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Major factors causing variation in bruise susceptibility of apples (*Malus domestica*) grown in New Zealand

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Abstract Loss of commercially valuable apples (*Malus domestica*) as a result of mechanical damage continues to be an issue for postharvest operators. Four important varieties ('Royal Gala', 'Braeburn', 'Granny Smith', and 'Splendour') have been investigated to establish the main influences on susceptibility to bruising. A new measure of susceptibility is introduced which describes the damage susceptibility of a population of apples—important from a commercial perspective. Seasonal variation is the main effect on susceptibility. Within a season, late harvest fruit are more susceptible to damage. The only other significant effect was time after harvest for 'Braeburn', with fruit on day of picking being more prone to bruising. Fruit temperature during handling (for 'Braeburn') and short-term storage (for 'Granny Smith') do not significantly affect commercially relevant susceptibility to bruising. Populations of 'Royal Gala' showed a wide variation in susceptibility to bruising compared with the other three varieties, which were more consistent in their response to impacts.

Keywords apple; bruising; damage

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INTRODUCTION

The susceptibility of apples (*Malus domestica* Borkh.) to bruising is a major issue for postharvest operators. Levels of damage sustained by the fruit can have an impact on returns to growers. By understanding the fruit's susceptibility to bruising it is possible to identify when to adopt techniques which will reduce the chances of sustaining high levels of damage, or identify varieties that require additional care when handling. Numerous studies have been carried out on apple damage but there is no consensus on the appropriate way to describe susceptibility. Some researchers use bruise area as the main indicator of damage, others bruise volume. Some research uses specialised indenters on a pendulum whereas others impact the apples onto a flat surface. In most instances the levels of impact energy used in susceptibility studies have been considerably higher than occur in practice. In general, an implicit assumption of these studies is that damage response at low energy levels can be extrapolated from damage response at high energy levels. Studies of typical impact energies in New Zealand postharvest handling systems has shown that these rarely exceed 0.1 J (Bollen & Dela Rue 1990). A summary of the relevant susceptibility studies is shown in Table 1 where the following calculations have been made to enable comparisons from the reported data. Drop heights have been converted into an impact energy, E = mgh (E, impact energy (J); m, fruit mass (kg); *g*, acceleration from gravity (m/s^2); h, drop height (m)) and, where possible, susceptibilities expressed as the bruise volume ratio relative to the impact energy (V/E). Where this was not possible, the susceptibility reported in the table is a percentage effect on susceptibility. Levels of significance are affected by the unit of measure. In some instances average fruit weights were not reported for drop and pendulum tests, and an average apple weight of 200 g has been used to convert drop height into estimated impact energy. The difficulty with comparing much of these data is that the methods of applying the impact vary, the shape of the impact surface varies,

Table 1 Summary of susceptibility studies. (NS, differences not significant.)

