Agronomic factors affecting the variability of squash fruit weight

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Abstract

Data from commercial crops grown in Gisborne, Hawke's Bay and Manawatu over 2 years were used to determine the weight distribution of buttercup squash, as new export markets are demanding fruit <1200 g. In plots where only fruit >900 g were harvested, a normal distribution gave the best fit to the variability of fruit weight, and the parameters varied with Year, Region and Site. In plots where all fruit were harvested, a bi-modal normal distribution described the fruit variability in half of the plots, due to a second fruit size peak with an average weight of about 700 g. While most plots showed a double flush of fruit set, there was less abortion of the second flush in these crops. Fruit from the first flush appear to form the bulk of the population of fruit >900 g. However, some fruit from the second flush reached sizes of 1500-1900 g, substantially larger than some fruit from the first flush. Thus, there is significant variability in individual fruit growth rate, making the prediction of fruit weight distribution difficult.

For fruit >900 g, up to 66 % of the variation in *m*, a measure of average fruit weight, was explained by planting density, fertility and environmental conditions, and 53% of the variability in *s*, a measure of the standard deviation of fruit weight, was explained by applied phosphorus and environmental conditions. There was wide variability in *s* between and within sites, suggesting it may be easier to manipulate *m* by planting density. To increase the proportion of crop that is <1200 g, planting densities should be 2.8 plants m^{-2}
Introduction

Introduction

Buttercup squash (Cucurbita maxima L.) is New Zealand's second largest export vegetable crop, worth $60M a year. Exported fruit must meet strict market requirements, which include being blemish free, of good colour, acceptable texture and flavour, larger than 1200 g and smaller than 2700 g. Fruit that do not meet these requirements are used to supply processors or the domestic market, and have little value for growers.

Many fruit that fall outside the export grade weight limits are otherwise acceptable, being free of blemish and having good texture. Only recently have export markets for these squash, especially fruit <1200 g, opened up, but developing these markets will require sufficient supply of fruit <1200 g. However, under current crop management, a large proportion of fruit from a crop fall within the weight limits set by the market, and there is little understanding of how to alter the weight distribution so that a greater proportion of the crop consists of fruit <1200 g.

The variability of crop weight distribution has been described for several crops including potatoes (Marshall and Thompson, 1986), apples (Zhang *et al.,* 2002), avocado (Zamet, 1997) and kiwifruit (Testolin and Costa, 1992). Generally, the distribution of fruit weight is described by a location parameter equivalent to the average weight, and a dispersion parameter, which is a measure of weight variability. The aim is to manipulate both these parameters by management practices, reducing the coefficient of variation (CV), and thus increasing the proportion of the crop that falls within the desired weight range.

There has been little research looking at the spread of fruit weight in buttercup squash crops. Most work has focussed on the optimum supply of fertilisers (Buwalda and Freeman, 1988; Buwalda, 1986; Buwalda and Freeman, 1986; Buwalda, 1987). Research carried out to establish the optimum planting density (Douglas *et al.*, 1990; Botwright *et al.,* 1998), noted that average fruit weight decreased as planting density increased, but no studies have attempted to describe the distribution of fruit weight, or seek ways of manipulating or controlling the distribution.

We describe the weight distribution of squash fruit from commercial crops grown in three regions of New Zealand, and examine some agronomic effects on the weight distribution of squash fruit, as a first attempt to identify what management practices growers may adopt to manipulate the fruit mass distribution of their crop.

Materials and Methods

Data collection

Data were collected from ten crops in each of two growing seasons (2000-2001 and 2001-2002), in the Manawatu, Hawke's Bay and Gisborne. All crops, except two in Hawke's Bay grown as experimental plots, were commercially grown for export. The experimental plots at Hawke's Bay were grown at the same site, but compared early and late plantings. Most sites were planted with the variety Delica, but a few were planted with Ajihei and Ebisu. These crops were part of a research survey looking at factors affecting storability of buttercup squash. Details of the crops are provided in Table 1.

Table 1. Details of sites used for data collection. The sites within a region were not the same paddock in year 2 as in year 1.

