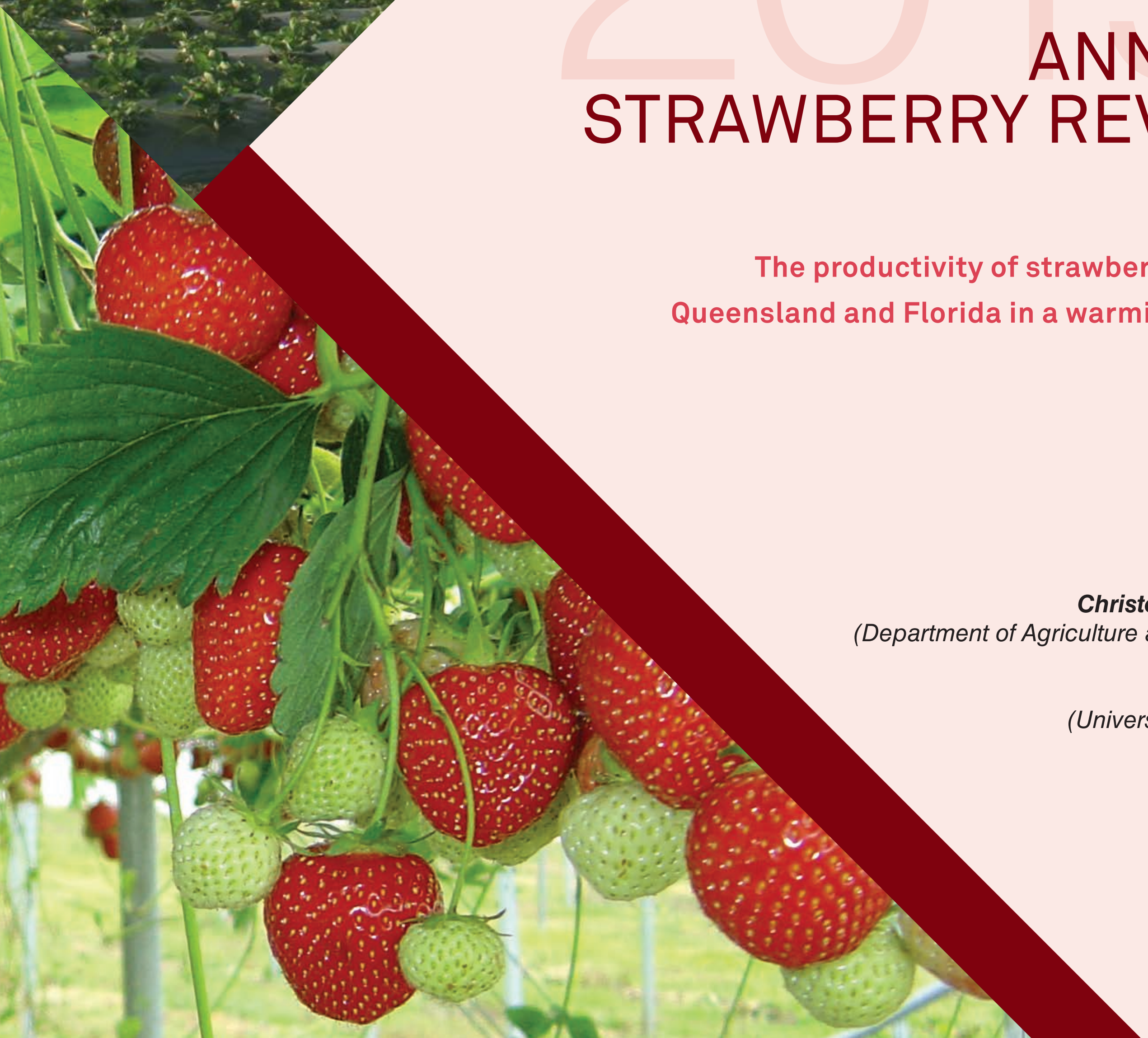

EDITION 1

2019 ANNUAL STRAWBERRY REVIEW

The productivity of strawberry fields in Queensland and Florida in a warming climate

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The productivity of strawberry fields in Queensland and Florida in a warming climate

Climate plays an important role in the productivity of strawberry fields, with environmental conditions affecting plant growth, yield and the incidences of diseases. The main scenarios for global climate change include an increase in the concentration of carbon dioxide (CO_2) and an increase in average temperatures. Studies in several crops have shown that there is an initial increase in productivity with climate change and then a decrease. The incidence of some plant diseases also may increase at higher temperatures.

The potential impacts of climate change on the performance of strawberries is not well understood. We report on studies to assess the productivity of strawberries in Queensland and Florida under a warming climate. In the first part of the work, the relationship between yield, fruit size, leaf area expansion and temperature was examined on the Sunshine Coast. In the second part of the work, the effect of different soil fumigants on the survival of the charcoal rot fungus *(Macrophomina phaseolina)* was examined in Florida.

This report has six sections and includes the results of following studies:

1. An overview of the strawberry industries in Queensland and Florida, and the likely impacts of climate change on agricultural crops, including strawberries
2. The relationship between yield and leaf area expansion in different cultivars in Queensland
3. The effect of defoliation on plant growth and yield of strawberries in Queensland
4. The effect of temperature on fruit development and yield of strawberries in Queensland
5. The effect of soil fumigants on the biology of the charcoal rot fungus in Florida
6. The implications of the various studies for commercial strawberry producers

The research showed that there is a strong relationship between yield and leaf area expansion. There was no evidence of excessive leaf production for high yields, although this may change with increasing temperatures. High temperatures decreased fruit size and productivity, suggesting that there may be problems for the two industries in the absence of heat-tolerant cultivars. The research in Florida showed that charcoal rot was only controlled if the fumigants were distributed throughout the soil profile. Some chemicals were more effective than others.

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The strawberry industries in Queensland and Florida

Strawberry growers in Australia produce about 90,000 tonnes of fruit worth AU$510 million each year. The main production centers are located in Queensland (41%), Victoria (36%) and Western Australia (11%). There are smaller industries in South Australia (7%), Tasmania (4%) and New South Wales (1%). The bulk of the crop in Queensland is produced from May to October on the Sunshine Coast.

