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FURTHER ANALYSIS OF THE RELATIONSHIP BETWEEN HARVEST MATURITY PARAMETERS AND THE STORAGE QUALITY OF COX APPLES

An analysis of three years' data

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CONTENTS

SUMMARY

1. This report is based on detailed analysis of data collected between 1994 and 1996 by participants in the Fruit Maturity Programme, funded by English Apples and Pears Ltd. It builds on a previous report (September 1996) which analyzed data from the first two years of the Programme.

2. In each year, Cox apples were picked from each orchard on 4 occasions, to provide a wide range in the maturity of the fruit at harvest. There were 30 orchards in 1994, 32 in 1995 and 31 in 1996. Twenty five of the orchards were used in all three years. Fruit was stored in controlled atmosphere (1.2% O_2, < 1% CO_2 at 3.5°C) at HRI - East Malling. Samples of fruit were removed in the following January and April and assessed immediately, and following storage in air at 18°C for a further 7 days, to simulate marketing.

3. Delaying picking results in larger fruit with improved sugar content, red colour and aromatic flavour, and reduced acidity. However, greenness and firmness decrease over time and storage problems can arise if fruit are picked too late. Stored fruit may lack firmness and have an unsatisfactory background colour, and there is a greater risk that storage rots and certain types of physiological disorders will occur. Fruit picked on the second or third picking date was generally judged to have the best eating characteristics.

4. In 1996, changes in fruit colour (ENFRU colour score), firmness, acidity and starch over the four picks were more gradual than in previous years. Following storage, fruit was generally greener than in previous years (Hunter 'a' colour) and had a lower incidence of rots but a higher incidence of bitter pit and late storage corking.

5. In the previous report we developed models for predicting ex-store firmness from harvest firmness. When these models were applied to the 1996 data they achieved a success rate of 75-87% in predicting whether the ex-store firmness in January or April would be above or below a threshold value (6.0 kg or 6.5 kg). This was comparable to the performance of the models in previous years, but data from these earlier years, unlike the 1996 data, were used to derive the models.

6. Updating the models by including the 1996 data made no difference to the recommendations for storage until January, to ensure a harvest firmness of 9.4 kg if the target ex-store firmness is 6.5 kg and 8.2 kg if the ex-store target is 6.0 kg. However, for storage until April the recommended firmness values at harvest are 10.7 kg and 9.2 kg for ex-store targets of 6.5 kg and 6.0 kg respectively. These are approximately 0.5 kg higher than the values recommended on the basis of the first two years' data, and may be difficult to achieve in practice. As in previous years, picking for adequate ex-store firmness almost always ensured adequate ex-store greenness.

7. Further analysis of the data showed that there were some systematic differences between years in ex-store firmness, over and above any differences attributable to fruit maturity at harvest. These may reflect differences in meteorological data in different years, but this cannot be investigated with the data from the Fruit Maturity Programme. There was some suggestion that fruit from trees on M9 rootstock were slightly firmer ex-store than fruit from trees on MM106, and that fruit from East Anglia were firmer than fruit from Kent/Sussex, again after allowing for maturity differences. However, it is not possible to draw definitive conclusions about these effects from the available data.

8. The results from the Fruit Maturity Programme were compared with results from an earlier Cox Survey, involving fruit stored from 24 orchards each year from 1983 to 1988. In the Cox Survey fruit were picked on a single occasion each year, and so fruit maturity at harvest is less variable. Year-to-year differences in the Cox Survey were greater than in the Fruit Maturity Programme, but could be explained partly by meteorological variables. Overall, the relationship between harvest firmness and ex-store firmness in the Cox Survey was somewhat different from the relationship in the Fruit Maturity Programme.

9. We investigated the possibility of using regular assessments of fruit firmness in the run-up to harvest to predict when firmness would reach certain values. The pattern of firmness decline was approximately linear, but, unfortunately, the variability in the data was such that reliable predictions are not possible.

1. INTRODUCTION

The Quality Fruit Group (QFG) was formed in response to the poor performance of Cox apples on the UK market in 1992 and 1993, particularly late in the storage season. The primary function of the QFG is to provide guidance to growers, store operators and marketers with a view to improving the eating quality of Cox through the marketing chain and effecting a continuous supply of high quality fruit from September to April.

The fact that the texture of the fruit was often poor was identified as a primary concern, and urgent consideration was given to ways of improving fruit firmness and juiciness. Harvest date has a major influence on the potential duration of storage and the loss of quality in store and an early decision of the QFG was to instigate a national programme to monitor changes in Cox maturity during the approach to harvest, as a means of providing detailed regional advice on when to harvest for long-term storage. The UK national maturity indexing programme, which began in 1994, was organised along the lines of similar programmes that have been carried out for many years in the US and South Africa. At the outset the criteria used to make recommendations on start and end dates for long-term storage were based on the starch iodine test and on ethylene evolution, to back up early prediction from full-bloom date and climatic data for the growing season. In the UK maturity programme, which involved approximately 30 orchards located in the major Cox growing regions of the UK, provision was made for the storage of fruit harvested on four occasions, which were then assessed for quality in January and April. This information was of immediate use as a means of judging the accuracy of picking date guidelines given at harvest but more importantly provided a substantial body of data with which to study relationships between ex-store quality attributes and harvest maturity parameters.

In 1996, the APRC commissioned HRI - East Malling to analyze the data that had been collected in the 1994 and 1995 growing seasons. We looked at various measures of fruit quality ex-store, and found that only fruit greenness (Hunter 'a' colour) and fruit firmness (penetrometer) were predictable from fruit characteristics measured at harvest. Regression models for these variables accounted for 50-70% of the overall variation in the two years.

It was argued that attention should be focused on fruit firmness because, when ex-store firmness is adequate (6.0 - 6.5 kg), ex-store colour is usually also adequate (Hunter 'a' colour ≥ 10, corresponding to a score of less than 3 on the ENFRU colour chart). The main predictor of ex-store firmness was harvest firmness, indicating that requirements for ex-store firmness can be translated into requirements for harvest firmness. Based on the data for 1994 and 1995, we estimated that to achieve an ex-store firmness of 6.0 kg would require fruit to be picked at a firmness of 8.2 kg for storage until January and 8.7 kg for storage until April. On average, fruit picked at these firmness levels should have an ex-store firmness of 6.0 kg, though individual consignments may, of course, be above or below this level. A detailed report of our work was provided to APRC in October 1996.

In this report we address three further aspects of this problem. First, we revisit the existing models for ex-store firmness and greenness in the light of the data from the 1996 crop. We examine the extent to which this additional year is in line with the previous two years. We also use the more extended data set to investigate the possible effects of growing region, growing system and rootstock on relationships between harvest measurements and ex-store quality, though, as will be seen, only limited conclusions can be drawn from these analyses.

Second, we compare the data from the three years of the Fruit Maturity Programme with data from a survey of 24 Cox orchards that ran from 1983-88. In that survey all fruit was harvested on a single date in each year, so there is less variation in fruit maturity at harvest. Nonetheless, a comparison of the two data sets seems worthwhile.

Finally, because of the importance of fruit firmness at harvest, we examine the extent to which it is possible to predict in advance when firmness will have declined to a specific value. If this were possible it would clearly help growers to plan for the harvest. This part of the project uses twice-weekly penetrometer readings that were collected as part of the Fruit Maturity Programme.

2. EXPERIMENT METHODS

The Fruit Maturity Programme collected data from 30 Cox orchards in 1994, 32 orchards in 1995 and 31 orchards in 1996. Twenty five of these orchards were used in all three years.

Fruit mineral analysis

In each year, samples of 30 fruit were collected from each orchard one week before the picking date recommended by F.A.S.T. Ltd. The concentrations (mg $100g^{-1}$) of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) in fruit from each orchard were determined by F.A.S.T. Ltd. Samples were also collected three weeks before the F.A.S.T.-recommended picking date, but we have not used these data because they are less complete. However, measurements of percentage dry matter were also made on this occasion and we have used these data.

Fruit attributes recorded at harvest

Fruit samples were taken on each pick date. Sampling and measurements were carried out jointly by F.A.S.T. Ltd and ADAS and full details of the methodology have been provided in Quality Fruit Group Reports for 1994-1996 (available from English Apples and Pears Ltd.). Measurements were made of fruit diameter and weight, background colour (ENFRU card), firmness (penetrometer mounted in a drill-stand), starch (iodine test), titratable acidity and soluble solids (sugar) concentration (refractometer).

These variables were used as possible predictors of ex-store quality. In addition a maturity (Streif) index was calculated from these data using the formula

$$\text{Streif index} = \frac{9.81 \times \text{Firmness}}{\text{Sugar} \times (100 - \text{Starch})}$$

where sugar and starch values are percentages and the constant 9.81 converts the units of firmness from kg to Newtons. The formula cannot be used when the starch value is 100% and in these instances a value of 99% was substituted. The more usual calculation of the Streif index requires that percentage starch is entered as an integer value between 1 (100% starch) and 10 (0% starch). However, the relationship between percentage starch and starch score is not linear and, for greater accuracy in statistical analysis, the use of the percentage starch values would seem to be preferable. A consequence of this is that the Streif index values given in this report (*e.g.* in Table 2) differ from those given in the harvest information provided by the QFG.

Storage

Two boxes of fruit (nominally 14 kg) were picked from each orchard on 1, 12, 22 September and 3 October in 1994, on 31 August and 11, 21, 29 September in 1995 and on 9, 16, 23 and 30 September in 1996 and delivered to HRI - East Malling on the same day. On arrival, fruit were sampled to obtain four netted samples of 20 fruit for each site, for storage in controlled atmosphere (1.2% O_2, < 1% CO_2) at 3.5°C until the following January or April. Samples were weighed, dipped in fungicide ('Ridomil mbc') at the recommended dose, and loaded into 0.5 tonne storage cabinets. Carbon dioxide was removed from the storage cabinets using external hydrated lime scrubbers and the oxygen concentration was controlled by an automatic control system which admitted air as necessary and maintained 1.2% O_2 (±0.1%). The low oxygen atmosphere was generated by the fruit, generally within two weeks of sealing the cabinets.

Assessment of stored fruit

Two of the four netted samples were removed in January (9 and 10 January 1995, 8 and 9 January 1996, 6 and 7 January 1997) and the other two in April (10 and 11 April in 1995, 9 and 10 April in 1996, 8 and 9 April 1997). On each occasion, one sample was examined immediately and the other was stored in air at 18°C for a further 7 days, to simulate 'shelf-life', before examination.

The samples were weighed, to enable the calculation of weight loss during storage, and ten apples were removed for measurement of colour using a Hunter colorimeter. This colorimeter measures three colour components labelled 'L', 'a' and 'b'. The 'L' value measures black ('L'=0) to white ('L'=100). The 'a' value is larger the greener the fruit and the 'b' value increases with increasing yellowness. (The Hunter 'a' values that are recorded are actually negative, but we ignore the negative sign throughout this report.) The firmness of the same ten fruits was measured with an automated penetrometer fitted with an 11mm probe. The number of rots per sample was recorded, and all fruit were cut and examined internally for the presence of physiological disorders. After the simulated 'shelf-life', firmness and colour were measured again, and, in addition, a few apples from each sample were tasted by Mr John Chapman of F.A.S.T. Ltd and scored for taste (sugar/acid balance), texture and Cox flavour. Mr Chapman uses a similar system in monitoring commercial stores. Maximum scores achievable for taste, texture and flavour were 5, 5 and 10 respectively. In 1997, tasting of the stored 1996 crop was done only at the January assessment.

3. STATISTICAL METHODS

This section describes the statistical methods that we have used, and gives some guidelines on interpretation of the output.

Tables of means

Tables of means calculated over orchards are accompanied generally by the standard error of the difference (s.e.d.) for comparing any two means. Observed differences in means may arise because of a genuine difference, or as a chance result of the particular fruit that were sampled. The s.e.d., which is based on orchard-to-orchard variation, allows one to estimate the probability that the difference is due to chance. If there are in fact no differences between treatments, the probability that the observed difference will, by chance, exceed twice the s.e.d. is approximately 1 in 20. Such differences are regarded conventionally as being 'statistically significant'.

To compare fruit mineral concentrations in different years (Table 1) we used a two-way analysis of variance (ANOVA) in which the orchards were treated as levels of a blocking factor. Thus comparisons between years are made *within* orchards. The comparison was restricted to those orchards (25 in total) that were present in all three years of the Fruit Maturity Programme (1994-1996). A further four orchards were excluded from the comparison because fruit mineral analysis data were missing in one or more years. Thus the comparison is based on 21 orchards.

To compare measurements taken on the fruit at harvest we have again used ANOVA with orchards treated as a blocking variable. Comparisons of years and picks are therefore made within orchards. Analysis was restricted to the 25 orchards that were present in all three years of the study. One orchard had no harvest data at pick 4 in 1995, but was nonetheless included in the other analyses. All other orchards had complete data in all three years.

For the analysis of post-harvest measurements we have used a more complex ANOVA. Orchard is again treated as a blocking variable, and the time of examination (January or April, immediately ex-store or after shelf-life) is treated as a nested factor within a particular combination of Year and Pick. This analysis gives rise to two separate s.e.d.s for different comparisons, as indicated in Tables 3-7.

To simplify the presentation we have sometimes, when this is justified statistically, pooled separate s.e.d.s to obtain a single s.e.d. that can be used to compare all values in a Table. The abbreviation d.f. in Tables denotes degrees of freedom.

Predictive models

The predictive models that we present are derived by the statistical technique known as multiple regression analysis. This technique is aimed at modelling a particular *response variable* (*e.g.* ex-store firmness) in terms of one or more *explanatory variables*. The potential explanatory variables available in this study were the fruit measurements taken at or near harvest, including mineral analysis data. In addition we examined the effect of various qualitative factors such as the location of the orchard (Kent/Sussex, East Anglia or West Midlands) and the rootstock (M9 or MM106).

Details of fitted regression models are given in tables such as the following:

Explanatory variable	Firmness, January ex-store
Constant	4.34 (5.06)
Diameter	-0.021 (1.91)
Firmness	0.37 (14.4)
r.s.d. (d.f.)	0.51 (241)
$\bar{R}^2$	61.9

The main entries in the table (4.34, -0.021, 0.37) are the *regression coefficients*. These indicate that the model is as follows:

$$\text{Ex-store firmness} = 4.34 - 0.021 \times \text{Diameter} + 0.37 \times \text{Firmness}$$

where the diameter and firmness on the right hand side of the equation are the measurements taken at harvest. The figures in brackets after the coefficients are the *t-values*. Roughly speaking, the larger the t-value, the more closely the explanatory variable is correlated with the response variable. At the bottom of the table, the *residual standard deviation* (r.s.d, calculated as the square root of the residual mean square) is a measure of the variability that remains in the data after fitting the regression model. The figure in brackets after the r.s.d. is the *residual degrees of freedom*. These values are included primarily for those who have some familiarity with regression analysis and provide information about the variability of the data. The final line gives the *percentage variance accounted for* ($\bar{R}^2$), a measure of how much of the overall variation in the data is explained by the regression model. Large values of $\bar{R}^2$ are desirable.

4. COMPARISON OF THE EFFECTS OF PICK DATE IN DIFFERENT YEARS

Fruit mineral analysis and dry matter

Table 1 shows mean values of fruit N, P, K, Ca and Mg concentrations (mg $100g^{-1}$) across 21 orchards that were included in all three years of the Fruit Maturity Programme, and for which mineral analysis data were available in all three years. Fruit dry matter (%) is also shown.

There were significant differences between years in the concentrations of all nutrients except nitrogen. Percentage dry matter also varied significantly between years. Percentage dry matter and fruit potassium concentration in 1996 were intermediate between their values in 1994 and 1995. However, concentrations of phosphorus, calcium and magnesium were lower in 1996 than in the previous two years.

Fruit measurements taken at harvest

Mean values for the four picks in each of the three growing seasons are shown in Table 2. In 1996, early indications from full-bloom and climatic data were that the fruit was likely to mature much later than in the previous two seasons. Therefore picks 1 and 2 were several days later than in the previous two years, whereas picks 3 and 4 were on approximately the same dates in all three years. Fruit weight and diameter were accordingly larger in 1996 than in previous years at picks 1 and 2, but the values at picks 3 and 4 were more similar in all years.

Progressive changes in fruit colour (ENFRU colour score), firmness and acidity over the four picks were less marked than in previous years. This was also true, to a lesser extent, of starch. Whilst this was due partly to the reduced time interval over which the four picks took place, fruit at the final pick in 1996 was considerably greener and firmer, and had higher acidity, than fruit at the final pick in previous years. In contrast, the increase in sugar content over the four picks in 1996 followed a very similar pattern to 1994. The pattern of decline in the Streif index over the four picks in 1996 was also similar to the pattern in 1994.

Post-harvest measurements

Although we shall focus our attention primarily on fruit firmness and greenness following storage, we begin by tabulating mean values of all post-harvest measurements made on fruit from each pick, so that data from the 1996 crop can be compared to previous years.

Percentage weight loss

In all three years weight loss was greater after shelf life than immediately ex-store, and was greater when fruit was stored until April than when stored only until January (Table 3). Except for Pick 3 fruit, weight loss was generally greater for the 1994 crop than in the two subsequent seasons.

Hunter 'L' colour

Hunter 'L' colour increased through successive pick dates and during the simulated shelf life period (Table 4). In most instances values from the 1996 crop were higher than in the previous two years.

Hunter 'a' colour

Hunter 'a' values decreased, indicating that the fruit became less green, with increasing pick date and during 'shelf life' (Table 5). Fruit were also less green at the April inspections than at the January inspections. Fruit harvested in 1996 were generally greener than fruit from the corresponding Pick in the two previous years.

Hunter 'b' colour

Hunter 'b' values increased, indicating that the fruit became more yellow, with increasing pick date and during 'shelf life' (Table 6). There were no consistent differences between years.

Fruit firmness

Fruit firmness decreased through successive pick dates and during shelf life (Table 7). At the April inspections fruit was less firm than at the corresponding January inspections. Fruit from Pick 1 in 1996 was less firm after storage than fruit from pick 1 in previous years.

Percentage of fruit with rots

The percentage of fruit that had rots was higher in fruit inspected in April than in fruit inspected in January (Table 8), and rotting increased during shelf life. In the first two years, the percentage of fruit that had rots increased with increasing pick date, but in the 1996 crop there was little rotting, even in fruit from picks 3 and 4.