		Year 1			Year 2		
Site	Region	Sowing Date	Harvest Date	Planting Density (m^{-2})	Sowing Date	Harvest Date	Planting Density (m^{-2})
1	Gisborne	19-Oct-00	31-Jan-01	1.57	21-Oct-01	8-Feb-02	1.9
2	Gisborne	19-Nov-00	24-Feb-01	1.36	31-Oct-01	7-Feb-02	1.67
3	Hawke's Bay	25-Oct-00	14-Feb-01	1.48	1-Nov-01	27-Feb-02	1.9
4	Hawke's Bay	4-Nov-00	15-Feb-01	1.59	20-Oct-01	10-Feb-02	1.48
5	Hawke's Bay	17-Nov-00	2-Mar-01	1.57	14-Nov-01	19-Feb-02	1.39
6	Hawke's Bay	5-Dec-00	14-Mar-01	2.22	6-Nov-01	12-Feb-02	2.22
7	Hawke's Bay	5-Dec-00	26-Mar-01	2.22	11-Dec-01	26-Mar-02	2.22
8	Manawatu	7-Dec-00	29-Mar-01	1.40	17-Dec-01	27-Mar-02	1.52
9	Manawatu	7-Dec-00	26-Mar-01	1.48	29-Dec-01	13-Apr-02	1.9
10	Manawatu	16-Dec-00	4-Apr-01	1.52	8-Dec-01	20-Mar-02	1.67

In each crop, three plots 8 m × 14 m were marked out soon after emergence and soil samples taken. Management records, including fertiliser application and any irrigation applied were obtained from growers at the end of the growing season.

In Year 1 (the 2000-2001 season) only fruit > 900 g were cut and binned. The fruit was then taken to a grading facility, where each individual fruit was weighed and graded. Any fruit <900 g were counted and bulk weighed. Rots were not included in the grading. In Year 2 (the 2001-2002 growing season), all fruit, except rots, were binned from all crops in Manawatu. For Hawke's Bay crops, fruit <900 g were counted into weight ranges of approximately 100 g and weighed, but for Gisborne crops, only a record of the total number of small fruit and their combined weight was recorded. In total, individual weight records were obtained from 9000 fruit over both seasons. Daily records of the number of fruit set were also obtained from six plots from three sites in Hawke's Bay in Year 2.

Data analysis

Fitting the distribution

All distributions were fitted using Genstat 6 (Genstat 6 Committee, 2001). For each field plot a normal quantile-quantile (Q-Q) plot with 95 % confidence limits was constructed using individual fruit mass (Glasbey *et al.*, 1993), to identify whether a normal, log-normal or beta distribution fitted the data best. Q-Q plots of data from crops grown in both seasons indicated that for some plots a log-normal distribution was suitable, but for most plots the individual fruit weight data were normally distributed, so a normal distribution was used to fit the data for fruit > 900 g from all plots in Year 1 and Year 2. An example of a fitted plot is shown in Figure 1. The distribution parameters are the location parameter *m*, a measure of the average fruit weight, and the dispersion parameter *s*, a measure of the variability of individual fruit weight.

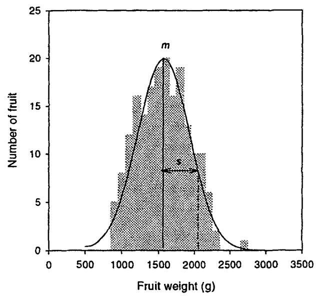

Figure 1. Normal distribution of fruit >900g. Parameters are *m*, a measure of average fruit weight and *s*, a measure of fruit weight variability.

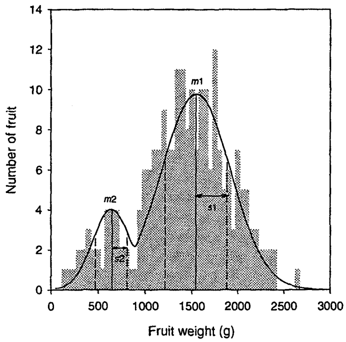

Figure 2. Bi-modal normal distribution of fruit all fruit. Parameters are *m*1 and *m*2 , measures of average fruit weight of the two populations, and *s*1 and *s*2 , measures of fruit weight variability, and *p*, the proportion of fruit that falls in the *m*1 population.

