9	19.2	3.2	27.4	4.4	4.3	19.3
Confidence Level(95.0%)	2.0	2.7	0.4	0.3	0.3	0.4	1.8	0.3	2.5	0.4	0.4	2.0

SD:Standard Deviation;Std E: Standard Error,SV: Sample Variance, CI: Coefficient of Interval;CV : Coefficient Variance.

Table 6 Statistical summary of monthly minimum temperature for the Monasavu station from 1989–2019

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Count	30	30	30	30	30	30	30	30	30	30	30	30
Mean	15.8	16.0	16.8	15.9	14.0	13.4	11.0	11.5	11.4	12.5	14.9	15.7
Std Error	0.6	0.6	0.2	0.2	0.2	0.3	0.6	0.5	0.8	0.7	0.2	0.2
Median	16.5	16.5	17.0	16.2	14.2	13.2	11.5	12.1	12.6	13.6	15.0	15.8
Mode	17.0	16.5	16.2	16.2	14.6	13.0	11.0	11.8	0.0	14.0	15.5	17.0
SD	3.2	3.3	1.2	1.2	1.0	1.5	3.2	2.5	4.2	3.6	1.1	1.2
SV	10.5	11.0	1.4	1.5	1.0	2.2	10.2	6.4	17.3	13.0	1.3	1.6
Kurtosis	20.61	19.84	0.42	1.28	-0.75	-0.85	8.98	14.98	4.08	8.92	-0.48	-0.27
Skewness	-4.21	-4.10	-0.56	-0.82	-0.42	0.09	-2.97	-3.39	-2.15	-2.97	0.19	-0.14
Range	19.0	18.9	5.1	5.5	3.6	5.5	14.2	14.0	16.2	15.8	4.5	5.0
Min	0.0	0.0	13.9	12.7	12.0	11.0	0.0	0.0	0.0	0.0	13.0	13.0
Max	19.0	18.9	19.0	18.2	15.6	16.5	14.2	14.0	16.2	15.8	17.5	18.0
Sum	474.0	480.1	504.1	478.0	420.9	403.2	331.3	345.8	343.4	374.6	447.8	472.3
CV	20.5	20.7	6.9	7.6	7.1	11.0	28.9	22.0	36.4	28.9	7.5	7.9
CI(95.0%)	1.2	1.2	0.4	0.5	0.4	0.6	1.2	0.9	1.6	1.3	0.4	0.5

SD:Standard Deviation;Std E: Standard Error,SV: Sample Variance, CI: Coefficient of Interval;CV : Coefficient Variance.

maximum temperature observed. This could be attributed to climate change, as the value is close to the global warming rate, estimated to be 0.6 °C for the past century (Papakostas et al. 2014).

Minimum temperature analysis

The mean minimum temperature observed for this region ranged from an average of 11–16 °C. January had the highest value of Kurtosis (20.6 °C) and the lowest value of Skewness (-4.21).

From the Mann–Kendall test (Table 7), the analysis showed that there was a positive trend for minimum temperature within the 30-year timeframe. The most pronounced change was observed in the month of October which showed an increase of 0.06 °C (MKZ = 2).

Changes in seed phenology in response to variation in precipitation and temperature

The key objective was to see if there was a change in seed phenology of *A. macrophylla* in response to the annual variability in temperature and precipitation.

As stated in the methodology section, the study was able to draw up the seed phenology calendar for *A. macrophylla* from the observations carried out over 19 years (2000 to 2019). The first fruit cones for *A. macrophylla* appeared from April to May, fruiting took place from July to October and fruit was fully matured 13 to 16 months later, between December to March. The fruit maturity phenology is in agreement with a previous study where observations stated that it takes place from February to March (Thomson 2006). However, there is a contrast in the months in which the first cones appear; it was observed to take place from April to May, a four to five month delay compared to the first sightings recorded to be undertaken in early January in Fiji (Thomson 2006).