Florida has a similar climate to south-east Queensland, with strawberries produced from December to April. The two areas share similar growing systems, cultivars and diseases. The total area under production in Florida is about 5,000 ha, providing fruit to the rest of the United States and Canada. Total production in Florida is about 120,000 tonnes of fruit worth US$450 million. Cultivars developed by the University of Florida account for more than 80% of plantings in Florida, and are important in Australia and elsewhere. There is a long history of collaboration between strawberry researchers in Queensland and Florida. Scientists in both areas have shared interests in plant improvement, agronomy and pathology.

Impact of climate change on the performance of agricultural crops

Numerous studies have highlighted the impact of climate change on the productivity of agricultural crops. Initially, there is an increase in photosynthesis under higher carbon dioxide concentrations and this can lead to an increase in plant growth and yield. However, in many crops, the leaves and the photosynthetic system adapt to the higher carbon dioxide concentrations and the benefits of higher carbon dioxide disappear.

Plants also respond to the increasing temperatures under climate change. At first, plant growth and yield increase. However, with higher temperatures, plant growth and yield eventually start to decline.

Most studies indicate lower yields in the long-term with climate change. Research in peppers (capsicums) in Korea indicated that yields decreased by 22 or 89% with different increases in carbon dioxide concentration and temperature. Yields of sweet orange in Brazil increased up to 600 ppm (parts per million) of carbon dioxide and 30°C, and decreased at higher carbon dioxide concentrations and higher temperatures. Yields of rice in the United States decreased by 7% for each 1°C increase in temperature above a critical temperature of 14.9°C.

Certain minimum temperatures are required for plant pathogens to develop and reproduce. High temperatures favour the germination and proliferation of spores in a range of pathogenic fungi. Some crops become more susceptible to pathogens because the genes that are associated with disease resistance fail at high temperatures. Overall, the incidence of plant diseases is likely to increase with climate change. For some crops, an increase in the incidence of certain diseases will make it difficult to grow the plants in particular regions.

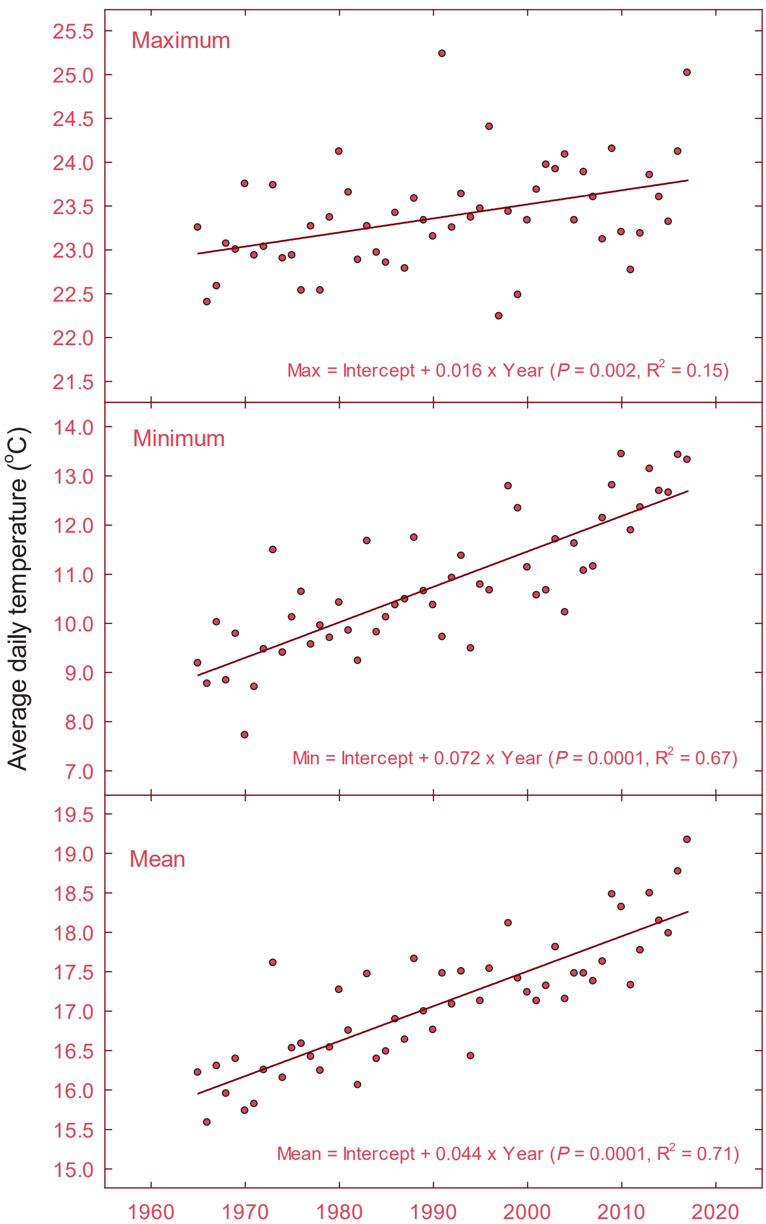

Figure 1. *Changes in the average maximum, minimum and mean daily temperatures from April to September at Nambour from 1965 to 2017 (N = 53 years). Temperatures during the night have increased more than temperatures during the day.*

Impact of climate change on strawberries

Climate change is likely to affect the strawberry industries in Queensland and Florida in the near future. There will be changes in plant growth, yield and the incidence of several diseases.

Temperature affects many aspects of growth, including leaf area expansion, flowering, and fruit development. Higher temperatures increase leaf area expansion, but reduce flowering. Higher temperatures also reduce the size of the fruit and the length of the growing season. These responses are likely to contribute to lower productivity in the absence of better adapted cultivars.

The incidence of some soil-borne diseases will increase under warmer conditions in the absence of resistant cultivars or effective soil fumigation. High temperatures favour the development of fungi such as the charcoal rot pathogen, *Macrophomina phaseolina*. This disease has become more important in Queensland and Florida, with most of the currently registered soil fumigants relatively ineffective due to their poor mobility in the soil.

Temperature conditions on the Sunshine Coast

Many studies have shown that average temperatures across the globe have increased over the past fifty years. It has also been demonstrated that the rate of warming varies from one region to the next and that there are differences between winter and summer and between days and nights. The effect of climate change on the productivity of crops will depend on the degree of warming, and whether the increase in temperature is mainly during winter or summer or during the day or the night.