Taste, texture and flavour

In all three years the taste (sugar/acid) score was highest for Pick 2 and Pick 3 fruit, and remained high for Pick 4 fruit, except in the first year (Table 9). Data from the 1996 crop were similar to the preceding year, except at Pick 1. The texture score was highest at Pick 2 in 1994, at Picks 1 and 2 in 1995 and at Picks 1, 2 and 3 in 1996. The Cox flavour score was highest for fruit from Picks 3 and 4 in 1994, from Pick 3 in 1995 and from Pick 4 in 1996. Values for 1996 were similar to the previous year, except for Pick 4.

Physiological disorders

One of the criteria for selecting orchards for this study was that fruit should have good storage potential. As a result, the incidence of physiological disorders was low and there were many zeros in the data. Because of this, we have not attempted any formal statistical analysis.

Bitter pit and late storage corking

The incidence of bitter pit and late storage corking was generally higher in the 1996 crop than in the previous two years, particularly in fruit from Picks 3 and 4 (Table 10). The incidence in January never exceeded 3%, but higher levels occurred in April. The incidence increased during shelf life.

Core flush

The incidence of core flush was low (<3%) in the 1995 and 1996 seasons, but higher levels occurred in samples from the 1994 crop stored until April (Table 11).

Breakdown

Breakdown was used as a general term to describe abnormalities of the flesh that were not considered to be either bitter pit or late storage corking. Its incidence was less than 1% in January assessments in all years, except for Pick 4 in 1994 (Table 12). Incidence was generally higher in April and again incidence for Pick 4 in 1994 was considerably higher than elsewhere.

Superficial scald

Fruit picked in 1995 developed superficial scald during the April shelf-life period at 18°C. The incidence for fruit from picks 1 to 4 was 22.0%, 2.5%, 0.5% and 0.7% respectively. Scald also occurred in the 1996 crop, but here the incidence never exceeded 1.2%.

5. PREDICTIVE MODELS OF FRUIT FIRMNESS FOLLOWING STORAGE

Summary of previous work

In our previous report, based on the first two years' data from the Fruit Maturity Programme, we investigated several predictive models of firmness. The most important variable determining firmness after storage was the firmness at harvest. Slightly better predictions of ex-store firmness could be obtained by taking into account fruit size at harvest, and the concentrations of potassium and phosphorus in the fruit close to harvest.

However, a model based solely on harvest firmness has two important advantages. First, and most obviously, it means that there is no need to measure the mineral composition of the fruit. Second, it allows recommendations about when to pick fruit to be formulated entirely in terms of harvest firmness. In the more complicated predictive models the recommended harvest firmness for storage until, say, January, would depend on the size and mineral status of the fruit. We therefore concentrated on the model based solely on harvest firmness, arguing that, although predictions of ex-store firmness were improved slightly by including the other variables, these improvements were not sufficient to warrant abandoning the simpler model.

Prediction of ex-store firmness in the 1996 crop using previous model

We begin by considering the reliability of the firmness guidelines developed from the 1994 and 1995 crops when they are applied to the 1996 crop. We first consider the higher target of 6.5 kg ex-store. To achieve this target, it was recommended that fruit should have a harvest firmness of at least 9.4 kg for storage until January and at least 10.2 kg for storage until April. Tables 13 and 14 show the numbers of fruit that were above or below the ex-store target firmness, classified by whether the harvest firmness was above or below the threshold level. Tables 15 and 16 show similar data for an ex-store target of 6.0 kg, for which the harvest firmness targets were 8.2 kg for storage until January and 8.7 kg for storage until April. Each Table shows the data for the each of the three growing seasons as a 2×2 table and indicate the percentage of consignments that were classified correctly, in the sense that the actual and predicted ex-store firmness values were either both below the target level or both above the target level.

The percentage of correct classifications ranged from 72-87%. Except for ex-store firmness in April at the higher target of 6.5 kg, the percentage was higher in 1994 than in 1995. However, the most important point to emerge from Tables 13-16 is that the percentage of correct classifications in 1996 was very similar to that in 1995, even though 1996 data were not used in developing the threshold values for harvest firmness.

Although the overall level of agreement for 1996 data was good, some more detailed aspects of the agreement are less satisfactory. For example, in Table 13, of the 50 consignments of fruit that had an ex-store firmness in January greater than 6.5 kg, only about half were predicted to have firmness above 6.5 kg. Perhaps more importantly, at the lower target of 6.0 kg, again in January (Table 15), approximately half of the consignments that had firmness below 6.0 kg were predicted to have firmness above this level.

Comparison of models using data from all three years

Table 17 shows the percentage variance accounted for by three regression models that were developed from the analysis of the first two years' data, based on harvest firmness of fruit only, on harvest firmness and diameter of fruit, and on harvest firmness and diameter and the concentrations of phosphorus and potassium in the fruit.

The upper half of Table 17 gives the percentage variances obtained from the first two years' data. Details of these models were presented in Tables 12-14 of our previous report on project SP104 (September 1996). The lower half of Table 17 gives the corresponding percentages when the same models are fitted to the data from all three years. For storage until January, the percentage variances accounted for are reduced by about 5% when data from the 1996 crop are included. This is true of inspections immediately ex-store and after simulated shelf life. For prediction of firmness immediately ex-store following storage until April, addition of the data from the 1996 crop results in a reduction of percentage variance accounted for of about 12%. However, for prediction of firmness after simulated shelf life, inclusion of the 1996 data has little effect on the percentage variance accounted for by the different models.

The differences between the percentage variances accounted for by different models are remarkably consistent in the upper and lower halves of Table 17. Thus for ex-store firmness, the inclusion of additional variables increases the percentage variance accounted for by only 3-6% compared to the model that is based on harvest firmness only. Therefore we argue again that it is preferable to concentrate on the simple model based solely on harvest firmness, for the reasons outlined above. However, for completeness, Tables 18-20 give details of all three models, when fitted to the full data set.

Figures 1-4 show the relationship between harvest firmness and post-harvest firmness of fruit at the four inspection times. Each Figure shows the data for each year separately, together with a combined plot of all the data. In each graph the solid line is the regression line (based only on the data shown in that graph) and the dashed lines are 95% prediction intervals. The prediction intervals indicate the range within which the post-harvest firmness of fruit from a particular orchard, with given harvest firmness, is predicted to lie. Typically the prediction intervals are about 2 kg wide. This indicates that most fruit consignments will have a post-harvest firmness that is within about 1 kg of the predicted value. The predicted post-harvest firmness will be too low for some orchards and too high for others.

Updated guidelines for harvest firmness

The regression models given in Table 18 imply that, for storage until January, harvest firmness should be 9.4 kg if the target firmness ex-store is 6.5 kg whereas, for a target firmness ex-store of 6.0 kg, harvest firmness should not be less than 8.2 kg. These values are unchanged from the values recommended on the basis of the analysis of the 1994 and 1995 data.

For storage until April, harvest firmness should be 10.7 kg if the target firmness ex-store is 6.5 kg whereas, for a target firmness ex-store of 6.0 kg, harvest firmness should not be less than 9.2 kg. These values are 0.5 kg higher than the values recommended on the basis of the analysis of the 1994 and 1995 data, reflecting the small changes in the regression coefficients that occur when the 1996 data are included.

Distribution of optimum picking date

We consider the 'optimum' picking date to be the last pick date on which the harvest firmness is not less than the appropriate threshold value discussed in the previous section. Generally, firmness in a particular orchard declines steadily through the progressive pick dates. However, in 1996 the general decline in firmness was much more gradual and, as a result, there were instances in which the measured value of firmness *increased* slightly from one pick to the next. These anomalies are a result of sampling fluctuations (harvest firmness values are estimated from a sample of 20 fruit) and do not reflect a genuine increase in firmness. Nonetheless, because of such anomalies, it is possible that, for example, fruit may be deemed too soft at Pick 2, but sufficiently firm at Pick 3, if the true firmness is close to the threshold value at these picks. In such circumstances we have taken the later pick to be the 'optimal' pick date.

Table 21 shows the distribution of optimum pick dates. In some instances, particularly in 1996 and more generally when attempting to store fruit until April for an ex-store firmness of 6.5 kg, the fruit was already too soft at the first pick date. Thus, in addition to the four picks, there is an additional category for 'before pick 1'. The effects of the unusually slow firmness decline in 1996 are again apparent from Table 21. For example, for storage until January with an ex-store target of 6.5 kg, fruit from most orchards was already too soft at Pick 1 in 1996, although for almost a third of the orchards the target firmness value didn't occur until pick 3 or pick 4. At the lower ex-store target of 6.0 kg the optimum picking date was pick 3 or pick 4 for almost all orchards.

Table 22 shows some data on ex-store fruit greenness of fruit picked at the optimum picking date for firmness. Hunter 'a' values need to be in excess of 10 to conform to a score of less than 3 on the ENFRU colour chart. Table 22 shows that most fruit achieve satisfactory greenness (Hunter 'a' value ≥ 10). This confirms the finding in our previous report that it is unnecessary to develop specfic models of fruit greenness; if fruit is picked with a view to achieving satisfactory firmness, it will almost always have adequate green colour.

Finally, Table 23 shows the overall quality score of fruit picked on the optimum predicted picking date. We have doubled the taste and texture scores, which were originally on a 0-5 scale, and added these to the Cox flavour score, which is on a 0-10 scale, to give a combined score on a 0-30 scale, in which all three components have equal importance. Table 23 shows the mean total score over all orchards for which the total score could be calculated (*i.e.* excluding those for which the optimum picking date was 'before pick 1'). Data are presented only for storage until January, because fruit were not tasted in April 1996 (data for April storage of fruit grown in 1994 and 1995 were given in the previous report on project SP104, September 1996.) In the 1994 and 1995 growing seasons, fruit picked later, for a target of 6.0 kg rather than 6.5 kg, had a higher mean quality score, but there was no significant difference for 1996 fruit. The mean scores for the later picked fruit were very similar in all three years.

Effects of year and orchard

The aim of the predictive models is to capture much of the year-to-year and orchard-to-orchard variation in post-harvest firmness, using measurements that are available at harvest. Nonetheless, some residual effects of these factors may remain, and this can be investigated by including these factors in the regression model. Thus we can, for example, assess whether there are significant differences between years in ex-store firmness after allowing for any differences in harvest firmness.

We applied this approach to investigate residual year effects on ex-store firmness in January and April, using the simplest predictive model based on harvest firmness only (Table 18) and the more complicated model that involves harvest firmness and diameter, and fruit concentrations of phosphorus and potassium (Table 20). For January ex-store firmness there were significant residual year effects for the simpler model ($P<0.05$), but for the more complicated model the effects were no longer significant. For April ex-store firmness, residual year effects were significant when added to both models ($P<0.001$), though the effects themselves were smaller in the more complicated model. The estimated year-to-year differences ranged from 0.1 kg to 0.5 kg.

These analyses suggest that ex-store firmness may vary between years for reasons additional to annual differences in fruit maturity at harvest. This may in turn be a result of year-to-year differences in weather conditions at certain points in the growing season. Investigation of the effects of meteorological variables would, however, require a longer run of data than the three years provided by the Fruit Maturity Programme.

A similar analysis showed that, after allowing for year-to-year effects, there were significant residual effects of orchards. Thus, some orchards tended to give higher ex-store firmness values than would be predicted by the maturity status of their fruit at harvest, and others tended to give lower ex-store firmness values than predicted. However, as would be expected with only three years' data, the individual orchard effects, the largest of which were about 0.5 kg, were estimated poorly with standard errors usually exceeding 0.2 kg.

As with year-to-year effects, orchard-to-orchard effects are not really useful for predictive purposes unless they can be shown to be due to measurable characteristics of the orchards. Two such characteristics were recorded as part of the Fruit Maturity Programme: the rootstock (M9 or MM106) and the growing system (single- or multi-row beds). We had hoped also to be able to examine the effect of scion (conventional Cox or Queen Cox) but these data were not available. However, in addition to rootstock and growing system, the geographical location of the orchard was available. Orchards were grouped into three regions, Kent/Sussex, East Anglia (Essex, Suffolk and Norfolk) and West Midlands (Herefordshire, Worcestershire and Gloucestershire).

Unfortunately, as shown in Table 24, these factors were far from equally balanced in the data set. This is to be expected in a survey such as the Fruit Maturity Programme, where balancing out these factors was not an objective in the design of the survey. Nonetheless, the lack of balance does place severe limitations on the extent to which the effects of these factors can be investigated. Nonetheless, based on Table 24, we did attempt three comparisons.

First, restricting ourselves to orchards in the Kent/Sussex region growing on M9 rootstock, we compared single-row beds (4 orchards) with multi-row beds (4 orchards). However, there was no significant effect of growing system on either January or April ex-store firmness.

Second, restricting ourselves to orchards in the Kent/Sussex region growing in single-row beds, we compared M9 (4 orchards) with MM106 (4 orchards). Here there was a suggestion that fruit growing on M9 were slightly firmer ex-store than fruit growing on MM106. However, the effect was small (about 0.2 kg) and not strongly significant ($P<0.05$ in January; $P<0.1$ in April). Nonetheless, this effect may warrant future study in a properly designed experiment.

Finally we compared the Kent/Sussex region with the East Anglia region. For this we used orchards on M9 in multi-row beds and orchards on MM106 in single-row beds. This gave, in total, 8 orchards in Kent/Sussex and 7 orchards in East Anglia. The analysis strongly suggested ($P<0.001$) that fruit from East Anglia were firmer ex-store than fruit from Kent/Sussex, after allowing for differences in fruit maturity at harvest. The estimated difference was about 0.25 kg for January and April ex-store values. However, whilst this does appear to indicate a small, but genuine, difference, it is unclear whether the origins of the difference are really geographical, because some of the orchards in Kent are in fact very close to some of those in Essex (counted as East Anglia) and experienced very similar climatic conditions during fruit development.

6. COMPARISON WITH A PREVIOUS STUDY OF STORAGE QUALITY IN COX

During the 1980's, a large experiment, which we shall refer to as the Cox Survey, was conducted to study the storage quality of Cox fruit from 24 orchards in six successive seasons. Although all the fruit were harvested on a single date in each year, the geographical spread of the orchards ensured that there was variability in the maturity of the fruit at harvest. In this section of the report therefore we examine the extent to which the data from that experiment are compatible with the models developed from the more recent data collected through the Fruit Maturity Programme.

Brief experiment details of the Cox Survey

The study ran from 1983-1988 and included four orchards from each of six regions: Norfolk, Suffolk, Essex, Herefordshire, East Kent and West Kent. In each region, four orchards were selected as being close to, and at a similar altitude to, a meteorological station which provided records of maximum and minimum temperatures and rainfall during the months of May to September. Two orchards in each region were on M9 rootstock and two on MM106. In each orchard, six trees of similar size and crop load were selected for sampling. Fruitlet samples and leaf samples were collected for mineral analysis in mid-July and in the second week of August respectively.

Fruit were harvested on a single date which varied between 21 and 23 September (approximately coincident with Pick 3 in the Fruit Maturity Programme). Fruit measurements taken at harvest included greenness (Hunter 'a' colour), diameter, dry weight and specific gravity (1985-1988 only). Firmness was measured using an Instron Model 1140 food texture analyzer fitted with an 11 mm probe driven at 200 mm min^{-1} into two opposite, peeled surfaces of each apple. The mineral status of the harvested fruit (concentrations of nitrogen, phosphorus, potassium, calcium, magnesium, manganese, boron, copper and zinc) was also determined.

Samples of fruit were stored in controlled atmosphere (1.2% O_2, < 1% CO_2 at 3.5 °C) for 35 weeks, until the following May, somewhat longer than in the Fruit Maturity Programme. Fruit were stored at HRI - East Malling, using the same storage containers as used for the Fruit Maturity Programme.

Comparison of results with those of the Fruit Maturity Programme

Figure 5 shows the relationship between ex-store firmness and harvest firmness in the six years of the Cox Survey. These may be compared with Figure 3 which shows the corresponding plots for the three years of the Fruit Maturity Programme, though Figure 3 relates to storage until April whereas Figure 5 is for storage until May. One important difference is in the range of harvest firmness values. In the six-year experiment, the harvest firmness values for most orchards cover a range of about 2 kg which is substantially less than the range in any of the years of the Fruit Maturity Programme. This is to be expected because in the Fruit Maturity Programme the fruit are harvested over a period of about a month, specifically to induce a wide range of fruit maturity. In the Cox Survey all fruit were harvested on the same date, and the variability in maturity is due to differences between growing regions.

Figure 6 shows the data from the April inspection of fruit harvested at Pick 3 of the Fruit Maturity Programme, and these provide a more direct comparison with the data shown in Figure 5. It is apparent that the year-to-year differences in harvest firmness are greater for the Cox Survey data; in 1984 most fruit were softer than 8 kg at harvest, whereas in 1985-88 most fruit were firmer than 8 kg. There is a correspondingly wider range of ex-store firmness values.

On each of the plots in Figures 5 and 6 we have shown the fitted relationship (solid lines) between April ex-store firmness and harvest firmness derived from all four picks, and all three years, of the Fruit Maturity Programme (the equation is given in Table 14). This provides a reasonable fit to all three data sets shown in Figure 6. The fit to the data in Figure 5 is inevitably less good, because these data were not used in deriving the model. The general tendency is to overestimate ex-store firmness in 1983 and 1984, when harvest firmness was generally low, and underestimate ex-store firmness in subsequent years when harvest firmness was generally higher. This suggests that data from the Cox Survey follow a steeper line than data from the Fruit Maturity Programme. This is confirmed in Figure 7, which plots the data from all six years of the Cox Survey and the data from all three years of the Fruit Maturity Programme (Pick 3 data only). The solid line in both plots is the same regression line shown in Figures 5 and 6. The steeper dashed line in the upper part of Figure 7 is the regression line fitted to the Cox Survey data.

Differences between the regression lines may relate to the methods used for measuring fruit firmness in the two studies. It is clear from related studies that firmness measurements made with the hand-operated penetrometer are usually higher than those recorded using the automated version at HRI - East Malling. The largest differences occur on firmer, less mature consignments. In the Fruit Maturity Programme, harvest firmness measurements were made using the manual method, whilst ex-store measurements were made using the automated instrument. Use of the automated instrument at harvest would have been likely to produce a steeper regression line in this study, in better agreement with the earlier 6-year study, where firmness measurements at harvest and ex-store were made using an automated instrument. However, the hand-held penetrometer is currently the industry standard for firmness measurements.

Regression models fitted to the Cox Survey data

We conclude this section of the report by commenting briefly on the regression models that we have developed to predict ex-store firmness in a separate, MAFF-funded, project based on the Cox Survey data.

