RELATIONSHIP BETWEEN TEMPERATURE IN OCTOBER AND NOVEMBER AND YIELD

J. Dixon and R. Barber
Avocado Industry Council Ltd., P.O. Box 13267, Tauranga 3110
Corresponding author: jonathandixon@nzavaocado.co.nz

ABSTRACT

The avocado tree often has an alternate bearing yield pattern. This pattern is often ascribed to pollination and fruit set being reduced by low temperatures during flowering and in the initial stages of fruit set in spring mid-October to mid-November. For avocado cultivars the best temperatures for the most effective pollination is thought to be 25°C during the day and 20°C nights. New Zealand avocado orchards are in regions with mean annual temperatures about 14°C considered to be at the climatic margin for successful avocado production. Therefore, the temperature during flowering and the initial fruit set period should allow avocado growers to predict fruit set. A study was conducted over several years to determine the relationship between temperature and yield. The yield of orchards was not correlated with average temperature, the number of pollination events, average temperature during flower opening, chilling hours or heat unit hours. It was not possible to make predictions of yields based on measurements of temperatures over the main flowering and fruit set period. There appeared to be an upper limit of yield at each average temperature that indicates temperature limits yield if other undefined factors are not limiting or are negative and lower the yield. The relationship between yields and temperature is more complex than often thought. Other factors limiting yield may be the phenology of the alternate bearing cycle, plant hormone relationships, pollination efficiency and tree nutrient status. By considering temperature as the only factor determining successful fruit set other important factors that limit fruit set are likely to be poorly managed by avocado growers. This may explain why successful management of alternate bearing has so far proven to be elusive.

Keywords: fruit set, pollination events, heat units, chilling hours

INTRODUCTION

The avocado is generally considered to be a subtropical tree prone to alternate bearing and irregular cropping (Whiley, 2002). Inconsistent crops affect the income of orchards and can make marketing programmes a challenge where there are large amounts of fruit available in one year and less fruit available in other years. The reason for the erratic cropping of avocado trees is not clearly understood but is often ascribed to pollination and fruit set being sensitive to low temperatures during flowering and in the initial stages of fruit set (Gazit and Degani, 2002). Low temperatures at flowering have been proposed by Coit (1927) to negatively affect fruit yields where he claimed that heat units calculated from the weekly average of daily maximum temperatures over a two year period was correlated to yield on two orchards. In an analysis of the bearing patterns of 598 'Fuerte' avocado trees in California from 1928 to 1934 Hodgson and Cameron (1935) also claimed that yields were correlated with mean temperatures during the period of bloom, January to March. The hypothesis was that large crop years were associated with bloom periods of above average mean temperatures and all low crop years followed bloom periods of below average mean temperatures.

Based on the claims by Coit (1927) and Hodgson and Cameron (1935) many avocado researchers consider that low temperatures during flowering and fruit set determine the yield. A number of researchers have reported that various temperature scenarios determine avocado fruit set. For example, fruit set was reported not to occur in California when the mean daily temperature is less than or equal to 13°C (Hodgson, 1947). Mean night temperatures below 8°C have been claimed to result in little or no fruit set of 'Fuerte' trees in California (Gillespie, 1956). Other researchers have suggested that low temperatures did not have an overriding affect on pollination and fruit set. Sedgely (1977a) reported that low temperatures below 10°C may delay or retard flowering and fruit set but are not detrimental. Temperatures of 17-24°C days and 9-12°C nights during several consecutive days did not affect the flowering and fruit set process of 'Hass' avocado flowers (Argaman, 1983). Under the low temperatures that typically occur during flowering 'Fuerte' pollen was found to be viable and germinate readily down to 4.4°C (Schroeder, 1942) indicating that a negative effect of low temperatures on 'Fuerte' fruit set is not due to poor pollen viability and germination.

Early research studies (1920's to 1930's) investigated the effect of temperature on fruit set and yield for the 'Fuerte' cultivar. Later researchers noted that there is a considerable difference in avocado cultivars in their tolerance to low temperatures during flowering and fruit set that is related to the type A and type B flower opening behaviour (Peterson, 1956; Sedgley and Grant, 1982/83). Type A cultivars (for example 'Hass', 'Reed') can withstand periods of low temperatures during flowering with less adverse effects on pollen tube growth and fruit set than type B cultivars (for example: 'Bacon', 'Ettinger', 'Fuerte', 'Zutano') (Griswold, 1945; Sedgley and Grant, 1982/83).

