Effects of Temperature, Light, and Rainfall on Superficial Scald Susceptibility in Apples

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Superficial scald is a disorder of apples (*Malus domestica* Borkh.) and pears (*Pyrus communis* L.) that usually develops only after several months of cold storage, especially upon transfer of these fruit to warm conditions. There is a genetic component to its occurrence, since some cultivars (e.g., 'Gala' and 'Empire') almost never develop the disorder, while others (e.g., 'Granny Smith' and 'Delicious') are very susceptible; many other cultivars lie somewhere between these extremes. Actual development of scald is regulated by postharvest conditions such as temperature, time, and O₂ and CO₂ concentrations in the storage atmosphere. However, what is of importance in this colloquium is that the potential for scald development within a susceptible cultivar is highly variable among years, locations, and harvests, its susceptibility being determined by preharvest environmental conditions and fruit maturity at harvest.

Since the earliest investigations of scald, it has been recognized that, with later harvest (more advanced maturity), fruit generally become less scald-susceptible (e.g., Brooks et al., 1919). In addition, Smock (1953) reported that more scald occurred in years when relatively high temperatures occurred during the 6 weeks preceding harvest. Fidler (1957) viewed the situation differently, observing that lower temperatures during the 6 weeks preceding harvest reduced scald occurrence. In 1961, Merritt et al. provided a quantification, proposing that 10 °C was the orchard temperature below which some protection from scald developed, and that counting preharvest hours below 10 °C might serve as an indicator of scald susceptibility at harvest. Morris (1964) later concluded that 12.8 °C was correlated more closely with scald susceptibility than 10 °C, but recent studies by Blanpied et al. (1991) and Weis et al. (1993) have shown consistently strong correlations between preharvest hours below 10 °C and scald susceptibility.

Light intensity and soil moisture conditions also appear to influence scald susceptibility. The well-recognized facts that scald is much more likely to occur on the shaded portion of a fruit and that poorly colored fruit within a cultivar are more likely to develop scald suggest that high light intensity, which stimulates anthocyanin formation, reduces scald susceptibility, and this was experimentally demonstrated by Barden and Bramlage (1994). The relationship of soil moisture to scald is less clear. Fidler (1957) concluded that greater rainfall near harvest decreased scald susceptibility, but fruit heavily irrigated late in the season appeared to be more scald-susceptible (Brooks et al., 1919; Loetter et al., 1985).

EXPERIMENTAL APPROACH

For nearly 10 years we have collected data at the Univ. of Massachusetts Horticultural Research Center, Belchertown, on the relationships between preharvest environmental conditions and fruit maturity at harvest and development of scald on apples after prolonged cold storage. These studies show consistently strong relationships between preharvest hours below 10 °C and scald occurrence on 'Cortland' and 'Delicious' apples. However, when we examined data from New Zealand for scald on 'Delicious' and 'Granny Smith' apples, this relationship often was not expressed (Bramlage and Watkins, 1994). Furthermore, several colleagues have stated privately that they have

obtained different results from ours when examining data from their growing region. Clearly, a larger and more broadly collected data base was needed to resolve these differences. Thus, we solicited data from colleagues from many global locations to statistically examine the effects of preharvest temperature, light, and rainfall, as well as fruit maturity, on scald susceptibility of apples from a global perspective.

Data were obtained from West Virginia and Washington in the United States, Nova Scotia and British Columbia in Canada, the Elgin and High Noon regions of the Republic of South Africa, and the Otago, Canterbury, Nelson, Hawkes Bay, Waikato, and Auckland districts of New Zealand. Data included various cultivars, but by far the largest data set was for 'Delicious' and only this cultivar will be considered here (Table 1). These data were collected from commercial settings and thus are free from artifacts that might have been created experimentally.

Since this was a retrospective collection of data, they were not obtained under a common protocol. However, in all cases fruit were stored in air near 0 °C for at least 20 weeks and scald was assessed after about 7 days at ≈20 °C. In nearly all locations scald varied from 0% to 100% among fruit lots. Fruit were harvested at various stages of maturity within a year, and data were almost always available for more than 1 year. In most cases hourly preharvest temperature records were available, and, in most cases, fruit maturity was determined at harvest using a starch-iodine test similar to that of Priest and Loughheed (1988), in which advancing maturity is indicated by an increasing score as fruit tissue becomes less stained upon application of an iodine solution.