In comparison, examination of data from plots where all fruit were measured in Year 2 suggested that individual fruit mass had a bimodal normal distribution. As individual fruit data <900 g were not available for all plots in Year 2, data tabulated into 100 g mass ranges were used to fit the distributions. An example of a fitted bimodal normal distribution for a field plot is shown in Figure 2. The distribution parameters are *m*1 and *m*2, a measure of the average fruit mass, *s*1 and *s*2, a measure of the spread of fruit mass, and *p* a measure of the proportion of the fruit that is in the *m*1 population.

A distribution fit to the combined data from all plots at a given site was also performed to investigate if the data from a single site could be adequately represented as coming from a single population. Measures of skewness and kurtosis were also recorded, and tested for departure from normality, by the method of Snedecor and Cochran (1980).

Statistical analysis

The number of sites in each region differed, so an unbalanced analysis of variance using Genstat 6 (Genstat 6 Committee, 2001) was performed to determine if there were any Year or Region or Site effects on *m* and *s* and CV. To determine the effects of planting density, fertiliser application and other management factors on values of *m* and *s* stepwise forward regression was used to identify the parameters providing the best fit to the data.

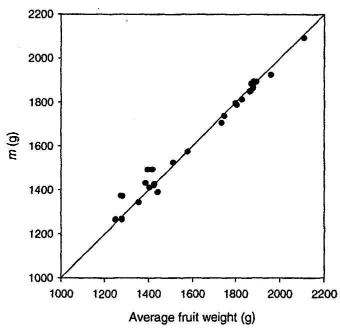

Figure 3. Relationship between mean fruit weight (yield/number of fruit) and *m*. Solid line indicates the 1:1 ratio. The regression equation is y = 121(± 40) + 0.93 (± 0.03), R^2 = 98.3.

Results

Distribution of fruit >900 g

Analysis of individual distributions indicated that there was significant skewness in 46 % of field plots and significant kurtosis in 30 % of field plots. Of all plots that had significant skewness, 85 % showed positive skewness. Kurtosis was split evenly between positive and negative values. Analysis of variance showed no significant difference between Year, Region or Site in kurtosis or skewness, and that most of the variability was between plots within a site. Plots with more than 130 fruit tended to show no significant skewness or kurtosis, and combining the plots from a site resulted in fits with no significant departures from normality. This suggests that the skewness and kurtosis are most likely caused by random variability within plots, especially where the sample size was small, and should not be considered an indication that the normal distribution is not an adequate descriptor of the variability of fruit weight. Further evidence for this was that the values of the mean fruit weight (yield/number of fruit) are equivalent to values of *m* (Figure 3), indicating that the median and mean were similar, a necessary condition for a normal distribution.

Distribution of all fruit

In year 2, half the plots showed a statistically improved fit when a bi-modal normal distribution was used to describe the spread of weight, compared to using a uni-modal normal distribution. For all other plots, a normal distribution gave a better fit. The value of *p* for the bi-modal distribution ranged from 0.8-0.9, averaging 0.87, indicating that on average 87 % of fruit are in the *m*1 population. The use of *t* tests showed that the values of *m*1 were not different to the values of *m*, so that the population that makes up the *m*1 population consists mainly of fruit >900 g. Values of *m*2 averaged 702 g, and ranged from 554 to 802 g.

There were no consistent relationships between any combination of *m*1, *m*2, *s*1 or *s*2 parameters, indicating that the parameter values of the *m*2 population were not related to the parameters of the *m*1 population. This suggests that the parameter values of the *m*2 population cannot be predicted based on the size of the *m*1 population.

Year and region effects on m and s

The effect of Year and Region on values of *m*, *s* and CV are shown in Table 2. There was a significant ($P<0.001$) decrease of *m* from Year 1 to Year 2, but a significant increase in *s* and CV ($P<0.05$ and 0.001 respectively) from Year 1 to Year 2. Thus in Year 2, there was a decrease in average fruit mass, but an increase in the variability of fruit mass.