Major conclusions	Reference	Impact energy*	Sample size	Notes
Temperature effects				
Increase in volume (11%) McIntosh; 32°C > 4°C	Nelson & Mohsenin (1968)	0.9–2.6 J	25	
Increase in susceptibility (2.57 ml/J, 4.26 ml/J) Golden Delicious; 30°C > 0°	Saltveit (1984)	0.49 J	40	
NS volume % change, Granny Smith; 18°C, 1°C	Klein (1987)	0.16 J, 0.63 J	40	New Zealand apples, stored
Increase in susceptibility (15.1 ml/J, 13.5 ml/J) Golden Delicious and (16.7 ml/J,15.6 ml/J), Red Delicious; 0°C > 21°C	Zhang & Hyde (1992)	0.55 J	28	
Increase in diameter (11%) Granny Smith; 0°C > 10°C, 0°C, 20°C, 30°C NS	Mowatt (1997)	0.13 J, 0.21 J	105	New Zealand apples
Storage effects				
Decrease in width and depth over first 7 weeks, after 11 weeks NS, pooled varieties	Hyde & Ingle (1968)	0.16 J	30	2°C
Decrease in volume %, 7% after 3 weeks, 11% after 6 weeks, 16% after 12 weeks	Klein (1987)	0.16 J, 0.63 J	40	1°C New Zealand apples
Decrease in area over 19 weeks; 25% Law Rome, 40% Golden Delicious, 30% McIntosh	Timm et al (1989)	0.07 J	14	1°C
Decrease over 9 weeks (3.30–3.00 ml/J) Golden Delicious, (3.35–2.73 ml/J) Golden Supreme	Garcia et al (1995)	0.04 J	270	
Decrease in area over 31 weeks Granny Smith	Pang (1993)	0.15–1.3 J	105	New Zealand apples
NS volume change over 20 weeks Granny Smith, Delicious, Jonathan	Holt & Schoorl (1984)	0.78 J	–	2°C
Increase in volume 0–12 weeks, Ida Red, McIntosh; 12–24 weeks NS	Bruzewitz & Bartsch (1989)	0.07–0.35 J	30	
Increase in area (3%) at 2.5 weeks, Splendour	Mowatt (1997)	0.13 J, 0.21 J	20	New Zealand apples
Harvest maturity				
Late > Early, width and depth (4%) pooled varieties	Hyde & Ingle (1968)	0.16 J	30	
Late > Early, diameter (10%) Granny Smith and (45%) Royal Gala	Mowatt (1997)	0.13 J, 0.21 J	120	New Zealand apples
Early > Late (4.5 ml/J, 2.6 ml/J) Golden Delicious	Diener et al. (1979)	0.05–0.53 J	40	
Seasonal variation				
Mean 3.42 ml/J Bramleys; max. +20%, min. –14%	Johnson & Dover (1990)	0.19 J	–	5 seasons.
Variation from 0% to 36% not consistent between variety within year for 6 varieties	Hyde & Ingle (1968)	0.16 J	30	2 seasons—5 varieties
NS for volume Granny Smith and Gala	Klein (1987)	0.16 J, 0.63 J	40	2 seasons. New Zealand apples
Mean diameter 0–3% variation; from orchard surveys, Granny Smith and Royal Gala	Mowatt (1997)	0.32 J	120	2 seasons. New Zealand apples
Variety				
Golden Delicious (9.0 ml/J), Granny Smith (9.5 ml/J), Jonathan (8.5 ml/J) all NS	Holt & Schoorl (1984)	0.78 J	–	
Gala, Granny Smith (6.1 ml/J) NS	Klein (1987)	0.16 J, 0.63 J	40	New Zealand apples
Granny Smith > Royal Gala, for bruise diameter (12%)	Mowatt (1997)	0.13, 0.21 J	–	Estimate data New Zealand apples
Braeburn (9.3 ml/J), Granny Smith (10.2 ml/J), Splendour (10.8 ml/J), Fuji (11.6 ml/J) all NS	Pang (1993)	0.15–1.3 J	105	Used slope of $A/E^{0.4}$ New Zealand apples

*Impact energy estimated from drop height where not specified in paper.

and the energy levels vary. All these factors can potentially affect the resultant bruise size and produce estimates of susceptibility that are not comparable with other techniques.

From a commercial perspective the useful descriptor of bruise susceptibility is one which describes the likelihood that a proportion of a population of fruit sustains bruises greater than a commercial grading threshold (e.g., 1 cm^2). Bollen et al. (2000) have presented such a susceptibility measure, based on the logistic function, and this method for describing susceptibility is used in this paper to discuss the susceptibility of apple varieties grown in New Zealand at impact energies which are common to the postharvest handling system.

Time after harvest

Once an apple has been harvested it starts to lose water. This results in a loss of turgor which can potentially have an effect on susceptibility. Mowatt (1997) investigated this phenomenon by running a 400-fruit sample across a small commercial grader four times and then assessing the fruit for bruising. The average bruise area per fruit dropped from 1.59 cm^2/fruit at harvest, to 1.28 cm^2 after 1 day, to 1.17 cm^2 after 3 days, and 0.85 cm^2 after 9 days. A recommendation was made that fruit should be packed after 1 day.