Research has shown that average maximum, minimum and mean daily temperatures from April to September at Nambour have increased over the past 53 years (Figure 1). Overall, minimum temperatures have increased more than maximum temperatures. The average daily mean temperature has increased from about 16.0°C in 1965 to about 18.0°C in 2017. These changes in temperature are likely to affect the development of strawberry plants on the Sunshine Coast. They are also likely to increase the incidence of some soil-borne diseases.

It can be concluded that temperatures on the Sunshine Coast are likely to increase with climate change. These increases in temperatures are likely to change the pattern of plant development, increase the incidence of plant diseases, and decrease the productivity of commercial strawberry fields.

The relationship between productivity and leaf growth in different strawberry cultivars (Christopher Menzel)

Fruit growth in strawberry plants is strongly dependent on photosynthesis in the leaves. However, excessive leaf production can reduce productivity. This is because too many leaves can shade the lower part of the canopy and reduce overall photosynthesis. The new leaves can also compete directly with the fruit for photosynthates.

The relationship between yield and leaf growth in strawberries was examined in south-east Queensland. Information was collected on the rate of leaf production over several seasons, and whether leaf production was related to temperatures and radiation in the different experiments. Additional information was collected to determine whether there was any relationship between potential yield and leaf production. A strong positive relationship would indicate that yields might be increased by increasing leaf production. A poor or negative relationship would indicate over-crowding or competition between the fruit and the leaves.

Twenty-three experiments were conducted to explore the changes in leaf growth in strawberries on the Sunshine Coast (Table 1). Seven cultivars and breeding lines were planted between 17 March and 5 May from 2004 to 2016 and the number of fully-expanded leaves per plant (net number of leaves per plant), dry weight of the flowers and immature fruit, and yield recorded. The dry weight of the flowers and immature fruit was used as an index of potential productivity and is less affected by wet weather than the final fruit harvest. Information was also collected on daily maximum and minimum temperatures and solar radiation.

Changes in the number of leaves per plant over the season followed a linear pattern, with new leaves emerging over the whole of the growing season. On average, a new leaf was produced every six to seven days, with 27 leaves on each plant at the end of the season. Examples are provided on the changes in leaf production for early and late plantings of 'Festival' in 2010 and 'Fortuna' in 2011 (Figure 2).

The average daily mean temperature ranged from 15.7° to 17.8°C, and the average daily solar radiation ranged from 13.0 to 15.9 MJ per m^2. There was no clear relationship between the mean rate of leaf production (a new leaf produced every four to ten days) and average temperatures and radiation in the different experiments.

Exp.	Year	Interval between successive leaves (Days)	Max. number of leaves per plant	Average d. wt. of the flowers & immature fruit (g per plant)	Yield (g per plant)
1	2004	7.0	17.2	-	189
2	2005	6.2	25.4	-	702
3	2006	5.6	26.9	-	480
4a	2007	4.7	34.2	6.8	727
4b	2007	5.8	23.4	4.1	560
5a	2008	8.1	22.2	7.3	1092
5b	2008	9.7	18.8	3.5	510
6a	2009	5.9	30.8	7.2	934
6b	2009	6.8	24.3	4.0	555
7a	2010	3.9	46.8	9.5	876
7b	2010	5.8	29.0	5.1	642
8a	2010	4.6	32.1	7.1	827
8b	2010	6.2	26.5	3.9	478
9a	2011	6.3	28.4	7.2	966
9b	2011	7.7	22.2	4.0	740
10a	2011	7.0	21.4	5.0	823
10b	2011	9.3	18.3	3.0	643
11	2012	5.9	37.1	10.6	720
12	2013	4.7	34.5	9.0	480
13	2014	6.3	30.4	5.9	796
14a	2015	6.3	28.0	9.2	1123
14b	2015	6.8	26.0	8.7	1037
15	2016	6.6	27.1	8.1	991
Mean		*6.4*	*27.4*	*6.5*	*734*

Table 1. *Details of the experiments conducted to investigate productivity and leaf growth in strawberries in Queensland.*