From this study, it can be seen that the ideal climatic conditions for fruit cones to appear is when the precipitation range is from 300–467 mm per month, with a maximum temperature range from 26–28 °C and a minimum temperature range between 14–16 °C. Comparing this to the precipitation and temperature range for the month of January, it can be seen that its maximum and minimum temperature falls within the favourable/desired range, however, the month of January had a higher precipitation value of 652 mm. This suggests that an increase in precipitation might delay the emergence of fruits. Furthermore, phenological monitoring using the phenological calendar revealed that

Table 7 Mann-Kendall test results for annual precipitation, and maximum and minimum temperatures for the Monasavu Weather Station from 1989–2019

	Annual precipitation (1989–2019)			Maximum temperature (1989–2019)			Minimum temperature (1989–2019)		
Month	MKZ	Signif.	Sen's slope	MKZ	Signif.	Sen's slope	MKZ	Signif.	Sen's slope
Jan	-1		-4.62	1.43	ns	0.029	-0.64	ns	-0.18
Feb	0.14		0.378	2.09	**	0.04	0.43	ns	0.014
Mar	-1.46		-7.1	0.11	ns	0	1.2	ns	0.033
Apr	-0.3		-0.82	0.95	ns	0.014	0.5	ns	0.008
May	-0.11		-0.393	0.88	ns	0.013	0.04	ns	0
Jun	-1.25		-2.467	1.38	ns	0.017	0.14	ns	0.004
Jul	0.61		-1.37	1.99	**	0.042	0.25	ns	0.004
Aug	0.18		0.712	0.48	ns	0.008	0.68	ns	0.021
Sep	-0.29		-0.7	1.26	ns	0.037	1.48	ns	0.058
Oct	2	**	10.021	0.81	ns	0.011	2.22	**	0.063
Nov	0.96		3.995	1.54	ns	0.028	1.56	ns	0.4
Dec	1.57		8.464	0.91	ns	0.3	0.57	ns	0.011

ZMK is a Mann-Kendall trend test, Sen's slope is the change (days/annual), **,* is statistically significant at 0.05 and 0.1 probability level, ns is non-significant trend at 0.1, Signif = significance there was a deviation of the expected fruiting and maturity seasons, as moderate fruiting now took place from November to February which then gradually lightened in March. Moreover, there was no fruit development or post dispersal observed from April to October which are the non-cyclone seasons. And interestingly, the time frame in which the statistically significant increase in temperature of 0.04 (July) and precipitation of 10 mm (October) were also recorded.

It appears that the species responses to the variation in precipitation and temperature over time by delaying fruiting. Even if it does fruit, there has been no heavy fruiting observed with significantly higher levels of rainfall.

Another factor that can affect the emergence of cones, fruiting and maturity intensities of *A. macrophylla* is that its phenological development stages fall within the timeframe of the cyclone season in Fiji, i.e. from November to April. The heavy precipitation and winds during this season can have an impact on the development of fruits and maturity.

Impact of changes in variation of temperature and precipitation on fruit weight and seed production

A further objective was to determine the effects of changes in temperature and precipitation on fruit weight, dry weight and seed production of *A. macrophylla*.

For the 10 year timeframe in which seed collection took place, records in the seed collection register book showed a huge variance between the fruit weight, seeds and germinant produced, tabulated below and graphically shown in Figure 2.

Table 8 Observation of fruiting and maturity from 2000–2009

Month	Phenological rating
Jan	2
Feb	2
Mar	1
Apr	0
May	0
Jun	0
Jul	0
Aug	0
Sep	0
Oct	0
Nov	2
Dec	2

Table 9 Records of fruit weight, number of seeds and germinant of *Agathis macrophylla*

Year	Mean fruit weight (g)	Total no. of seeds collected	No. of germiants
2009	0	0	0
2010	735	19,304	2,184
2011	108	3,504	2,197
2013	241	3,753	1,929
2014	176	5,190	4,218
2015	206	4,087	2,762
2017	202	11,829	0
2018	304	6.812	973
2019	371	11,758	1,922