Less information was available for preharvest rainfall and light conditions. Where available, rainfall was calculated as mean mm per day during a defined period. Light intensity was measured daily at Elgin, R.S.A. as megajoules per m². In Massachusetts light was subjectively scored as 0 = cloudy all day, 1 = fair all day, and 1.5 = partly cloudy, based on U.S. Weather Bureau records from a site near the orchard.

A total of 1186 lots of 'Delicious' apples was evaluated, but the number of samples varied greatly among individual locations (Table 1). Because preharvest information that was available varied among locations and years within a location, differing subsets of these data had to be used as various combinations of variables were considered. Thus, the number of samples (N) included in an analysis is shown in all tables. The most complete sets of data were from Massachusetts and Elgin, R.S.A.

The Tobit Procedure (Tobin, 1958) was used to analyze data, since in over 10% of 'Delicious' fruit lots sampled, no scald developed. This procedure is an Ordinary Least Squares analysis with a limit established beyond which the function is a constant, and here that limit was 0% scald. Multiple regression equations were developed to determine how much variation in scald development could be explained by measured variables. Regression equations for specific geographical locations and for several years in a location were compared using the Chow (1960) Test to determine if the equations differed. SHAZAM statistical software (White et al., 1990) was used to analyze the data. Various transformations of data were performed and compared, but since they had no consistent effects on 'Delicious' results, data presented here were generated without transformations.

RELATIONSHIPS UNDER MASSACHUSETTS CONDITIONS

To provide a point for reference, we first evaluated the relationships among preharvest conditions and scald development on 'Delicious' apples in Massachusetts.

For interpreting results of the regression equations generated, it is

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Table 1. Data points available for globally relating preharvest environmental conditions and fruit maturity at harvest (starch scores) to scald development on 'Delicious' apples.

Location ²	No. of years	Total fruit lots	Number of lots where data include:			
			Hourly temp.	Starch scores	Rainfall	Light
Can, British Columbia	3	213	213	213	0	0
NZ, Hawkes Bay	4	30	7	20	20	0
Nelson	3	27	27	19	19	0
Canterbury	1	9	9	9	0	0
Otago	2	18	0	18	18	0
RSA, Elgin	4	290	290	250	230	230
High Noon	3	72	72	0	0	0
USA, Massachusetts	8	344	252	273	261	273
Washington	5	145	0	145	0	0
West Virginia	8	38	38	0	0	0
Total	41	1186	908	947	548	503

²Can = Canada; NZ = New Zealand; RSA = Republic of South Africa.

essential to recognize the high degree of correlation that existed among the "independent" preharvest variables. For the simple correlations among a representative set of the variables that we examined, it is immediately apparent that nearly all variables were strongly interconnected with each other (Table 2). Consider harvest date, which was the number of days from 3 Aug. to harvest of a lot of fruit. It was negatively correlated with scald, as expected, but also was strongly correlated with every other variable. This should be no surprise since, as harvest date was delayed, mean temperature generally fell because it was autumn, so harvest date and average temperatures were negatively correlated. Harvest date was positively correlated with days above 30 °C because with longer time there was more opportunity for a high-temperature event to occur, even though it was autumn. Also, under Massachusetts conditions, mean rainfall increased with later harvest, but so did the number of sunny days, indicating that October typically includes alternating heavy rains and sunny days. However, these relationships may be unique to this geographical area, and different correlations existed in other geographical regions. Differing weather patterns cause these variables to "fit together" differently, which altered their relationships to scald, depending on geographical location.

The high degree of correlation among variables makes it impossible to accurately quantify the contributions of individual variables through regression analyses, since the contribution of one variable is confounded with the contributions of others with which it is correlated. The order in which variables are placed in a series of stepwise multiple regression equations can greatly influence the results; the later a variable is included, the more of its effect likely will have been removed through interactions with preceding variables. Therefore, these equations only will portray the amount of variation accounted for through the additional measurement of a given variable. Nevertheless, if the contribution is significant, this is evidence that the variable played a significant role in scald susceptibility, and the greater the contribution, the greater the probable role of that variable. However, if an independent variable that is correlated with one or more other independent variables in an equation is not statistically significant, this does not mean it is not related to scald susceptibility; its contribution may be masked by a correlated variable.