The simple model illustrated by the dashed line in the upper part of Figure 7, which is based solely on harvest firmness accounts for 55% of the variance in the Cox Survey data. A second model, incorporating leaf nitrogen concentration and fruit dry weight at harvest increases the percentage variance accounted for to 67%. A third model, that uses meteorological data, gives a percentage variance accounted for of 76%. This latter model is based on harvest measurements of fruit firmness, greenness (Hunter 'a' colour) and nitrogen concentration, leaf boron concentration, total rainfall in July and August, average daily maximum temperature in June and average daily minimum temperature in September (up to the date of harvest only). These meteorological variables account for some of the year-to-year variability in the data.

7. FIRMNESS DECLINE PRIOR TO HARVEST

We have argued in previous sections of this report that fruit should achieve certain target levels of firmness at harvest if they are intended for long-term storage. It would therefore be very useful to be able to predict in advance the date at which the crop was likely to reach the target firmness level. In this section of the report we investigate patterns of firmness decline in the run-up to harvest to ascertain the extent to which such predictions might be possible.

Data

During the three years of the Fruit Maturity Programme, fruit firmness was measured approximately twice-weekly from late August until the end of September. Firmness was measured with a penetrometer mounted in a drill-stand, using samples of 20 fruit from each orchard. This provided, in total, 93 patterns of firmness decline which are plotted individually in Figures 8-19.

Rate of firmness decline

Each of the graphs in Figures 8-19 includes a fitted linear regression line. In most instances the fit is quite reasonable, though the individual firmness measurements are often quite scattered around the fitted line.

In Figures 21 and 22 we summarize some of the characteristics of the fitted regression lines using *boxplots*. Figure 20 illustrates the main characteristics of a boxplot. Boxplots provide a visual summary of the distribution of a variable. The main box indicates the *quartiles* of the distribution. One quarter of the distribution lies below the lower quartile, and one quarter lies above the upper quartile. Located within the box is a horizontal line, indicating the *median* of the distribution, that is the point that is greater than half of the values in the distribution and less than the other half. Vertical lines extending from the box indicate the upper and lower 10% points of the distribution. Thus the central 80% of the distribution lies between these two points. Finally, points lying outside this central range are plotted individually. This is particularly helpful in identifying unusually small or large values.

The upper part of Figure 21 shows boxplots of the estimated rate of firmness decline, given in units of kg week^{-1}. There are quite large differences between years, with the rate being highest in 1995 and lowest in 1996. Analysis of variance, restricting the data to the 25 orchards that were present in all three years (those numbered 1-11, 14-20 and 22-28 in Figs 8-19), confirms that differences between years are statistically significant, but shows that there were no significant differences between orchards. On the other hand, analysis of initial firmness values again shows that there were significant differences between years (initial firmness being greatest in 1995 and least in 1996) and also shows that there were significant differences between orchards. This latter difference is largely due to orchards 25-28 which had a high initial firmness in all three years; all these orchards are located in the West Midlands.

The lower part of Figure 21 shows the residual standard deviation (r.s.d.) from the regression. This is a measure of the scatter of the points about the fitted line, and is important in determining the precision of predictions based on the fitted line. The units of the r.s.d. are kg. Differences between years are less marked here, though the r.s.d. tended to be higher in 1996 than in the previous two years.

The regression lines may be used to estimate the date on which each orchard achieved a given firmness value. For illustration, we consider a firmness value of 8.2 kg, the threshold value recommended for storing fruit until January to achieve an ex-store firmness of 6.0 kg. The upper part of Figure 22 shows boxplots of this estimated date. In 1994 and 1995, the median date was around the 20th September, but in 1996 this occurred about 10 days later, at the end of September. This is a reflection of the slower rate of decline in firmness in 1996. The boxplots also show that in all three years the distribution of dates was very skewed, with some orchards estimated to achieve the target firmness up to a month after the median date. These orchards had firmness values well above the target level when data recording stopped at the end of September, and they therefore represent genuine predictions. For the remaining orchards, the estimated date occurs within the sampling period, and the regression line simply smooths out some of the variability in the estimates of firmness on different dates.

The lower part of Figure 22 shows the standard errors of the estimated dates, in units of days. These were calculated using an approximate formula (equation 5.35 in *Beyond ANOVA: Basics of Applied Statistics*, by R.G. Miller, Jr.). Thus, in 1994 and 1995, most estimates had standard errors of less than 1.5 days, implying that the estimates are quite reliable. In 1996, standard errors were about twice as large as in previous years, reflecting the slower rate of firmness decline and the larger r.s.d. value in that year. Typically, in 1996, a 95% confidence interval for the date at which the firmness reached 8.2 kg would cover a period of about 10 days (approximately four times the standard error).

What is really of interest, however, is the possibility of *predicting in advance* the date at which a given firmness will be reached, and, unfortunately, the magnitude of the standard errors in Figure 22 suggests that this may not be an achievable aim. To investigate this further we have considered the problem in the following form. We suppose that observations are taken every d days beginning on 20th August, when the firmness is y_0. The rate of firmness decline is β, the target firmness is y_T, and the r.s.d. is s. Then the approximate standard error of the predicted date at which firmness will reach y_T, based on n firmness measurements can be shown to be given by the formula

$$\frac{s}{|\beta|}\sqrt{\frac{1}{n}+\frac{12\left(\frac{(y_t-y_0)}{\beta}-(n-1)d\right)^2}{n(n-1)(n+1)d^2}}$$

To allow some specific calculations to be made we assume that the r.s.d. is 0.5 kg, that the sampling interval is d = 3.5 days (twice-weekly sampling) and that the target firmness is y_T = 8.2 kg. We then consider various combinations of initial firmness (y_0) and rate of firmness decline (β) such that the target firmness is achieved on 15th, 20th or 25th September. We can then use the formula to calculate the standard error for different numbers of samples (n).

Table 25 shows the results of these calculations. The standard errors, which usually exceed 3 days, appear to be too large to consider predictions to be useful, except perhaps when the rate of firmness decline is very rapid. Even then, however, reasonable predictions cannot be made unless sampling continues to within perhaps 10 days of the date at which the target firmness value will be achieved. Moreover, these theoretical standard errors are likely to be somewhat optimistic, because they are based on an exact statistical model. In practice, departures from the model, such as occasional anomalous firmness values, or slightly nonlinear patterns of firmness decline, would result in predictions being less reliable than is suggested by the model. In addition, the formula for calculating the standard error assumes that the slope parameter β is estimated by least squares regression. Cruder attempts to estimate the rate of firmness decline which might be more practical for individual growers to use, for example by fitting a line to the data 'by eye', would reduce further the reliability of predictions.

Our conclusion is that, although firmness appears to decline roughly linearly in the run up to harvest, the actual relationship in individual orchards is too variable to allow reliable forward projections of the dates on which particular firmness values are likely to be achieved.

TABLE 1

Fruit mineral concentrations (mg $100g^{-1}$) and percentage dry matter. Data are means of 21 orchards that were included in 1994, 1995 and 1996 and which had no missing mineral analysis data. Values for individual orchards were determined from samples of 30 fruit.

Element	1994	1995	1996	s.e.d. (40 d.f.)
Nitrogen (N)	58.4	61.6	59.2	2.63
Phosphorus (P)	12.7	13.3	11.5	0.34
Potassium (K)	132.9	152.2	137.0	3.77
Calcium (Ca)	5.74	5.73	4.79	0.255
Magnesium (Mg)	6.21	6.44	5.97	0.128
% Dry matter	15.7	17.9	16.7	0.22

TABLE 2

The effect of pick date on fruit characteristics at harvest. The tabulated values are means of the 25 orchards that were included in all three years. The individual values for each orchard were themselves means of 20 fruit samples.

		Pick			
Variable	Year	1	2	3	4
Weight (g)	1994	108	117	126	131
	1995	106	116	129	135
	1996	119	127	130	136
s.e.d. = 4.5 (263 d.f.)					
Diameter (mm)	1994	62.2	64.0	65.9	66.9
	1995	61.4	64.2	66.4	67.4
	1996	65.2	66.5	66.6	68.3
s.e.d. = 0.86 (263 d.f.)					
Colour (ENFRU score*)	1994	1.2	1.7	2.2	3.0
	1995	1.1	1.5	2.2	2.8
	1996	1.6	1.2	1.4	1.9
s.e.d. = 0.10 (263 d.f.)					
Firmness (kg)	1994	10.4	9.3	8.9	7.1
	1995	11.0	9.6	8.6	7.6
	1996	9.6	9.1	9.1	8.5
s.e.d. = 0.16 (263 d.f.)					
Acidity ($g\,kg^{-1}$)	1994	10.4	9.8	9.4	8.2
	1995	11.6	10.6	9.5	8.9
	1996	10.9	10.8	10.4	10.3
s.e.d. = 0.22 (263 d.f.)					

Sugar (%soluble solids)	1994	11.9	12.6	13.6	14.4
	1995	13.0	14.2	15.0	16.0
	1996	12.3	12.9	13.5	14.2
s.e.d. = 0.18 (263 d.f.)					
Starch (% black)	1994	83.5	69.2	49.0	31.9
	1995	97.7	77.2	55.6	44.2
	1996	89.8	74.3	62.4	49.0
s.e.d. = 2.03 (263 d.f.)					
Streif Index	1994	1.50	0.44	0.15	0.08
	1995	6.86	3.34	1.57	1.26
	1996	2.45	0.44	0.22	0.13

* ENFRU card, 1 = green, 4 = yellow

TABLE 3

The effect of pick date and duration of storage on weight loss, expressed as a percentage of harvest weight. Tabulated values are means of the 25 orchards that were included in all three years.

		Pick			
Assessment time	Season	1	2	3	4
January, ex-store	1994/5	4.2	1.2	1.1	3.9
	1995/6	3.4	1.1	1.9	2.3
	1996/7	2.6	1.4	3.1	1.9
January, shelf life	1994/5	5.9	3.6	3.7	7.8
	1995/6	4.5	3.2	4.5	4.8
	1996/7	4.9	3.1	4.3	3.1
April, ex-store	1994/5	4.7	4.4	2.8	6.6
	1995/6	3.5	3.5	3.5	3.4
	1996/7	3.0	3.0	4.0	4.5
April, shelf life	1994/5	6.6	7.0	6.6	-
	1995/6	4.2	5.8	6.1	5.3
	1996/7	4.8	6.0	6.1	6.2

s.e.d. = 0.40 (832 d.f.) for comparing different assessment times for a particular pick in a particular year

s.e.d. = 0.47 (905 d.f.) for other comparisons.

TABLE 4

The effect of pick date and duration of storage on Hunter 'L' colour. Tabulated values are means of the 25 orchards that were included in all three years of the Fruit Maturity Programme.

		Pick			
Assessment time	Season	1	2	3	4
January, ex-store	1994/5	59.9	60.9	62.4	-
	1995/6	60.6	61.7	62.6	-
	1996/7	61.6	62.5	64.0	65.4
January, shelf life	1994/5	61.3	63.4	64.5	-
	1995/6	64.1	64.7	65.4	-
	1996/7	64.6	64.5	66.3	67.7
April, ex-store	1994/5	61.6	62.2	62.2	-
	1995/6	59.2	60.9	62.5	-
	1996/7	61.9	62.4	64.0	64.9
April, shelf life	1994/5	64.7	65.6	65.4	-
	1995/6	61.9	62.8	63.3	-
	1996/7	63.9	64.7	-	-

s.e.d. = 0.31 (601 d.f.) for comparing different assessment times for a particular pick in a particular year

s.e.d. = 0.46 (432 d.f.) for other comparisons.

\- red colour had developed to an extent that precluded measurement of background colour in fruit from many or all of the orchards

TABLE 5

The effect of pick date and duration of storage on Hunter 'a' colour. Tabulated values are means of the 25 orchards that were included in all three years of the Fruit Maturity Programme.

		Pick			
Assessment time	Season	1	2	3	4
January, ex-store	1994/5	13.6	12.5	10.8	-
	1995/6	14.2	12.8	11.3	-
	1996/7	14.3	13.7	12.2	11.6
January, shelf life	1994/5	11.1	10.7	9.9	-
	1995/6	12.0	10.3	8.6	-
	1996/7	12.5	11.8	9.9	9.0
April, ex-store	1994/5	12.7	11.3	10.4	-
	1995/6	13.0	11.9	10.3	-
	1996/7	13.6	13.5	11.5	11.0
April, shelf life	1994/5	10.9	9.3	8.3	-
	1995/6	11.8	9.7	8.8	-
	1996/7	11.6	10.2	-	-

s.e.d. = 0.24 (601 d.f.) for comparing different assessment times for a particular pick in a particular year

s.e.d. = 0.29 (628 d.f.) for other comparisons.

\- red colour had developed to an extent that precluded measurement of background colour in fruit from many or all of the orchards

TABLE 6

The effect of pick date and duration of storage on Hunter 'b' colour. Tabulated values are means of the 25 orchards that were included in all three years of the Fruit Maturity Programme.

		Pick			
Assessment time	Season	1	2	3	4
January, ex-store	1994/5	30.3	31.3	31.3	-
	1995/6	30.4	32.0	32.5	-
	1996/7	30.4	30.8	31.3	32.7
January, shelf life	1994/5	32.7	33.7	34.4	-
	1995/6	33.0	33.3	34.2	-
	1996/7	32.0	33.7	34.4	35.5
April, ex-store	1994/5	30.7	31.4	32.3	-
	1995/6	30.5	31.5	32.8	-
	1996/7	30.8	31.1	31.5	32.7
April, shelf life	1994/5	33.1	34.1	33.9	-
	1995/6	32.7	33.5	34.5	-
	1996/7	33.5	33.8	-	-

s.e.d. = 0.48 (601 d.f.) for comparing different assessment times for a particular pick in a particular year

s.e.d. = 0.52 (767 d.f.) for other comparisons.

\- red colour had developed to an extent that precluded measurement of background colour in fruit from many or all of the orchards

TABLE 7

The effect of pick date and duration of storage on fruit firmness (kg). Tabulated values are means of the 25 orchards that were included in all three years of the Fruit Maturity Programme.

		Pick			
Assessment time	Season	1	2	3	4
January, ex-store	1994/5	7.3	6.5	6.0	5.5
	1995/6	7.2	6.1	6.0	6.0
	1996/7	6.6	6.5	6.6	5.6
January, shelf life	1994/5	6.8	6.0	5.7	5.3
	1995/6	6.3	5.6	5.4	5.3
	1996/7	5.9	5.7	5.8	5.0
April, ex-store	1994/5	7.0	6.4	5.9	5.3
	1995/6	6.7	5.8	5.9	5.6
	1996/7	6.1	5.7	6.1	5.2
April, shelf life	1994/5	6.3	5.7	5.5	-
	1995/6	6.1	5.6	5.5	5.1
	1996/7	5.6	5.3	5.4	4.6

s.e.d. = 0.083 (834 d.f.) for comparing different assessment times for a particular pick in a particular year

s.e.d. = 0.121 (571 d.f.) for other comparisons.

TABLE 8

The effect of pick date and duration of storage on the percentage of fruit with rots. Tabulated values are means of the 25 orchards that were included in all three years of the Fruit Maturity Programme.

		Pick			
Assessment time	Season	1	2	3	4
January, ex-store	1994/5	0	0.4	0.8	18.4
	1995/6	0	0.6	1.0	4.5
	1996/7	0	0.4	0.6	0
January, shelf life	1994/5	0.8	1.0	1.4	35.1
	1995/6	0.4	2.8	3.6	3.6
	1996/7	0.8	1.2	0.6	0.9
April, ex-store	1994/5	1.6	2.2	6.0	72.7
	1995/6	0.8	1.2	6.4	20.1
	1996/7	1.4	0.4	2.0	3.4
April, shelf life	1994/5	1.4	1.8	19.0	-
	1995/6	1.4	3.4	9.6	19.4
	1996/7	1.8	1.8	6.0	2.6

TABLE 9

The effect of pick date and duration of storage on fruit taste, texture and flavour. Tabulated values are means of the 25 orchards that were included in all three years of the Fruit Maturity Programme. Fruit were assessed in January, by Mr. John Chapman of F.A.S.T. Ltd., following a period of shelf life after removal from storage.

		Pick			
Variable	Season	1	2	3	4
Taste (sugar/acid) (maximum 5)					
	1994/5	2.4	4.8	5.0	3.8
	1995/6	2.3	4.7	4.8	4.4
s.e.d. = 0.26 (259 d.f.)	1996/7	3.4	4.5	4.9	4.5
Texture (maximum 5)					
	1994/5	2.7	4.2	3.5	2.4
	1995/6	4.1	4.0	3.4	2.9
s.e.d. = 0.22 (259 d.f.)	1996/7	4.3	4.4	4.4	2.4
Cox flavour (maximum 10)					
	1994/5	2.3	5.5	6.6	6.5
	1995/6	2.3	4.8	5.6	3.9
s.e.d. = 0.25 (259 d.f.)	1996/7	2.8	4.8	5.6	6.6

TABLE 10

The effect of pick date and duration of storage on the incidence of bitter pit and late storage corking. Data are the mean percentage of affected fruit from the 25 orchards that were included in all three years of the Fruit Maturity Programme. Individual orchard percentages were based on samples of approximately 20 fruit.

		Pick			
Assessment time	Season	1	2	3	4
January, ex-store	1994/5	0.4	0.2	0.2	0.2
	1995/6	0	0	0.4	0.9
	1996/7	0.2	0.2	0.8	1.6
January, shelf life	1994/5	1.0	0.4	0	1.1
	1995/6	0.4	1.4	0.2	3.0
	1996/7	2.4	0.6	1.8	2.6
April, ex-store	1994/5	3.8	4.9	1.0	0.6
	1995/6	1.4	4.0	3.6	1.1
	1996/7	4.8	4.0	11.2	4.0
April, shelf life	1994/5	4.8	12.0	8.4	-
	1995/6	1.8	8.4	5.5	2.9
	1996/7	2.9	8.2	16.6	7.0

TABLE 11

The effect of pick date and duration of storage on the incidence of core flush. Data are the mean percentage of affected fruit from the 25 orchards that were included in all three years of the Fruit Maturity Programme. Individual orchard percentages were based on samples of approximately 20 fruit.