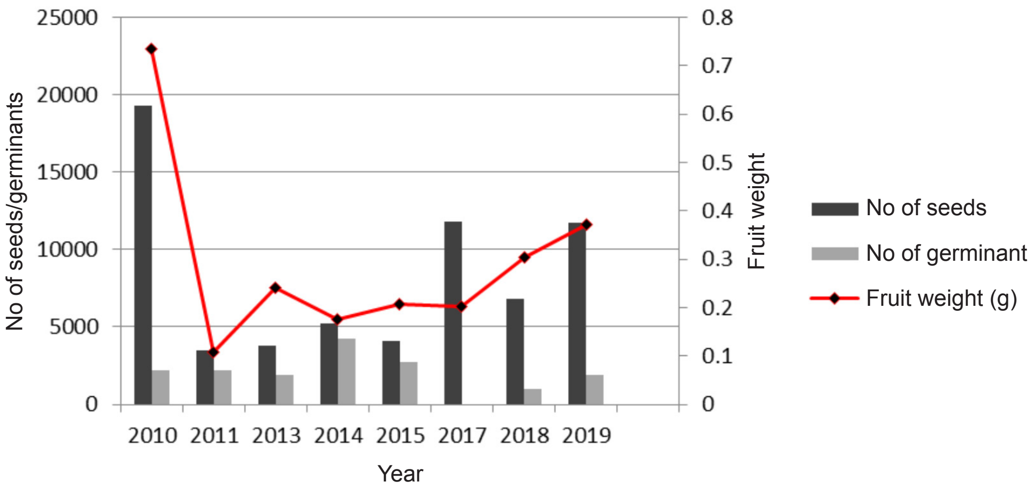

Figure 2 Fruit weight, seed and germination trend of *Agathis macrophylla* between 2010–2019

Table 10 Statistical analysis of mean fruit weight, total number of seeds collected and number of germinants produced from 2000–2019

	Fruit weight	Seeds	Germinants
Count	10	10	10
Mean	0.24	6986	1835
Standard error	0.07	1799.43	396.64
CV	87.70	81.44	68.37

CV = coefficient of variation

The fruit weight for the 10 year collection had a mean weight of 0. 24 kg resulting in 5618 seeds and 1795 germinants (Table 10).

The coefficient of variation of mean fruit weight, total number of seed collected and number of germinant counted ranged between 68–87% underlining the significant variability between them.

Analysing the relationship between the number of seeds collected and germinant produced, the results showed that there is a decline between the number of viable seeds collected and the number of germinant produced with a -0.01 correlation between them, which calls for a concerted conservation effort to address the low levels of fruit production.

Much current phenological research is directed towards understanding the effects of climate change, but it can be difficult to attribute shifts in phenology to climate change (Rosenzweig et al. 2008, Menzel 2013). Researchers have suggested that the minimum time series length in which a detection of a change in phenology can be identified is 20 years, and this is a research area that the Ministry of Forestry needs to undertake for selected priority native tree species (Sparks and Menzel 2002).

Agathis macrophylla has a maturation period over more than one year (up to 15 months) and with the observed low levels of fruit production and high portions of non-viable seeds, a more concerted seed production and collection effort is needed. It is imperative that phenological studies and seed collection needs to be carried out on a regular (fortnightly) basis and not monthly as per the current practice, as this will ensure that more accurate observations are made and that fruits are not collected prematurely.

Furthermore, due to the fact that the seeds are classified as short lived orthodox (and cannot be effectively stored between years), exemplifies the need for the identification and immediate protection of mother trees and a moratorium on its harvest during fruiting, flowering and maturity seasons and the establishment of seed stands.

CONCLUSIONS

One option available for providing a regular supply of *Agathis* and other native conifer seedlings for reforestation programs is to germinate larger numbers of seedlings following mast seed years, and hold them in the nursery under 70% shade of cloth/low light levels, without fertilising.

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