In Massachusetts, preharvest temperature apparently was a major factor in scald susceptibility of 'Delicious' apples (Table 3). Average temperature from 3 Aug. to harvest was positively correlated with scald development and accounted for 16% ($R^2 = 0.16$) of its variation. However, specific low-temperature events appeared to be much more important. As number of days below 6 °C, 8 °C, or 10 °C increased, scald susceptibility decreased at a rate about equal among these temperature limits, but 12 °C apparently was not cold enough to produce this effect efficiently, since days below 12 °C accounted for far less of the variation. (It should be noted that, in earlier, unpublished analyses, we found that *days* when temperature fell below a certain temperature was more useful than *hours* below that temperature. "Hours" have been used extensively since the report of Merritt et al. in 1961.) These results suggest that, when temperature fell below 10 °C, something happened in the fruit that reduced scald susceptibility, and

Table 2. Simple correlation coefficients among some variables related to scald development on 'Delicious' apples in Massachusetts during 8 years. N = 344.

Variable	Harvest date ²	Percent scald	Days ≤10 °C	Days ≥30 °C	Average temperature	Rainfall
Pct. scald	-0.76					
Days ≤10 °C	+0.86	-0.67				
Days ≥30 °C	+0.33	-0.53	+0.13			
Avg. temp. ³	-0.66	+0.41	-0.85	+0.35		
Rainfall ⁴	+0.34	-0.29	+0.39	-0.02	-0.49	
Sun ⁵	+0.27	-0.31	+0.07	+0.76	+0.38	-0.22

²Number of days from 3 Aug. to harvest date.

³Mean temperature from 3 Aug. to harvest.

⁴Mean daily rainfall (mm-day⁻¹) for period from 24 Aug. to harvest.

⁵Mean sunshine score from 1 Sept. to harvest.

it made little difference if temperature fell lower or how many hours per day this condition lasted.

Measuring fruit maturity (as starch score) at harvest accounted for little scald variation beyond that of temperature, except when days below 12 °C was the low-temperature variable (Table 3). This result shows that, in this location, the change in maturity of 'Delicious' is consistently related to increasing number of days below 10 °C, and "days below 10 °C" already had accounted for most of the maturity effect. Including rainfall after late August in regression equations significantly increased R^2 values in most cases, and it was negatively correlated with scald. Including sunshine from late August did not increase R^2 values very much except in the "days below 12 °C" equation, where it, too, was negatively correlated with scald.

These results demonstrate that under multiyear commercial conditions in Massachusetts, low temperature, maturation, late-season rainfall, and late-season sunshine probably all contributed to reduction in scald susceptibility of 'Delicious' apples. Among these, an increasing number of days when temperature fell below 10 °C appeared to have the greatest individual impact; but, collectively, these variables accounted for 56% to 64% of variation in scald development among lots of fruit, harvest date, and years.

THE GLOBAL PERSPECTIVE

When all of the available data were evaluated, a high degree of correlation existed among variables (data not shown), as it did in Massachusetts (Table 2). Another highly important point was displayed when all 1186 fruit lots were used to generate equations of the form: Pct scald = $B_0 + B_1$ (days after), where B_0 is a constant, B_1 is a coefficient, and "days after" indicates the number of days from 10 Jan. (southern hemisphere) or 12 Aug. (northern hemisphere) to fruit harvest. When neither B_0 nor B_1 was allowed to vary by location, $R^2 = 0.22$. When B_0 but not B_1 , or B_1 but not B_0 , was allowed to vary by location, $R^2 = 0.32$ and 0.29, respectively. When both B_0 and B_1 were allowed to vary by location, $R^2 = 0.49$. Not only were these R^2 values significantly different, but Chow's Test (Chow, 1960) showed that the equations were significantly different from each other. Thus, there was

no single equation to represent variations in scald susceptibility: the influence of variables differed with location, and, for maximum information, separate equations needed to be generated in which all B values were allowed to vary by location. Similar tests showed also that, within a location, equations significantly differed among years, and, where indicated, coefficients have been allowed to vary among years

Table 3. Contributions (R^2) of some preharvest variables and maturity of fruit at harvest (starch score) to variation in scald susceptibility of Massachusetts 'Delicious' apples during 6 years. Equations are of the form: Pct. scald = B_0 (a constant) + B_1 (avg. temp.) + ... + B_5 (sunshine). N = 273. Coefficients were not allowed to vary with year.

Independent variable	Days below ^z			
	6 °C	8 °C	10 °C	12 °C
	R^2			
Average temp. ^y	0.16	0.16	0.16	0.16
Plus days below ^z	0.53	0.50	0.47	0.25
Plus starch score	0.55	0.51	0.51	0.33
Plus rainfall ^x	0.62	0.55	0.56	0.34
Plus sunshine ^w	0.64	0.56	0.56	0.58

^zNumber of preharvest days in which temperature was at or below temperature indicated.

