

Crop load manipulation and fruit cracking in sweet cherry (*Prunus avium* L.)

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Abstract: Yield loss from rain-induced fruit cracking is a perpetual risk associated with the production of sweet cherries, and is difficult to manage due to the unpredictability of fruit responses to late season rainfall. The aim of this five-year study was to investigate the relationship between fruit crop load and incidence of cracking. The results showed a negative correlation between crop load and incidence of fruit cracking, and it was found in both natural and manipulated crop load trials for all varieties studied and in all seasons assessed. The effect of crop load on final cracking levels are determined post cell division. Results from this study showed that fruit width was positively correlated with cuticular cracking but, contrary to what has been purported in literature, no relationship between concentration of soluble sugars or firmness with the incidence of cracking was found. This study has confirmed that crop load should be a major consideration in orchard practices in developing strategies to manage fruit cracking.

1. Introduction

Cherry fruit size and quality is an important factor in production and sales of sweet cherry fruit (Proebsting and Mills, 1981). Sweet cherry trees are typically upright, vigorous and non-precocious (Lang *et al.*, 2004) so orchard management practices focus on achieving high yields of premium quality fruit through balancing reproductive and vegetative growth. Manipulation of the number of fruits (crop load) on the tree, and leaf area, can be used to encourage larger and sweeter fruit through balanced carbohydrate supply and demand (Lang *et al.*, 2004; Spayd *et al.*, 1986; Whiting and Lang, 2004). However, in many of these studies, yield losses due to cracking have not been presented (Proebsting and Mills, 1981) even when the economic losses due to cracking can be significant (Hanson and Proebsting, 1996). Given that cracking can be induced by internal vascular flow (Measham *et al.*, 2009), it is posited that higher crop loads will reduce the incidence of cracking through increased competition between fruit for assimilate supply.

It has been previously hypothesised that higher crop loads increase competition between fruit for carbohydrates and that lower crop loads result in higher assimilate supply for individual fruit (Spayd *et al.*, 1986), and that there can be a resultant increase in size (Spayd *et al.*, 1986) and concentration of sugars (Proebsting and Mills,

1981). It has also been noted however, that lower crop loads are associated with increased vegetative growth (Kappel, 1991) and that current season's vegetative growth is a strong sink for carbohydrates. Diurnal translocation of sugars from leaves to fruit can be variable (Richardson, 1998), and therefore it is difficult to assess relationships between sugars and cracking as a result of internally supplied excess water.

Cherry fruits are strong sinks (Ayala and Lang, 2008) and it has been noted that removal of spur leaves had little effect on fruit quality because alternative supplies of carbohydrates were sourced (Whiting and Lang, 2004). Fruit and leaf ratio can be manipulated for optimum quality. Two flower buds per spur has been suggested as the ideal (Whiting and Lang, 2004). An interaction between fruit and leaves was also implicated in the development of cracking, in a study by Measham *et al.* (2010), which showed that leaf removal decreased the development of side cracks in cherry fruit during the few weeks prior to harvest. Furthermore, diurnal water potential gradients and evaporative demands on the leaf influenced vascular flow to the fruit demonstrating a local fruit and leaf interaction.

Thus, given that fruit size (Simon, 2006) and sugar levels (Christensen, 1996) have been associated with the development of cracking, and Simon (2006) cites two studies (Bullock, 1952; Way, 1967) that found trees with high loads that showed little cracking within variety, the potential for crop load manipulation to influence fruit cracking warrants investigation. The aim of this present study is to further examine this relationship between crop load and cracking.

2. Materials and Methods

Plant material

Mature trees, grown on F12/1 rootstock, were used in all field trials. Trials were undertaken from late October to late January during seasons 2005/06, 2006/07, 2007/08 and 2010/11 in two commercial orchards in Huonville and Old Beach, Tasmania (Australia). All orchards were subjected to standard industry management practices. To investigate the effect of crop load on fruit cracking and type, five manipulated crop load trials were undertaken in years with late summer rainfall; Trials 1 and 2 in seasons 2005/06 and 2006/07 respectively, Trials 3, 4 and 5 in season 2010/11. A study of fruit properties from Trial 5 was undertaken. In addition, a survey of natural crop load and fruit properties over three years (2005/06, 2006/07, 2007/08) was performed. The relationship between levels of cracking *in situ* and the cracking potential using the cracking index (Christensen, 1972) was also evaluated.