Fuerte (type B cultivar) flowers in California did not open in temperature conditions where the daily maximum and minimum temperatures were in the range of 17.8°C-21.1°C and 7.2°C-11.7°C (Lesley and Bringhurst, 1951). However, in Australia, flowers of 'Fuerte' avocado trees opened under a day/night temperature regime of 17°C/12°C (Sedgley, 1977a) although the percentage of flowers opening each day increased as the temperature increased. The germination of 'Fuerte' pollen grains and the growth rate of pollen tubes at 17°C was only 40% the rate at 25°C. At 17°C pollen tubes take about 5.8 hours to grow about 3.5mm in order to reach the ovary compared to 2.3 hours at 25°C (Sedgley, 1977a; Sedgely and Buttrose, 1978). For 'Fuerte' avocado flowers and pollen 17°C was considered to be unsuitable for effective pollination and 25°C ideal. Extrapolating these findings to other avocado cultivars has given rise to the expectation that for all avocado cultivars the most effective pollination that results in good yields the temperatures over flowering need to be 25°C during the day and 20°C nights.

In contrast, the cultivar 'Hass' has been found to be capable of setting fruit at lower temperatures than the cultivar 'Fuerte' (Sedgley and Annells, 1981). At cool temperatures, 17°C days, the duration of the bloom was increased for 'Hass' trees, the percentage of flowers opening each day was reduced and the length of time the flowers opened when functionally female was reduced with the functionally male time increased. Compared to the fruit set of the cultivar 'Fuerte' under the same temperature conditions there are more effectively pollinated 'Hass' flowers. Therefore, 'Hass' flowers were considered to be more tolerant of cooler temperatures than 'Fuerte' flowers (Sedgley and Annells, 1981). Based on the study by Sedgely and Annells (1981) the minimum temperature conditions for effective pollination of Hass avocado flowers has been set at 17°C day and 12°C night. However, given there was still effective pollination at these temperatures the low temperature limit for effective pollination of Hass flowers has not been defined.

Pollen transfer to the flowers in the female stage is considered necessary for the most effective pollination as hand pollination of male stage stigmas did not result in fruit set (Peterson, 1955; Sedgley, 1977b). The timing and duration of the opening of avocado flowers at the female stage and male stage has been determined to be temperature dependent (Sedgley, 1977a). Low temperatures change the time of day when the flowers open reducing the length of time the flowers are in the female gender. Low night temperatures change female flower opening from the morning to the afternoon (Bringhurst, 1951).

The later opening of female flowers is considered to be harmful for pollination as there is less opportunity for pollination when the female opening time is short and there is insufficient time for the pollen tube to grow to the ovule. Structural and biochemical changes in the stigma and style have been shown to occur as the flower moves from female opening to male opening, where starch is depleted and callose is deposited in the style (Sedgley, 1979). The callose then blocks the pollen tube from reaching the ovule. These changes are likely to mean that while pollen could be placed on the stigma in the male stage effective self pollination in the male gender did not happen (Peterson, 1955). Therefore for effective pollination pollen needs to be deposited onto the stigma in the female flower opening. Temperatures during the time the flowers are open in the female stage could be related to effective pollination. Warm temperatures would result in greater flower open times in the female stage, greater bee activity and a high growth rate of the pollen tube down the style. The greater amount of effective pollination should then lead to greater yields.

Avocado flowers are generally considered to require an insect pollinator as avocado trees enclosed in cages that excluded large flying insects had no or very few fruit set compared to heavy fruit sets in caged trees with bees and un-caged trees (Lesley and Bringhurst, 1951; Peterson, 1955; Robbertse *et al.*, 1998). Although effective wind pollination has been claimed to occur on avocados (Davenport *et al.*, 1984), trees in cages carefully maintained to exclude bees set very few (1 to 2) or no fruit (Degani *et al.*, 2003). Such results indicate that wind pollination will at best only result in a very small amount of fruit set. Without bees commercially viable crops of Hass avocados do not occur (Degani *et al.*, 2003). Bee activity on flowers has been observed to be greater during warm days than in cold and cloudy weather (Peterson, 1955).