^yMean temperature between 3 Aug. and harvest.

^xMean daily rainfall (mm-day⁻¹) from 24 Aug. to harvest.

^wMean sunshine score from 1 Sept. to harvest.

Table 4. Contributions (R^2) of average preharvest temperature and fruit maturity at harvest (starch score) to variations in scald susceptibility of 'Delicious' apples globally. Equations are of the form: Pct. scald = B_0 (a constant) + B_1 (avg. temp.) + B_2 (starch score). Coefficients were allowed to vary with year.

Location ^z	No. of years	N	Average temp. ^y	Plus starch score
				R^2
Can, British Columbia	3	213	0.34	0.45
NZ, Hawkes Bay	3	20	0.88	0.96
Nelson	2	19	0.63	0.64
RSA, Elgin	4	250	0.65	0.89
High Noon	3	72	0.58	---
USA, West Virginia	5	33	0.70	---

^zCan = Canada; NZ = New Zealand; RSA = Republic of South Africa.

^yMean temperature between 3 Aug. (northern hemisphere) or 1 Jan. (southern hemisphere) and harvest.

Table 5. Contributions (R^2) of preharvest temperatures to variations in scald susceptibility of 'Delicious' apples globally. Equations are of the form: Pct. scald = B_0 (a constant) + B_1 (avg. temp.) + B_2 (days below x) + B_3 (days above 25 °C). All coefficients were allowed to vary with year.

Location ^y	N	Variables	Days below ^z			
			6 °C	8 °C	10 °C	12 °C
			R^2			
Can, British Columbia	213	Avg. temp. ^x	0.34	0.34	0.34	0.34
		+ Days below ^z	0.45	0.44	0.49	0.47
		+ Days above 25 °C ^w	0.48	0.47	0.52	0.48
NZ, Hawkes Bay	7	Avg. temp. ^x	0.82	0.82	0.82	0.82
		+ Days below ^z	---	0.92	0.91	0.90
		+ Days above 25 °C ^w	---	0.93	0.92	0.94
Nelson	27	Avg. temp. ^x	0.70	0.70	0.70	0.70
		+ Days below ^z	0.85	0.86	0.87	0.72
		+ Days above 25 °C ^w	0.89	0.91	0.92	0.87
RSA, Elgin	290	Avg. temp. ^x	0.67	0.67	0.67	0.67
		+ Days below ^z	---	0.86	0.86	0.83
		+ Days above 25 °C ^w	---	0.87	0.87	0.84
High Noon	72	Avg. temp. ^x	0.58	0.58	0.58	0.58
		+ Days below ^z	---	---	0.76	0.78
		+ Days above 25 °C ^w	---	---	0.80	0.80
USA, West Virginia	38	Avg. temp. ^x	0.70	0.70	0.70	0.70
		+ Days below ^z	0.80	0.85	0.85	0.87
		+ Days above 25 °C ^w	0.92	0.92	0.92	0.91

^zNumber of days at or below 6 °C, 8 °C, 10 °C, or 12 °C from 3 Aug. (northern hemisphere) or 1 Jan. (southern hemisphere) to harvest.

^yCan = Canada; NZ = New Zealand; RSA = Republic of South Africa.

^xMean temperature from 3 Aug. (northern hemisphere) or 1 Jan. (southern hemisphere) to harvest.

^wNumber of days with recorded temperature above 25 °C during the week before harvest.

within a location in these data.

Globally, within a year, average temperature from 1 Jan. (southern hemisphere) or 3 Aug. (northern hemisphere) accounted for much more scald variation than it did in Massachusetts (Table 4 vs. Table 3), being positively correlated with percent scald. Furthermore, maturity measurement, expressed as starch score, usually substantially increased the amount of variance being accounted for (Table 4). When low-temperature events were taken into account, days below 6 °C, 8 °C, or 10 °C invariably increased the R^2 values significantly over average temperature alone (Table 5). However, in no other location was the impact as great as in Massachusetts (Table 5 vs. Table 3), and days below 12 °C usually was as effective as days below 10 °C or lower, in contrast to Massachusetts conditions. To test the effect of high-temperature events on scald susceptibility, number of days during the week immediately preceding harvest in which the temperature rose above 25 °C was inserted as a variable in the equations. In British Columbia, Hawkes Bay, NZ, and Elgin, RSA, it added little to variance already accounted for by average temperature and low-temperature events, but in Nelson, NZ and High Noon, RSA, it was significantly and positively correlated with scald occurrence. West Virginia had the highest mean temperature among sites in this study (data not shown), and there "days above 25 °C" substantially increased R^2 values. Thus, high-temperature events apparently can increase scald susceptibility just as low-temperature events apparently can decrease it. Perhaps the most striking feature in Table 5 is that various temperature criteria accounted for at least 80% of variability in scald susceptibility in five of the six locations.