Manipulated crop load trials

To assess the impact of crop load on crack development, manipulated crop load trials were undertaken on one variety 'Simone' at one site (Huonville) in two seasons: 2005/06 (Trial 1) and 2006/07 (Trial 2). Three further manipulated crop load trials were undertaken on different varieties and sites in one season, 2010/11; on variety 'Sweetheart' at Huonville and Old Beach (Trial 3 and 4 respectively), and on variety 'Regina' at Huonville (Trial 5). These varieties were chosen due to the variety of crack types they had previously displayed in earlier studies (Measham *et al.*, 2009) in Tasmania; 'Simone' showed a tendency for cuticular cracks, 'Regina' for side cracks' and 'Sweetheart' for both.

In Trials 1 and 2, treatments included a low, medium and high crop load, which aimed for 2, 5 or 8 fruit per cm² trunk cross sectional area (TCSA) respectively in a randomised complete block design with three replicates (whole tree plots). Treatments were applied at pit-hardening during stage II of fruit growth and development which occurred post bloom at 4 weeks after full bloom (4WAFB). Where the high crop load specified could not be reached, natural crop load was determined and used.

In Trials 3, 4 and 5, treatments included a low, medium and high crop load, applied at three different growth stages in a factorial design with five replicates (whole tree plots). Crop load was achieved by thinning each bud to 1, 2 or 4 floral buds per spur and applied pre bloom (PrB) at dormant bud stage, full bloom (FB) and post bloom (PoB) at four weeks after full bloom. In addition, for Trial 3, a sub sample of 30 non-cracked blemish-free fruits were randomly selected from each replicate tree for individual fruit assessments for size, total soluble solids, and firmness. Mean fruit property values were used to assess relationships with crop load, and with the incidence of cracking *in situ*.

In all trials cracking incidence was determined at harvest. Fruits from each treatment were additionally as-

sessed for cracking index (using 50 non cracked fruits per variety). In all manipulated crop load trials, the actual crop load achieved for all trial trees was recorded.

Natural crop load and fruit properties survey

Natural crop load was recorded at harvest over three seasons on three randomly selected whole trees of available varieties which included 'Kordia', 'Lapin', 'Regina', 'Simone', 'Sweetheart', 'Sylvia' and 'Van'. All fruits were harvested and cracking levels recorded. Cracking incidence recorded at harvest was assessed in relation to natural crop load.

In addition, for each season non-cracked blemish-free fruit from each variety was grouped, and a sub sample of 30 non-cracked fruits were selected for individual fruit assessments for size, weight, total soluble solids, stem length and skin thickness. Mean fruit property values were used to assess the relationship with the incidence of cracking *in situ* for each variety.

Also in 2007/08, fruits from available varieties were assessed for cracking with the cracking index immersion method (Christensen, 1972). The relationship between the cracking index and the level of cracking recorded in the field was investigated. Given that this immersion method depends on water uptake across the skin, the impact of stem removal on uptake and the subsequent index value was also investigated using additional sub samples from variety 'Simone' with stems either removed or left intact.

Measurements

Cracking incidence was determined as per Measham *et al.* (2009), but with apical-end cracks and stem-end cracks combined to give a level of cuticular cracks. Measham *et al.* (2010) concluded that these crack types were likely to be induced through the same mode of water uptake. Cracking index was determined using the immersion method developed by Verner and Blodget (1931) as cited in and refined by Christensen (1972).

All fruit were harvested between 7 A.M. and 12 noon and cracking assessments, morphological measurements and laboratory-based measurements were undertaken on the same day as harvest. Climate data for the months preceding and during harvest was obtained from the Australian Bureau of Meteorology Stations at Huonville (situated less than 5 km from the trial site) and at Old Beach using a PM-K208 PM-11 Phytomonitor Weather Station.

Determination of crop load

Prior to treatment application in manipulated crop load trials, tree girth was measured in centimetres at a point 5 cm above the graft union. TCSA was calculated for each tree for the area (A) of a circle using the formula ($A = C^2/4\pi$), where C = circumference (cm) as described in Measham *et al.* (2009). Crop load was determined as total fruit number per TCSA. To determine natural crop load, all fruits from each tree were counted and crop load expressed as number of fruit per TCSA.