In New Zealand, commercial avocado orchards are based in regions where the mean annual temperatures are about 14°C (Wolstenholme, 2002) which is considered to be at the climatic margins for successful avocado production. The temperatures during the main flowering period in spring mid-October to mid-November are often quoted by New Zealand industry commentators to be the greatest limiting factor to achieving successful yields each year. Establishing the relationship between temperature during flowering and the initial fruit set period would be useful to allow avocado growers to better predict fruit set. Knowledge of the likely fruit set would then allow orchard management decisions to be made that relate more to the yields on the trees. For example, when the temperatures are predicting a poor fruit set year fertilser inputs could be managed to prevent excessive vegetative growth. In order to use temperature measurements during flowering for predicting yield the relationship between temperature and yields needs to be well defined. A study was conducted over several years where the shade air temperature was recorded every few hours on avocado orchards located in two of the main avocado growing regions of New Zealand. This study examined the relationship between temperature and yield to better define the influence of temperature during flowering on yield.

MATERIALS AND METHODS

For each of the years 2002, 2003, 2004 and 2005 the shade air temperature at 1.5m height within the canopy of a single 'Hass' avocado tree representative of the trees within the orchard was recorded every two hours from 15 October to 15 November. Temperatures were recorded using temperature microloggers (HortPlus, Cambridge, New Zealand) placed in a Stevenson screen arrangement attached to a post. Yields from individual orchards were collected from the New Zealand avocado industry database and presented as tonnes per hectare. The number of orchards used to record temperatures was 23 in 2002, 29 in 2003, 42 in 2004 and 40 in 2005. The orchards used represented a sample of the typical range of orchards within the two largest avocado producing regions, Western Bay of Plenty and mid-Northland.

The temperature data from the main flowering period 15 October to 15 November was used to calculate the daily average temperature, average maximum temperature and minimum temperature. The number of effective pollination periods was calculated in three ways: the number of times when the night minimum temperature exceeded 10°C for three consecutive days; the number of times when the day time temperature exceeded 17°C and the night temperature exceeded 11°C for two consecutive days (Hopping, 1981); and the number of times when the day time temperature exceeded or equalled 19°C and the night temperature exceeded or equalled 14°C. The average temperature during the time of day when the flowers were most likely to be in the female opening was calculated from the temperatures recorded from the hours 10:00 to 16:00. The number of chilling hours was calculated as the sum of hours when the temperature was below a threshold of 10°C or 12°C. The number of heat units was calculated as the sum of hours when the temperature exceeded 17°C or 20°C.

The data was analysed for difference between years using a One-Way ANOVA using Minitab version 13.31.

RESULTS

Average yields for the orchards each year were not statistically different (Table 1). However, yields from the 2004 fruit set were about 3 to 4 tonnes/ha greater than for the fruit set from the years 2002, 2003 and 2005. The average temperature for the period 15 October to 15 November was similar for the years 2002 and 2003 and similar for the years 2004 and 2005. The average temperature in the years 2004 and 2005 was about 1°C higher than the years 2002 and 2003. The average daily maximum temperature was similar each year and was slightly higher in 2004 and 2005 than in 2002 and 2003. The daily minimum temperatures were about 1.5°C lower in 2002 and 2003 than in 2004 and 2005. The average temperature during the main period of the day when flowers could be open in the female gender (10:00 to 16:00 hours) was lower in 2002 and 2003 than in 2004 and 2005 by 0.8 to 0.6°C.

Table 1. Average yield, temperatures, pollination events and hours above or below temperature thresholds for the main flowering period (15 October to 15 November) of the years 2002 to 2005.

Year	2002	2003	2004	2005
Yield (tonnes/ha)	8.1	7.6	11.7	7.1
Temperature (°C)	14.0b[1]	14.1b	15.2a	15.1a
Daily maximum temperature (°C)	19.4	19.4	19.9	19.7
Daily minimum temperature (°C)	10.1b	9.9b	11.4a	11.6a
Number of pollination events (three consecutive nights above 10°C)	3.7b	4.1b	12.9a	12.6a
Number of pollination events (two consecutive days, day > 17°C night > 11°C)	3.7c	3.2c	10.6a	7.0b
Number of pollination events (day >= 19°C night >= 14°C)	0.0	0.0	0.0	0.0
Temperature during the hours 10:00 to 16:00	17.7b	17.9b	18.5a	18.5a
Number of hours < 10°C	234.3a	204.8a	99.6b	55.3c
Number of hours < 12°C	571.8a	548.0a	289.3b	226.0c
Number of hours > 17°C	359.0b	387.7b	550.0a	537.3a
Number of hours > 20°C	64.8ab	58.7b	120.1a	110.5ab

[1]Means with the same letter within a row were not significantly different according to a One-Way Analysis of Variance using a Tukey's Family error rate of 5%.