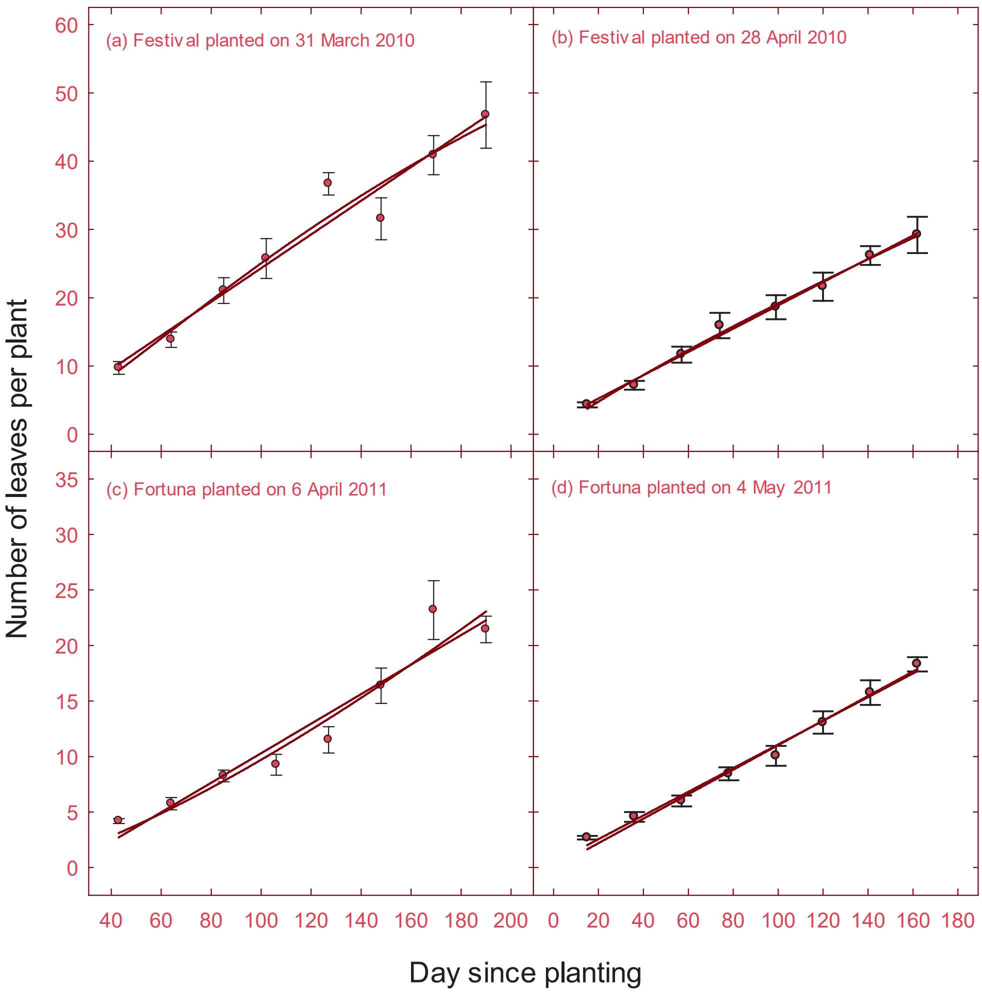

Figure 2. *Changes in leaf production in 'Festival' and 'Fortuna' strawberries planted at two different times in Queensland in 2010 and 2011. Changes in the number of leaves per plant over the season followed a linear pattern, with new leaves emerging over the whole of the growing season. Data are the means of four replicates per treatment. Linear and sigmoid relationships shown.*

Average yield was 734 g per plant in the different experiments and average mean seasonal dry weight of the flowers and immature fruit was 6.5 g per plant. Yield was only weakly related to the dry weight of the flowers and immature fruit. This was because rain damaged the fruit and increased the incidence of grey mould and other diseases in some years. Potential yield as indicated by the dry weight of the flowers and immature fruit increased up to about 40 to 45 leaves per plant (Figure 3). Several studies overseas have shown a strong relationship between yield and flowering. Heavy flowering usually leads to large crops.

Strawberries in south-east Queensland produced a new leaf every four to ten days. The rate of leaf production varied with the year, cultivar and time of planting but there was no clear relationship between the average rate of leaf production and average temperatures or solar radiation. These results indicate that environmental conditions were favourable for the initiation and emergence of new leaves. Potential yield increased up to about 40 to 45 leaves per plant, indicating that cropping in this environment is strongly related to leaf production.

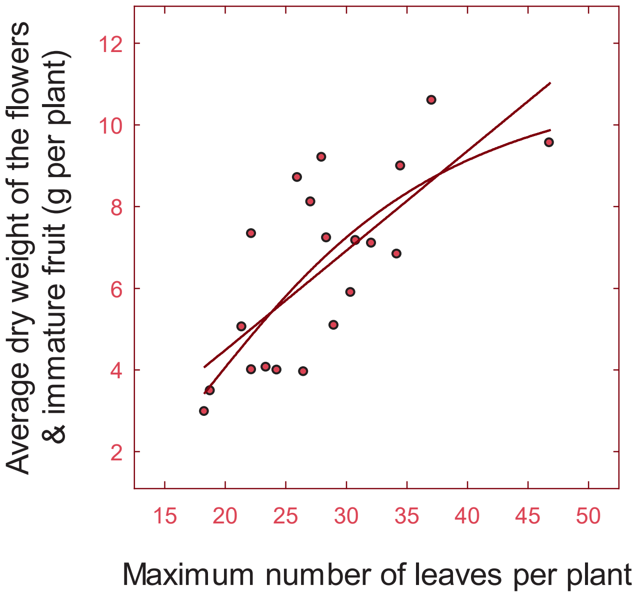

Figure 3. *Relationships between average dry weight of the flowers and immature fruit (potential yield) and maximum leaf production in strawberries in Queensland. Potential yield increased up to about 40 to 45 leaves per plant. Data are the means of two to six replicates (mostly four) per treatment. Linear and sigmoid relationships shown.*

The close relationship between potential yield and the number of leaves suggests that there was little competition for light at high rates of leaf production or that there was strong competition between the fruit and the new leaves. The relationship between yield and leaf production should be explored in other cultivars to determine the impact of plant breeding on productivity in this environment. Studies in California showed that new leaves increased fruit production for part of the season, but competed with fruit production at other times.

The strong relationship between potential yield and leaf production in south-east Queensland suggests that cropping could be increased by increasing the productivity of the leaves. This could be achieved through plant breeding by developing new cultivars with more or larger leaves. Another approach could be to extend the life span of individual leaves or to alter the arrangement of the leaves on the plant to improve overall light interception. Higher temperatures under climate change may change the relationship between productivity and leaf area. There is evidence that in some crops decreasing rather than increasing leaf area will increase yields in the future. Research in soybean has shown that some cultivars overinvest in leaves and this can decrease yields by about 10%. Studies are required to determine the pattern of plant development in different strawberry cultivars and the likely impact of higher temperatures on productivity. Efforts need to be made to breed heat tolerant cultivars.

Effect of leaf area expansion on the yields of strawberries (Christopher Menzel)

An experiment was conducted to investigate the effect of leaf area expansion on the performance of 'Festival' strawberries growing in south-east Queensland. We were interested in determining whether leaf area expansion would affect the pattern of production as well as the yields of the plants. Increasing temperatures under climate change are likely to change the pattern of leaf growth in this environment. High temperatures can reduce leaf initiation, reduce the size of the leaves and increase the rate of the leaf senescence.

At the start of cropping in mid-June, groups of plants were defoliated to remove 25, 50 or 75% of the mature leaves on each plant. Control plants were left intact. Information was collected on plant growth, marketable and non-marketable yield and fruit fresh weight. Fruit weighing less than 12 grams were considered non-marketable.