Fruit property tests

Fruit size, weight and total soluble solid (TSS) concentration (brix^o) were measured as described in Measham *et al.* (2009). Fruit firmness was measured using a Bioworks Inc. Firmtech 2 with values recorded using ControlSoft software. Stem length (mm) was measured using Vernier callipers and skin thickness was recorded microscopically using a Nikon SMZ800 dissecting microscope.

Statistical analyses

To assess the relationship between crop load and cracking incidence, and crop load with mean fruit properties,

data were subject to linear regression tests and ANOVA. Interactions between crop load and timing of thinning to desired load were determined prior to assessing main effects. Analysis of proportion data was performed on transformed data in order to meet the assumptions of analysis.

To assess the effect of natural crop load on fruit properties after accounting for variety, mean fruit property data were subject to ANOVA using variety as a fixed factor, and then to ANCOVA (crop load as the covariate) using PROC GLM (SPSS version 17). Unless specified, all results identified as ‘significant’ are at probability level of 0.05.

3. Results

Manipulated crop load trials

All manipulated crop load trials received rainfall in the three weeks prior to harvest. In 2005/06 and 2006/07 there was a similar amount of rainfall (37 mm and 41 mm respectively). Trials 3 and 4 in 2010/11 experienced 49 mm and 50 mm rainfall respectively and Trial 5 received 42 mm rainfall (differing due to harvest dates).

A negative linear relationship between actual crop load and total cracking incidence was recorded for variety ‘Simone’ over both seasons (2005/06 and 2006/07) (Fig. 1). The effect was greater in season 2005/06 than 2006/07, as indicated by the significantly greater magnitude of the slope for each crack type (Slope (B) = -4.69 and -0.77 for total and side cracks and -0.69 and -0.30 for cuticular cracks).

In 2010/11 a significant interaction ($P = 0.045$) between level and timing of crop load on total cracking in variety ‘Sweetheart’ at Huonville (Trial 3) (Fig. 2), but not at Old Beach (Trial 4). At Huonville (Trial 3), within thinning times, no significant effect of crop load at the dormant (PrB) or full bloom (FB) thinning times was seen, but there was a significant effect on total ($P = 0.025$) and side ($P = 0.029$) cracks (but not on cuticular cracks) when