The average number of pollination events consisting of three consecutive nights above 10°C was greater in 2004 and 2005 than in 2002 and 2003 (Table 1). The average number of pollination events calculated from two consecutive days where the day exceeded 17°C and the night exceeded 11°C was lowest in the years 2002 and 2003 (Table 1). In 2004 the average number of pollination events was the highest with the average number of pollination events in 2005 intermediate to 2003 and 2004. There were no days where the day temperature exceeded or equalled 19°C and the night temperature exceeded or equalled 14°C.

There were more chilling hours using either a threshold of 10°C or 12°C in 2002 and 2003 than 2004 and 2005 (Table 1). There were more chilling hours in 2004 than 2005. There were more heat units using thresholds of 17°C or 20°C in 2004 and 2005 than in 2002 and 2003 (Table 1). Heat units tended to be the greatest in 2004.

The yield of individual orchards was not correlated with individual orchards average temperature, the number of pollination events, the average temperature during flower opening, chilling hours or heat unit hours (Table 2).

There was no clear relationship between yield in the following year and the average temperature during the flowering period, 15 October to 15 November, each year (Figure 1). The warmest year for flowering was in 2004 and the coolest year was 2002. Yields from individual orchards were very variable within each year and there was a wide scatter of yields at each temperature. In 2004 there were five orchards where the average temperature was above 16°C but three of those orchards had yields less than 5 t/ha and two orchards yields of over 17 t/ha (Figure 1). The lowest average temperatures were about 13°C in 2002, 2003 and 2005 where out of six orchards four of the orchards had yields below 5 t/ha and two of the orchards yields from 8.5 to 14 t/ha.

There was no relationship between pollination events based on two consecutive day time temperatures above 17°C and night temperatures above 11°C (Figure 2). The most pollination events were in the years 2004 where 17 orchards out of 42 and 2005 where 10 orchards out of 40 had 12 or more pollination event periods (Figure 2). However, in 2004 six of the orchards had 5 t/ha or less yield despite the high number of pollination events. In 2005, five out of the ten orchards had 5 t/ha or less yield when there were greater than 12 pollination events.

There was no relationship between heat units as hours above 17°C and yield each year (Figure 3). There were more orchards with over 700 hours above 17°C in 2004 and 2005 than in 2002 and 2003. In 2004 3 out of 7 orchards had more than 700 hours above 17°C but less than 5 t/ha crops and in 2005 5 out of 9 orchards had less than 5 t/ha yields despite more than 700 hours above 17°C (Figure 3).

Table 2. The correlation coefficients of individual orchard yields and average temperature, number of pollination events and chilling hours and heat units for the main flowering period (15 October to 15 November) of the years 2002 to 2005.

	r	p
Temperature (°C)	0.100	0.250
Number of pollination events (three consecutive nights above 10°C)	0.060	0.470
Number of pollination events (two consecutive days, day > 17°C night > 11°C)	0.127	0.146
Temperature during the hours 10:00 to 16:00	-0.023	0.796
Number of hours < 10°C	-0.115	0.188
Number of hours < 12°C	-0.124	0.155
Number of hours > 17°C	-0.011	0.897
Number of hours > 20°C	-0.056	0.525