		Pick			
Assessment time	Season	1	2	3	4
January, ex-store	1994/5	0	1.2	0.2	0
	1995/6	0	0	0	0
	1996/7	0	0	0	0
January, shelf life	1994/5	0.2	1.2	0.2	1.4
	1995/6	0	0.4	0	0.2
	1996/7	0.2	0.2	0.6	0.2
April, ex-store	1994/5	1.5	10.0	6.6	6.5
	1995/6	0	0	0.4	0.2
	1996/7	0.4	0.6	0	0
April, shelf life	1994/5	5.4	11.9	11.8	-
	1995/6	1.0	1.1	0.9	0.9
	1996/7	0.4	3.0	1.8	2.2

TABLE 12

The effect of pick date and duration of storage on the incidence of senescent breakdown. Data are the mean percentage of affected fruit from the 25 orchards that were included in all three years of the Fruit Maturity Programme. Individual orchard percentages were based on samples of approximately 20 fruit.

		Pick			
Assessment time	Season	1	2	3	4
January, ex-store	1994/5	0	0	0	2.5
	1995/6	0	0	0	0.7
	1996/7	0	0	0.2	0.6
January, shelf life	1994/5	0	0.2	0.2	4.0
	1995/6	0	0	0.6	0.6
	1996/7	0.6	0.2	0.4	0.8
April, ex-store	1994/5	0.6	1.6	0	5.8
	1995/6	1.6	1.2	2.2	1.4
	1996/7	0.4	1.0	0	0.4
April, shelf life	1994/5	0.4	1.0	2.0	-
	1995/6	0.4	1.8	3.0	4.1
	1996/7	0.6	0.8	1.8	3.2

TABLE 13

Classification of fruit according to whether the observed and predicted ex-store firmness in January was below or above 6.5 kg. The prediction is determined by whether the harvest firmness of the fruit is below or above 9.4 kg. The classification is shown separately for the three growing seasons. Data from the 1994/5 and 1995/6 storage seasons were used to formulate the recommended harvest firmness of 9.4 kg.

	Predicted	January ex-store firmness	
Season	ex-store firmness	< 6.5 kg	≥ 6.5 kg
1994/5	< 6.5 kg	60	13
	≥ 6.5 kg	7	37
		(83% correct)	
1995/6	< 6.5 kg	58	14
	≥ 6.5 kg	15	40
		(77% correct)	
1996/7	< 6.5 kg	67	24
	≥ 6.5 kg	7	26
		(75% correct)	

TABLE 14

Classification of fruit according to whether the observed and predicted ex-store firmness in April was below or above 6.5 kg. The prediction is determined by whether the harvest firmness of the fruit is below or above 10.2 kg. The classification is shown separately for the three growing seasons. Data from the 1994/5 and 1995/6 storage seasons were used to formulate the recommended harvest firmness of 10.2 kg.

	Predicted	April ex-store firmness	
Season	ex-store firmness	< 6.5 kg	≥ 6.5 kg
1994/5	< 6.5 kg	70	24
	≥ 6.5 kg	2	18
		(77% correct)	
1995/6	< 6.5 kg	79	8
	≥ 6.5 kg	14	26
		(83% correct)	
1996/7	< 6.5 kg	99	5
	≥ 6.5 kg	11	9
		(87% correct)	

TABLE 15

Classification of fruit according to whether the observed and predicted ex-store firmness in January was below or above 6.0 kg. The prediction is determined by whether the harvest firmness of the fruit is below or above 8.2 kg. The classification is shown separately for the three growing seasons. Data from the 1994/5 and 1995/6 storage seasons were used to formulate the recommended harvest firmness of 8.2 kg.

	Predicted	January ex-store firmness	
Season	ex-store firmness	< 6.0 kg	≥ 6.0 kg
1994/5	< 6.0 kg	33	3
	≥ 6.0 kg	12	69
		(87% correct)	
1995/6	< 6.0 kg	29	13
	≥ 6.0 kg	20	65
		(74% correct)	
1996/7	< 6.0 kg	20	10
	≥ 6.0 kg	21	73
		(75% correct)	

TABLE 16

Classification of fruit according to whether the observed and predicted ex-store firmness in April was below or above 6.0 kg. The prediction is determined by whether the harvest firmness of the fruit is below or above 8.7 kg. The classification is shown separately for the three growing seasons. Data from the 1994/5 and 1995/6 storage seasons were used to formulate the recommended harvest firmness of 8.7 kg.

	Predicted	April ex-store firmness	
Season	ex-store firmness	< 6.0 kg	≥ 6.0 kg
1994/5	< 6.0 kg	40	10
	≥ 6.0 kg	8	56
		(84% correct)	
1995/6	< 6.0 kg	43	14
	≥ 6.0 kg	22	48
		(72% correct)	
1996/7	< 6.0 kg	54	9
	≥ 6.0 kg	22	39
		(75% correct)	

TABLE 17

Percentage variance accounted for by different models of ex-store firmness when these models are fitted either to data from the 1994 and 1995 growing seasons only (as in previous report on project SP104) or to the data from all three years.

	Time of post-harvest firmness measurement			
	January		April	
Explanatory variables	Ex-store	Shelf life	Ex-store	Shelf life
1994 and 1995 crops				
Harvest firmness	61	52	52	44
Harvest firmness and diameter	62	55	55	48
Harvest firmness and diameter, concentrations of phosphorus and potassium	64	60	58	55
1994, 1995 and 1996 crops				
Harvest firmness	56	48	40	43
Harvest firmness and diameter	57	51	43	48
Harvest firmness and diameter, concentrations of phosphorus and potassium	59	55	46	56

TABLE 18

Regression models for post harvest firmness (kg) based solely on harvest firmness (kg). Models were fitted to data from all three years. The Table shows regression coefficients with t-values in brackets, the residual standard deviation (r.s.d.) and its degrees of freedom, and the percentage variance accounted for ($\bar{R}^2$). See the Statistical Methods Section for more details.

Explanatory variable	January assessment		April assessment	
	Ex-store	Shelf-life	Ex-store	Shelf-life
Constant	2.73 (15.8)	3.00 (19.3)	2.98 (14.9)	2.58 (13.7)
Firmness	0.40 (21.3)	0.30 (18.0)	0.33 (15.2)	0.32 (15.8)
r.s.d. (d.f.)	0.53 (350)	0.48 (351)	0.61 (347)	0.50 (323)
$\bar{R}^2$	56.2	47.8	39.9	43.4

TABLE 19

Regression models for post harvest firmness (kg) based on harvest firmness (kg) and diameter (mm). Models were fitted to data from all three years. The Table shows regression coefficients with t-values in brackets, the residual standard deviation (r.s.d.) and its degrees of freedom, and the percentage variance accounted for ($\bar{R}^2$). See the Statistical Methods Section for more details.

Explanatory variable	January assessment		April assessment	
	Ex-store	Shelf-life	Ex-store	Shelf-life
Constant	4.49 (6.81)	5.56 (9.50)	6.27 (8.35)	5.88 (9.23)
Size	-0.023 (2.77)	-0.034 (4.53)	-0.044 (4.54)	-0.043 (5.41)
Firmness	0.37 (17.9)	0.27 (14.5)	0.28 (11.9)	0.27 (12.4)
r.s.d. (d.f.)	0.52 (349)	0.46 (350)	0.59 (346)	0.48 (322)
$\bar{R}^2$	57.0	50.6	43.1	47.9

TABLE 20

Regression models for post harvest firmness (kg) based on harvest firmness (kg) and diameter (mm), and on fruit P and K concentrations (mg $100g^{-1}$). Models were fitted to data from all three years. The Table shows regression coefficients with t-values in brackets, the residual standard deviation (r.s.d.) and its degrees of freedom, and the percentage variance accounted for ($\bar{R}^2$). See the Statistical Methods Section for more details.

Explanatory variable	January assessment		April assessment	
	Ex-store	Shelf-life	Ex-store	Shelf-life
Constant	3.23 (4.53)	4.06 (6.55)	4.69 (5.80)	3.85 (5.96)
Size	-0.010 (1.15)	-0.019 (2.44)	-0.028 (2.79)	-0.024 (3.06)
Firmness	0.39 (18.6)	0.28 (15.7)	0.30 (12.7)	0.28 (14.0)
Fruit P	0.089 (4.08)	0.11 (5.62)	0.11 (4.48)	0.15 (7.45)
Fruit K	-0.0062 (3.61)	-0.0071 (4.75)	-0.0070 (3.63)	-0.0085 (5.52)
r.s.d. (d.f.)	0.51 (347)	0.44 (348)	0.57 (344)	0.45 (320)
$\bar{R}^2$	59.1	55.0	46.3	55.9

TABLE 21

Distribution of optimum pick dates for 1994, 1995 and 1996 seasons. The optimum pick date is the last occasion on which harvest firmness is sufficiently great to predict that ex-store firmness will be at least 6.5 kg (upper part of Table) or 6.0 kg (lower part of Table). The table shows the number of orchards for which the optimum pick date was pick 1, 2, 3 or 4. For some orchards, and particularly to achieve a firmness of at least 6.5 kg after storage until April, fruit was too soft even at the first pick. The number of orchards for which this occurred is shown in the column headed 'Before pick 1'.

			Pick			
Store until	Season	Before pick 1	1	2	3	4
To achieve 6.5 kg ex-store						
January	1994/5	1	19	3	4	3
January	1995/6	0	17	9	2	4
January	1996/7	20	2	0	4	5
April	1994/5	22	4	2	2	0
April	1995/6	14	12	3	3	0
April	1996/7	24	2	1	4	0
To achieve 6.0 kg ex-store						
January	1994/5	0	0	7	19	4
January	1995/6	0	1	9	16	6
January	1996/7	1	1	0	12	17
April	1994/5	1	15	5	6	3
April	1995/6	0	14	12	2	4
April	1996/7	15	5	2	2	7

TABLE 22

Classification of ex-store greenness (Hunter 'a' colour) of fruit picked at the predicted optimum harvest date to achieve ex-store firmness of 6.5 kg (upper half of Table) or 6.0 kg (lower half of Table) in either January or April. The Table shows the number of orchards for which the Hunter 'a' value was below or above 10. Some orchards are excluded because the optimum predicted pick date was before the first actual harvest, or because the ex-store greenness value could not be recorded, for example because the fruit had extensive rotting.

		Hunter 'a' colour	
Store until	Season	< 10	≥ 10
To achieve 6.5 kg ex-store			
January	1994/5	1	27
January	1995/6	0	27
January	1996/7	0	9
April	1994/5	0	8
April	1995/6	1	17
April	1996/7	0	7
To achieve 6.0 kg ex-store			
January	1994/5	6	20
January	1995/6	0	23
January	1996/7	1	19
April	1994/5	3	23
April	1995/6	1	27
April	1996/7	1	13

TABLE 23

Overall fruit quality score (maximum 30) of fruit picked at the predicted optimum harvest date to achieve ex-store firmness of 6.5 kg (upper half of Table) or 6.0 kg (lower half of Table) in January. Some orchards are excluded because the optimum predicted pick date was before the first actual harvest.

Store until	Season	Number of orchards	Overall quality score Mean (s.e.)
To achieve 6.5 kg ex-store			
January	1994/5	29	15.7 (1.02)
January	1995/6	31	19.2 (0.79)
January	1996/7	11	22.5 (0.64)
To achieve 6.0 kg ex-store			
January	1994/5	30	22.4 (0.52)
January	1995/6	28	22.3 (0.58)
January	1996/7	28	22.1 (0.58)

TABLE 24

Number of orchards with different combinations of rootstock, growing system and growing region. There are 23 orchards in total, comprising the 25 orchards that were included in all three years of the Fruit Maturity Programme, with two orchards excluded because of missing data.

		Growing region		
Rootstock	Growing system	Kent/Sussex	East Anglia	West Midlands
M9	Single row	4	0	1
	Multi-row	4	5	0
MM106	Single row	4	2	2
	Multi-row	0	0	1

TABLE 25

Theoretical standard errors (in units of days) for prediction of the date at which fruit firmness reaches 8.2 kg. The first column gives fruit firmness on the initial sampling date (20th Aug). The second column gives the actual date on which firmness reaches 8.2 kg. These two values determine the rate of firmness decline, which is shown in the third column. The remaining columns give the standard errors of prediction if twice-weekly sampling is continued until the date indicated (*n* is the number of firmness assessments undertaken).

Initial	Date of 8.2kg	Rate of firmness	Twice weekly sampling until		
firmness (kg)	firmness	decline (kg $week^{-1}$)	3 Sep (n=4)	6/7 Sep (n=5)	10 Sep (n=6)
10	15 Sep	0.48	5.5	3.3	3.2
10	20 Sep	0.41	11.3	6.1	3.8
10	25 Sep	0.35	19.2	10.9	6.6
12	20 Sep	0.86	5.4	2.9	1.8
12	25 Sep	0.74	9.1	5.2	3.1

Figure 1. Relationship between harvest firmness and ex-store firmness in January.

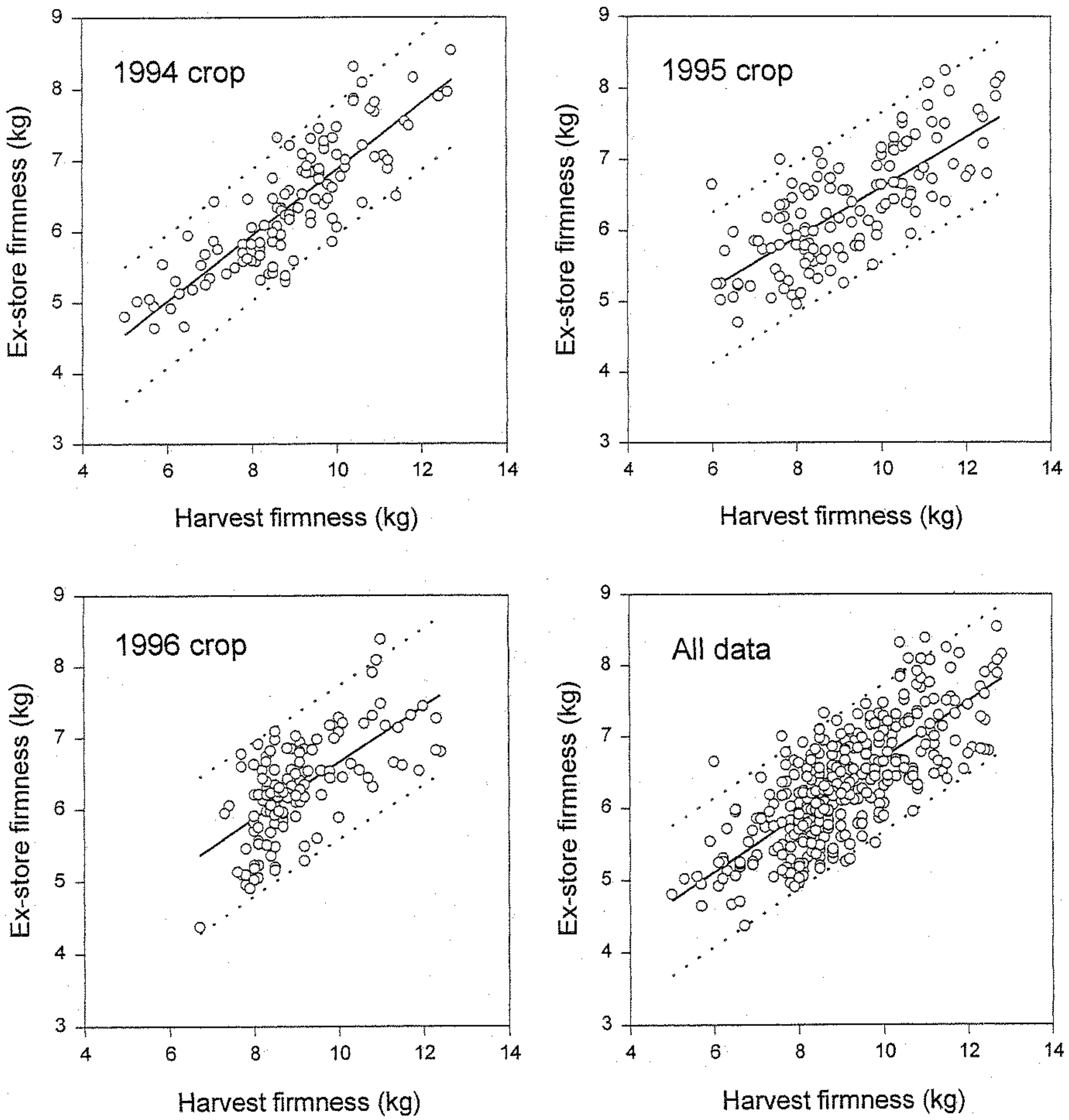


Figure 2. Relationship between harvest firmness and firmness in January, following simulated shelf life.

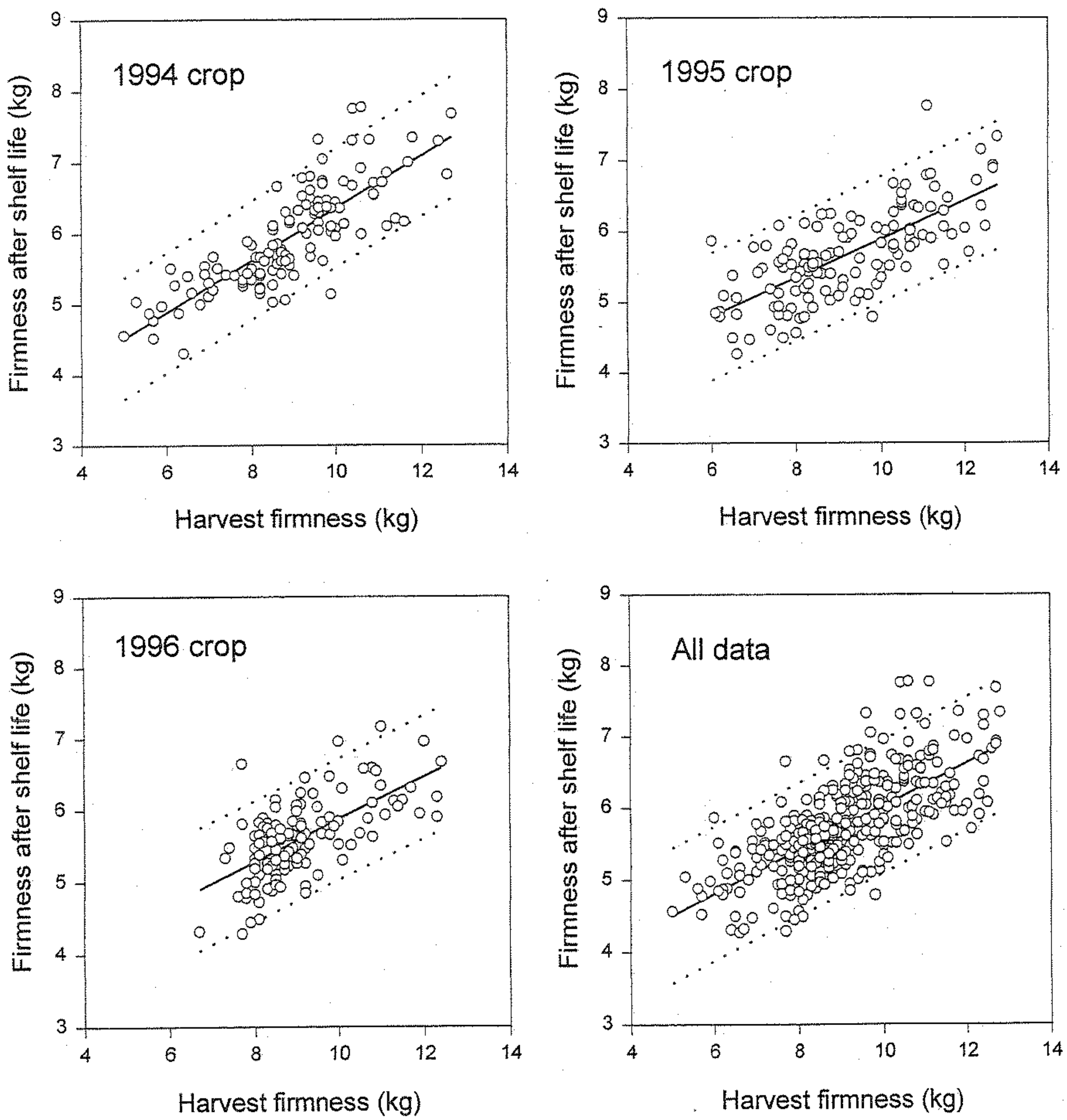


Figure 3. Relationship between harvest firmness and ex-store firmness in April.

