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Degree Days as a Method to Estimate the Optimum Harvest Date of 'Conference' Pears

Grzegorz P Łysiak

Department of Ornamental Plants, Dendrology and Pomology, Poznan University of Life Sciences, ul. Dąbrowskiego 159, 60-594 Poznań, Poland; glysiak@up.poznan.pl

Abstract: The European pear is a climacteric fruit species characterized by high storability. 'Conference', a pear cultivar very popular on the market, can be stored in a CA room without major losses for half a year. However, for 'Conference' storage to be successful, the fruit must be harvested fully developed even before it enters the climatic maturation phase. Harvested too early or too late, pears will taste bad, have physiological disorders and will be poorly storable. Among the various methods used to determine the optimal harvest date, the degree-days method, which relies on the sum of active temperatures, seems to be relatively accurate and easy to apply. During 11 years of study, 'Conference' pears were harvested on 4 dates (every 4-5 days) chosen based on measurements and observations, and then, after a six-month storage period, the optimum harvest date was determined. During the growing season, temperature was measured using an automatic weather station to calculate the sum of active temperatures from full bloom to the optimal harvest date. Measurements made after storage were analysed and the sum of active temperatures needed for the proper development of 'Conference' pear was calculated to be 2469 degree days. The calculations are very accurate because the dispersion calculated using the standard deviation was only 20 °. The base temperature with the smallest error was 0 °. On the basis of the study results, this method can be recommended as useful for determining the optimal harvest date.

Keywords: Sum of active temperatures; SAT; CA storage; physiological disorders; TSS; length of growth; harvest date estimation

1. Introduction

The 'Conference' pear is one of the most important pear cultivars. Its annual production is little less than 100,000 tonnes in Europe alone, making up a share of about 45% of pear production on the continent [1]. 'Conference' owes this status to high productivity, easy cultivation, high storability [2] and popularity among consumers [3].

Only pears picked at the optimum maturity stage are suitable for storage for over 6 months because of better storage potential and organoleptic quality [4,5]. Storage of 'Conference' pears for 180 days in normal atmosphere is not economically viable, even if the fruit is subjected to 1-MCP treatment; at the same time, it is profitable to store 'Conference' pears in a controlled atmosphere for the same period, regardless of whether 1-MCP was applied or not [2]. Fruit harvested when still unripe will shrivel more easily [6] and will be more vulnerable to physiological disorders and diseases [7,8]. Over-mature fruit is likely to become soft and mealy [9] and has an insipid flavour after a short period of storage [10].

Correct determination of the harvest date is crucial for pome fruit storability [11]. There are many methods for determining the Optimum Harvest Date (OHD) [7], but there is no perfect method; moreover, the more accurate the method, the more difficult and expensive it is to perform [12]. One of the simplest methods to determine the OHD of pome species is to assess the disintegration of starch or to use the calendar [11]. However, these methods are burdened with an error of 7-10 days, and thus they are not reliable enough when it comes to selecting fruit for long-term storage. Their advantage is that

they are simple and that everyone can carry them out. A very accurate method is the ethylene method showing current ethylene production by fruit [10]. However, this method requires specialized equipment which is often not available to producers or advisory centers [12]. Therefore, the search for a simple and cheap method that will allow very accurate determination of the harvest date is still ongoing.

The thermometer design principles introduced by René Antoine Ferchault de Réaumur in 1730 and then the concept of heat units proposed by Nicolas Clément in 1825 provided agricultural sciences with a useful tool to study physiological stages of development of various organisms (cultivated or parasitic) [14], such as the moment of departure of single-generation pests, or the first generation of multi-generational pests [15].

This type of research is based on agroclimatic indices, such as the sum of active temperatures (SAT), growing degree days (GDD), and latitude-temperature index (LTI). They are highly useful agronomic variables closely related to plant development [16]. In the second half of the twentieth century, European research centres created phenological models on the basis of temperature measurements to predict when a specific stage of development of a species or cultivar occurs [17]. Many models have been developed for vines – they enable determining the date of budbreak based on degree days [18] after the plant has passed the full dormancy period, i.e. the required number of chilling hours. The use of these methods allows assessing the suitability of a given cultivar for the local climate [19]. Similar principles are also followed by researchers introducing to cultivation new species, such as *Cornus mas* L. [19] and *Actinidia arguta* in northern Poland [20], or new peach cultivars (*Prunus persica*) in the Czech Republic [21], or new olive cultivars (*Olea europaea* L. var *europaea*) in Italy [22].