Temperature effects

The temperature at which fruit is handled is a common concern, with postharvest operators not normally packing fruit straight out of coolstore in the belief that it is more likely to damage. The evidence to date is evenly split with a set of similar studies, some of which show an increase in susceptibility with temperature, and others which show a decrease. Nelson & Mohsenin (1968) subjected fruit to impacts in a pendulum rig at high energy levels (0.9–2.6 J). They showed an 11% decrease in susceptibility (V/E_a) for 'McIntosh' if impacted at 4°C instead of 32°C, where E_a is the energy absorbed during the impact. Saltveit (1984) had a similar finding with 'Starkrimson' and 'Golden Delicious' (Table 1). Klein (1987) saw no difference in bruise size for 'Granny Smith' impacted at 1°C or 18°C. Zhang & Hyde (1992) used high energy drop impacts (0.55 J) and they found that for both 'Red Delicious' and 'Golden Delicious', susceptibilities between 0°C and 7°C or between 14°C and 21°C were not significantly different. 'Golden Delicious' showed a 10% larger volume at 0°C over 21°C, and 'Red Delicious' an increase of 15%. Mowatt (1997) using 'Granny Smith' found an 11% increase in bruise area at 0°C over samples at 10°C, 20°C, and 30°C.

Storage effects

Storage of apples can have several effects on damage susceptibility. The length of time in storage results in maturity changes and weight loss, both of which potentially have an effect on changing susceptibility. Most studies (Table 1) show a decline in susceptibility with time. In some of these studies there was a rapid decline early in the storage period (Klein 1987) but for others rapid decline came later (Hyde & Ingle 1968). Bruzewitz & Bartsch (1989) showed the reverse relationship. This study was conducted at lower energy levels than Klein, Hyde & Ingle, Pang & Holt, and Schoorl (Table 1). After 12 weeks of storage, bruise volumes on 'Ida Red' and 'McIntosh' were 30% larger than at harvest but did not further increase significantly by 24 weeks. An increase in susceptibility has also been reported by Mowatt (1997) for 'Splendour' where a 3% increase was found early in the storage period.

Harvest maturity

Numerous physiological changes are underway as the fruit approaches maturity and it is possible that these will have some impact on damage susceptibility. Johnson & Dover (1990) tracked susceptibility for 'Bramley Seedless' over a period extending 2 weeks either side of the commercial harvest period. The bruise volume/harvest date relationship was linear with a positive slope (increasing with maturity), based on a standard 0.19 J impact. However, over a 5-year period the slopes were not consistent.

In studies over 2 years with six Danish apple varieties, Kampp & Nissen (1990) found there was a general trend to increased susceptibility with later maturity. There was little difference between early and mid-season fruit. Hyde & Ingle (1968) found an increase in susceptibility (V/E) of 4% between early and late harvests (pooled for five varieties). Klein (1987) reported an increase in bruise weight of 11% as the season progressed for pooled 'Gala' and 'Granny Smith' data. Mowatt (1997) found the individual increases to be 10% of bruised area for 'Granny Smith' and a 45% increase for 'Royal Gala'. Late season 'Royal Gala' and late season 'Granny Smith' produced similar sized bruises from the 0.32 J impactor test. The one contrary result was from Diener et al. (1979) where late harvest susceptibility (V/E) dropped by 70%, but the harvest dates were 4 weeks apart.