Elgin, RSA, was the only location other than Massachusetts in which data were available for all variables under consideration (Table 1). Average temperature, low-temperature events, maturity, rainfall, and sunshine variables were placed in stepwise multiple regression equations in that order (Table 6). Note that the effect of average temperature was far less than that shown for Elgin in Table 5. This difference exists because the coefficients in the equations in Table 5 were allowed to vary by year, while those in Table 6 were not. Because large year-to-year variation in scald development existed unaccompanied by corresponding variation in average preharvest temperatures, low-temperature events did not account for much variation in this data set, the strongest factor being maturity. Late-season rainfall contributed significantly to R^2 when days below 10 °C were not counted. However, in no equation did differences in late-season sunshine account for more than 2% of additional variation. As with the Massachusetts data (Table 3), these results suggest that increasing late-

Table 6. Contributions (R^2) of some preharvest variables and maturity of fruit at harvest (starch scores) to variations in scald susceptibility of 'Delicious' apples in Elgin, R.S.A. Equations are of the form: Pct. scald = B_0 (a constant) + B_1 (avg. temp.) + ... + B_5 (sun). $N = 230$. Coefficients were not allowed to vary with year.

Independent variable	Days below ^z		
	8 °C	10 °C	12 °C
	R^2		
Avg. temp. ^y	0.11	0.11	0.11
Plus days below ^z	0.20	0.22	0.11
Plus starch score	0.71	0.83	0.58
Plus rain ^x	0.72	0.83	0.69
Plus sun ^w	0.74	0.85	0.71

^zNumber of days at or below 8 °C, 10 °C, or 12 °C from 1 Jan. to harvest.

^yMean temperature between 1 Jan. and harvest.

^xMean daily rainfall (mm) between 22 Jan. and harvest.

^wMean light intensity ($MJ \cdot m^{-2}$) between 1 Feb. and harvest.

season rainfall and sunshine can reduce scald susceptibility, but the effects either are not large or are obscured by correlation with other preharvest variables.

CONCLUSIONS

These globally derived results demonstrate that increasing amounts of preharvest low temperature, rainfall, and sunshine, as well as advancing fruit maturity, do contribute to reduction of scald susceptibility of 'Delicious' apples under commercial conditions, while late-season high temperatures increase their susceptibility. However, a high degree of correlation among these variables makes it difficult to quantify their individual effects. Furthermore, their relationships to scald varied among geographical locations as well as within years in a location, showing that the ways in which these variables happen to coincide over time influence their impacts on scald susceptibility.

It appears that low-temperature and high-temperature events (days in which temperature falls below or rises above a certain temperature) have specific effects in reducing and increasing, respectively, scald susceptibility. It is not clear whether the critical low temperature is 10 °C or 12 °C, since results varied among locations, but little extra benefit was gained from a fall to 8 °C or 6 °C. Since "hours below" was a less effective criterion than "days below," the length of time at a low temperature probably was less important than the frequency of these events. Only "days above 25 °C" was tested as a high-temperature event here due to limited amounts of data; thus 25 °C may not be the optimum high-temperature reference point.

Our long-term objective in initiating this study was to determine whether or not scald can be predicted at harvest time, to facilitate decision-making regarding the appropriate postharvest scald-control measures needed. It is obvious from these findings that any successful scald-prediction equation will have to be generated from data gathered

within a specific geographical area, since prevailing weather patterns affect the interactions among variables in determining scald susceptibility. Data not presented here show that prediction equations also vary with cultivar, probably due to genetic differences and the fact that they mature at different times and, therefore, under diverse combinations of environmental conditions. Nevertheless, the equations developed here accounted for the great proportion of scald variation among fruit lots within a location; temperature and maturity, two easily measurable variables, appeared to account for most of this variation. Therefore, one can remain optimistic that a successful scald-prediction equation is an achievable goal if the objective is to characterize broad categories, e.g., very susceptible, moderately susceptible, and not very susceptible fruit, and the user recognizes that some risk is involved in following the predictions.

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