The dates of the beginning and end of vegetation of specific species as well as the time they reach the key development phases in individual years have been used by many researchers to create models illustrating the speed of the climate change caused by the greenhouse effect [23,24]. They count the number of days by which the period during which a certain required sum of active temperatures is achieved for plants and various biological processes is reduced, as well as observe the changes to the range of occurrence of various organisms and broadly understood phytogeography [19, 20, 24].

The advantage of using the sum of active temperatures is that no daily tedious temperature measurements are needed to determine the daily average temperature. An own meteo station transmitting electronically meteorological data to the cellular network on an ongoing basis allows users to easily calculate the sum of active temperatures [25]. The only difficulty that users may face in this context is the lack of calculations and formulas for a given species or cultivar and the lack of information on the base temperature that should be used to calculate the sum of active temperatures, usually in the range from -2 to +10 °C [26].

This paper describes research conducted for many years to determine (1) the sum of active temperatures from flowering to harvest for 'Conference' pears, (2) the base temperature that gives the highest accuracy of measurement for this cultivar, and (3) the harvest window for this method.

2. Materials and Methods

2.1. Materials and Location

The experiment was conducted in the experimental orchard and laboratory of the Department of Pomology of the University of Life Sciences in Poznan (52°31' north latitude and 16°38' east longitude). 'Conference' pears were collected from trees grafted on Quince S1, planted at spacing of 4 × 1.5 m in spring 2002. The tree crowns were trained as wide spindles. There were 192 trees in three rows, selected from a bigger plot to ensure trees with equal vigour and size. The pear orchard was maintained according to the standard commercial practice for integrated fruit production.

2.2. Sampling

There were two sizes of fruit samples depending on whether the fruit was to be stored (big sample) or only qualitative measurements were to be made (small sample). Pears were collected every 4–5 days starting some weeks before the estimated OHD. The small sample consisted of 20 pears picked from at least 10 trees, from 100 to 160 cm high, outside part of the tree, from the same east-southern side. Pears over or under size, infected by pests or diseases were rejected. The fruit had to represent the stage of maturity (in size and colour) of fruit to be harvested during the main harvest. In most years of the experiment, also the fruit intended for cold storage was collected on the last four sampling dates (big sample). The big samples were harvested according to the same rules as those applicable to the small samples.

The fruit samples intended for storage were considerably larger than the fruit samples collected solely for measurement purposes and were placed in 4 boxes per 10–12 kg each box. The total number of fruit harvested for storage was approximately 300 pears per each harvest date. The dates of each sampling and of the harvest are shown in Table 1.

2.3. Measurements

2.3.1. In the orchard, the dates of the basic phenological phases were recorded, with particular emphasis on full bloom.

“Full bloom” was defined as the point in time when 80 percent of the blossoms on the north side of the tree were open.

2.3.2. Temperature

Four data loggers HOBO® – Plus4 made by ONSET Computers were put on trees in the orchard, in shaded places 2 meters above the ground, and set to measure the temperature every 2 hours. The measurement accuracy was 0.1 deg. Readouts were downloaded from the loggers once a month until the last harvest date. The results obtained from the four loggers provided the basis for the calculation of (a) the average daily temperature and (b) the cumulative temperature, for which the values of 0.0°C, 4.0°C, 5.0°C, 10.0°C, and 15.0°C were taken respectively as the base temperature. The calculations were conducted in reference to the OHD obtained through applying the procedure described in section “Storage condition and evaluation of storability”. For all years of experiment the mean and standard deviation were calculated.

2.3.3. Maturity and ripening at harvest were evaluated according to the well-known standard methods:

- firmness: penetrometer (probe – 8 mm in depth, 11 mm in diameter), two opposite sides of the fruit, in N,
- total soluble solids (TSS): refractometer, in %,
- starch disintegration: a 10-point scale where 1 is no conversion and 10 is totally converted,
- titratable acidity (TA): titration with 1n NaOH to 8.1 pH, mval/100 ml,
- ethylene production: around 1 kg of pears were put in a gas-tight box; after an hour, ethylene concentration was measured and converted into 1000 g of fruit.

All the above measures were made to make a decision on the date of the first harvest. Subsequent harvests were conducted every 4–5 days. There were four harvests within 16–20 days in each year of the experiment.

2.3.4. Storage conditions and evaluation of storability.

Fruit was stored in a CA storage room at $-0.5 \pm 0.5^\circ\text{C}$ and around 90% RH for approximately 6 months. The schedule of all measurements is shown in table 1. The storability of individual pear samples was evaluated after the same number of days of storage

following their harvest date. The evaluation consisted of the judgment and measurements. The judgment was based on sensory tests, incidence of diseases and disorders, and internal quality criteria (firmness, sweetness, sourness), whereas the measurements comprised the measurement of TSS, TA, firmness and fruit mass loss.

