Postharvest Biology and Technology 201 (2023) 112344

Contents lists available at ScienceDirect

Postharvest Biology and Technology

journal homepage: www.elsevier.com/locate/postharvbio

Multiple factors affecting occurrence of soft scald and fungal decay in apple during storage

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ARTICLE INFO

Keywords:
Soft scald
Disorder
Fungal decay
Fruit
Gradual cooling
Maturity

ABSTRACT

Some apple cultivars are highly susceptible to soft scald, a physiological disorder that can lead to large losses. The effect of harvest time, gradual cooling regimes and storage conditions on soft scald and fungal decay was investigated in two common apple cultivars, 'Aroma' and 'Frida' in a three year trial 2018–2020. Further, possible relationships between weather conditions during the growing season and 28 d before harvest and soft scald incidence along with fungal decay after storage were studied. The year with the highest rainfall had the highest incidence of soft scald and fungal decay. Our results suggest that the relative humidity during a period of 28 d before harvest was important for later development of soft scald in 'Frida', and together the results from 'Frida' and 'Aroma' showed a moderate correlation between relative humidity and soft scald. Gradual cooling showed conflicting results, and no treatment consistently lowered soft scald incidence. Gradual cooling led to inconclusive results, and storage in ambient air led to higher incidence of soft scald as compared to some investigated ULO storage conditions. Advanced maturity was associated with soft scald development and more fungal decay in one out of three years in 'Aroma', but did not affect incidence in 'Frida'. The etiology of soft scald seems to be dependent of multiple factors.

1. Introduction

Lately there has been an increased focus on reducing food loss and waste along the food chain. Losses occur all along the food chain and can be considerable also in the primary production (Gustavsson et al., 2011). In apple storage, as much as 10% of the fruit can be lost due to physiological disorders, and much more due to fungal decay. This is both an environmental and economic problem as many resources have been put into growing and storing fruit (Tahir, 2014).

Soft scald can cause substantial losses during storage of apples, and in severe cases up to 30% of the stored fruit can be lost (DeLong et al., 2004; Watkins et al., 2004). Affected fruit develops band-like browning of the upper part of the skin and flesh of the fruit. The disorder is considered to be a chilling injury where tissue affected by soft scald is clearly discernable from unaffected tissue and prone to fungal attack (Brooks and Harley, 1934; DeEll and Ehsani-Moghaddam, 2010). It is not clear exactly how and why the disorder develops, though it is most likely a form of metabolic disturbance, as ethylene blockers such as 1-MCP and controlled atmosphere storage may decrease incidence (Blankenship and Dole, 2003; DeLong et al., 2006; Fan and Mattheis, 1999; Watkins et al., 2004). Genes associated with stress reactions have been found to be upregulated in fruit affected by soft scald (Leisso et al., 2016). Further, changes in acetaldehyde and ethanol metabolism, as well as altered composition of fatty acids, have also been found in fruit affected by soft scald (Al Shoffe et al., 2018; Hopkirk and Wills, 1981). Despite the lack of knowledge of the mechanisms behind the occurrence of soft scald, some methods to decrease incidence have been suggested, although effectiveness seems to be varying with e.g. year and orchard location (Moran et al., 2009; Moran et al., 2010; Watkins et al., 2004).

Many factors both before and during storage seem to affect the incidence of soft scald. Some apple cultivars are more prone to develop soft scald than others (Leisso et al., 2016). Thus, there seems to be a genetic factor controlling soft scald susceptibility. Storage conditions can also trigger development of soft scald, since low storage temperatures have been suggested to lead to higher levels of soft scald, while a gradual cooling of the fruit may reduce the risk (Watkins et al., 2005;

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https://doi.org/10.1016/j.postharvbio.2023.112344
Received 8 December 2022; Received in revised form 17 February 2023; Accepted 28 March 2023
Available online 1 April 2023
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Watkins et al., 2004). Preharvest conditions like weather and mineral content of the fruit are other factors suggested to be involved in soft scald development (Al Shoffe et al., 2020; Lachapelle et al., 2013; Tong et al., 2003). Fruit affected by soft scald have been shown to contain higher levels of phosphorus, boron and magnesium, while manganese levels were lower than in unaffected fruit (Tong et al., 2003). Wet conditions after full bloom until the flowers were 0.01 m in diameter, cool conditions early in development of the fruit, and warm weather late in fruit development have all been suggested to increase soft scald incidence (Lachapelle et al., 2013). Late harvest was found to increase risk of soft scald (Watkins et al., 2005). Thus, multiple factors, or a combination of factors, seem to be able to induce the incidence of soft scald, though what physiological reactions in the fruit that are triggered still remain to be understood.