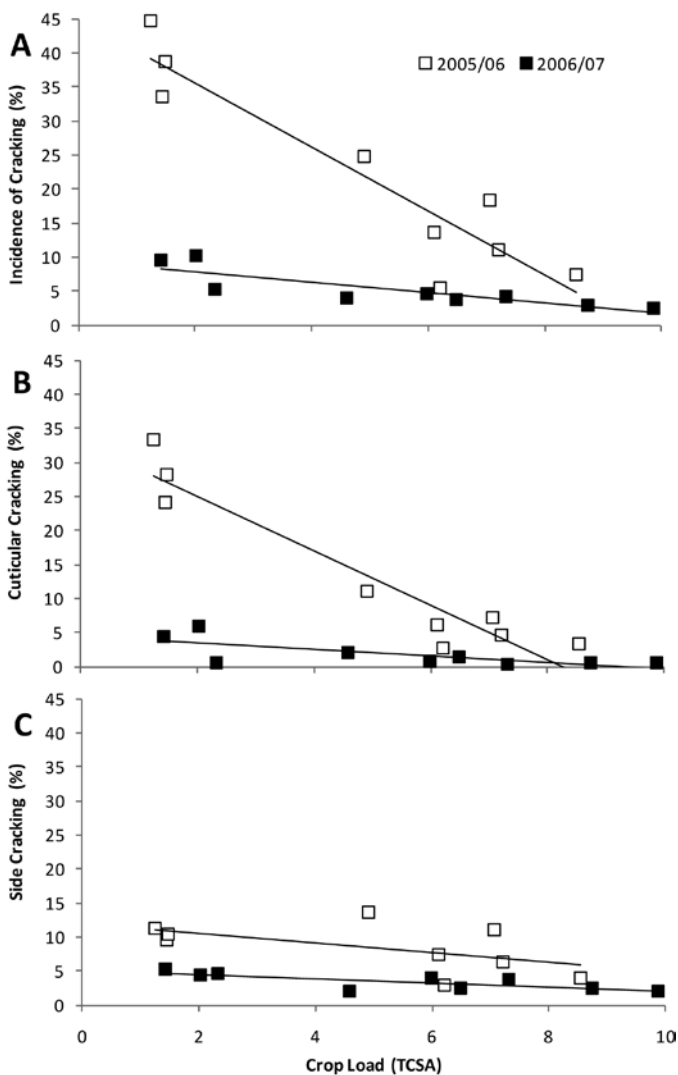


Fig. 1 - Percentage of total cracked fruit (A), cuticular-cracked fruit (B) and side-cracked fruit (C) with actual crop load (TCSA) for variety ‘Simone’. Each point is for an individual tree. A significant relationship was found between actual crop load and total cracking incidence in 2005/06 ($R^2 = 0.903$, $P < 0.001$) and 2006/07 ($R^2 = 0.511$, $P = 0.03$), cuticular cracking 2005/06 ($R^2 = 0.907$, $P < 0.001$) and 2006/07 ($R^2 = 0.540$, $P = 0.02$) and side cracking in 2006/07 ($R^2 = 0.575$, $P = 0.02$). A significant difference between seasons was found for total cracking and cuticular cracking. Slope (B) of the linear regressions calculated for crop load and cracking incidence were significantly different between years.

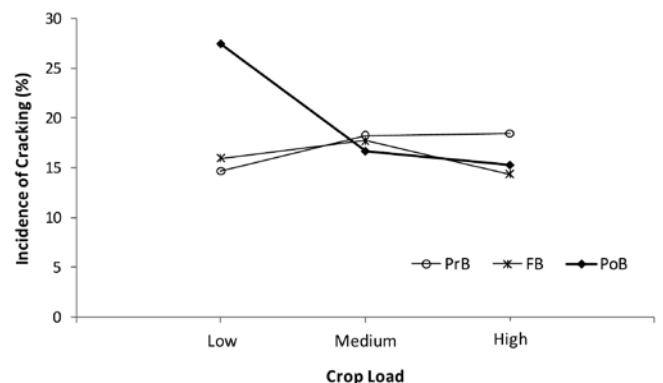


Fig. 2 - Incidence of total cracking at Huonville for variety ‘Sweetheart’ under low, medium and high crop loads applied at dormant bud stage (PB), full bloom (FB) and four weeks after full bloom (PoB). A significant interaction between crop load level and application timing was evident; low crop load resulted in a significantly higher level of cracking within the post bloom application time only.

thinning was applied post bloom (PoB) (Table 1). High and medium crop load levels set by post bloom thinning resulted in significantly fewer cracked fruit than low crop loads. At Old Beach (Trial 4), there was no interaction between crop load level and timing of thinning; there was, however, a significant main effect of crop load on both

Table 1 - Incidence of total and side cracking in 'Sweetheart' at Huonville under high, medium and low crop loads applied post bloom

Crack type	Crop load	Cracking incidence
Total	High	15.22 a
	Medium	16.62 a
	Low	27.40 b
Side	High	11.30 a
	Medium	12.44 a
	Low	22.89 b

For each crack type, values followed by different letters indicate a significant difference ($P < 0.05$).

total ($P = 0.01$) and side ($P = 0.01$) cracks, but not on cuticular cracks. A significant main effect of crop load on total ($P < 0.001$) and side ($P < 0.001$) cracks was also seen in variety 'Regina' at Huonville (Trial 5) (Fig. 3).

There was an interaction of crop load level and timing of thinning on fruit size in 'Regina' (Fig. 4) where low crop loads resulted in smaller fruit when thinned pre bloom or post bloom. Thinning at full bloom gave smaller fruit with medium loads. No interaction was found for fruit soluble solids or firmness; furthermore, no main effect of crop load or timing was found for fruit firmness. There was a significant main effect of crop load ($P = 0.008$) and timing of thinning ($P = 0.013$) on soluble solids with fruit from medium crop loads, and post bloom thinning displaying the highest soluble solids. No fruit properties were correlated with cracking levels except for fruit size, which was positively correlated ($P = 0.01$) with cuticular cracks only.