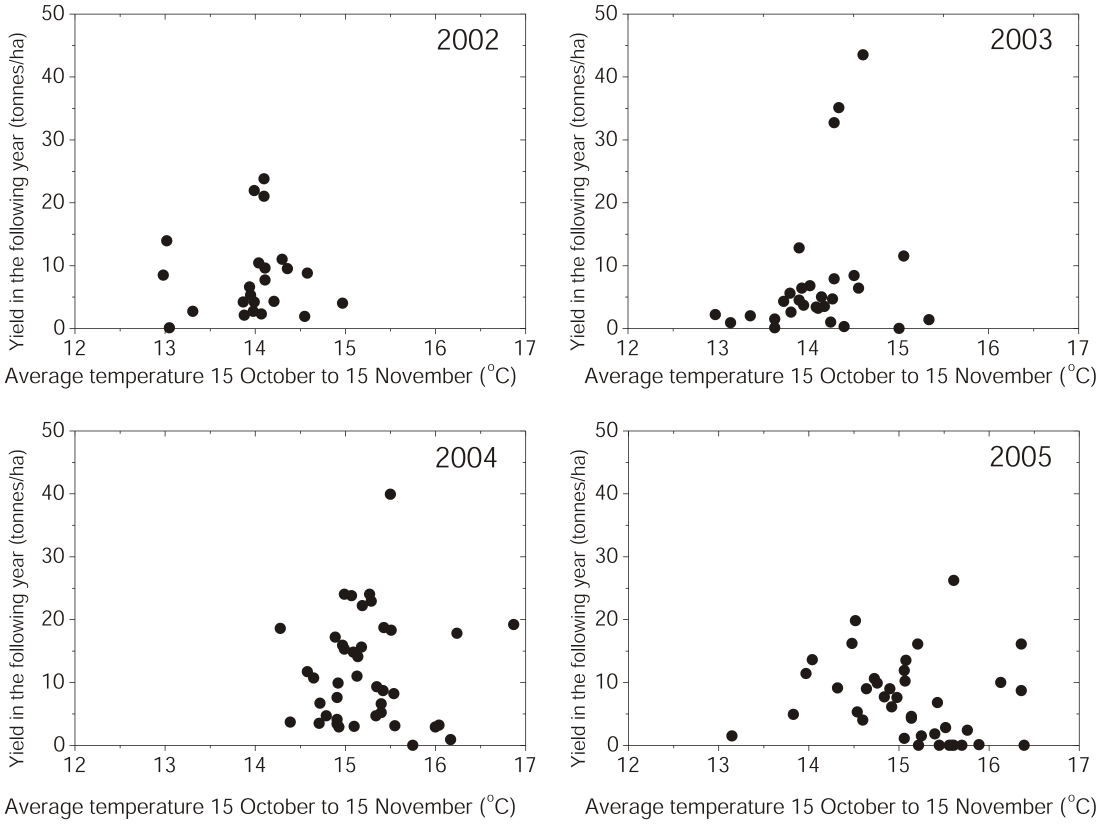

Figure 1. Average temperature during the main flowering period in spring in the years 2002 to 2005 and the yield at harvest in the following year for individual orchards.

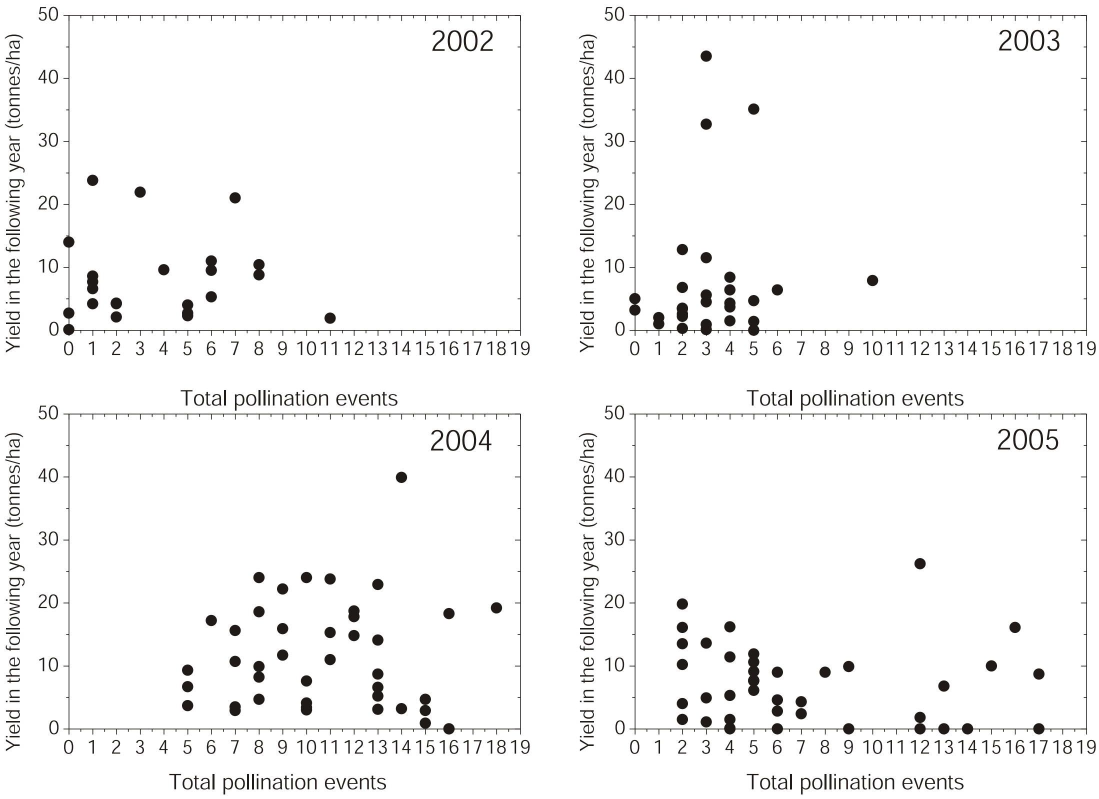

Figure 2. Total pollination events (two consecutive days where the daytime temperature was greater than 17°C and the night time temperature was greater than 11°C) during the main flowering period in spring in the years 2002 to 2005 and the yield at harvest in the following year for individual orchards.