While attempting to minimize soft scald incidence, effects on other storage disorders and diseases have to be monitored. 'Frida' and 'Aroma' are two cultivars that are common and commercially important in the Nordic countries (Tahir et al., 2014). As for other common cultivars in this area, under Nordic conditions the most common storage diseases are caused by *Neofabraea spp*, *Colletotrichum spp.*, *Penicillium expansum, Botrytis cinerea* and *Monilinia spp.* (Maxin et al., 2012; Tahir, 2014).

A reduction of soft scald incidence as well as fungal decay is one of the main objectives of apple producers (Ishangulyyev et al., 2019). However, to reduce the losses due to soft scald, a better understanding of the factors inducing this disorder is needed. It has been shown that different atmospheric conditions affect fungal decay (Tahir, II, Nybom, 2013). Delayed CA (holding in cold ambient air before CA) has been reported previously (DeEll et al., 2016). Therefore, in this investigation the effects of storage conditions on both soft scald and fungal decay were studied simultaneously.

The aim of the present study was to evaluate how possible relationships between weather conditions during the season, from full bloom to harvest, affect soft scald incidence, fungal decay and fruit quality. Further, the investigation also aimed to assess how maturity level at harvest influence the incidence of soft scald as well as storage diseases and other disorders. In addition, the effects of gradual cooling and storage atmosphere on soft scald incidence, fungal decay and fruit quality were investigated.

2. Material and methods

The investigation was performed on fruit harvested in commercial apple orchards in Scania in the southern part of Sweden and were subjected to standard fertilization and IPM (Integrated Pest Management) practice with pesticide applications during the growing season. Before harvest, fruit was treated with fungicides (boscalid + pyraclostrobin, withdrawal period 7 days) to reduce storage diseases. According to commercial practice in Sweden, there were no postharvest treatments with fungicides. Fruit was harvested at different occasions, subjected to different cooling conditions as described in Table 1, and stored in either ULO (ultra-low oxygen), CA (controlled atmosphere) storage or in ambient air storage. Effects of weather conditions during the growing period on fruit storability were also examined. The cultivar 'Aroma' was harvested in 2018, 2019 and 2020 in western Scania at the same orchards and blocks (55°43'26.6"N 13°05'52.8"E), and 'Frida' in 2019 and 2020 in eastern Scania at the same orchard and blocks both years (55°37'35.6"N 14°16'21.9"E). Both cultivars were grown according to modern practices in commercial orchards. For each cultivar 20 trees were chosen that were between 8 and 20 years old at the start of the trial, 'Aroma' apples were on M9 rootstock while 'Frida' was on an unknown rootstock Table 2.

Table 1
Storage conditions for 'Aroma' and 'Frida'. 'Aroma' was exposed to all storage conditions while 'Frida' was stored either in ambient atmosphere or "ULO1".

	ULO1	ULO2	ULO3	CA	Ambient atmosphere
O_2 (kPa)	1	1	1	2	21
CO_2 (kPa)	1	2	3	2	0.04
Temperature, °C	2	2	2	2	2
Relative humidity	95 (%)	95 (%)	95 (%)	95 (%)	95 (%)

2.1. Harvest time, gradual cooling and storage conditions

Each year, fruit was harvested at three occasions, and the second harvest represented commercial maturity stage for harvest, determined by a combination of Streif index and days after full bloom (DAFB). Streif index was calculated as:

Firmness (kg cm $^{-2}$)* [SSC (%) * Starch degradation stage]$^{-1}$. (Streif, 1996).

A lot of 450 'Aroma' or 'Frida' apples were picked at each occasion, and divided into three groups with 150 fruit in each (Fig. 1). The first group was kept in ambient atmosphere at 10 °C for 5 d, then at 4 °C for 5 d (gradual cooling). 'Aroma' was then divided into five subgroups and stored in experimental equipment for fruit storage (CO_2 incubator, model 3141, Thermo, Marietta, OH, USA), at 2 °C under five different conditions (ULO, CA or ambient air) as shown in Table 1. The second group was kept at 2 °C in ambient atmosphere for 10 d, divided into five subgroups and stored in five different storage chambers as described above. The third group was directly after harvest divided into five subgroups, which were stored in the five storage chambers (Table 1) without any initial cooling. 'Frida' was subjected to the same gradual cooling as 'Aroma', however, after storage the fruit was stored either at a commercial fruit producer in ULO conditions (1 kPa O_2, 1 kPA CO_2, 2 °C) or in ambient atmosphere.