Seasonal variation

With any biological product there will be variations related to the individual growing seasons. The most comprehensive examination of seasonal variation has been carried out by Johnson & Dover (1990) who measured 'Bramley Seedless' susceptibility (V/E) over 6 years (see Table 1). The level of variation was considerably higher than many of the other effects which have already been discussed. Hyde & Ingle (1968) replicated experiments over two seasons and seasonal variation in V/E ranged from 0% to 36%. Kampp & Nissen (1990) noted a similar effect with a further complication that the effect was not consistent across a season. With early harvest fruit, two varieties ('Gloster' and 'Golden Delicious') were lower in the second year (1985), one remained unchanged and four increased in susceptibility. For the late harvests two were lower ('Gloster' and 'McIntosh'), three were unchanged and two increased ('Golden Delicious' and 'Jonagold'). In orchard surveys in New Zealand over 2 years (Mowatt 1997) there was only a 3% variation in mean bruise diameter. Klein (1987) similarly noted no significant variation in 2 years of 'Granny Smith' and 'Gala' data.

Variety

From the earliest days of damage susceptibility research, differences between varieties have been a common focus of study. North American research generally ranks 'McIntosh' as the most susceptible variety followed by 'Red Delicious', with 'Golden Delicious' being the least susceptible (Timm et al. 1989; Schulte et al. 1992; Zhang & Hyde 1992). Research on varieties of commercial significance to New Zealand are also summarised in Table 1. Of the three studies, Mowatt (1997) determined 'Granny Smith' to be more susceptible than 'Royal Gala', and Pang (1993) showed 'Braeburn' to be less susceptible than 'Granny Smith', 'Fuji', and 'Splendour' (all of which were not significantly different). Klein (1987) ranked several commercially significant varieties based on a bruise weight percentage (BWP) measure. This placed 'Golden Delicious' among the least susceptible; 'Granny Smith' and 'Braeburn' were grouped as being more susceptible; and 'Red Delicious', 'Gala', and 'Cox's Orange Pippin' were defined as the most susceptible. In another analysis in the same paper, however, the differences between 'Granny Smith' and 'Gala' were shown to be not significant.

EXPERIMENTAL METHOD

Fruit samples were collected from a commercial orchard in the Waikato, New Zealand, over a period of several years. Count 100 fruit (200 ± 10 g) were used for all assessments to minimise the effects of size and shape variability. Fruit were returned to the laboratory in single layer trays to avoid damage and impacted using a pendulum impactor to provide impact energies equivalent to vertical drops

Table 2 Experimental detail.

	Variety	Harvest (maturity)	Year	Test parameter
Time after harvest	Braeburn	Early	3	In orchard
	Braeburn	Early	3	After 24 h
Temperature effect	Braeburn	Late	4	26°C
	Braeburn	Late	4	8°C
Storage effect	Granny Smith	Early	2	After 24 h
	Granny Smith	Early	2	After 18 days
	Granny Smith	Early	2	After 100 days
Maturity	Royal Gala	Early/late	1	Harvest 10 days apart
	Granny Smith	Early/late	1	Harvest 17 days apart
	Braeburn	Early/late	3	Harvest 18 days apart
Seasonal variation	Granny Smith	Mid	3, 4, 5	
	Royal Gala	Early	1, 2	
	Braeburn	Late	3, 4	
Variety	Granny Smith	Early/mid/late	1, 2, 3, 4, 5	
	Royal Gala	Early/late	1, 2	
	Braeburn	Early/late	3, 4	
	Splendour	Mid	3	

Mohsenin (1986). The impactor consisted of two 600 mm long nylon wires suspending a small brass ring (approximately weightless). An individual fruit was placed in the ring, drawn back to the appropriate drop height and released to impact upon a flat steel plate. After each impact the fruit was rotated 90º and re-impacted to give 4 impacts per fruit, all on the cheek. Six impact energies were used ranging from 0.009 to 0.119 J, equivalent to drop heights of 5–60 mm for fruit with an average weight of 200 g. For the storage effect run, the energy range was increased to 0.372 J for the 100 days after harvest test as it was anticipated that susceptibility would be lower. Sixteen fruit were dropped at each energy level for a total of 384 potential bruises per data set. Each impact site was marked on the fruit with a pen. The energy levels were selected to produce a bruise size population, for 1 cm^2 bruises, from 0% to 100%. After impacting, the fruit was set aside for 24 h at room temperature to allow the bruise colour to develop. Each impact site was then sectioned, perpendicular to the surface through the centre of the contact area, and the width, depth, and depth to the top of the bruise were measured to calculate bruise areas and volumes. This can be said to be conservative from a commercial perspective as where the bruise occurs on a red part of the apple it was not always visible under the skin.