Cracking indices determined for all treatments in Trials 3, 4 and 5 are given in Table 2. There was a significant relationship ($P = 0.017$) between index and total cracking

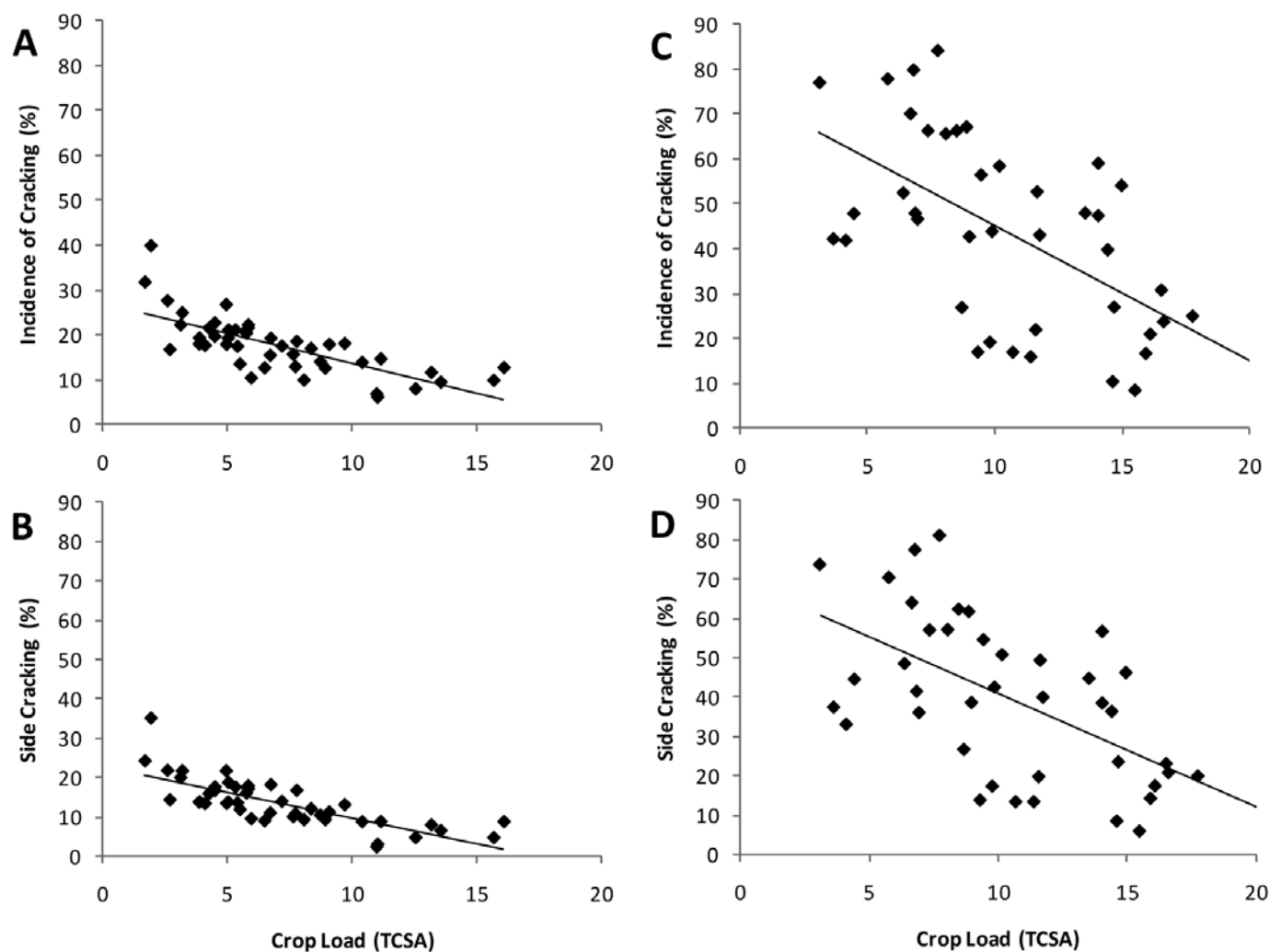


Fig. 3 - Percentage of total cracked fruit (A) ($R^2 = 0.69$) and side-cracked fruit (B) ($R^2 = 0.59$) with actual crop load (TCSA) for variety 'Regina' and percentage of total cracked fruit (C) ($R^2 = 0.33$) and side-cracked fruit (D) ($R^2 = 0.32$) with actual crop load (TCSA) for variety 'Sweetheart'. Each point is for an individual tree. Significant relationships were found between crop load and total cracking incidence and between crop load and side cracking.

recorded *in situ* for Trail 3 only; no relationship was evident between cracking index and cracking *in situ* for Trial 4 or 5.