Table 2. *Effect of defoliation on average seasonal plant growth in 'Festival' strawberries. The plants had 0, 25, 50 or 75% of the mature leaves removed in mid-June. Data are the means of four replicates per treatment, pooled over six harvests.*

Treatment	No. of leaves per plant	Leaf area (cm^2 per plant)	Dry weight (g per plant)		
			Leaves	Crowns	Roots
Control	14.8	1745	13.7	3.7	1.3
Light defoliation	12.7	1444	11.3	3.3	1.2
Moderate defoliation	12.5	1341	10.3	3.3	1.1
Severe defoliation	10.6	1141	8.4	2.9	1.1

Defoliation decreased leaf production, leaf area expansion and leaf dry weight compared with the controls, but had a small or no effect on the growth of the crowns and roots (Table 2). Overall, the plants that were defoliated were smaller than the controls. Moderate or severe defoliation decreased yield (total and marketable) compared with the control (Table 3). Severe defoliation also decreased average fruit fresh weight (total and marketable) compared with the control and increased the percentage of non-marketable fruit weighing less than 12 g.

The changes in cumulative marketable yield followed a sigmoid pattern over the growing season (Figure 4). The estimated maximum yield reflected the absolute yield of the different treatments, with productivity decreasing with the level of defoliation. The time to reach maximum growth rate were similar in the different treatments. Defoliation decreased total productivity but did not shift the pattern of production.

Treatment	Yield (g per plant)			Average fruit fresh weight (g)		
	MKT	Non-MKT	Total	MKT	Non-MKT	Total
Control	268	33	305	18.4	9.8	16.1
Light defoliation	226	53	283	17.6	9.7	14.9
Moderate defoliation	186	59	249	17.3	9.8	14.2
Severe defoliation	154	64	218	16.2	9.1	12.8

Table 3. *Effect of defoliation on yield and average fruit fresh weight in 'Festival' strawberries. The plants had 0, 25, 50 or 75% of the mature leaves removed in mid-June. Data are the means of four replicates per treatment. MKT = marketable fruit and Non-MKT = non-marketable fruit (less than 12 g).*

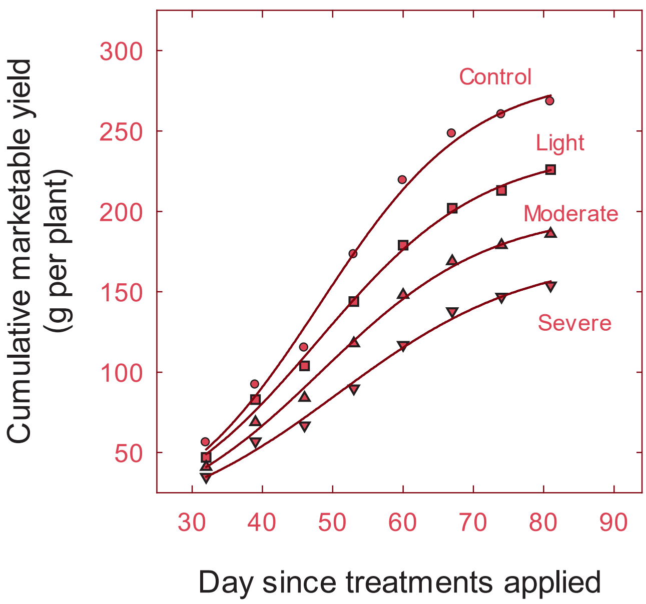

Figure 4. *Effect of defoliation on the changes in cumulative marketable yield in 'Festival strawberries. The plants had 0, 25, 50 or 75% of the mature leaves removed in mid-June. Data are the means of four replicates per treatment. Defoliation reduced the yields of the plants compared with the controls, but did not shift the pattern of production.*

Changes in leaf area expansion affected plant growth and fruiting in the strawberries growing in south-east Queensland. Removing some of the leaves on each plant reduced subsequent leaf production, yield and average fruit growth. These results confirm the importance of leaf production on the productivity of strawberries in this environment. This will probably become more important under climate change. Initially, there will be a net increase in leaf production as temperatures increase, but eventually leaf production will decline. There could also be changes in the size and longevity of the leaves. There was a different response to defoliation on yield and the pattern of fruit production. Defoliation decreasing productivity, but did not affect the pattern of production. The plants had lower yields after the leaves were removed, but they had similar cycles of fruiting. It is possible that there might have been a different response if the leaves were removed from the plants earlier in the season.

There is some evidence that increasing yields in some crops under climate change will be associated with decreasing, rather than increasing leaf areas. Studies are required to determine if this response is likely in strawberries.

Effect of plant development and temperature on fruit growth in strawberries (Christopher Menzel)

One of the major issues affecting strawberry production in south-east Queensland and elsewhere is the production of small fruit. Small fruit reduce marketable yields, and increase the costs of harvesting the crop. A study in Italy showed that for each one gram increase in average fruit fresh weight, the cost of harvesting was reduced by about €500 per ha.

An experiment was conducted to investigate the effect of plant development and temperature on fruit growth in 'Festival' strawberries on the Sunshine Coast. Groups of plants were defoliated to remove half of the mature leaves on each plant, thinned to remove all the inflorescences carrying flowers and fruit on each plant, or defoliated and thinned. Control plants were left intact. The main objective of the study was determine whether changes in leaf area and crop load affected the decline in fruit weight that typically occurs as the season progresses in Queensland. Information was collected on the relationship between fruit size and temperature in the different treatments.

Table 4. *Effect of defoliation and thinning on yield and average fruit fresh weight in 'Festival' strawberries. The plants had half of the mature leaves removed or all the inflorescences carrying flowers and fruit removed in June. Data are the means of four replicates per treatment. MKT = marketable fruit and Non-MKT = non-marketable fruit (less than 12 g).*

Treatment	Yield (g per plant)			Average fruit fresh weight (g)		
	MKT	Non-MKT	Total	MKT	Non-MKT	Total
Control	853	138	991	19.0	8.9	16.4
Defoliation	676	157	834	18.3	9.1	15.3
Thinning	725	118	843	19.9	8.8	17.4
Defoliation + thinning	651	130	780	18.6	8.8	15.9

Groups of plants had 50% of their mature leaves removed, or all their inflorescences carrying flowers and fruit removed, or both treatments applied. Control plants were left undefoliated and unthinned. There were 12.8 leaves per plant on the controls at the start of the experiment on 28 June (Day 1), and 10.1 flowers and immature fruit per plant. There were no mature fruit on the plants at this time. Information was collected on yield, fruit production and average fruit fresh weight every week over the following 16 weeks until late October. Fruit were classified as mature when they were 75% coloured. The fruit were classified as marketable (12 g or greater) or non-marketable (less than 12 g).