The experimental layout is summarised in Table 2.

All fruit were harvested within the dates prescribed for commercial harvest. From a practical experimental consideration it was necessary to impact fruit at least 24 h after harvest, to allow time for collection and return to the laboratory. To establish the time after harvest effect on susceptibility, one set of impacts were carried out in the orchard, where 'Braeburn' apples roughly fitting the size specification were harvested and weighed. Those within the 100 count range were then impacted within 10 min of harvest.

The effect of fruit temperature was assessed using two sets of 'Braeburn' apples; one was held in a warmed room overnight and a second set was cooled to 6°C. Both sets of fruit were impacted the following day with impacts and sample sets randomised to minimise the effects of time after harvest. The cooled fruit warmed slightly during the procedure and had an average surface temperature of 8°C when impacted. This reflects commercial reality as fruit is handled through a water dump which warms the fruit up to at least 10°C. The fruit held in the warmed room averaged 26°C.

Effects of the length of storage time on susceptibility were evaluated using 'Granny Smith' apples. The fruit sample was divided into three subsamples of 64 fruit per energy level and the first set impacted 1 day after harvest. The second set was impacted 18 days after harvest and a final set impacted 100 days after harvest. The fruit was held in a 1°C (±0.5°C) coolstore.

The effect of fruit maturity was assessed using fruit from early and late in the commercial harvest period. The early harvest was defined as fruit harvested within 7 days of the commercial opening date for harvest and the late harvest was within 4 days of the closing date. The time between harvests of samples is summarised in Table 2. Seasonal variation was assessed for 'Braeburn' and 'Royal Gala' by repeating impacts for apples from the same orchard over 2 years. The second year harvest time was at about the same time in the commercial harvest window. In addition, 3 years of comparisons were performed for 'Granny Smith' using apples of the same maturity as determined by starch index (SI). The SI was used as the indicator of maturity as this is the parameter which changes most markedly over the harvest period. Fruit were collected from the orchard when the SI sampling by the grower indicated that levels had reached 3.2. A further sample of 10 fruit was assessed to establish the SI for the sample in each season; Year 3 SI = 3.2, Year 4 SI = 3.5, and Year 5 SI = 3.5.

All data were then pooled from the above evaluations to compare variety effects on susceptibility. In addition, one data set of 'Splendour', a variety recognised by industry as being highly susceptible, was included.

SUSCEPTIBILITY MEASURE

The definition of bruise susceptibility used for this study is the proportion of the sample population which sustains a bruise greater than 1 cm^2. The probability of bruising relationship with impact energy has been shown to be characterised by a logistic function Bollen et al. (2000). This is defined as:

$$p = \frac{e^{c+mE}}{1+e^{c+mE}}$$

where p is probability of a bruise >1 cm^2; E is impact energy; m is logistic slope constant; and c is logistic offset—equivalent to the intercept for a linear regression.

The main advantage of this analysis is that it provides an insight into the behaviour of the population as well as producing a descriptor similar to the more common measures of susceptibility (Table 1).

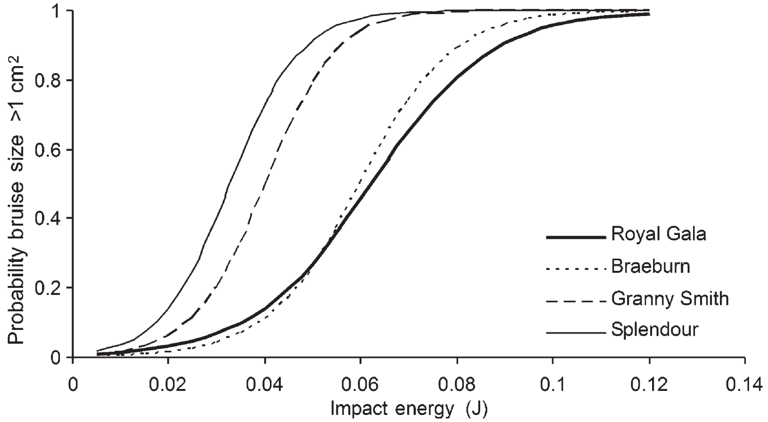

Fig. 1 Bruise susceptibility model for early and late harvested 'Royal Gala' apple (*Malus domestica*).