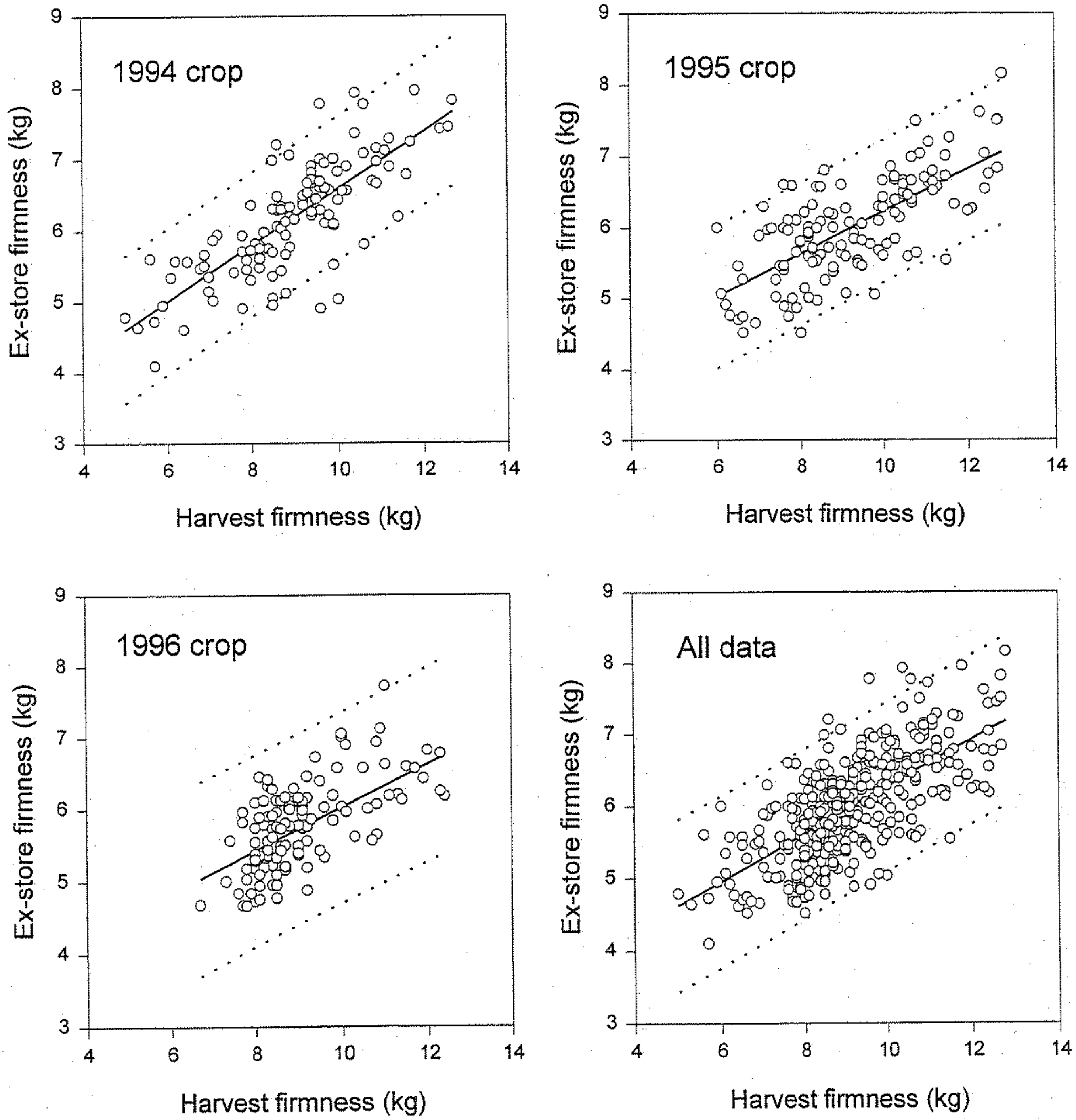


Figure 4. Relationship between harvest firmness and firmness in April, following simulated shelf life.

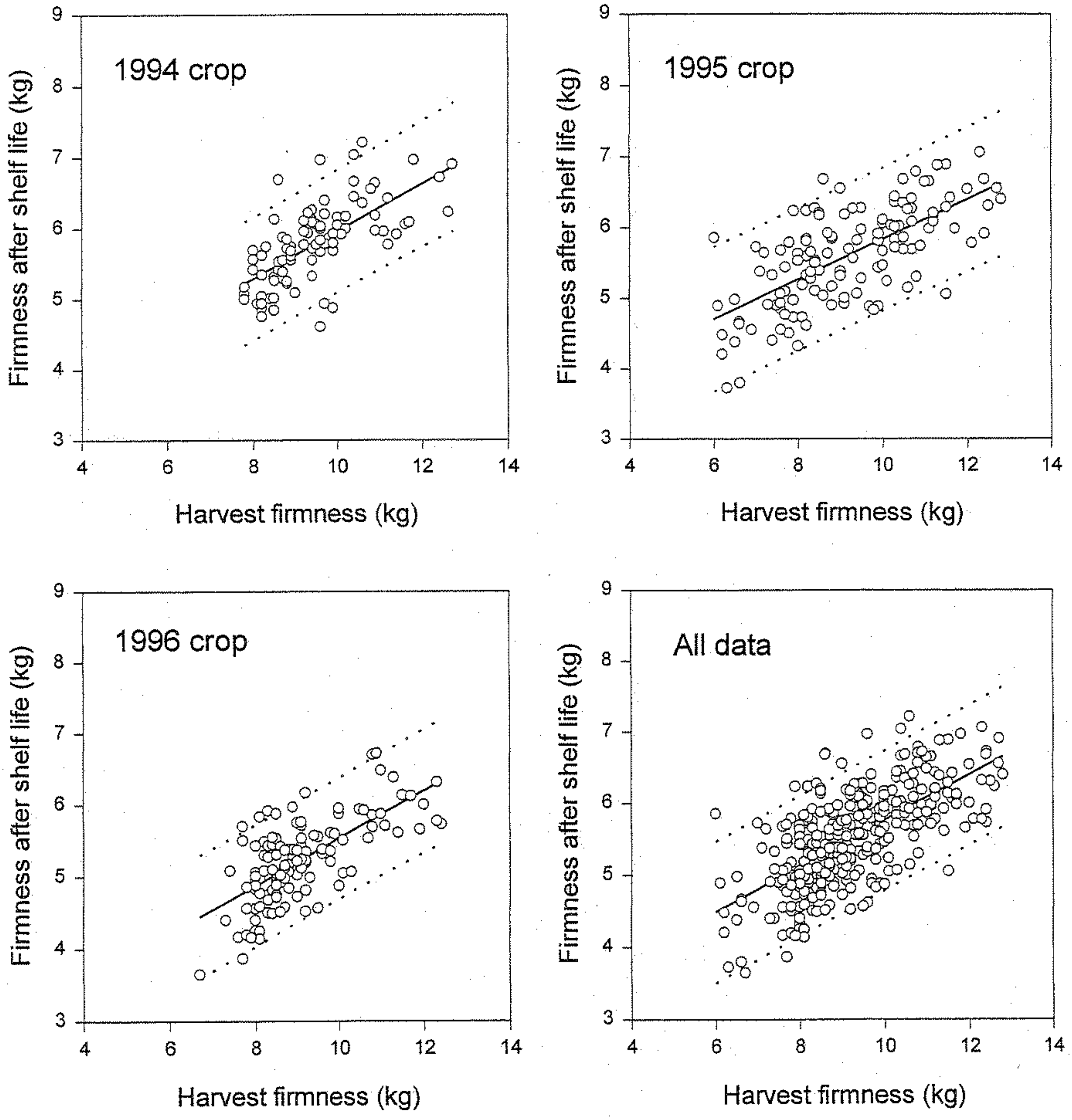


Figure 5. Relationship between harvest firmness and ex-store firmness in May for the six years of the Cox Survey. The lines are regression lines for April ex-store firmness developed from the Fruit Maturity Programme data.

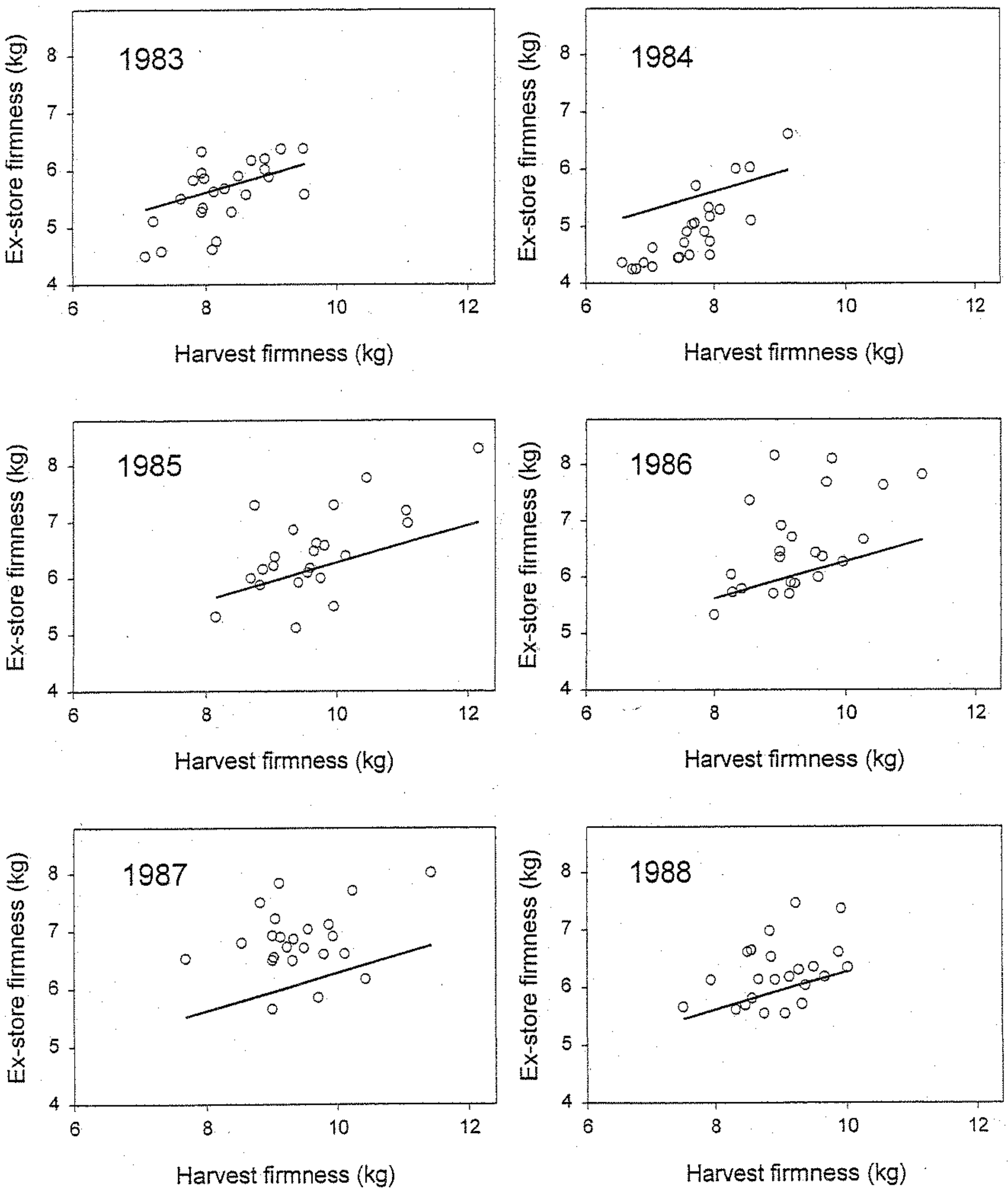


Figure 6. Relationship between harvest firmness and ex-store firmness in April for Pick 3 data from the Fruit Maturity Programme. The lines are regression lines fitted to the data from all four picks

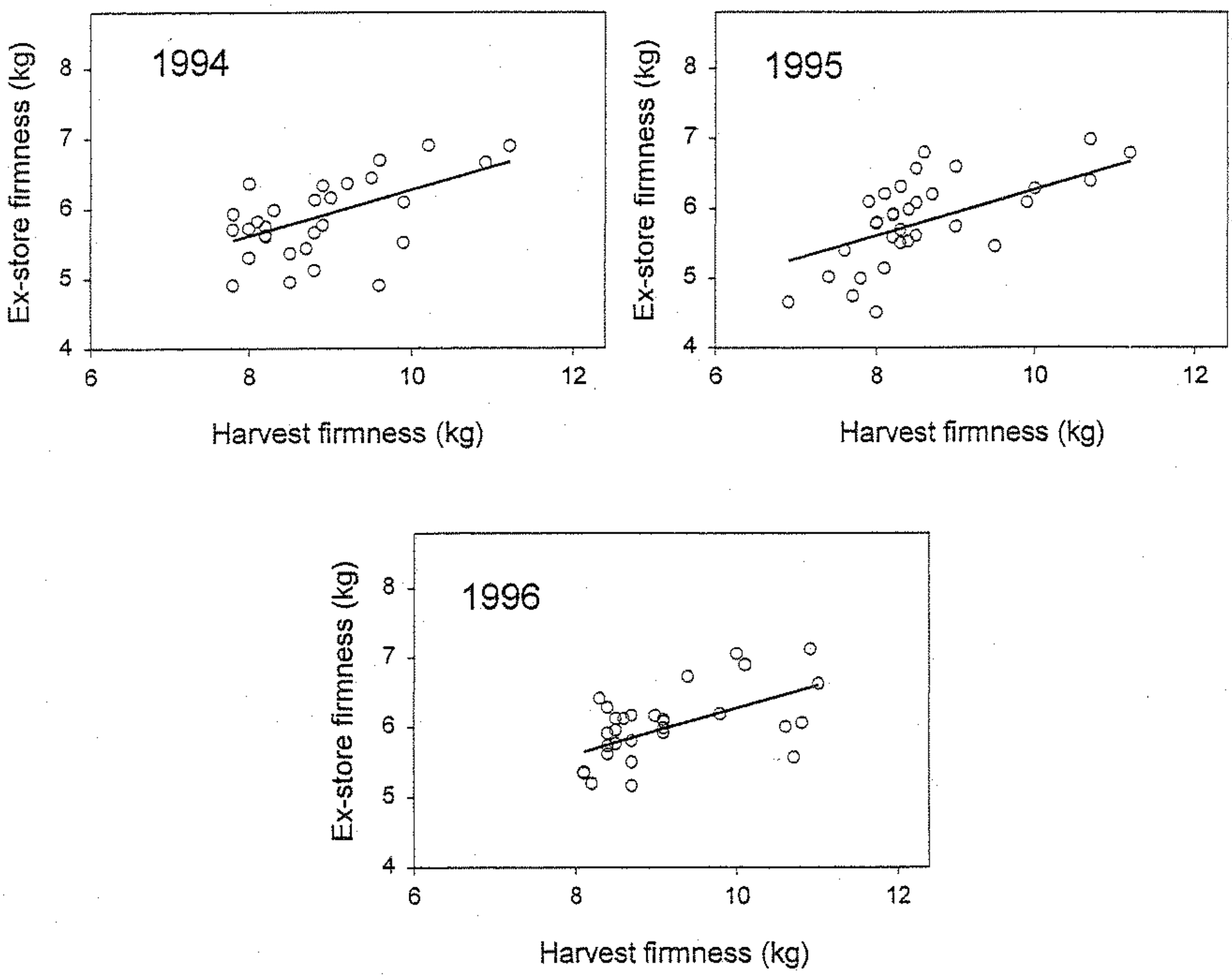


Figure 7. Relationship between harvest firmness and ex-store firmness in the Cox Survey and in the Fruit Maturity Programme. The solid lines are the regression lines fitted to the full data from the Fruit Maturity Programme. The dotted line in the upper Figure is the regression line for the Cox Survey data.