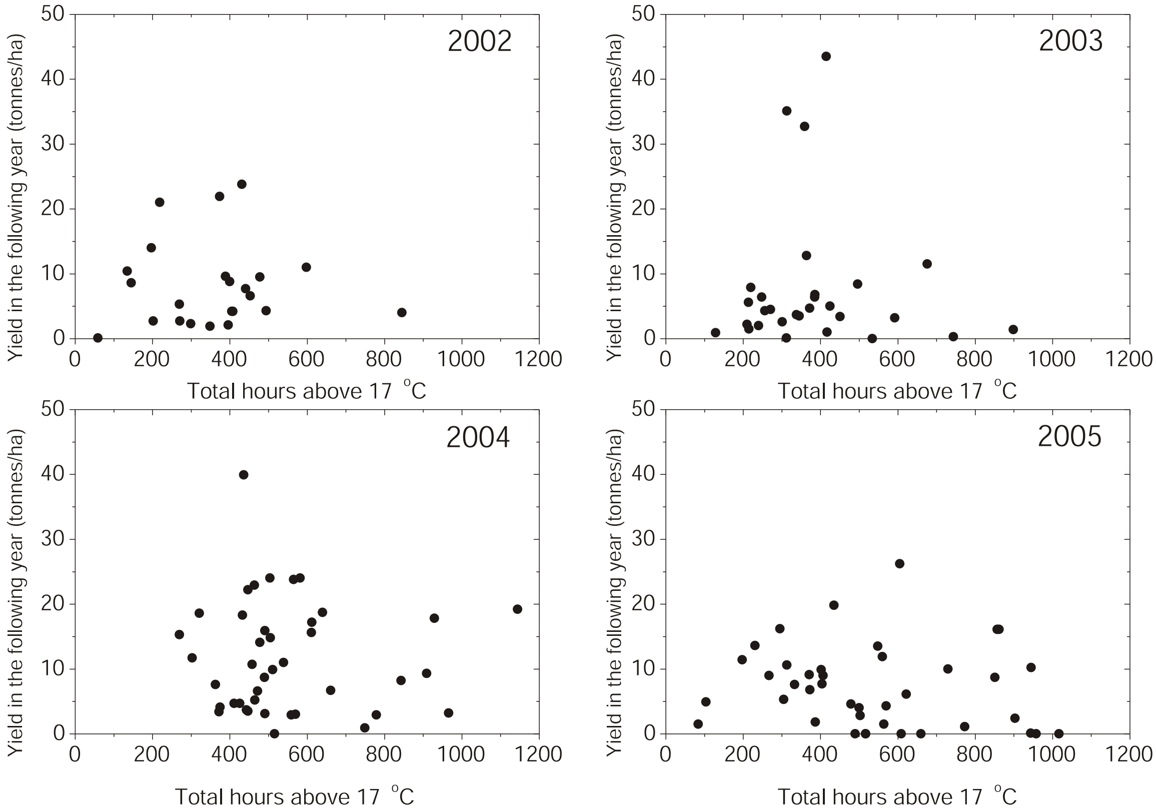

Figure 3. Total number of hours above 17°C during the main flowering period in spring in the years 2002 to 2005 and the yield at harvest in the following year for individual orchards.