Table 3 Effects of time after harvest, temperature, and short-term storage on the bruise susceptibility of apples (*Malus domestica*). (NS, not significant.)

			Level of significance
Braeburn			
Time after harvest effect	**At harvest**	**After 24 h**	
Common logit slope (m)	92.5	92.8	0.66 (NS)
Logit offset (C)	–6.41	–7.47	0.027
E_{50} energy (J)	0.069	0.081	
Temperature effect	**8°C**	**26°C**	
Common logit slope (m)	120.3	120.3	0.62 (NS)
Logit offset (C)	–6.00	–5.25	0.12 (NS)
E_{50} energy (J)	0.050	0.044	
Granny Smith			
Storage effect	**0 days**	**18 days**	
Common logit slope (m)	143.8	143.8	0.92 (NS)
Logit offset (C)	–5.34	–5.26	0.89 (NS)
E_{50} energy (J)	0.037	0.037	

The logistic constants were established and the differences examined using generalised linear model methods (McCullagh & Nelder 1983) fitting logistic curves to the relationships using Genstat. The analysis first tests for significance in differences between logistic slope constants. This test is to determine if there is evidence of differences in variability of bruise response in the sample populations. The second part of the analysis was a test of significance on the differences between logistic offsets for a common slope. This test determined if there was evidence of the treatment effect between the sample populations.

Additional to the above analysis the E_{50} energy was calculated. This is defined as the energy when 50% of the population sustains a bruise >1 cm^2. This is equivalent to the impact energy when the average bruise size is 1 cm^2. The difference in E_{50} energy between two treatments is also the measure of the shift of the logit curve along the energy axis and represents the change in energy which can be sustained, as a result of the treatment, to produce the same level of damage. The E_{50} comparison is only possible where the logistic functions have the same slope.

RESULTS AND DISCUSSION

The typical data generated by this analysis is shown in Fig. 1. Each data point represents the proportion of the 64 impact sites that sustained a bruise >1 cm^2. The analysis then fits the appropriate logistic curve to this data, which in Fig. 1 is m = 75.4, c = 5.06, and E_{50} = 0.067 J.

Time after harvest

The evaluation using 'Braeburn' confirmed the finding by Mowatt (1997) that the time after harvest can have an effect on susceptibility. Fruit impacted 24 h after harvest were significantly ($P = 0.027$) less susceptible to bruising than fruit impacted within 10 min of harvest. The E_{50} energy shifts up by 0.012 J after 24 h (Table 3), an increase of 17%. All subsequent evaluations were, however, for practical reasons, carried out in the laboratory at least 24 h after harvest. Therefore, these data suggest that all the other susceptibilities reported here may be slightly low when concerned with harvesting operations, but will be appropriate for other subsequent postharvest operations.

Temperature effects

There was no significant difference in susceptibility between the 8°C and 26°C for 'Braeburn' fruit (Table 3).

The most significant temperature effects reported in the literature (Table 1) are where fruit is impacted at very high energies (Table 1). The result of this trial suggests that the effect may be influenced by test method. Both other studies with New Zealand apples (Table 1) have also shown fruit temperature at time of impact to not be a significant factor. Fruit temperature when impacted at energy levels typical (0–0.1 J) of postharvest handling systems is not a major factor affecting bruise susceptibility.