After 2 months 'Aroma' apples from all storage conditions were assessed for soft scald and other physiological disorders, as well as fungal decay. Fungal decay, soft scald and other physiological disorders were recorded as either present or absent for each fruit (Leisso et al., 2019). Soft scald was identified according to the instructions in Hanrahan and McFerson (2014). As "Frida" apples were stored in a commercial storage facility we could not control when the storage room was opened. However, it was opened after five months storage each year with a variation within one week. Apples affected by pathogen rots or physiological disorders were removed. Of the healthy fruit, nine per treatment were subjected to quality tests. Firmness, measured by a penetrometer (Model FT 327; Effigy, Italy; plunger diameter of 11.1 *10^{-3} m, depth of 7.9 *10^{-3} m), was assessed on both the sunny and the shaded side of the fruit and an average was calculated. Soluble solid concentration (SSC) was measured by a digital refractometer (RFM80, Bellingham + Stanley, Tunbridge Wells, UK). The color of the apples were measured by a colorimeter (Minolta Ltd., Osaka, Japan) and a color index (CI) was calculated as (a*1000)(L*b)$^{-1}$ (López Camelo and Gómez, 2004). The measurements were repeated twice in 2018, i.e. after an additional two months, and then again after another month, and after that the experiment was terminated after a final recording of soft scald, fungal decay and quality parameters. In 2019 and 2020 the measurements were repeated once.

When the ULO storage room was opened after five months of storage, the 'Frida' apples, both in the ULO storage and in the ambient atmosphere, were assessed for physiological disorders and fungal decay, and nine healthy apples from each treatment were subjected to the same quality tests as described above for 'Aroma'.

2.2. Weather conditions

Solar radiation (MJ*m^{-2}), rainfall (L*m^{-2}), relative humidity, average daily temperature, daily highest temperature, and daily lowest temperature (°C) were recorded through the growing season, using weather stations (Vantage Pro, Davis, USA) located in the orchards. The time period 28 d before harvest was used for statistical analysis in

Table 2
Weather conditions during the whole growing season for 'Aroma' and 'Frida'. All values are average values calculated from daily measurements by weather stations located in the orchards.

	Year	Harvest	Average temperature °C	Maximum temperature °C	Minimum temperature °C	Relative humidity %	Season rainfall L*m^{-2}
Aroma	2018	H1	19.3	25.0	13.2	73.1	100
		H2	19.2	24.7	13.2	73.8	125
		H3	19.0	24.5	13.2	74.8	139
	2019	H1	16.5	21.2	11.9	80.1	207
		H2	16.6	21.3	11.9	80.3	219
		H3	16.5	21.1	12.0	80.8	287
	2020	H1	16.2	21.1	11.2	75.6	152
		H2	16.1	21.0	11.2	75.9	154
		H3	16.1	20.9	11.3	76.2	157
Frida	2019	H1	16.3	20.4	12.3	85.0	201
		H2	16.1	20.1	12.2	85.4	202
		H3	15.8	19.8	12.0	85.8	202
	2020	H1	15.3	20.0	11.0	79.5	151
		H2	15.3	19.9	11.0	79.5	169
		H3	15.3	20.0	11.0	79.4	171

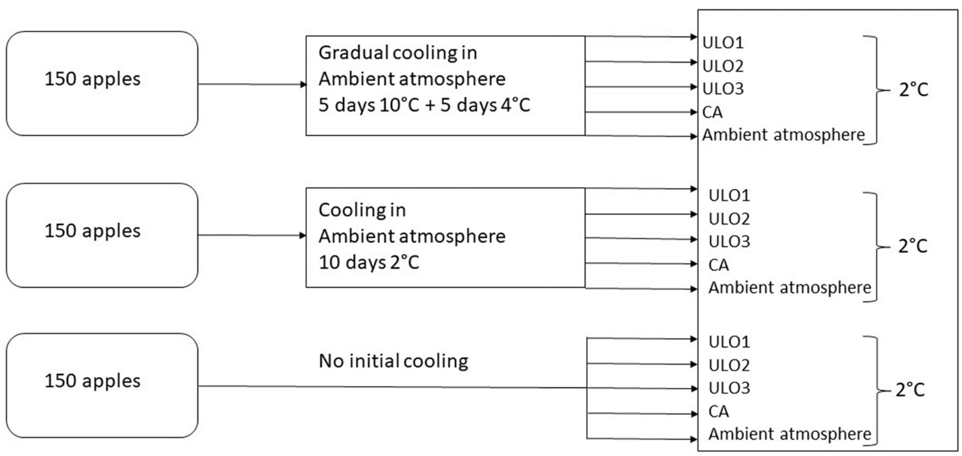

Fig. 1. Storage regime for 'Aroma' during the seasons 2018, 2019, and 2020 for one harvest occasion. This was repeated three times each year (i.e. three harvest occasions). The second occasion represented commercial harvest time.

accordance with previous investigations of weather conditions and their link to soft scald (Moran et al., 2009). Weather conditions were recorded every minute by the weather stations. In addition, weather parameters during the whole growing season (from full bloom to harvest) were summarized.