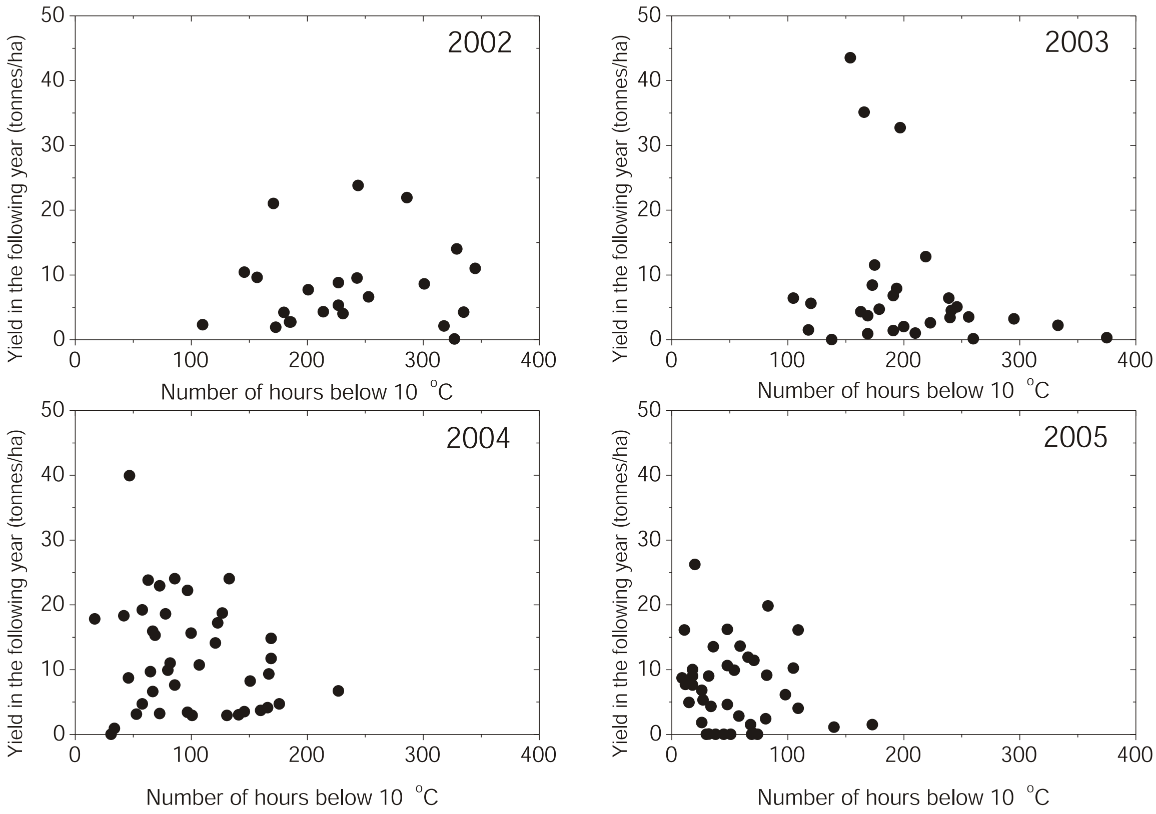

Figure 4. Total number of hours below 10°C during the main flowering period in spring in the years 2002 to 2005 and the yield at harvest in the following year for individual orchards.

The years 2002 and 2003 were colder in October and November than at the same time in 2004 and 2005. The number of chilling hours below 10°C was greater in 2002 and 2003 than in 2004 and 2005 (Figure 4). No orchards had less than 100 chilling hours in 2002 and 2003 while in 2004 26 out of 42 orchards and in 2005 35 out of 40 orchards had less than 100 chilling hours (Figure 4).

DISCUSSION

This study failed to show a clear relationship between temperature and yield. Although the average yield and temperature was greatest in 2004 the average yield was lower in 2005 when the average temperature was lower by only 0.1°C. The relationship between yield and different calculations of temperature were a wedge shaped scatter rather than showing a positive trend of increasing yield with increasing temperature. Therefore it was not possible to make predictions of yields based on measurements of temperatures over the main flowering and fruit set period. The data presented here shows that the relationship between yields and temperature is more complex than often claimed by industry commentators.

There appears to be an upper limit to the yields each year with average temperature that may indicate that temperature could be limiting yield if other as yet undefined factors are not limiting. The upper limit in yield appeared to increase with increasing temperature. Although Robbertse *et al.* (1998) stated that temperature was not the only factor affecting pollination and pollen tube growth they claimed that low temperature (below 20°C) was the overriding factor in effective pollination and only once a minimum temperature threshold had been reached did other factors interact. If this were true then there should have been a positive trend of increasing yield with increasing temperature in data. Such a pattern was not seen in the data collected from New Zealand avocado orchards. The patterns seen in the data here would suggest that under New Zealand conditions that temperature may well set the upper yield limit in any one year and other influences are then negative and lower the yield.