Natural crop load and fruit property trials

Lower natural crop loads had higher levels of cracking incidence (Fig. 5). Cracking incidence remained low (less than 5%) for crop loads higher than ten fruit per cm² TCSA in all years and for all crack types (Fig. 5). When only using data points of less than 10 fruit per cm² TCSA, relationships between cracking and crop load were found to be significant for all crack types in 2005/06 (total, R² = 0.893, P < 0.001; cuticular, R² = 0.853, P < 0.001; side, R² = 0.540, P = 0.006) and for total and cuticular cracks in 2006/07 (total, R² = 0.576, P = 0.005, cuticular, R² = 0.463, P = 0.03).

Across all varieties and seasons no significant relationship was found between any of the fruit property values with total cracking incidence or individual crack type incidence. Little difference can be observed between either

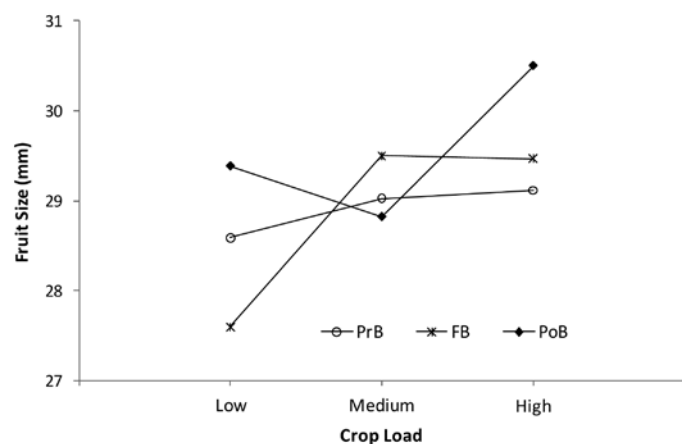


Fig. 4 - Fruit size (mm) determined for fruit from variety 'Regina' under low, medium and high crop loads applied at dormant bud stage (PrB), full bloom (FB) and four weeks after full bloom (PoB). A significant interaction between crop load and thinning time was found.

weight or total soluble solids and changes in crop load, except perhaps a slight trend in variety 'Sylvia' where a decrease in weight, but not in total soluble solids, occurs with a dramatic increase (three fold to 24 fruit per TCSA)

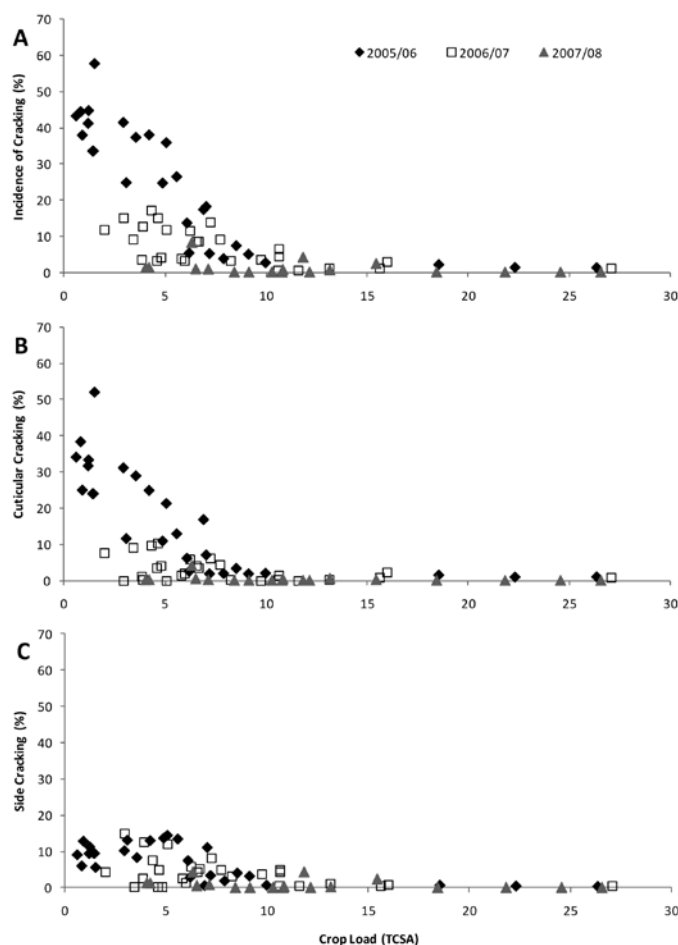


Fig. 5 - The percentage of total cracked fruit (A), cuticular-cracked fruit (B) and side-cracked fruit (C) with natural crop load (TCSA). Each point is for an individual tree. A significant relationship was found between crop load and total cracking incidence in 2005/06 and 2006/07, and between crop load and cuticular cracking in 2005/06, and between crop load and side cracking in 2005/06 and 2006/07.