2.3. Statistics

Statistical analyses were performed using Minitab software v 18.1 (Minitab, Inc., USA). Effects of harvest date, gradual cooling and storage atmosphere, respectively, on soft scald and fungal decay were calculated using Friedman's test with significance level 0.05 followed by pairwise tests if Friedman's test showed a significant difference. Each variable was considered separately, and the blocks were formed by combining observations with the same treatment levels for the two variables that for the two variables that were not the response in the test. For each type of weather observation, the data was merged for all days during 28 d, 21 d, 14 d, and 7 d before harvest and then correlation with soft scald incidence was calculated. The data for 2018, 2019 and 2020 was combined for 'Aroma', and 2019 and 2020 was combined for 'Frida' for correlation calculations for each variety. Lastly, the data for the two varieties and all years was also pooled and correlations were calculated the same way as above for the two varieties combined.

3. Results

3.1. Maturity at harvest

In 'Aroma', the levels of soft scald and fungal decay were higher in 2019, than in 2018 and 2020 (Figs. 2 and 3). Harvest date had no significant effect on neither soft scald incidence nor fungal decay in 2018, and only minor effect in 2020. In 2019, at the latest harvest both soft scald and fungal decay showed the highest frequency as compared with the first harvest, and the first harvest showed the lowest incidence of fungal decay. Streif index values for the harvested fruit are available in the supplemental material (Table 12).

In 'Frida' harvest date had no effect on soft scald incidence in any of the investigated years 2019 and 2020, and the same was the case in 'Frida' concerning fungal decay.

3.2. Weather conditions affecting soft scald

The weather conditions were very variable between the years. For 'Aroma' in 2018 temperatures were high with average maximum temperatures between 24.5 and 25 °C compared to 2019 (21.1–21.3 °C) and 2020 (20.9–21.1 °C) (Table2). Daily average temperature and average daily minimum temperature followed the same trend with higher numbers in 2018 than the other two years. 2019 stands out as a rainy (207–287 L*m^{-2}) and humid year (80.1–80.8% relative humidity) while the other years had between 100 and 157 L*m^{-2} rainfall. Relative

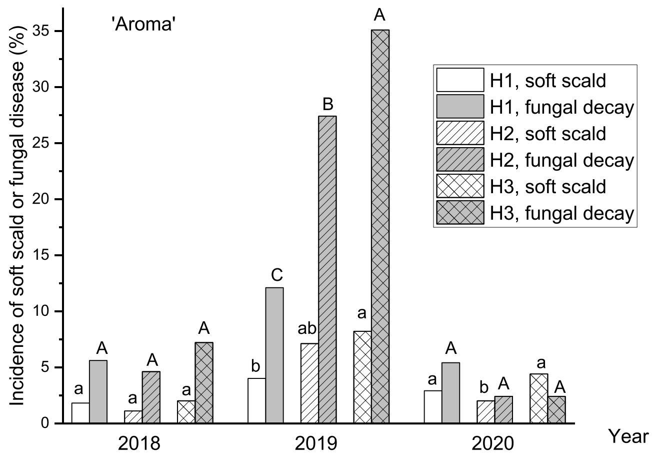

Fig. 2. Effect of harvest date on incidence of soft scald and fungal decay in 'Aroma' after storage. Maturity at harvest was determined based on Streif index and number of days after full bloom. H1: harvest one; H2: harvest two, H3: harvest 3, n = 150. Bars marked with the same letter (lowercase letters for soft scald and uppercase letters for fungal disease) within each year were not statistically significant different according to Friedman's test at $p \leq 0.05$.

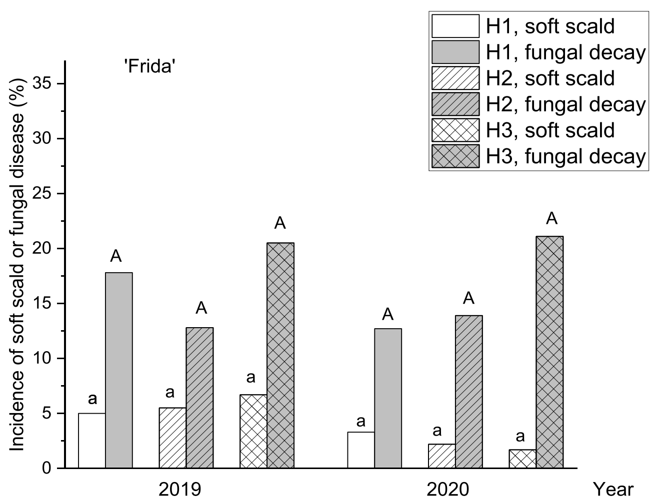

Fig. 3. Effect of harvest date on incidence of soft scald and fungal decay in 'Frida' after storage. Maturity at harvest was determined based on Streif index and number of days after full bloom. H1: harvest one; H2: harvest two, H3: harvest 3, n = 150. Bars marked with the same letter (lowercase letters for soft scald and uppercase letters for fungal disease) within each year were not statistically significant different according to Friedman's test at $p \leq 0.05$.

humidity was between 73.1 and 76.2 in 2018 and 2020. Frida also had higher relative humidity in 2019 (85–85.8) than in 2020 (79.4–79.5). Rainfall was also higher in 2019 (201–202 $L^{*}m^{-2}$) than in 2020 (151–171 $L^{*}m^{-2}$). Differences in temperature between 2019 and 2020 were small.