Storage effects

The experiment was set up with a common sample of 'Granny Smith' which was split into three subsamples. The maximum impact energy used for the sample that was impacted after 100 days (14.3 weeks) was 0.372 J. At this energy level only 3% of the bruises were greater than 1 cm^2. At all other lower energy levels no large bruising was observed. It was therefore not possible to fit a logistic function to these data, however, the bruise size had reduced dramatically over the 100 days. Over the short term (18 days at 1°C) there was no significant change in bruise susceptibility (Table 3). This pattern is similar to that observed by Timm et al. (1989). The variation in change in susceptibility with storage is complex as indicated by the divergence of results (Table 1). The exact effect must be strongly influenced by the actual storage conditions. For this study the fruit was conventionally stored in apple cartons, and the result is considered likely to typify the commercial reality.

Maturity

The variation in bruise susceptibility with maturity was determined for three varieties as summarised in Table 4. 'Royal Gala' samples did not vary significantly between the early and late harvest. A slight shortage of fruit on the orchard meant that the late harvest was earlier than anticipated and the fruit were harvested 10 days after the early harvest. Any changes in 'Royal Gala' susceptibility were not statistically significant over this short period. The susceptibility is shown in Fig. 2. The variability within the 'Royal Gala' population is high. A few fruit sustain a 1 cm^2 bruise at an energy of 0.02 J whereas some fruit do not sustain a 1 cm^2 bruise at 5 times the energy, 0.1 J.

Both 'Granny Smith' and 'Braeburn' showed a highly significant increase in susceptibility in the late harvest fruit (Table 4). The E_{50} energy was 27% lower for 'Granny Smith'. The energy required to bruise 'Braeburn' also dropped by 20% for the late harvest. These results concur with most previous studies (Table 1) but suggest the 45% variation between harvests observed by Mowatt (1997) may have been unusually high.

The logistic slopes for the three varieties are also shown in Table 4. As already discussed the slope of the 'Royal Gala' (75.4) equates to a highly variable population. In contrast, 'Braeburn' damage response is more consistent, and 'Granny Smith' is the most consistent.

Seasonal variation

Bruise susceptibility between seasons for similar harvest times is summarised in Table 5. For all three varieties the susceptibility is significantly different between years. The difference in impact energy to produce the same bruising levels in different years (difference between E_{50}) was up to 35% for 'Granny Smith' over 3 years, 48% for the 2 years of 'Royal Gala', and 20% for the 2 'Braeburn' sample populations. These results are consistent with the findings of Johnson & Dover (1990) and Hyde & Ingle (1968).

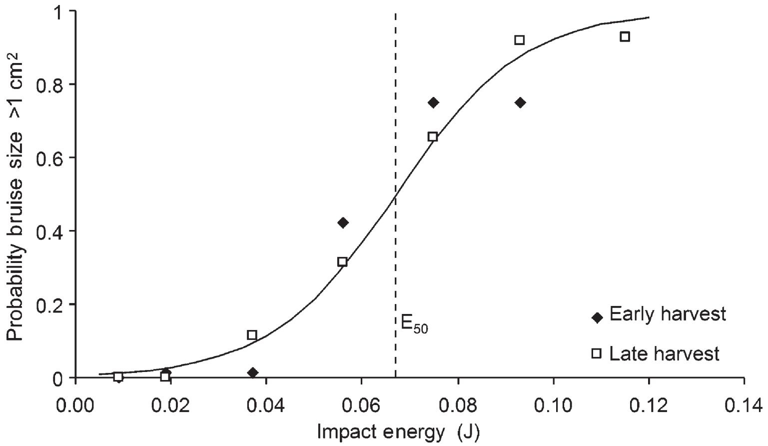

Fig. 2 Average bruise susceptibilities for four New Zealand apple (*Malus domestica*) varieties.

Table 4 Effect of the range of maturity during commercial harvest on the bruise susceptibility of apples (*Malus domestica*). (NS, not significant.)