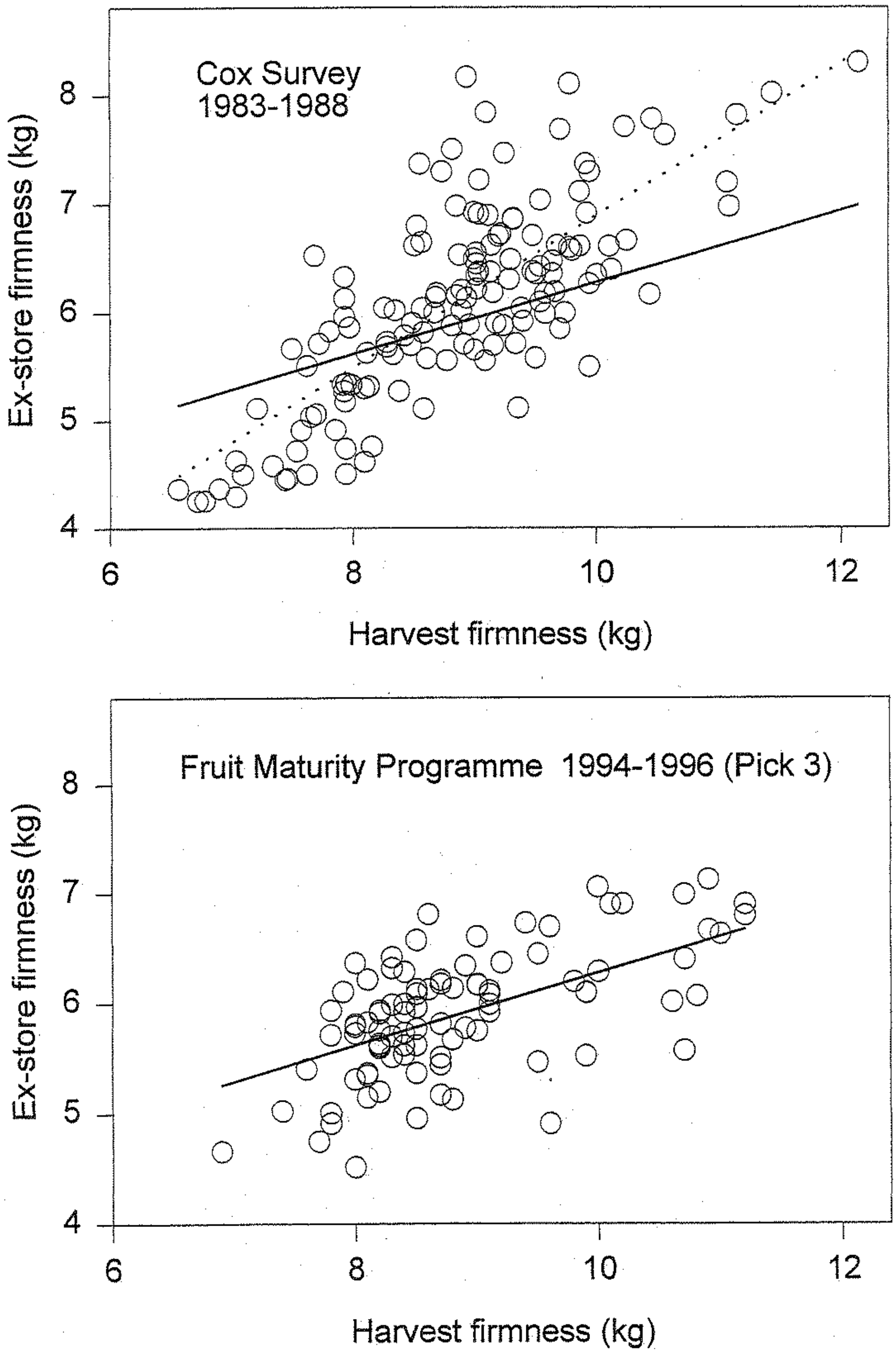


Figure 8. Firmness decline in 1994, orchards 1-8

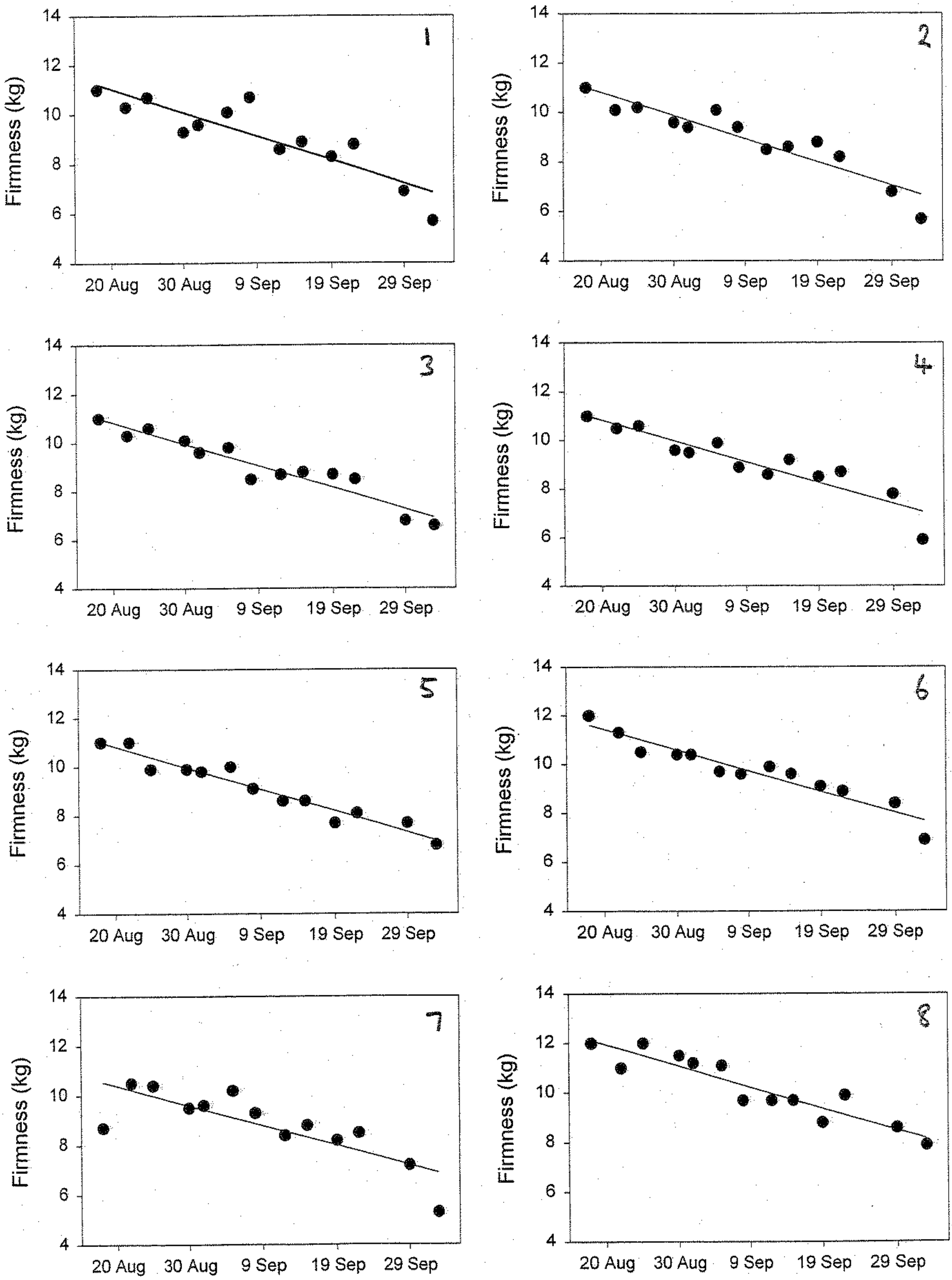


Figure 9. Firmness decline in 1994, orchards 9-16

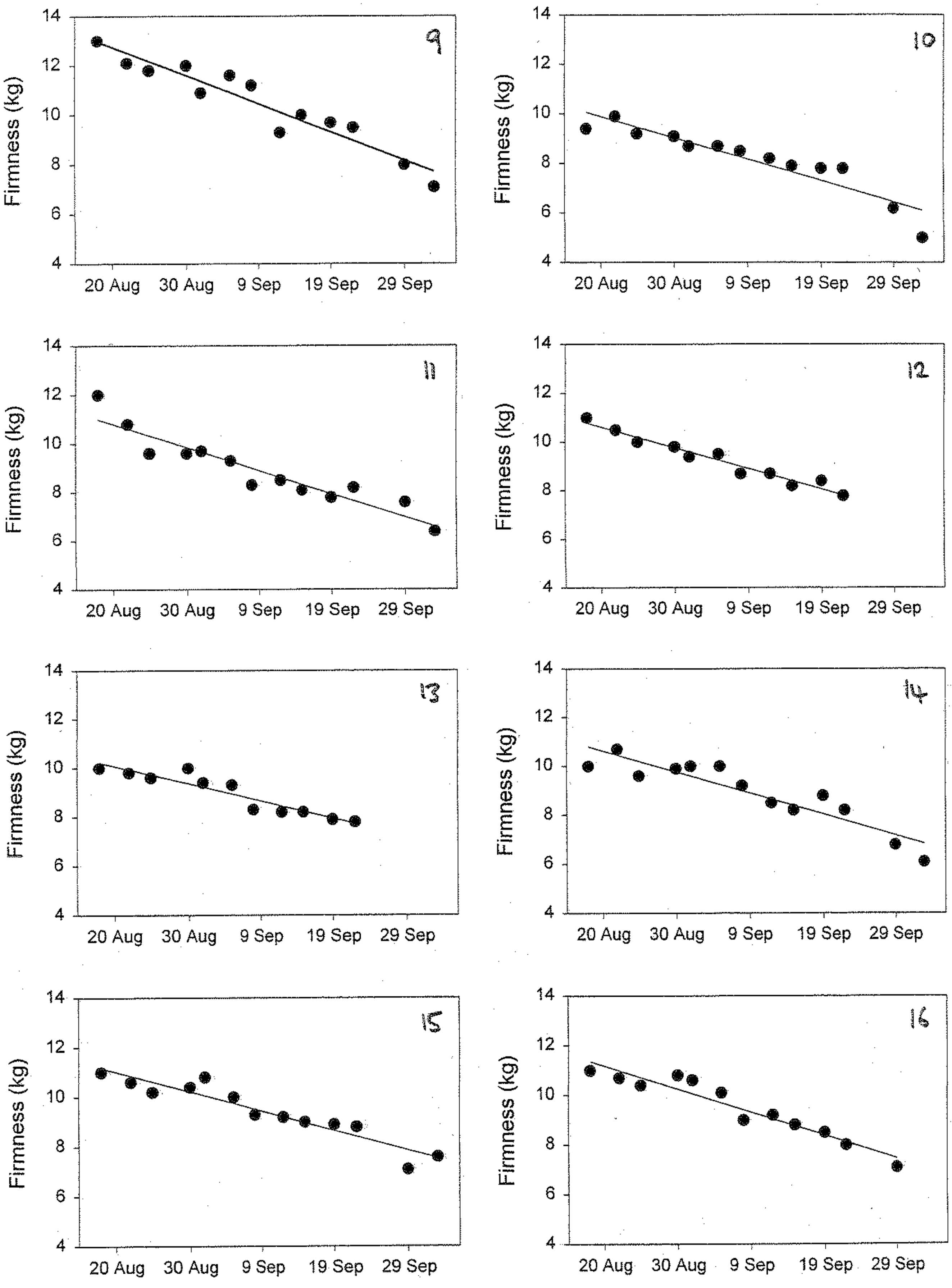


Figure 10. Firmness decline in 1994, orchards 17-24

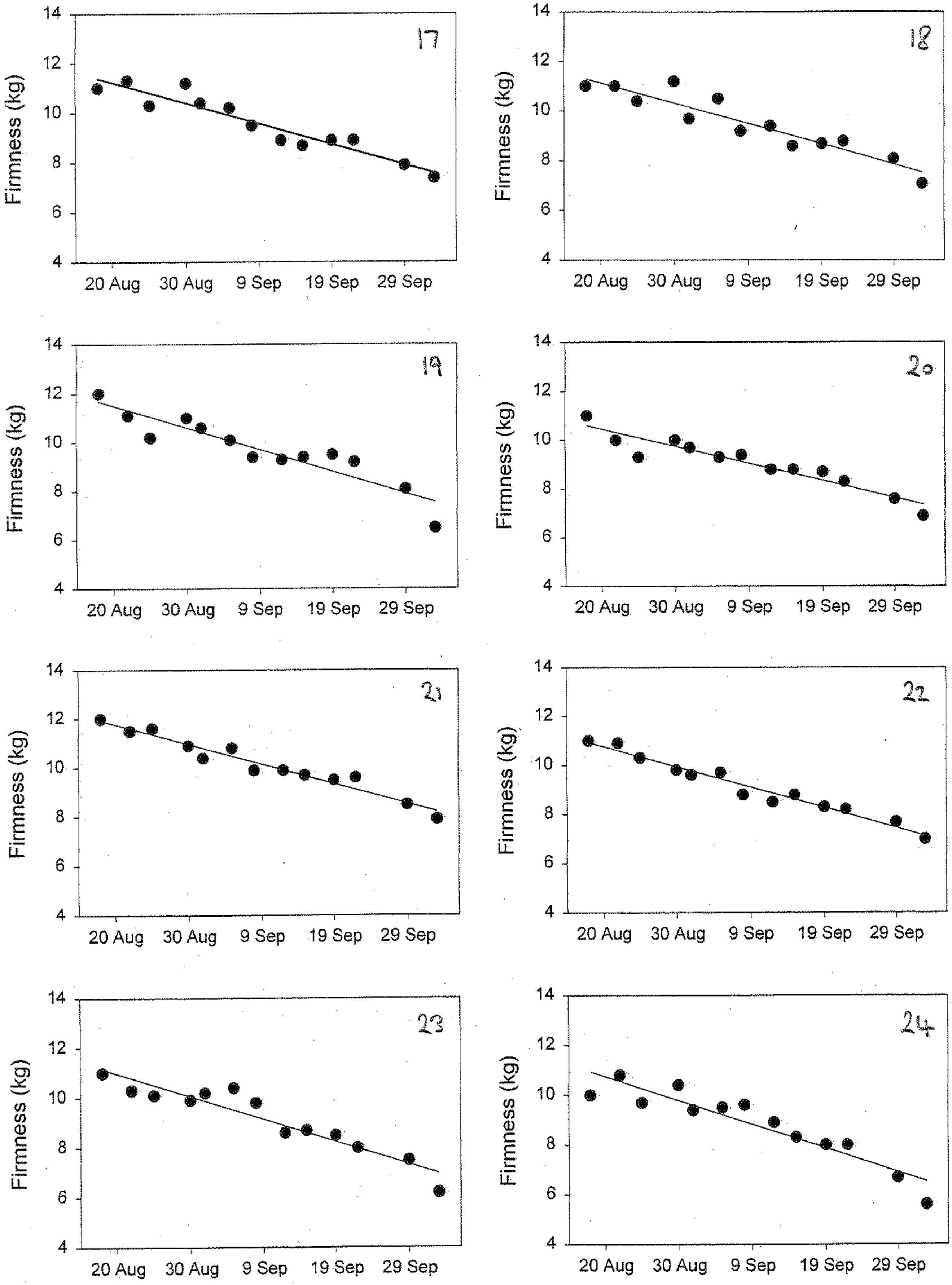


Figure 11. Firmness decline in 1994, orchards 25-30

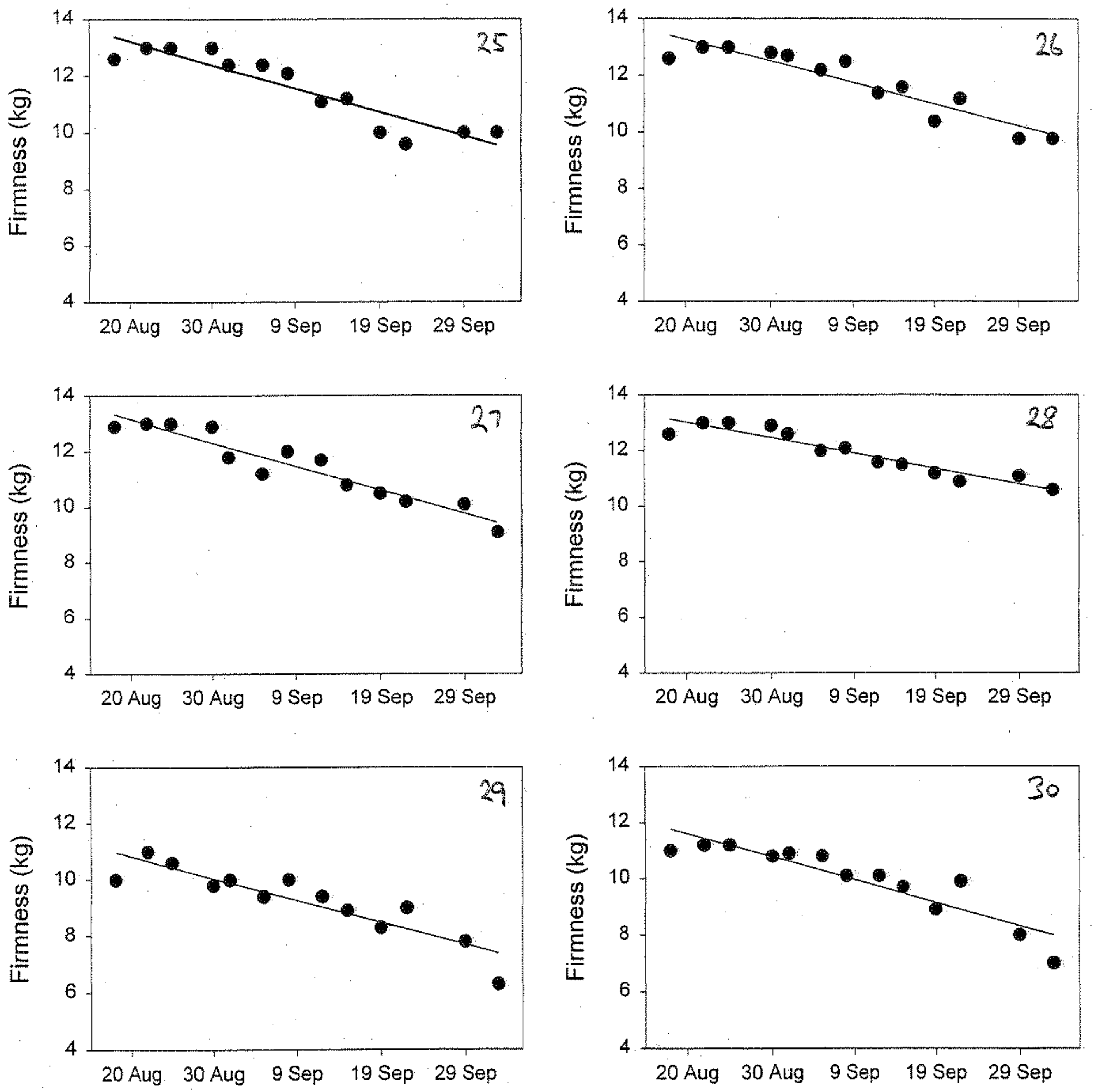


Figure 12. Firmness decline in 1995, orchards 1-8

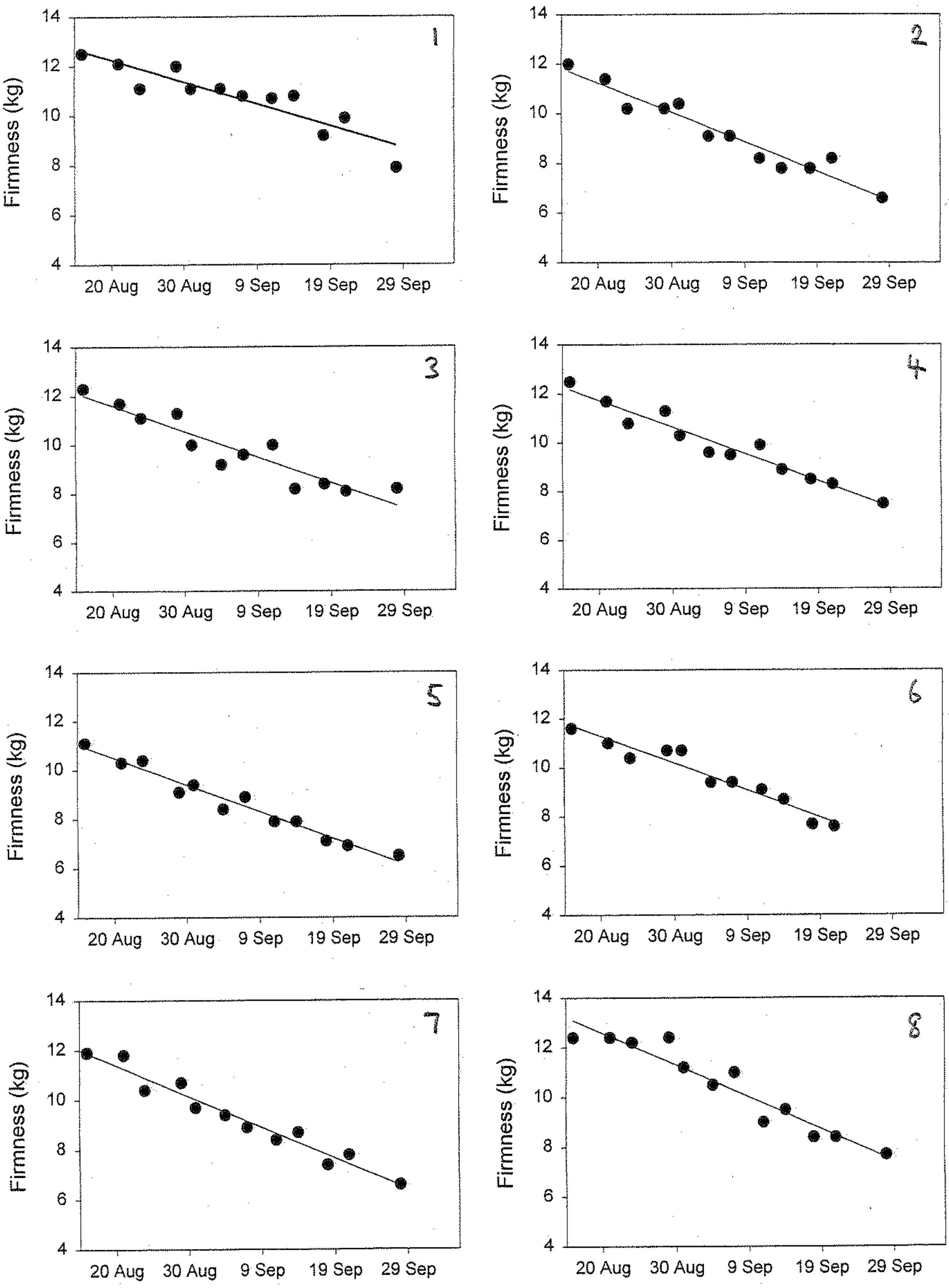


Figure 13. Firmness decline in 1995, orchards 9-16