Relative humidity showed strong positive correlations with soft scald for all investigated time periods in 'Frida' (Table 3). For 'Aroma' rainfall was close to significant for 7 DBH (p = 0.089), while for the other investigated factors for this cultivar the correlations were not significant (data not shown).

Relative humidity during the time period 28 d before harvest showed a medium strong positive correlation with soft scald when data from both cultivars were pooled (Table 4). Relative humidity was also close to significant for 21 DBH (p = 0.055), while for the other factors the correlations were not significant.

3.3. Cooling conditions and storage atmosphere

Initial storage treatment after harvest before storage in ambient or controlled atmosphere led to varying results on soft scald incidence (Tables 5 and 6). In 2018, the incidence of soft scald was highest for 'Aroma' when fruit was initially stored at 2 °C in ambient atmosphere while in 2020 this treatment led to the lowest incidence. In 2019, independent of the initial storage conditions for the first 10 d, no difference in the incidence of soft scald could be found for neither 'Aroma', nor for 'Frida'. No significant differences regarding incidence of soft scald could be found between the different initial storage treatments for 'Frida' in 2020.

Also for fungal decay no difference between the different storage treatments could be found for any of the cultivars.

The storage in different atmosphere conditions showed varying results between different years for both soft scald incidence and fungal decay. In 2019 and 2020 the soft scald incidence in both 'Aroma' and 'Frida' was highest when the fruit was stored in ambient atmosphere. 2018 in 'Aroma' there were no significant differences between ULO/CA and ambient atmosphere for soft scald. For 'Aroma' the fungal decay frequency was much higher in 2019, than in 2018 and 2020, and was high irrespective of storage condition. In 'Frida', both years showed the highest frequency of fungal decay in fruit stored in ambient atmosphere.

Carbon dioxide injury was not detected in any fruit, and other physiological disorders were rare.

Neither harvest time, storage treatment, nor storage atmosphere had any large effects on the investigated quality parameters. Color parameters L (range 54.5–64.7), a (range 2.9–19.0) and b values (range 26.7–36.1), as well as firmness (range 42.2–62.9 N) and SSC (range 12.4–15.5%) after storage did not show any remarkable differences for 'Aroma' (Table 7, 8 and 9 in the supplemental material). Similar results was found for quality parameters in 'Frida': L (range 59.0–65.1), a (range 5.5–16.1) and b values (range 31.3–36.6), firmness (range 46.7–73.3 N) and SSC (range 11.8–14.0%). (Table 10, 11 and 12 in the supplement material).

4. Discussion

Although investigated in a number of studies, which factors that initiate the development of soft scald during storage still remain elusive. It has long been considered to be a cold storage disorder (Brooks and Harley, 1934; Watkins et al., 2005), but trials with gradual cooling of apples after harvest have given various results (Hanrahan and McFerson,

Table 3
Correlation between climate conditions during the growing season and soft scald prevalence in 'Frida'. Weather conditions were recorded by weather stations in the orchards during 2019–2020, n = 450. DBH stands for "days before harvest".

Factor	7 DBH		14 DBH		21 DBH		28 DBH	
	r	p	r	p	r	p	r	p
Daily minimum temperature	-0.723	0.104	-0.357	0.488	-0.266	0.610	-0.347	0.500
Daily average temperature	-0.500	0.313	-0.267	0.609	-0.249	0.634	-0.325	0.530
Relative humidity	0.849	0.033	0.846	0.034	0.919	0.010	0.860	0.028
Rainfall	-0.056	0.915	-0.199	0.822	-0.128	0.809	0.155	0.769
Solar radiation	-0.291	0.575	-0.799	0.115	-0.351	0.495	-0.238	0.649

Table 4
Correlation between climate conditions during the growing season and soft scald prevalence in 'Aroma' and 'Frida', n = 900. Weather conditions were recorded by weather stations in the orchards during 2018–2020 for 'Aroma' and 2019–2020 for 'Frida'. DBH stands for "days before harvest".