Defoliation, thinning, or defoliation + thinning decreased yield (total and/or marketable) compared with the control (see Table 4). Defoliation, or defoliation + thinning decreased fruit weight (total and/or marketable fruit) compared with control, whereas thinning had the opposite effect. The incidence of small fruit increased towards the end of the growing season. There were weak negative relationships between fruit weight, and the number or weight of fruit on a plant during the early and middle part of the season. Fruit weight was strongly related to average daily mean temperature in the seven weeks before the fruit were harvested in the different treatments (Figure 5). Fruit weight decreased from 24 g to 8 g as the temperature increased from 16° to 20°C.

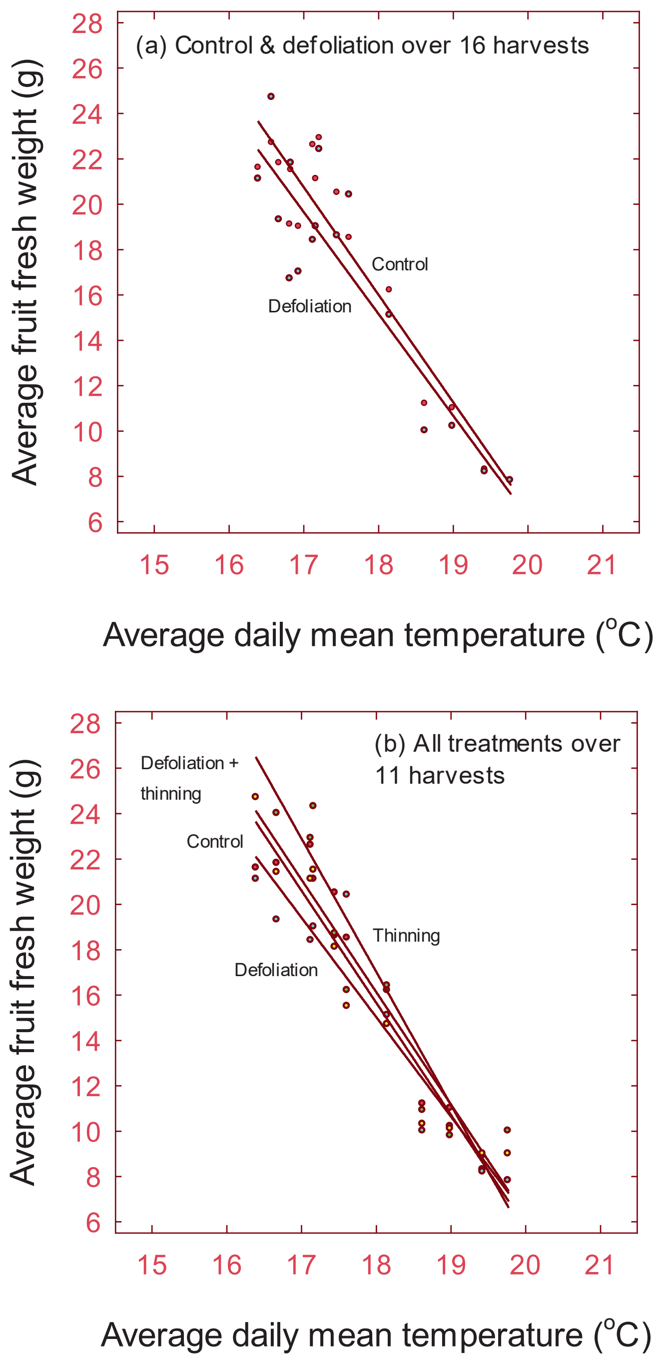

Figure. 5. *Relationship between average fruit fresh weight (marketable + non-marketable) and average daily mean temperature in the seven weeks before the fruit were harvested in 'Festival' strawberries. Data show the relationships for the four different treatments. First, there are the relationships for the whole 16-week season in the control and the defoliation treatment. Second, there are the relationships when the fruit were harvested from all the treatments over the last 11 weeks in the control, and in the defoliation, thinning, and defoliation + thinning treatments. Data are the means of four replicates per treatment.*

Removing the leaves, flowers and fruit changed plant dry matter production. There was some recovery in the plants after the treatments were applied, with new leaves and flowers initiated in the defoliated and thinned plants. Total yield was reduced by about 15% when plants were defoliated or thinned compared with the control, and by about 21% when they were defoliated and thinned. Defoliation, and defoliation + thinning decreased fruit weight by about 1 or 2 g compared with the control, whereas thinning had the reverse effect. In the current experiment, the plants were able to produce new leaves, flowers and fruit after the treatments were applied. The effect of defoliation on yield was greater than the effect on fruit size.

There is often a good relationship between productivity and leaf area expansion in strawberries. In contrast, there are few studies linking fruit size to leaf area expansion. Polish researchers examined the relationship between fruit weight and leaf area in seven cultivars with small leaves and six cultivars with large leaves. Mean fruit weight was 7.6 g and 9.1 g in the two groups of plants, and there was a strong correlation between fruit weight and total leaf area per plant in the sample. Further studies are required to determine whether this response occurs in cultivars grown in Queensland.

The average daily mean temperature from April to September at Nambour has increased by about 2.0°C from 1965 to 2017. In the current study, fruit weight decreased by about 4.5 g for every degree Celsius above a daily mean temperature of 16°C. Overall, the response to temperature was greater than the response to defoliation or thinning. Increasing the leaf area supporting the developing crop through plant breeding might improve fruit size in Queensland. The strong effect of temperature on fruit growth indicates that production on the Sunshine Coast might be a problem in the absence of heat-tolerant cultivars. Efforts need to be made to develop new cultivars suited to warmer growing conditions under climate change.

Management of charcoal rot with soil fumigants (Natalia Peres)

The charcoal rot fungus (*Macrophomina phaseolina*) infects the roots and crowns of the strawberries, with the plants wilting and dying and producing fewer fruit. The fungus has a wide range of hosts and persists in the soil for long periods. Low inoculum levels in the soil can readily infect host plants. Strawberry plants have been affected in all growing areas in Australia, including southern Queensland, Victoria and Western Australia. The disease is also important in northern America, including Florida. The disease can cause up to more than half of the plants to die before the end of the season in Florida.