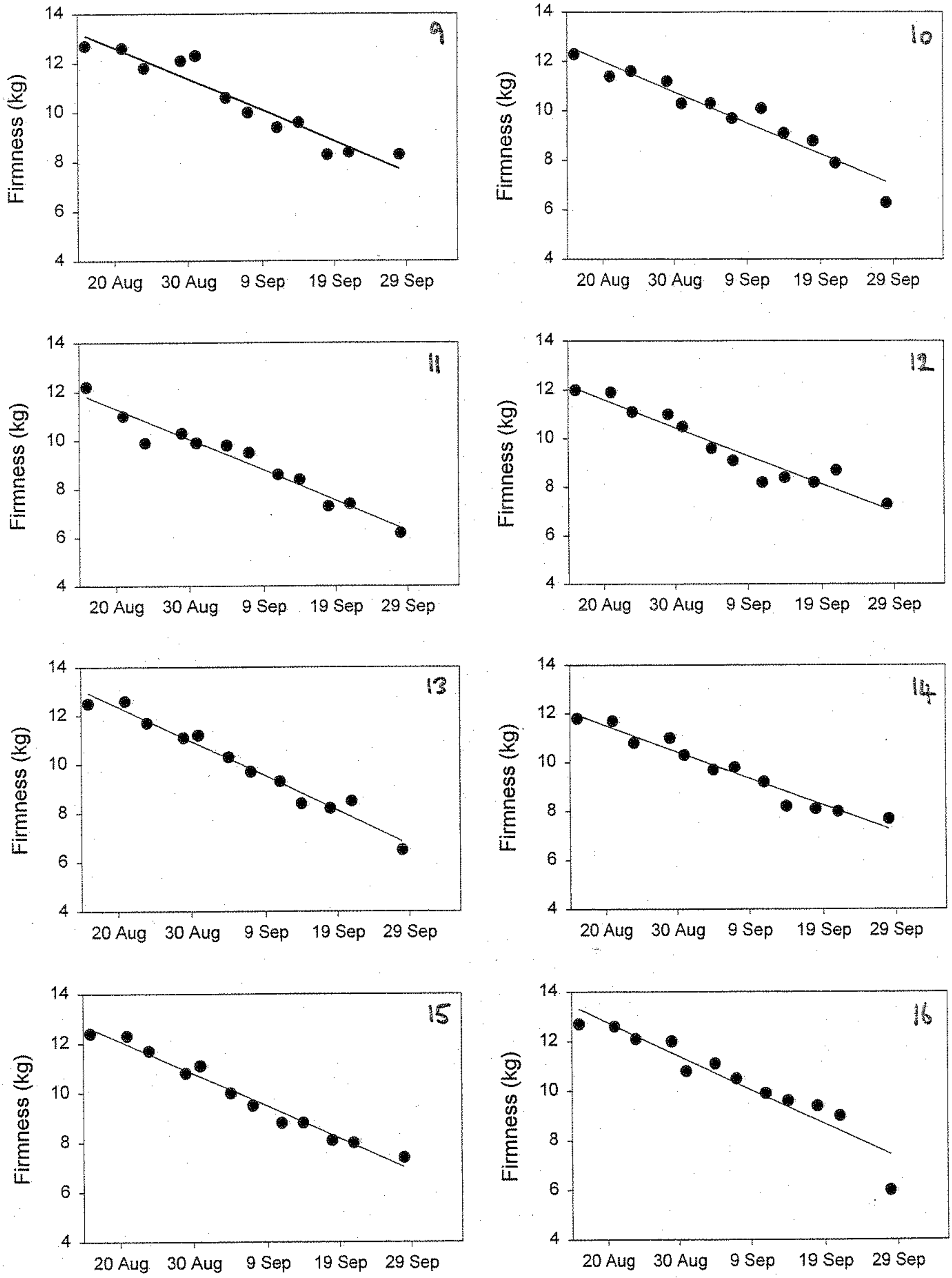


Figure 14. Firmness decline in 1995, orchards 17-24

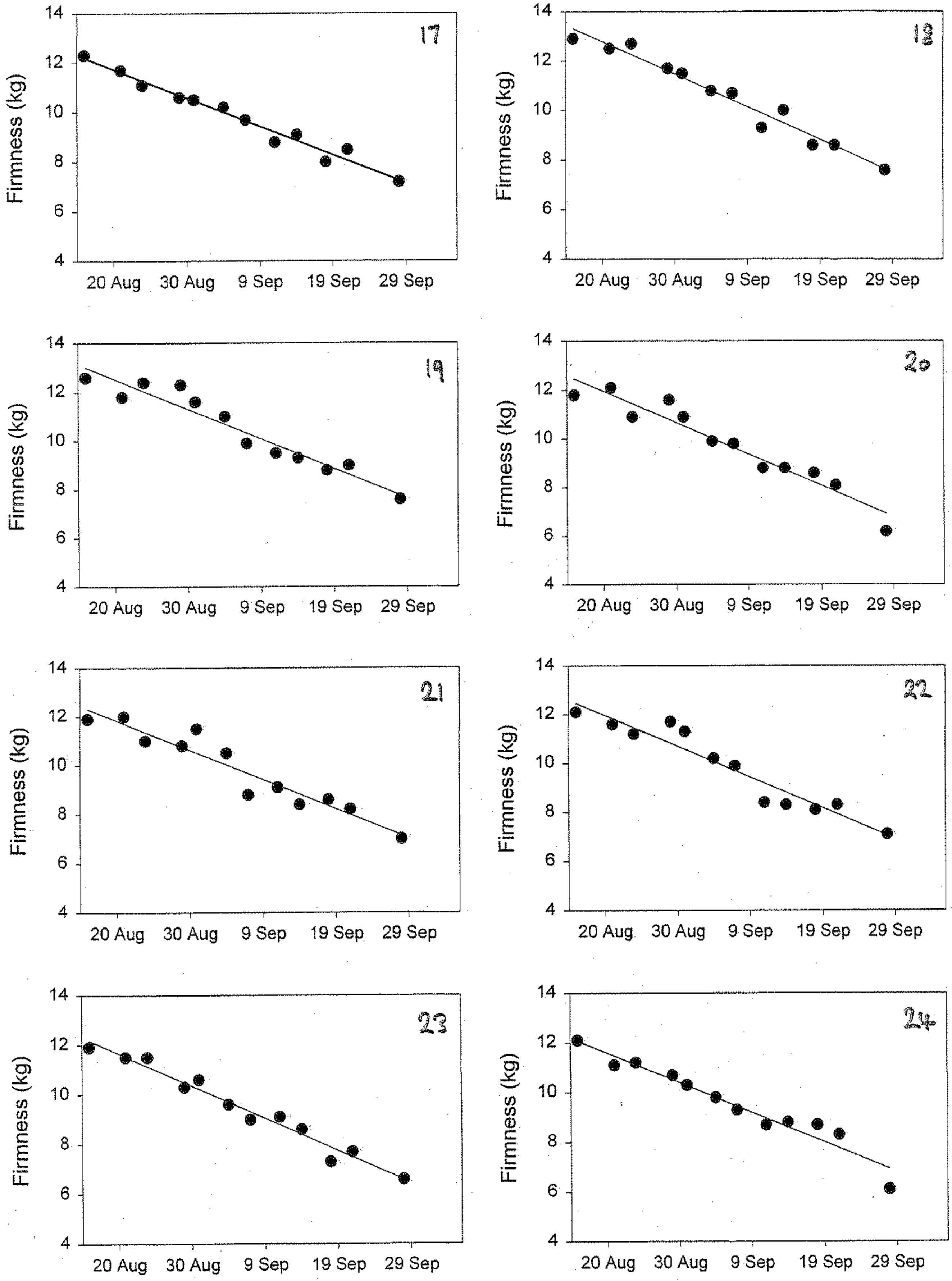


Figure 15. Firmness decline in 1995, orchards 25-32

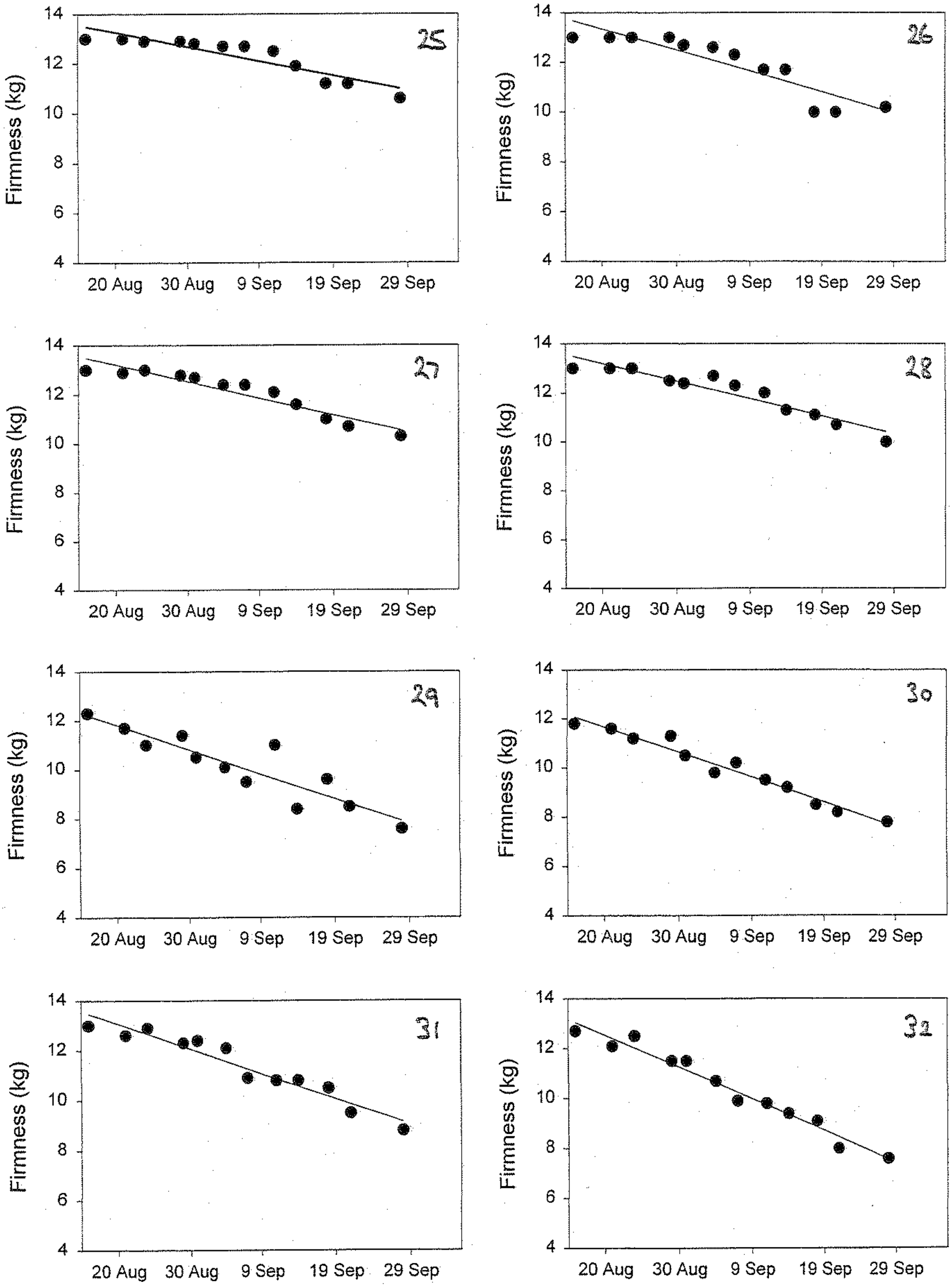


Figure 16. Firmness decline in 1996, orchards 1-8

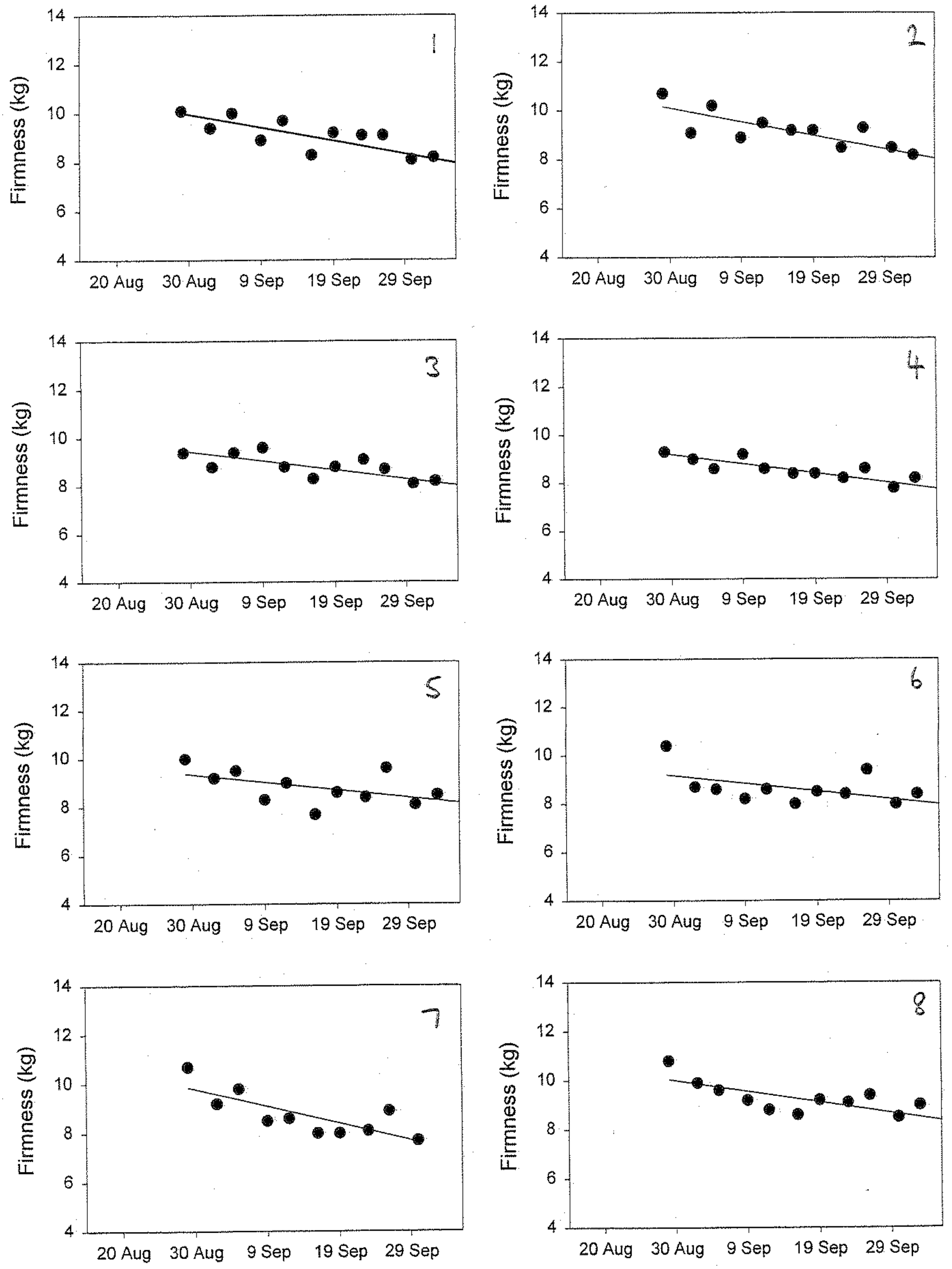


Figure 17. Firmness decline in 1996, orchards 9-16

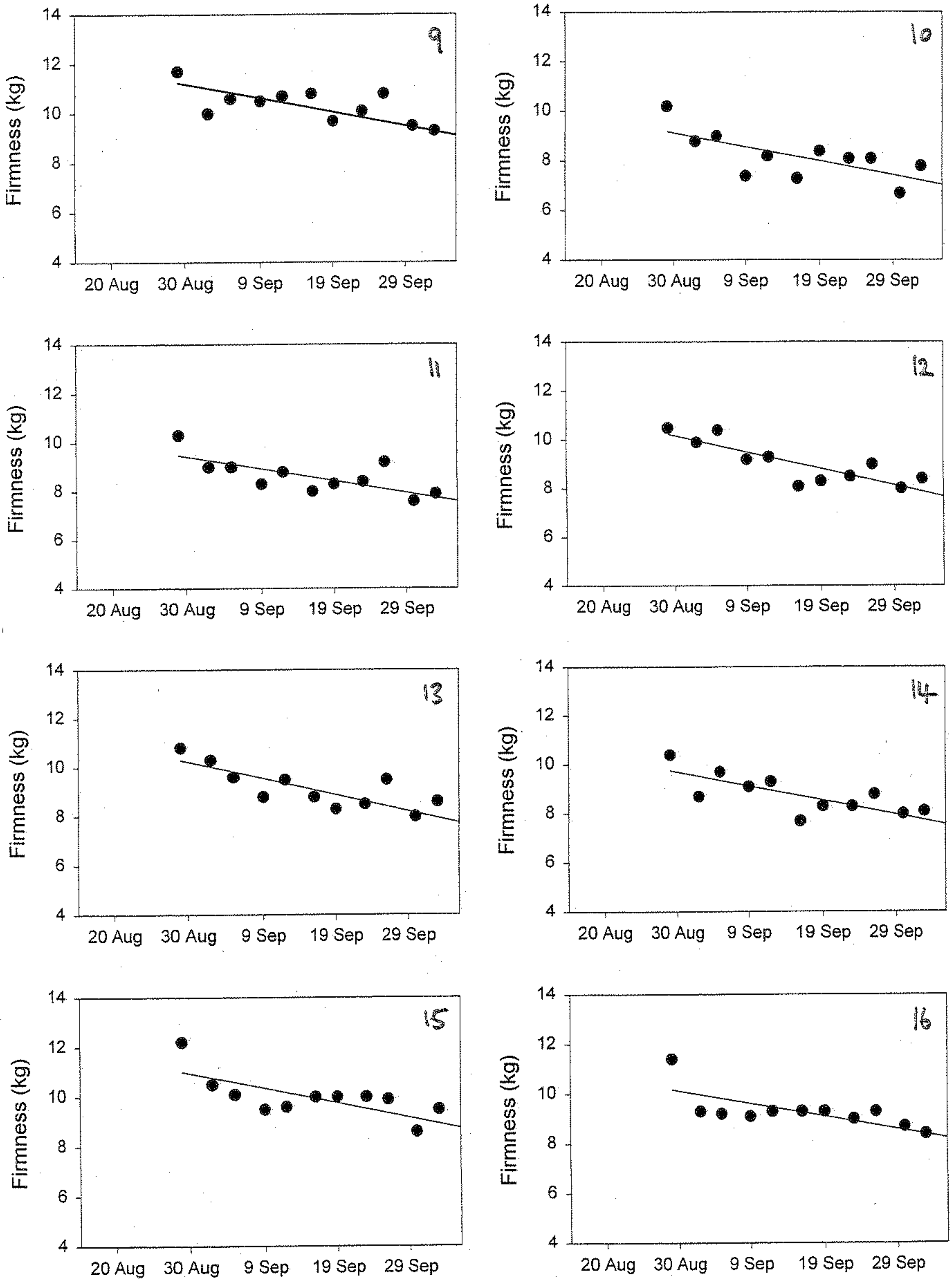


Figure 18. Firmness decline in 1996, orchards 17-24

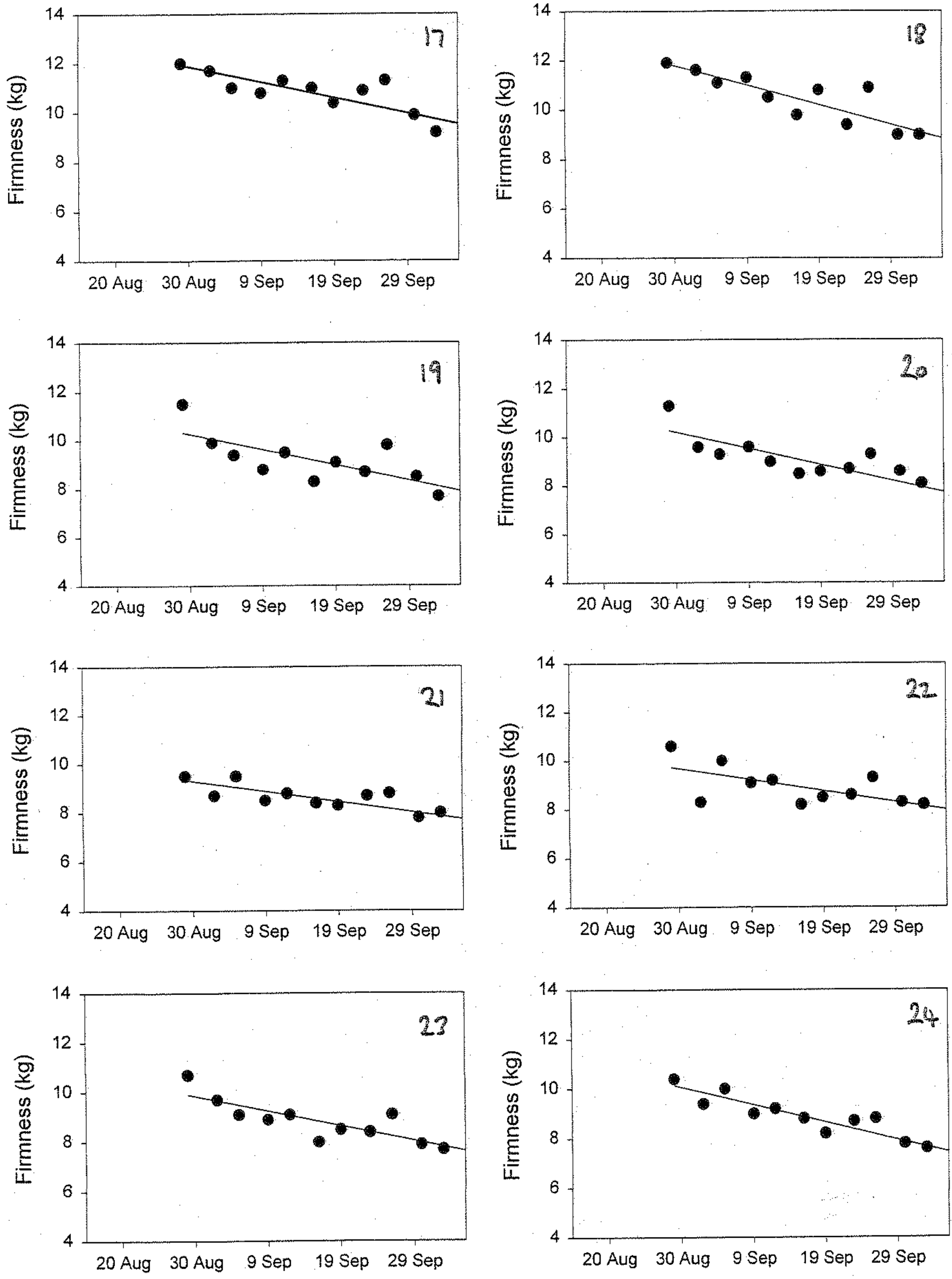