Factor	7 DBH		14 DBH		21 DBH		28 DBH	
	r	p	r	p	r	p	r	p
Daily minimum temperature	-0.161	0.566	-0.107	0.704	-0.169	0.547	-0.149	0.597
Daily average temperature	-0.158	0.574	-0.09	0.749	-0.144	0.608	-0.187	0.504
Relative humidity	0.393	0.147	0.403	0.137	0.505	0.055	0.528	0.043
Rainfall	0.463	0.082	0.23	0.41	0.08	0.777	-0.303	0.272
Solar radiation	-0.279	0.314	-0.282	0.308	-0.276	0.32	-0.081	0.775

Table 5
Effect of initial storage treatment n = 150, and storage atmosphere n = 30, on the incidence of soft scald and fungal decay in 'Aroma' 2018–2020. Fruit was subjected to initial storage treatment either 5 d at 10 °C followed by 5 d at 4 °C in ambient atmosphere, or 10 d at 2 °C in ambient atmosphere (gradual cooling), or was directly stored at 2 °C in the final CA/ULO condition or in an ambient atmosphere. After initial storage treatment, all fruit was transferred to 2 °C 95% RH storage. Storage conditions were as follows: ULO 1 was 1 kPa O_2 and 1 kPa CO_2, ULO 2 was 1 kPa O_2 and 2 kPa CO_2, ULO 3 was 1 kPa O_2 and 3 kPa CO_2, CA 4 was 2 kPa O_2 and 2 kPa CO_2 and storage atmosphere 5 was ambient atmosphere in ambient atmosphere storage. In 2018 fruit was stored for five months, while in 2019 and 2020 it was stored for four months. Means for a specific year followed by the same letter within a column are not significantly different according to Friedman's test at $p \leq 0.05$.

Year	Storage treatment	Soft scald (%)	Fungal decay (%)	Storage atmosphere	Soft scald (%)	Fungal decay (%)
2018	Gradual cooling	0.6 b	6.9 a	ULO1	1.5 a	11.8 a
	2 °C, ambient atmosphere	3.4 a	6.9 a	ULO2	1.5 a	3.2 a
	Direct final storage	0.9 b	3.6 a	ULO3	3.3 a	6.7 a
				CA	1.5 a	6.2 a
				Ambient atmosphere	0.4 a	1.1 b
2019	Gradual cooling	6.9 a	26.7 a	ULO1	1.1 b	26.3 b
	2 °C, ambient atmosphere	6.4 a	30.1 a	ULO2	2.3 b	26.7 a
	Direct final storage	6.0 a	17.9 a	ULO3	4.8 a	21.7 a
				CA	4.4 a	24.0 b
				Ambient atmosphere	19.6 a	25.9 b
2020	Gradual cooling	3.5 a	2.9 a	ULO1	1.1 a	3.3 a
	2 °C, ambient atmosphere	1.7 b	3.1 a	ULO2	1.1 a	2.2 a
	Direct final storage	4.0 a	4.2 a	ULO3	3.3 a	1.8 a
				CA	1.8 a	3.3 a
				Ambient atmosphere	8.1 b	6.4 a

Table 6
Effect of storage treatment, n = 150, and storage atmosphere n = 225 on the incidence of soft scald and fungal decay in 'Frida' 2019 and 2020. Fruit was subjected to initial storage treatment either 5 d at 10 °C followed by 5 d on 4 °C in ambient atmosphere, or 10 d at 2 °C in ambient atmosphere (gradual cooling), or was directly stored at 2 °C in the final ULO condition or in an ambient atmosphere. Storage condition 1 was CA-conditions at 1 kPa O_2 and 1 kPa CO_2 while storage condition 2 was ambient atmosphere storage in ambient atmosphere. Storage temperature in the final storage for five months was 2 °C, and 95% RH, both in CA and in ambient atmosphere. Means for a specific year followed by the same letter within a column are not significantly different according to Friedman's test at $p < 0.05$.

Year	Storage treatment	Soft scald (%)	Fungal decay (%)	Storage conditions	Soft scald (%)	Fungal decay (%)
2019	Gradual cooling	6.1 a	17.7 a	ULO1	3.3 b	10.3 b
	2 °C, ambient atmosphere	5.0 a	17.2 a	Ambient atmosphere	8.1 a	23.7 a
	Direct final storage	6.1 a	16.1 a			
2020	Gradual cooling	1.1 a	17.2 a	ULO1	0.0 b	13.3 b
	2 °C, ambient atmosphere	1.7 a	13.3 a	Ambient atmosphere	4.8 a	18.5 a
	Direct final storage	4.4 a	17.2 a			

2014; Moran et al., 2010) and several factors seem to influence the development of soft scald. In the present study the influence of different factors on soft scald incidence after storage has been investigated, namely maturity/harvest time, cooling and storage conditions, and pre-harvest weather conditions, following the time period from flowering to harvest of the fruit. Previous studies have usually focused on one or two of these parameters, which makes this study more comprehensive.