Table 2 - Cracking index (n = 50) determined for fruit from the three manipulated crop load trials (Trials 3, 4 and 5)

Time of Application	Crop Load	Cracking <i>in situ</i> (%)			Cracking index		
		Trial 3	Trial 4	Trial 5	Trial 3	Trial 4	Trial 5
Dormant	High	18	38	7	5	4	24
	Medium	18	32	11	10	6	16
	Low	14	59	28	11	15	21
Full Bloom	High	14	31	6	8	8	3
	Medium	18	39	11	9	7	7
	Low	16	69	26	8	14	7
4WAFB	High	15	28	7	6	9	4
	Medium	17	32	11	9	4	7
	Low	27	50	26	18	24	12

Mean incidence of total cracking is also given.

A significant correlation was found between cracking index and total cracking in Trial 3 only.

in crop load in the third season, 2007/08 (Fig. 6). A significant variety effect was found in fruit weight ($P = 0.02$), total soluble solids ($P = 0.001$) and stem length ($P < 0.001$). After accounting for variety, and analysing data using crop load as a covariate, a significant effect of crop load was found for fruit weight only ($P = 0.03$).

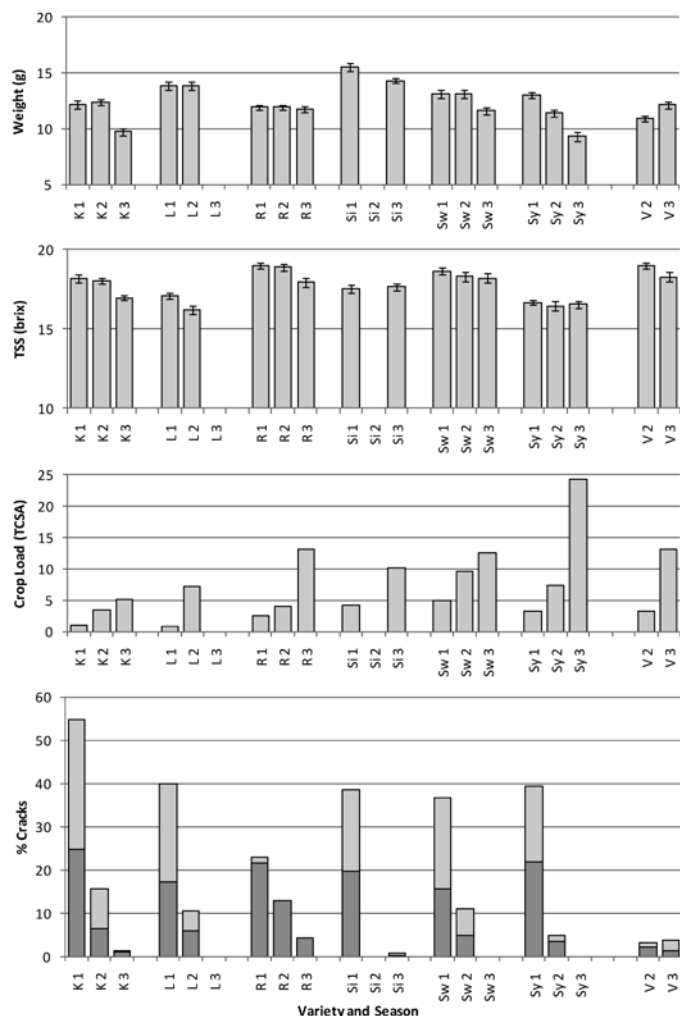


Fig. 6 - Mean fruit weight and total soluble solids for seven varieties over three seasons (error bars represent SEM, $n = 30$) with mean crop load levels ($n = 3$) and cracking incidence for the same varieties and seasons. For cracking incidence, expressed as percentage of total yield, columns represent total incidence, where light areas represent incidence of cuticular-cracked fruit, and dark areas represent incidence of side-cracked fruit. Horizontal axis labels represent variety by letter (K - Kordia, L - Lapin, R - Regina, Si - Simone, Sw - Sweetheart, Sy - Sylvia, V - Van) and season by number (1 - 2005/06, 2 - 2006/07, 3 - 2007/08).

A significant relationship between cracking index with total cracking incidence ($P = 0.011$) and incidence of side-cracked fruit ($P < 0.001$) was found. No significant relationship was found between cracking index and incidence of cuticular-cracked fruit. No differences were found between values for stemless fruit and fruit with stems attached (both had index values of 25).