Figure 19. Firmness decline in 1996, orchards 25-31

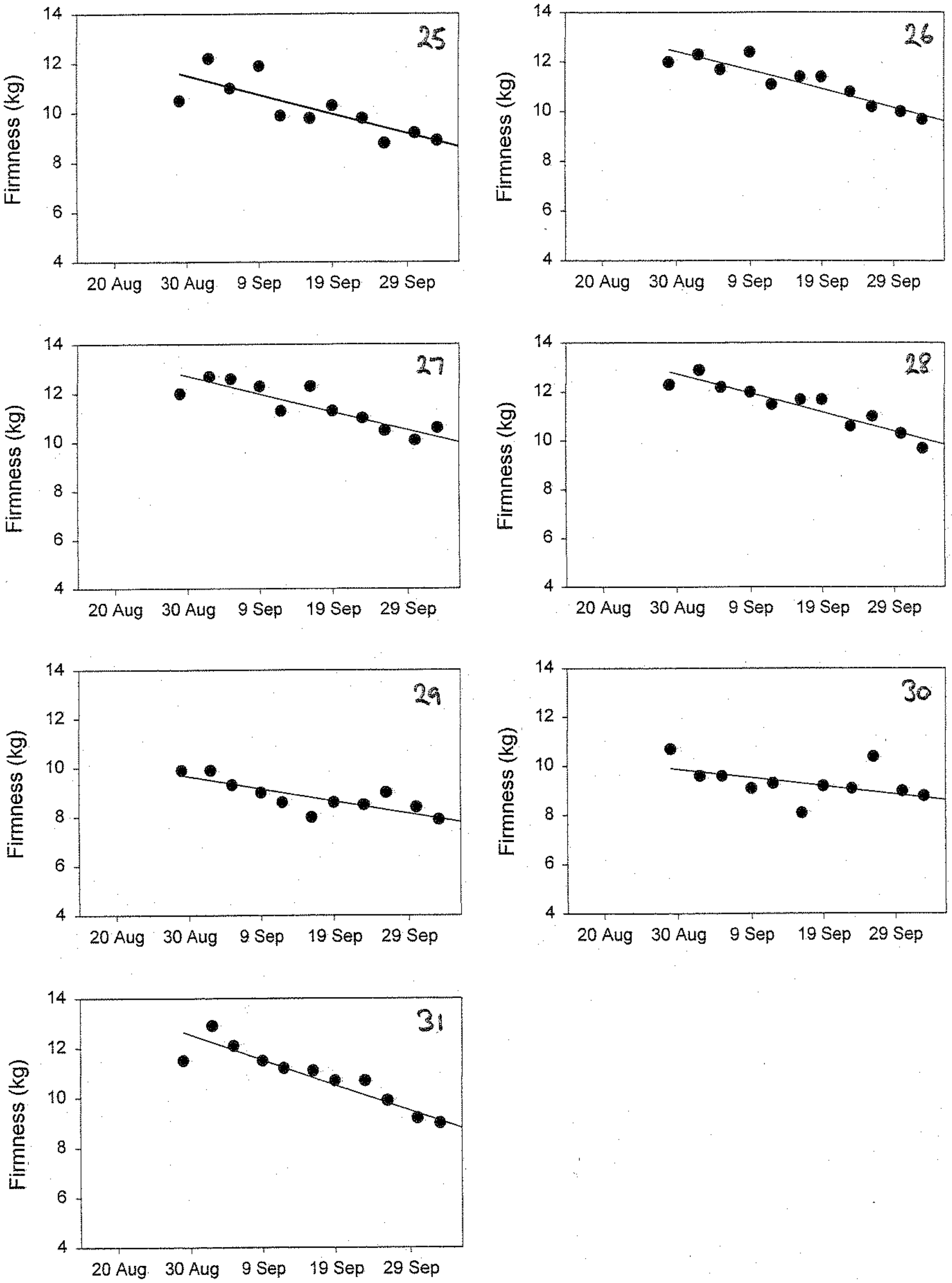
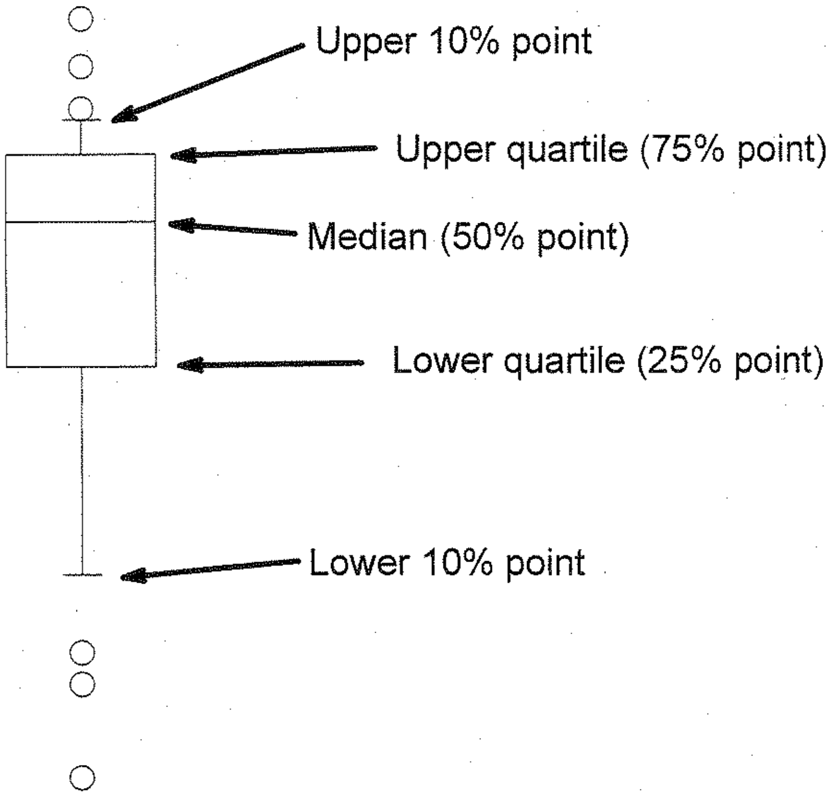


Figure 20. Interpretation of a boxplot



Individual points indicate values in the lower 10% or upper 10% of the distribution

Figure 21. Boxplots of firmness decline (kg week^{-1}) and residual standard deviation from regression (kg)

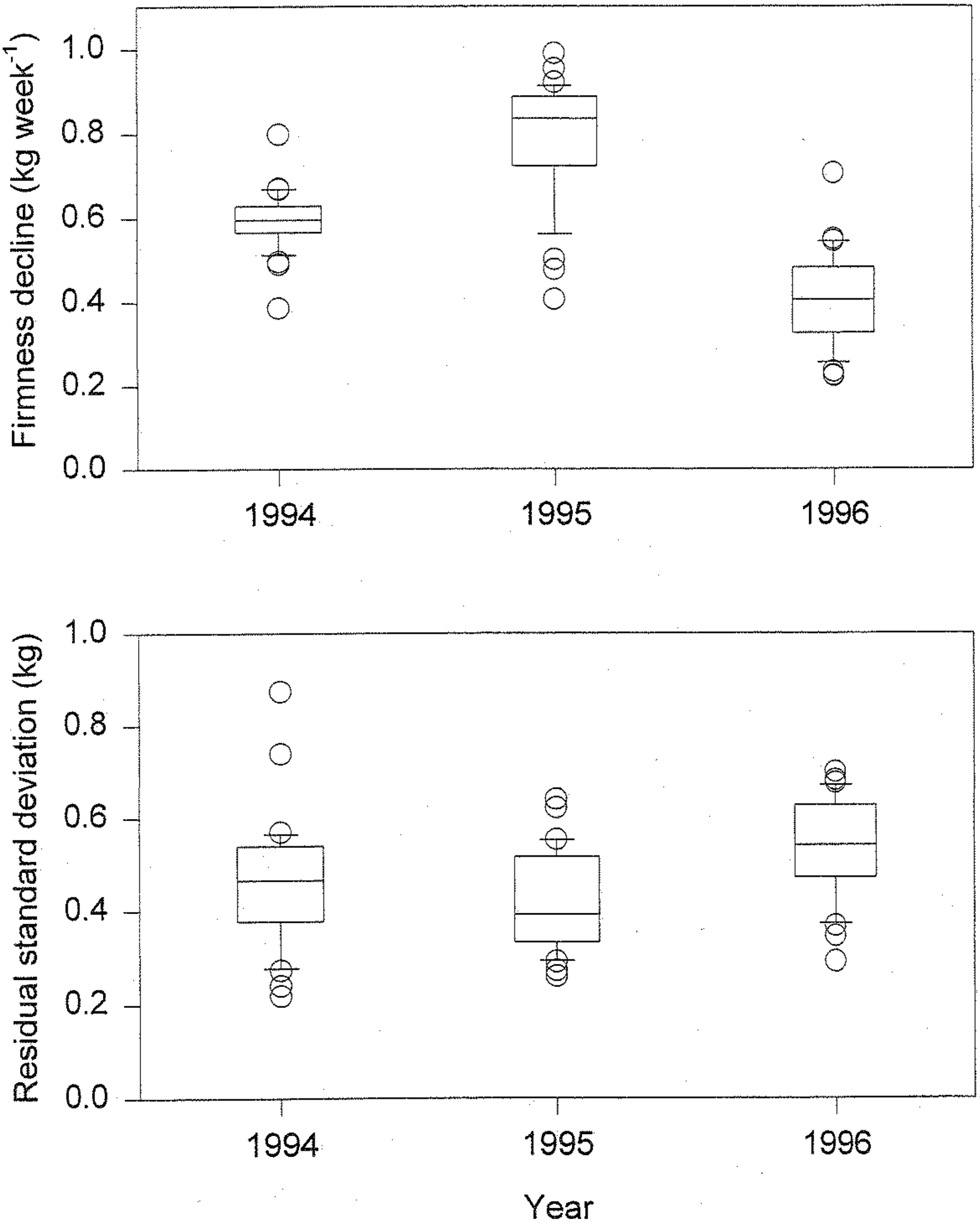


Figure 22. Boxplots of estimated date when firmness of 8.2 kg achieved and of the approximate standard error of this estimate