2.3.5. Evaluation

Each criterion was scored separately for each date of harvest. The scores were given according to following rules:

- Fruit mass loss was measured for each stored box. Twenty pears were numbered and weighed with an accuracy of 0.1 g before and after storage. A total 80 pears from one harvest were examined. Scores were given according to an analysis of variance between the harvest dates. If there were no significant differences between samples, each sample received the same score. If the analysis showed a significant difference, a sample could be scored 1, 2, 3 or 4. If fruit mass loss was significantly different for all individual samples under study, each sample received a different score from 1 to 4.
- Incidence of disorders and diseases was scored separately according to the same rules as those applied to fruit mass loss. After being taken out of the cold store, pears went through a week of shelf life at room temperature. Fruit infected with more than one disease was counted only once because it could no longer qualify as commercial quality fruit anyway. If the share of non-healthy fruit in a box was higher than 10%, a sample received 1 point independently of the analysis of variance. Fruit firmness after storage was measured in the same way as before storage and was scored using the mean N value. Fruit harder than 40 N could get up to four points depending on the results of the analysis of variance between fruit samples from different harvests. Consequently, fruit could receive 1, 2, 3 or 4 points if it was harder than 40 N and each sample was significantly different from other samples.
- TSS and TA were measured according to the rules presented above (2.2.3.). Fruit with TSS content of less than 11% and TA (understood as the content of citric acid) below 0.185 could not receive more than one point. Other fruit could be scored higher using the same rules as those applied to measure firmness.
- The point scale for the minimum firmness, TSS and TA values was developed independently based on the research by Konopacka et al. [27], which examined the relation between texture attributes and consumer preferences.
- Sensory tests were carried out twice: on the day after the end of storage and a week later. Fruit was evaluated by 3–5 professional judges according to the overall acceptance on the market along the following scale: 0 – no acceptance on market, 1 – poor acceptance, 2 – good, 3 – excellent. The average judgment was rounded to 1.0 point.

Table 1. Schedule of the experiment

No of measurement	Years and dates										
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Date of full bloom	21.04.	23.04.	25.04.	21.04.	30.04.	24.04.	17.04.	19.04.	25.04.	29.04.	18.04.
1M	28.08.	-	15.08.	16.08.	25.08.	24.08.	17.08.	23.08.	29.08.	-	-
2M	01.09.	15.08.	20.08.	21.08.	30.08.	28.08.	21.08.	27.08.	02.09.	24.08.	01.09.
3M	05.09.	20.08.	24.08.	25.08.	03.09.	01.09.	26.08.	01.09.	05.09.	27.08.	05.09.
4M	10.09.	25.08.	28.08.	30.08.	08.09.	06.09.	30.08.	04.09.	09.09.	31.09.	09.09.
5M, 1S	15.09.	29.08.	02.09.	03.09.	12.09.	11.09.	04.09.	08.09.	13.09.	07.09.	13.09.
6M, 2S	19.09.	03.09.	07.09.	07.09.	17.09.	16.09.	09.09.	12.09.	17.09.	12.09.	18.09.
7M, 3S	24.09.	08.09.	12.09.	11.09.	21.09.	20.09.	13.09.	16.09.	21.09.	16.09.	22.09.

8M, 3S	29.09.	13.09.	16.09.	16.09.	26.09.	24.09.	18.09.	20.09.	25.09.	20.09.	26.09.
Date of end of storage of first harvest in days	22.03.08	16.03.09	07.03.10	02.03.11	15.03.12	20.03.13	12.03.14	21.03.15	10.03.16	21.03.17	17.03.08
Length of storage in days	190	200	185	181	186	190	190	195	185	190	

3. Results and Discussion

Weather is the main source of variability in plant development in individual years. Climate change and the potential for more extreme temperature events will impact plant productivity [28]. The largest difference in the date of full bloom of pear trees during the study period was nearly two weeks (Table 1). Certainly, this difference had to affect the optimal harvest date (OHD).

Too early harvest of pears intended for long-term storage results in excessive transpiration, lower sugar content and worse taste, and may also cause the occurrence of physiological diseases [29]. Too late harvest of 'Conference' pears was found to trigger a substantially higher incidence of flesh browning disorders such as core browning, flesh browning and cavities [30]. Moreover, fruit harvested too late have less storage capacity, because it becomes overripe faster and is more susceptible to fungal diseases.