4. Discussion and Conclusions

Lower crop loads resulted in a greater incidence of fruit cracking in sweet cherry. This was seen in both manipulated crop loads and in the natural crop load survey. Responses to rainfall and the difference in magnitude of cracking between 2005/06 and 2006/07 confirm a strong seasonal impact on crack development, consistent with the findings of Measham *et al.* (2009). However, rainfall *per se* did not account for the differences in cracking between seasons, suggesting that other environmental parameters and fruit growth patterns are also important in the development of cracks.

Fruit development is important in crack susceptibility as all post bloom thinning showed increased cracking with lower crop loads. This implies that the effect of crop load on final cracking levels are determined post cell division, and cracking is therefore more likely to be attributable to cell expansion during the later stages of growth. Cell expansion is a function of internal water entry, which has been linked to increased rates of side-cracked fruit (Measham *et al.*, 2010). This also supports the findings of Yamaguchi *et al.* (2002) who linked cracking susceptibility at harvest to cell length. Pre bloom thinning would therefore be the preferable option for manipulating crop load for size whilst minimising the risk of cracking.

In addition, the development of the cuticle during early growth stages should be investigated with regard to cuticle integrity during the later periods of development. The number of cuticular-cracked fruits in low fruit load trees increased significantly in 'Simone'. During cell expansion, relative canopy cover on a whole tree basis in low fruit load trees, compared to high load trees, may prevent moisture loss from the fruit surface through reduced airflow around fruit bunches in a timely and effective manner, confirming the importance of leaf:fruit ratio in quality management decisions (Whiting and Lang, 2004).

In contrast to other studies (Spayd *et al.*, 1986; Whiting and Lang, 2004) cracking susceptibility in this study did not seem to be related to fruit quality properties, nor did increased crop load limit fruit size or sugar accumulation, or enhance firmness (Christensen, 1996) in any of the manipulated crop load trails.

In the natural crop load survey, variation in fruit properties was mostly influenced by variety, with crop load only further influencing fruit weight, but not size, sugar level, stem length or skin thickness. Cracking incidence was also not significantly correlated with the fruit properties recorded. This is in contrast with accepted views that both fruit size (Simon, 2006) and sugar levels (Christensen, 1996) are closely linked with cracking. Studies suggesting vegetative growth provides a strong photoassimilate sink in apricots (Costes *et al.*, 2000) support these results whereby fruit crop load may not strongly influence source:sink relationships. Results from both the manipulated and natural crop load trials do confirm studies that report no differences in sugar levels between varieties of varying cracking susceptibility (Moing *et al.*, 2004).

Furthermore, the results of the present study can be explained by the level of crop load achieved under normal orchard practice. Fruit loads were relatively low in trees from this study with the majority being lower than 15 fruits per cm² TCSA; the highest value reached was about 27 fruits per cm² TCSA, or the equivalent of just over 2000 fruits on a tree with a trunk circumference of 30 cm. It is possible that fruit quality (size and sugars) was not diminishing under this scenario as there were still available resources within the tree from which to draw. This finding highlights the strong potential for encouraging good fruit set, and subsequent crop load, as a practical and viable management tool in mitigating yield losses from rain-induced cherry fruit cracking, given the significant reduction in cracked fruit with increased crop loads.

The incidence of cracking recorded *in situ* was correlated with the cracking index for varieties in the natural crop load survey but for only one of the manipulated crop load trials. The cracking index procedure may not necessarily be reliable for predicting cracking susceptibility given the differences found in cracking incidence with crop load, with seasons (Measham *et al.*, 2009), and when compared to other growing regions (Christensen, 1996; Greco *et al.*, 2008). The strong correlation between cracking index and the incidence of side cracks recorded *in situ* supports the build up of turgor within the fruit as a likely driver of side cracking (Sekse, 1995), which can be somewhat mitigated by skin and cuticular properties. This could be due to differences in shape; curvature of the skin has been related to cracking susceptibility (Sawada, 1934), and could also explain why size was the only fruit parameter positively correlated with cuticular cracking.

This study has confirmed that crop load management can be successfully used to mitigate cracking without compromising fruit size. The results from this study did not confirm the relationship between fruit size, or sugar, and the incidence or cracking, but highlight the importance of skin properties in crack development.

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