High temperatures favour the development of the charcoal rot pathogen. Symptoms of the disease and levels of mortality in susceptible plants often increase when soil temperatures range from 28° to 35°C. Strawberry plants often succumb to the disease during warm weather when irrigation is suboptimal. The fungus produces resistant microsclerotia, compact masses of hardened mycelia that help the pathogen survive for long periods in the soil and infect new plants. These structures are produced in the host tissues and are released into the soil as the infected plant decays. The sclerotia of some fungi can survive in a dry environment for several years. This feature can complicate methods to control the fungi if they are pathogenic.

Effective soil fumigation usually keeps charcoal rot below economically important levels in most fields. The disease has become more prominent in Australia and Florida since the phasing out of methyl bromide as an effective soil fumigant. Many of the current replacements for the standard fumigant are less effective. This has led some producers to abandon soil fumigation completely. Many of the losses in Australia have occurred in non-fumigated soil, suggesting that non-fumigated soils are the major culprit for the increased incidence of charcoal rot.

The efficacy of soil fumigants for the control of the charcoal rot pathogen was evaluated in 2016/2017 and 2017/2018 in Dover in Florida. The efficacy of fumigant treatments was determined by evaluating the survival of inoculum on infested corn-cob litter buried in the centers and sides of plastic-covered beds. Different products, concentrations, and application methods were compared with methyl bromide and a non-treated control (Tables 5 and 6).

Table 5. *Effect of soil fumigation on the recovery of* Macrophomina phaseolina *colony-forming units (CFUs) applied to a strawberry field in Dover, Florida in 2016. Each value is the average of two beds, four plots and three replicate dilutions per bag. All the shank-applied fumigants were injected via two shanks 35 cm apart and 25 cm deep into the bed using nitrogen as the propellant through a two-row fumigation rig. Vapor Safe is a polyethylene mulch. TIF = totally impermeable film and VIF = virtually impermeable film.*

Treatment	Application method	Rate	Number of *M. phaseolina* CFUs per bag		
			Soil depth of 7.6 cm in the centre of the bed	Soil depth of 20.3 cm in the centre of the bed	Soil depth of 7.6 cm in the side of the bed
Control	-	-	529	577	484
Methyl bromide + chloropicrin (50:50)	Shank + Vapor Safe	358 kg per ha	0	0	0
1,3-dichloropropene:chloropicrin (63:35)	Shank + VIF	327 L per ha	0	0	0
1,3-dichloropropene:chloropicrin (39:60)	Shank + VIF	336 kg per ha	122	559	76
1,3-dichloropropene:chloropicrin (20/80)	Shank + VIF	215 L per ha	0	0	0
Chloropicrin (100)	Shank + VIF	202 L per ha	11	48	24
Potassium *N*-methyldithiocarbamate (100)	Drip + VIF	560 L per ha	0	0	1
Dimethyl disulfide:chloropicrin (79:21)	Shank + TIF	281 L per ha	248	518	374
Dimethyl disulfide (EC):chloropicrin (79:21)	Drip + TIF	281 L per ha	0	0	76
Allyl isothiocyanate (100)	Drip + VIF	281 L per ha	0	0	137

Table 6. *Effect of soil fumigation on the recovery of* Macrophomina phaseolina *colony-forming units (CFUs) applied to a strawberry field in Dover, Florida in 2017. Information was also collected on the recovery of the pathogen in strawberry crowns and on plant mortality. For the data on CFUs, each value is the average of two beds, four plots and three replicate dilutions per bag. For the data on plant mortality, each value is the average of the number of wilted and dead plants in two beds and four plots per treatment. The shank-applied fumigants were injected via two shanks 35 cm apart and 25 cm deep into the bed using nitrogen as the propellant through a two-row fumigation rig.*

Treatment	Application method	Rate	Number of *M. phaseolina* CFUs per bag			Number of *M. phaseolina* CFUs per g crown weight at soil depth of 7.6 cm in the side of the bed	Percentage of plants dying
			Soil depth of 7.6 cm in the centre of the bed	Soil depth of 20.3 cm in the centre of the bed	Soil depth of 7.6 cm in the side of the bed		
Control	-	-	197	192	519	189	35
1,3-dichloropropene:chloropicrin (63:35)	Shank	281 L per ha	0	0	0	0	9
1,3-dichloropropene:chloropicrin (39:60)	Shank	336 kg per ha	0	0	0	0	9
1,3-dichloropropene:chloropicrin (20:80)	Shank	358 kg per ha	0	0	0	0	9
Chloropicrin (100)	Shank	358 kg per ha	0	3	25	1	11
Potassium *N*-methyldithiocarbamate (100)	Drip	562 L per ha	0	0	1	1	9
Dimethyl disulfide:chloropicrin (79:21)	Shank	374 L per ha	36	85	57	32	10

The number of colony forming units (CFUs) of the pathogen per gram of soil was determined after plating the recovered infested corn-cob litter on semi-selective medium and incubating at 30°C in the dark. The number of colonies was counted after seven days. In the second season, the recovery of the pathogen in the crowns of strawberry plants was determined, along with the percentage of strawberry plants dying in each plot.

In the first season, shank applications of 1,3-dichloropropene:chloropicrin (63:35) (Telone C35) and 1,3-dichloropropene:chloropicrin (20:80) (Piclor 80) under virtually impermeable film, and drip-tape applications of potassium *N*-methyldithiocarbamate (Kpam) nearly or completely eliminated CFUs of the pathogen in the strawberry beds (Table 5). These treatments were as effective as the methyl bromide + chloropicrin (50:50) (MeBr 50) standard. In contrast, dimethyl disulfide (EC):chloropicrin (79:21) (DMDS EC + Pic EC) and allyl isothiocyanate (100) (Dominus) were only effective in the center of the beds. Dimethyl disulfide:chloropicrin (79:21) (DMDS + Pic) applied through shank was ineffective at all sampling sites (Table 5).

In the second season, all the chemical treatments reduced the level of inoculum in the centers and sides of the beds compared with the control (Table 6). These treatments also reduced the recovery of the pathogen in the strawberry crowns. Overall, dimethyl disulfide:chloropicrin (79:21) was less effective than the other treatments. All the chemical treatments reduced the number of plants dying compared with the control, with no clear differences amongst the various strategies (Table 6).