The values of *m* and CV varied between regions ($P<0.001$), but *s* did not (Table 2). Manawatu had the lowest value of *m* at 1610 g, 7 % lower than the value of 1729 g for crops grown in Gisborne. Since *m* was lower in Manawatu, while *s* remained the same, the CV was greater for crops grown in Manawatu. There was a significant ($P<0.05$) Year×Region interaction in the value of *m* and CV. Values of *m* in Gisborne were similar in both years, but in contrast were 7 % lower in Year 2 for crops grown in Hawke's Bay and Manawatu. There was a concomitant increase in CV in Year 2 in these regions.

Table 2. Differences in parameters m1, s1 and CV1 between years and regions.

Year	*m* (g)	*s* (g)	CV (%)
2000-2001	1706	322	18.8
2001-2002	1641	352	21.5
LSD (5%)	53	26	2.8
Significance	***	*	***
Region			
Gisborne	1729	343	19.9
Hawke's Bay	1683	334	19.9
Manawatu	1610	336	20.8
LSD (5%)	77	37	0.6
Significance	***	ns	***
Year×Region	*	ns	*

The differing response of *m* and *s* suggests that they are influenced by different factors and are independent. The poor relationship between *m* and *s* (Figure 4) substantiates this assumption. While *s* does tend to increase with *m*, there was a large scatter with increases in *m* explaining only 48 % of the variation in *s*.

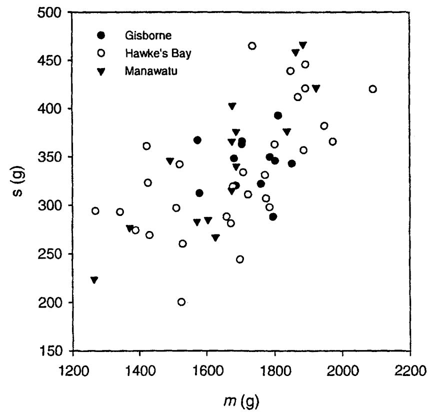

Figure 4. Relationship between *m* and *s* for the different regions.

Variation in m

Analysis of variance using Year and Site as treatment effects showed that there was significant ($P<0.002$) variation in *m* between sites (data not shown). In Year 1, the value of *m* ranged from 1602 to 1937g, a difference of 17 % and in Year 2, *m* ranged from 1327 to 1967 g, a difference of 33 %. Whilst on average the smallest *m* values were obtained from Manawatu sites, the largest *m* value in Manawatu was 1822 g, similar to *m* values from sites in Gisborne and Hawke's Bay in both seasons. Thus there was considerable variation in values of *m* across the sites.

Reasons for the variation in *m* values between sites were explored with forward step regression analysis using GenStat. The regression (Table 3) indicated that the value of *m* was influenced by planting density, nitrogen supply (available soil N + fertiliser N) and P application. The Year effect indicated an average reduction of 84 g in *m* in Year 2. Altogether, these factors explained 66 % of the variation in *m* values over all plots. Averaging the results from each plot in a site improved the fit and explained 95 % of the variation in *m*. The variability between plots grown at the same site was quite considerable. We did not have density data from individual plots at each site, but it is possible that inclusion of this data may help explain more of the variability in *m*. Based on the regression equation, largest values of *m* are obtained at a planting density of 1.64 plants m^{-2}.

The inclusion of Year as a significant factor in the regression indicated that environmental variables also play a role in determining *m*.

Table 3. Factors influencing the value of m.

Factor	Value	s.e	Significance ($P<$)	R^2
Constant	654	597		
Density[1] Lin	1418	667	0.002	13.5
Density Quad	-430	187	0.001	36.2
N supply[2]	-0.65	0.28	0.001	39.0
Applied P[3] Lin	15.2	2.48	0.001	48.5
Applied P Quad	-0.22	0.04	0.001	61.4
Year	-83.9	30.6	0.001	66.0

[1]plant population density [2]nitrogen supply (soil + fertiliser) [3]applied phosphorus fertiliser

Variation in *s*

Analysis of variance using Year and Site as treatment effects showed a significant ($P<0.001$) variation in *s* between sites (data not shown). In Year 1 *s* ranged from 200 to 403 g, an increase of 102 % for the higher value, and in Year 2, *s* ranged from 224 to 467 g, an increase of 108 %. The largest *s* values occurred in Manawatu grown crops in both years, the smallest in Hawke's Bay grown crops, though the largest *s* value in Hawke's Bay of 452 was similar to the values from crops grown in Manawatu. While the average *s* values in each region were similar (Table 2), there was quite a large variation in s among sites in each region (data not shown).