Several experiments have been performed based on the assumption that gradual cooling directly after harvest, before cold storage, may facilitate the adaptation to the cold temperature and decrease the incidence of the disorder (Al Shoffe et al., 2018; DeLong et al., 2006). However, gradual cooling seems to result in less soft scald in some cases, while in other cases no differences have been found (Al Shoffe and Watkins, 2018; Moran et al., 2010). Results found in this investigation seem to mirror the inconsistent previous results as we found no storage treatments that consistently lowered soft scald incidence for all years.

Variations in the weather conditions between the investigated years seemed to have a pronounced influence. Since storage conditions and cultivation practice were identical between the years, other factors must have affected the development of soft scald. The weather conditions were variable between the years, and especially in 2018, the temperature was higher than average during the growing season, with high summer temperature peaks, resulting in an average daily maximum temperature during the fruit growing season being more than 3 °C higher in 2018, than in 2019 and 2020 (values from local weather stations). On the other hand, the rainfall during the growing season in 2019 was about double amount than in 2018 and about 50% higher than in 2020 in the orchard where 'Aroma' was harvested, while it was about 30–50% higher in 2019 than in 2020 in the orchard where 'Frida' was harvested. In addition, the relative humidity (RH) differed between years. Year 2019 stands out as having higher relative humidity as compared with 2018 and 2020 for 'Aroma', and as compared with 2020 for 'Frida'.

The higher RH might have lowered the rate of evaporation from the fruit surface in the orchard, resulting in wetter surface conditions. In 2019, there were relatively high levels of soft scald regardless of harvest time, preconditioning or storage conditions. Corresponding to the different weather conditions in the investigated years, the average RH in the weeks preceding the harvest was found to correlate with incidence of soft scald, especially for 'Frida'. Other physiological disorders have been connected to wet conditions during the growing season, e.g. russeting of apples, visible as brown and corky areas at the surface of the fruit, has been suggested to appear under conditions of frequent rains, high humidity or dew, particularly during early fruit development (Faust and Shear, 1972; Chen et al., 2020). The occurrence of skin spot on some cultivars, especially 'Elstar' and occasionally 'Golden Delicious', was found to be associated with numerous exposures of surface wetness, caused by rain or dew during late stages of fruit development (Winkler et al., 2014). Supporting the findings related to humidity and soft scald frequency in this investigation, in a previous investigation the disorder was found to be strongly related to precipitation 90–120 d after bloom, as well as number of days when RH was higher than 85% (Moran et al., 2009). Wet conditions was found to be one of the major factors influencing soft scald while modeling the effects of preharvest conditions (Lachapelle et al., 2013).

Wet conditions before the harvest result in more turgid cells, and in analogy with what has been found for overly irrigated fruit and also for fruit harvested after heavy rainfall, this could result in micro-cracking, thinner cuticle, and subsequent higher water loss (Lufu et al., 2020). Cuticle formation has been found to be affected negatively by humid conditions, rendering the cuticle to be thin (Faust and Shear, 1972; Chen et al., 2020), and surface moisture may cause microcracks (Knoche and Grimm, 2008). While investigating microstructure of apples affected by soft scald, a previous investigation found that the cuticle of soft-scalded peel had tears, while the cuticle of unaffected peel was intact, which might indicate wax weakness, though tears in the cuticle was only discernable in stored fruit where the damage was visible and not directly at harvest (Xu et al., 2017). Recent findings indicate a more intimate interaction between the cuticle and epidermal cells, and it has been suggested that the cuticle should be understood as the outermost region of epidermal cell walls, and is important both for physical support and for regulating water status (Lara et al. 2019). While the soft scald disorder seems to develop in the outer cell layers, this interaction can be important to study further. Possibly changes in cuticle properties resulting in a higher water loss in soft scald affected tissue, could lead to a more rapid cooling due to increased heat transfer during evaporation, and contribute to tissue damage in affected fruit.