As observed for the relationship of average temperature with yield there appeared to be an upper limit to the yield with increasing pollination events in each year. The upper limit followed a declining trend with increasing pollination events in the years 2002, 2003 and 2005 but was increasing in 2004. This is a puzzling observation that, apart from the 2005 year, contradicts the average temperature observations. Namely, that the more warm day/night periods the poorer the yield. An explanation may be that when there is sufficient shoot growth competing with fruit set, the warmer conditions promote shoot growth over fruit set. For most orchards the year 2004 was an 'on' flowering year with little shoot growth to compete with the flowering and fruit set.

For heat units there was a complex pattern with yield without the indication of a readily apparent upper limit to yield. Heat units would be considered to affect the flower opening pattern (Gazit and Degani, 2002) and bee activity (Robbertse *et al.*, 1995) thereby being closely associated with fruit set. That there was no clear relationship between heat units and yield indicates that temperature is not the only factor in determining successful yields.

For chilling hours there appears to be upper limits to the yields where the chilling hours could be limiting yields. The upper limit appears to increase with decreasing chilling hours but the number of chilling hours where the limits are set changes each year. In 2004 the upper limit follows a line from no yield at 250 chilling hours to about 50 tonnes for zero chilling hours. In 2005 the upper limit line has no yields at 200 chilling hours to about 30 tonnes at zero chilling hours. Orchards with yields below the upper limit line could have other factors limiting their productivity. In 2002 and 2003 the pattern was different as these years were cooler all orchards had at least 100 chilling hours. The upper limit was not as clearly defined as in

2004 and 2005 but can be estimated to be at no yield about 400 chilling hours and between 35 and 45 tonnes at zero chilling hours.

Cool temperatures during the flowering period are often claimed to be responsible for the poor yields often seen on New Zealand avocado orchards. It is assumed that the cooler conditions prevent adequate pollen tube growth and fertilisation of the ovule. Therefore as the number of chilling hours increases yields should decrease. Research in Israel has shown that cool (less than 10°C) or cold (less than 5°C) nights over flowering have less influence on fruit set than is generally thought. For example three days at 15°C day and 5°C night for nine days after pollination did not affect fruit set in 'Fuerte' or 'Ettinger' (Gafni, 1984). Low temperatures of 3 and 4°C for two nights did not cause abscission of 8 to 9 day old 'Fuerte' fruitlets and 'Ettinger' pollinated by 'Hass' had 31% initial set of normal fruitlets when kept for three weeks at 17/12°C (day/night) after pollination (Argaman, 1983). At low night temperatures of 4 to 5°C minimum 'Ettinger' flowers had 21 to 52% ovary penetration when sampled at the male stage (Shoval, 1987). Excellent fruit set has been observed at high elevations in Mexico even though the temperatures are cool and disrupt the normal female flower opening pattern (Gazit and Degani, 2002). These observations suggest that the night temperatures typically measured in New Zealand avocado orchards are not unusual and may not be the overriding limit to fruit set. Hass avocado trees grown in New Zealand may have adapted to cooler conditions or are being actively managed to compensate for the cool temperatures, e.g. higher leaf nitrogen levels are used as they are thought to protect from the cold. Therefore the temperature limits and thresholds may be lower than for 'Hass' avocados grown in warmer climates. Further studies would be needed to better establish the role low temperatures play on aspects of avocado fruit set under New Zealand conditions.

In the main growing regions of New Zealand of Northland and the Bay of Plenty the orchard in this study had average temperatures between 13°C and 16.5°C. We suggest these temperatures are within a range that is suitable for good fruit set of Hass avocados. In parts of Mexico, the presumed native habitat of the avocado, at altitudes of 1400 to 2700m the temperatures over the flowering period are similar (Wolstenholme, 2002) to those measured at low altitude in New Zealand. Based on a consideration of temperature alone the climate of the main commercial growing areas should not be limiting avocado yields.

The lack of a clear relationship between yield and temperature strongly suggests that temperature alone is not an overriding influence on yield but is one of a number of factors that determine the yield each year. Other important factors limiting yield may be related to the phenology of the alternate bearing cycle, plant hormone relationships, pollination efficiency, tree nutrient status and so on. By only ascribing successful fruit set to the temperature conditions over flowering and fruit set, the necessary factors that could limit fruit set requiring horticultural management are likely to be poorly managed by avocado growers. This may explain why, in part, successful management of alternate bearing has so far proven to be elusive.

CONCLUSIONS

Despite overseas research that claims to show a positive relationship of temperature to fruit set the yield in the following year did not correlate with average temperature during flowering, number of pollination events, chilling hours below 10°C or heat units above 17°C. There are other factors limiting yields that can be more important than temperature.

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