There was no clear relationship between the recovery of the pathogen in the crowns and in the soil, and between the percentage of the plants dying and the recovery of the pathogen in the crowns (Figure 6). The chemical treatments were in one group and the control was in another group. Sampling of the dying plants indicated the presence of pathogenic nematodes and fungi (*Colletotrichum* sp. and *Phytophthora* sp.) as well as *M. phaseolina*. Several non-pathogenic fungi were also isolated from the crowns of the wilting plants.

These results demonstrate that fumigants must be uniformly distributed within the soil profile to control charcoal rot. Many of the alternative fumigants do not disperse as well as methyl bromide. The effect of fumigation using multiple drip-tapes or multiple port rigs needs to be evaluated in future experiments. Further research is required on the control of this important disease which is likely to affect strawberry fields in many warm-growing areas.

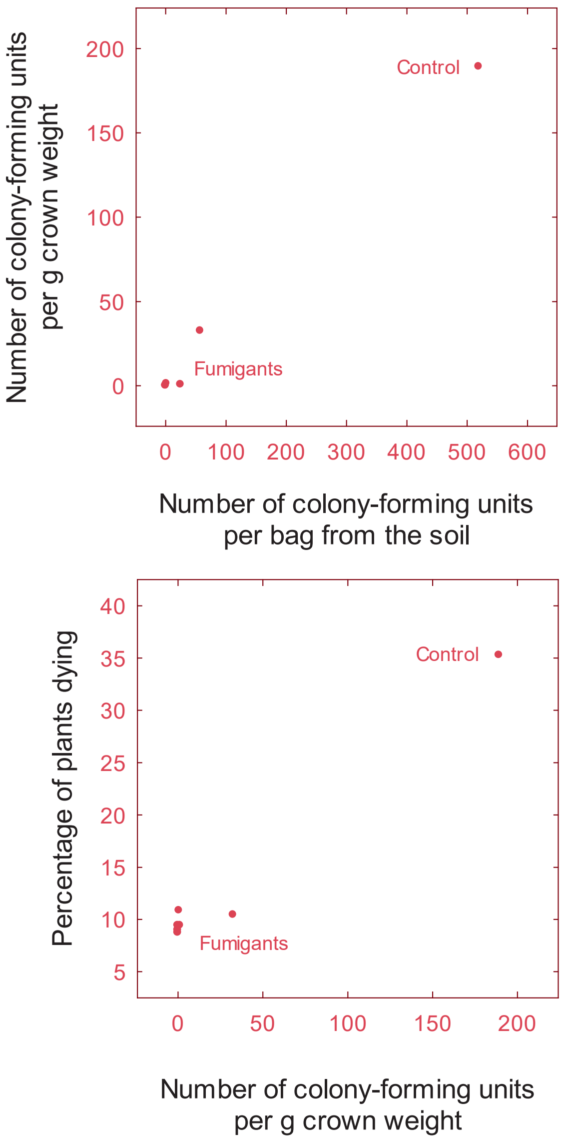

Figure 6. *Relationships between the recovery of the* Macrophomina phaseolina *in the crowns and in the soil, and between the percentage of the plants dying and the recovery of the pathogen in the crowns in a fumigation experiment in a strawberry field in Dover, Florida in 2017.*

Implications of the research for strawberry growers

The main scenarios for global climate change include an increase in the concentration of carbon dioxide (CO_2) and an increase in average temperatures. In many crops, there is an initial increase in productivity with climate change and then a decrease. Several experiments were conducted to examine the performance of strawberry plants in Queensland and Florida in a warming climate.

There was a strong relationship between yield and leaf area in strawberries growing on the Sunshine Coast, with maximum yields recorded with about 40 to 45 leaves per plant. There is some evidence that increasing temperatures will change the relationship between productivity and leaf area, and that decreasing rather than increasing leaf area will increase yields in the future. In other experiments in Queensland, fruit weight decreased by about 4.5 g for every degree Celsius above a daily mean temperature of 16°C. The strong effect of temperature on fruit growth indicates that production on the Sunshine Coast might be a problem in the absence of heat-tolerant cultivars.

Higher temperatures are likely to increase the incidence of charcoal rot in strawberry fields. Research conducted in Florida demonstrated that fumigants must be well distributed within the soil profile to control the disease. Many of the alternative fumigants do not disperse as well as methyl bromide. The effect of fumigation using multiple drip-tapes or multiple port rigs needs to be evaluated in future experiments to improve the control of this pathogen.

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Not all the chemicals mentioned in this report are currently registered for use on strawberry nursery or fruit production fields. Please check current registrations for strawberries before using any of the chemicals. The product label is the official authority and should be used to verify all data relating to the use of a chemical.

Researcher profiles

Christopher Menzel

Dr Menzel is a Principal Horticulturist for DAF and has conducted research for the strawberry industry in Australia for the past 14 years. He has more than 35 years of experience in tropical horticulture. Chris is an Associate of the *Journal of Horticultural Science & Biotechnology* and served on the Editorial Board of *Scientia Horticulturae* for several years. Dr Menzel led research that examined transplant agronomy, and the control of crown rot and lethal yellows in strawberry fields. He led research examining the potential of protected cropping of strawberry plants on the Sunshine Coast. Some of this research was conducted in collaboration with colleagues from the University of Florida. Chris also led the work conducted with Apollo Gomez and Lindsay Smith to screen chemicals for the control of plant and fruit diseases in strawberry crops. This work supported changes for the use of captan and thiram in commercial strawberry fields in Australia.

Natalia Peres

Dr Peres is a Professor from the University of Florida in the United States. Natalia's main area of research is on fruit and plant diseases affecting strawberry crops. She has conducted research on the genetics and pathogenicity of different groups of the crown rot fungi. Dr Peres has also investigated different strategies for the control of grey mould, powdery mildew and black spot, important diseases affecting the crop in Florida and Australia. She has developed programs to assist commercial growers to decide when to apply fungicides to their crops. Natalia leads a team of plant pathology specialists at the University of Florida and has supervised several post-graduate students. She has been a major contributor to activities of the American Phytopathology Society (APS). Dr Peres has strong links with the research program at DAF, and among other projects has been assessing fumigants for the control of charcoal rot of strawberry.

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