If the disorder of soft scald is linked to an inability of outer fruit tissue to acclimate to the cool temperatures during initial phase of storage, possibly due to increased heat transfer and more rapid cooling, the progress of the damage might be associated to cellular membrane function. In a previous investigation, fatty acid composition in fruit tissue affected by soft scald was found to be different than in sound fruit tissue, and the content of linoleic acid was lower in affected tissue (Hopkirk and Wills, 1981). Cold acclimation in plants have in general been found to be linked to an increasing proportion of unsaturated fatty acids, such as linoleic acid (C18:2) and linolenic acid (C18:3) (Badea and Basu, 2009; Wang et al., 2006). In addition, more cold-tolerant cultivars have been found to have the ability to change their fatty acid composition to a higher proportion of unsaturated fatty acids when subjected to lower temperatures than less cold tolerant cultivars (Tian et al., 2022). Membrane lipid functionality is considered important for maintaining cell homeostasis. The presence of one or more double bonds in the unsaturated fatty acids make it difficult for the molecules to pack tightly in the membrane, and will thereby increase the fluidity of the membrane. The increasing proportion of unsaturated fatty acids of the membrane lipids during the cold acclimation will thus maintain the membrane functionality at lower temperatures (Marangoni et al., 1996). In addition, recently an investigation found that genes involved in lipid peroxidation showed increased expression in fruit with soft scald, which also implicate that membrane functionality might be an important factor in connection with soft scald (Leisso et al., 2016). However, these physiological reactions can be considered as descriptive of the changes that take place, and not explaining the reasons for them to occur.

In the present study, the latest harvested fruit of 'Aroma' in one out of three years, 2019, developed more soft scald, confirming the findings in previous studies (Moran et al., 2010; Watkins et al., 2005), though in the year 2018 and 2020 when the incidence of soft scald was lower, no clear tendency was found. In 'Frida' maturity did not have a significant effect on soft scald development. Ripening of fruit has been shown to affect the mechanical properties of the cuticle, increasing stiffness and reducing its deformability, which would lower the force needed to break it (Lara et al., 2019). This might be of relevance for the increasing susceptibility of more mature fruit to the disorder.

In this investigation, storage of fruit in ambient atmosphere lead to higher incidence of soft scald in both 'Aroma' and 'Frida' as compared with storage in ULO conditions with the lowest oxygen content. To our knowledge, few investigations have been performed where soft scald incidence have been monitored at different concentrations of oxygen present during storage. A recent study found no conclusive results in apples stored in air or in 1.5–0.3 kPa oxygen, while in the first year there was more soft scald found among fruit stored at the lower oxygen levels, but the second year no difference was found (Mattheis and Rudell, 2021). Apple fruit stored in CA-storage tended to develop less soft scald than fruit stored in air (DeLong et al., 2006). Since long time it has been known that lowering oxygen levels during storage reduces respiration rate, ethylene biosynthesis, senescence, fruit maturation and affects expression of genes (Wright et al., 2015). These general effects on cell metabolism might also affect the development of soft scald.

Fungal decay varied between the investigated years and treatments, and showed similar yearly variation as soft scald. In 2019 there was more decay than the other years. Weather conditions can effect pathogens such as *Colletotrichum* ssp. which benefit from a hot, humid weather (Borve and Stensvand, 2007). 2019 was more humid than the other years (Table 2) which could possibly explain the increased decay that year. Optimal harvest time is another important factor in decreasing soft scald incidence (Valiuskaite et al., 2006). In 'Aroma' there was an increase in decay only in 2019 with maturity, possible due to softer fruit which is more sensitive to pathogens (Ahmadi-Afzadi et al., 2013). No conclusive results could be found in the effects on fungal decay regarding the different storage treatments or storage conditions. Multiple factors, alone or in combination, seem to be able to create the conditions in the fruit that initiate soft scald. The varying response the different years to the storage treatment after harvest indicate that environmental factors bring about the prerequisites needed in the fruit tissue for the disorder to occur, though previous findings (e.g. Lachapelle et al., 2013) point to that other factors than humidity before harvest can also be important. Other environmental factors might result in similar changes in the fruit tissue needed for the disorder to develop.

In conclusion, weather conditions during the season appeared to influence the development of soft scald, and especially wet conditions during the growing season and before harvest seemed to be important. The average relative humidity in the weeks preceding the harvest was found to correlate with incidence of soft scald, especially for 'Frida'. For 'Aroma', maturity affected fungal decay to a great extent in the year with high frequency, 2019, but had no effect the other years. Maturity had only effect on the incidence of soft scald in 2019 in 'Aroma'. In 'Frida' maturity did not show any significant effect on soft scald, nor in fungal decay. Gradual cooling did not lead to any conclusive results as compared with other storage treatments in any of the investigated cultivars. ULO storage conditions, especially ULO1 and ULO2 for 'Aroma', and ULO1 for 'Frida', resulted in lower incidence of soft scald as compared with storage in ambient atmosphere in 2019 and 2020, though no conclusive results were found for fungal decay.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was funded by an Industry PhD program of the Swedish Government (ref. no. N2017/036895/ SK) and Äppelriket Österlen, Ekonomisk Förening, Kivik, Sweden. We especially thank personnel at Balsgård research station; Stefan Olsson and Barbro Johnsson. We are also grateful for valuable advice in statistics from Jan-Eric Englund, Swedish University of Agricultural Sciences in Alnarp.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.postharvbio.2023.112344.

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