	Early harvest	Late harvest	Level of significance
Granny Smith			
Common logit slope (m)	213.4	213.4	0.085
Logit offset (C)	–9.68	–7.03	1.5×10^{-07}
E_{50} energy (J)	0.045	0.033	
Royal Gala			
Common logit slope (m)	75.4	75.4	0.999 (NS)
Logit offset (C)	–5.06	–5.06	0.0999 (NS)
E_{50} energy (J)	0.067	0.067	
Braeburn			
Common logit slope (m)	93.5	93.5	0.75 (NS)
Logit offset (C)	–7.53	–6.09	0.008
E_{50} energy (J)	0.081	0.065	

Table 5 Variation in susceptibility of apple (*Malus domestica*) to bruising between seasons. (NS, not significant.)

	Year 1	Year 2	Year 3	Level of significance
Granny Smith				
Common logit slope (m)	108.6	108.6	108.6	0.56 (NS)
Logit offset (C)	–4.48	–5.60	–3.71	0.004
E_{50} energy (J)	0.041	0.052	0.034	
Royal Gala				
Common logit slope (m)	85.8	85.8	85.8	0.18 (NS)
Logit offset (C)	–4.10	–5.75		0.003
E_{50} energy (J)	0.048	0.067		
Braeburn				
Common logit slope (m)	101.7	101.7	101.7	0.38 (NS)
Logit offset (C)	–6.62	–5.15		0.0001
E_{50} energy (J)	0.065	0.051		

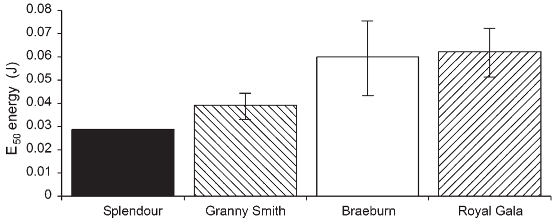

Fig. 3 Mean bruise energy for an average bruise size of 1 cm^2 (only one sample set for 'Splendour' apple (*Malus domestica*)).

The logistic slope 'Granny Smith' sample populations for this part of the study (Table 5) suggest the natural variability is closer to 'Braeburn', with 'Royal Gala' more variable.

Variety effect

All the data were pooled to establish characteristic susceptibility models for the four varieties assessed in this research. The analysis showed no significant logistic slope effects for the pooled data and so it is possible to describe each variety with a characteristic slope. Fig. 2 shows the average susceptibility for each variety based on all the data. The average E_{50} energy is shown in Fig. 3. The bars show the standard deviation for all the sample populations. 'Granny Smith' data show less variation than 'Royal Gala', and 'Braeburn' show the most variation. There was only one sample for 'Splendour'.

Investigating the susceptibilities in Fig. 3 further shows 'Splendour' to be the most bruise susceptible, closely followed by 'Granny Smith'. 'Braeburn' and 'Royal Gala' are less susceptible. Based on the E_{50} analysis, which relates to the conventional method for describing susceptibility (average bruise size), 'Royal Gala' is slightly less susceptible than 'Braeburn'. The objective of commercial apple handling is to minimise the number of bruises greater than 1 cm^2 so the important part of the susceptibility curve is the tail of the distribution. The higher variability within 'Royal Gala' population means that when considering only a low probability level the susceptibility approaches that of 'Granny Smith', whereas 'Braeburn' remains significantly less susceptible.

CONCLUSIONS

The major effect on bruise susceptibility noted in this study was seasonal variation which ranged from 20% to 48%. The only other major effects noted were within-season variation between early and late harvest of up to 27%, and time after harvest with a drop of 17% over the first 24 h. Short-term storage and temperature do not have significant effects on susceptibility for typical postharvest system impact energies.

The logistic susceptibility analysis showed that for a low level of bruises (>1 cm^2), 'Splendour' was the most susceptible variety, closely followed by 'Granny Smith' and 'Royal Gala', and with 'Braeburn' the least susceptible.

It can also be concluded that for use with instrumentation that measures impact acceleration it will be necessary to have a susceptibility model which relates to the fruit of interest. This is likely to require some form of susceptibility measurement every season, as this is the primary cause of variation.

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