The variation in *s* was examined using forward stepwise regression in Genstat. In contrast to *m*, values of *s* did not respond to planting density, but only applied P fertiliser and N supply (Table 4). Year also had a significant effect, suggesting environmental variables may play a role in determining the variability of squash mass. However, these factors only explain 53 % of the variability in *s* values. Averaging plot values for each site improved the fit, explaining 75 % of the variation in *s*. Clearly, there are other factors that have a large effect on squash fruit weight dispersion.

Table 4. Factors influencing the values of *s*.

Factor	Value	s.e	Significance ($P<$)	R^2
Constant	250	19.5		
Applied P[3] Lin	12.5	2.4	0.001	22.5
Applied P Quad	-0.27	0.06	0.001	35.7
Applied P Lin × N supply[2]	-0.05	0.01	0.001	40.0
Applied P quad × N supply	0.001	0.0003	0.001	45.7
Year	34.7	11.8	0.005	53.0

[2,3]as in Table 3

Formation of the m2 population

Data from daily records of fruit set showed that there were two flushes of fruit set (Figure 5). A large number of fruit were set in the first flush, and these would form the bulk of the *m*1 population, and a smaller number of fruit set in the second flush, which would form the bulk of the *m*2 population. However, on average only 75 % of fruit were set in the first flush, and at least 30 % of fruit set in the second flush reached sizes of 1500 - 1900 g, and would contribute to the *m*1 population. In addition, approximately 10 % of fruit set in the first flush only reached sizes of 800 – 900 g, providing fruit that would fit in the *m*2 population.

Plots that showed no bi-modal distribution of fruit weight also had two flushes of fruit set, but the second flush was not as pronounced, or there was greater abortion of fruit set in the second flush.

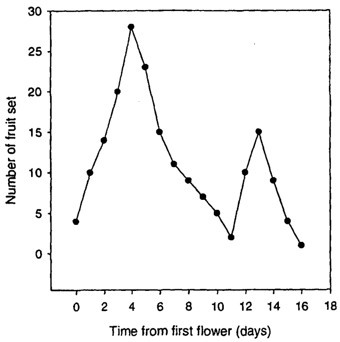

Figure 5. Number of fruit set on each day of flowering.

Discussion

A normal distribution seems to be suitable for describing the variability in weight of squash fruit > 900 g. The use of a normal distribution to describe variability in organ size or weight is similar to results obtained for potatoes (Marshall and Thompson, 1986; Wurr *et al.*, 1993) and apples (Zhang *et al.*, 2002). Where all fruit is available, a bi-modal distribution can be used to describe the spread of fruit weight, and this is again similar to results found when all sizes of potatoes have been used (Hide and Welham, 1992).

Compared with potatoes where the bi-modal distribution appears to be consistent, in squash there may not always be an *m*2 population. The evidence suggests that this is due to there being no second flush of flowering and fruit set, or the abortion of a substantial number of fruit from the second flush. There has been little research into factors affecting the flush of flowering and fruit set of buttercup squash, or into factors affecting the abortion of fruit. Since the *m*2 population can provide a substantial proportion of the fruit < 900 g, it will be useful to determine factors that influence the establishment of an *m*2 population. However, it is not only the pattern of fruit set that is important. Since approximately 75 % of fruit are set in the first flush, but the *m*1 population consists of 85 % of the fruit by number, there is a substantial contribution to the *m*1 population by fruit set in the second flush that reach sizes >1200 g, including sizes of 1500-1900 g. This indicates that there may be considerable variation in the growth rate of individual fruit, making the modelling of fruit weight distribution difficult using approaches such as distributional delays (Olesen and Grevsen, 2000). An approach where the average fruit growth rate and its variance is used (Gandar *et al.*, 1996; Hall and Gandar, 1996), may give a more useful approach to modelling the weight distribution of squash fruit.

For the main population of fruit, the dispersion parameter *s* of fruit weight seemed to be affected by the application of P fertiliser. The response to P was quadratic (Table 4), so *s* increased with P to a maximum and then decreased with higher P applications. Research on tomatoes has shown that P improves flower production, pollen production per plant, pollen production per flower and fruit set (Poulton *et al.*, 2002). It is possible that P is improving the reproductive capacity of squash plants, resulting in a smaller spread of flowering and fruit set, leading to smaller *s* values at higher P applications. The contribution of nitrogen supply and Year to *s* values though, does suggest that environmental conditions and fertility affect *s*, possibly by affecting individual fruit growth rate. This variation in fruit growth rate, resulting in early set fruit being smaller than later set fruit could increase *s* values.

The Year effect was most likely due to heavy rainfalls in Year 2 waterlogging soils in Hawke's Bay and Manawatu just after planting, or as the crops were beginning to be established. This resulted in uneven emergence and reduced yields. Combining the likely variation in fruit growth rate with plants of different maturities in the same paddock, it is likely that these conditions lead to increases in *s* values as shown in Table 2. However, the combination of P and N fertility, together with the Year effect only explained 53 % of the variation in *s* between crops. Plots within an individual paddock varied considerably in their s values, suggesting that environmental or edaphic conditions at the plot level have an effect on *s*. These could include conditions that influence pollination of flowers and fruit set.

Plant population density influenced the mean weight of fruit *m* (Table 3), is due to density effects on fruit size (Douglas *et al.*, 1990; Botwright *et al.*, 1998). However, the quadratic response found here differs to that of Douglas *et al.* (1990) who found that average fruit size decreased from 1900 g at populations of 0.4 plants m^{-2} to 1200 g at populations of 2.5 plants m^{-2}. Botwright *et al.*, (1998) reported similar effects of density, and also indicated that increased abortion at lower plant densities resulted in fewer larger fruit per plant. In the experiment reported here there were slightly more fruit per plant at low densities, which could have altered the distribution of fruit weight. It should also be noted that many of the low density crops were badly affected by waterlogging and had reduced yields and smaller fruit, which may have caused the quadratic response.

For maximum *m*, the suggested plant population is 1.64 plants m^{-2}, slightly lower than the recommendation of 1.8 to 2.2 plants m^{-2} made by Douglas *et al.* (1990) for optimising marketable yield, but higher than the 1.1 plants m^{-2} suggested by Botwright *et al.* (1998). To obtain an average fruit weight of approximately 1250 g, the data of Douglas *et al.* (1990) and Botwright *et al.* (1998) indicate that planting density should be 2.3 – 2.6 plants m^{-2}. These densities are higher than the currently used commercial planting densities, and so were not used in the experiments presented here. Considering only the density effects (Table 3), and extrapolating the data presented here, suggests that a planting density of 2.8 plants m^{-2} is needed to obtain an average fruit weight of 1200 g, very similar to the results of Douglas *et al.* (1990) and Botwright *et al.* (1998). However, there may be considerable variation in the final average fruit weight for a given planting density depending on the fertility and environmental conditions affecting the growth of the crop (Table 3).

Conclusions

Taking the average *m* and *s* value from Table 2, results in 7 % of the crop having weights between 800 –1200 g. Assuming that a plant density of 2.8 plants m^{-2} gives an average fruit weight of 1200 g, and that *s* remains the same, then 25 % of the crop will fall between the weights of 800 - 1200 g. Thus, plant density appears to provide considerable promise for influencing the weight distribution of squash fruit, though the effects of fertiliser and environmental conditions will need to be taken into account.

It seems that it may be more difficult to control the spread of fruit size *s*, due to environmental conditions influencing the spread of flowering and fruit set, and because there appears to be a wide variation in the growth rate of individual fruit, with late set fruit reaching larger sizes than early set fruit. Fertiliser application may have some effect on reducing *s*, but even if, on average, *s* remains the same, considerable impacts on the proportion of the crop in the desired weight grades can occur through changes in plant density.

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