'Conference' pears harvested on the optimal harvest date can be kept for 2 to 4 months in an ordinary cold store and for about 6 months in a CA cold store [31]. Various modern types of cold stores with a controlled atmosphere in which fruit metabolism is maintained on the verge between aerobic and anaerobic respiration as well as the use of substances that slow down the ripening processes, such as 1 MCP, allow one to extend the fruit storage period [32,33], but cannot correct the negative effects of too early or too late harvest. In such cases, even the best technology will not improve fruit quality after a few months [2]. In this study, pears were stored for at least half a year because only at the end of the storage period the qualitative differences were large enough to enable the identification of correct harvest dates. Fruit was stored from 181 days (2010) to 200 days (2008). Each of the four samples was stored for the same period of time.

A number of studies have shown that fruit firmness gradually decreases during ripening due to progressive enzymatic degradation of cell wall polymers, alteration in cell wall structure caused by degradation processes (e.g., polygalacturonase) and also polysaccharide degradation, which leads to the breakdown of starch, cellulose and hemicellulose. These changes result in a loss of integrity of the middle lamella, which is rich in pectins that control cell-to-cell adhesion, thus influencing the texture of the fruit [7, 33, 34, 35].

Firmness was one of the features examined at all stages of the experiment. The first examination was carried out at least three weeks before the expected harvest date (Table 1.) and was usually over or slightly below 80 N (see the data in Supplementary Material - SM1). The decrease in firmness varied between years and depended mostly on the course of the weather. On the first harvest date, fruit firmness ranged from 62.5 to 72.4 N and thus happened to match the recommendations given in Switzerland or Great Britain for 'Conference' pears. This is a very good result, but the firmness of the fruit harvested on subsequent dates already approached the lower firmness limit of 55 N [1,2]. Firmness could be considered a pretty accurate indicator to determine OHD; however, many studies show that it is too variable and too strongly depends on weather, fertilization, or rootstock [36, 37, 38]. This study confirms this, as the difference in firmness between OHD in individual years was 12.8 N (Table 1).

Other traditional indicators are not very stable, either. In many countries, tables illustrating the starch decomposition pattern have been created [39,40,41,42]. The starch iodine test has long shown promise as a simple means of assessing pome fruit maturity. The method is based on the enzymatic hydrolysis of starch to sugar as fruit ripens. It

starts in the core area and then proceeds in the cortical tissue in a pattern characteristic of the cultivar. However, the rate of these changes was very small and there was practically no or only a slight difference between the starch index measurements in some years so that the error in the assessment of a sample against the standard starch-iodine staining pattern could have been several times greater.

Developed in the 1980s, Josef Streif's 1983 maturity index [43] has been in many countries a very popular tool for setting the date for harvesting apples for long storage. The index is based on the determination of firmness (kg, 11 mm probe), refractometric value (% soluble solids) and starch conversion (scale 1-10) and is calculated as follows: firmness (F) divided by refractometer value (R) and divided by starch conversion stage (S): $F/R \times S$ index. In British studies, it showed good stability for a change in 'Conference' cultivar [44]. According to the authors' recommendations, the optimal value is about 0.7. However, the results obtained in this study are different. The average value on the day of the optimal harvest is 80% higher, which suggests that for 'Conference' pears the Streif index is at least debatable. Furthermore, the standard deviation shows high variability that appeared when the average index value was calculated.

Table 2. Maturity indices

1

Year	Date			AT	Maturity indicators												
	F	OHD	No		Sum of active temperatures							Quality parameters					
					0°C	1°C	2°C	3°C	5°C	10°C	15°C	FR	TSS	SDI	StI	TA	TSS/TA
2007	21.04	15.09	147	16.6	2457	2309	2161	2013	1719	1002	405	65.9	10.8	7.4	1.25	0.186	58.2
2008	23.04	03.09	133	18.6	2495	2362	2227	2093	1825	1155	527	65.6	11.5	7.0	1.26	0.278	41.3
2009	25.04	07.09	135	18.2	2478	2343	2206	2070	1798	1111	502	63.2	11.4	6.6	1.71	0.182	62.5
2010	21.04	11.09	143	17.1	2467	2324	2179	2035	1747	1046	463	60.2	11.4	8.2	0.97	0.171	66.9
2011	30.04	17.09	140	17.3	2427	2287	2145	2004	1713	1032	402	70.2	11.2	8.7	1.08	0.188	59.6
2012	24.04	16.09	145	17.0	2478	2333	2186	2040	1748	1023	391	63,4	12.2	6.2	1.72	0.180	68.1
2013	17.04	04.09	140	17.5	2467	2327	2185	2044	1762	950	435	64.2	11.5	7.0	1.22	0.314	36.7
2014	19.04	12.09	146	16.6	2446	2300	2152	2005	1692	1078	407	65.2	11.5	7.3	1.21	0.188	61.1
2015	25.04	17.09	145	17.1	2480	2335	2188	2042	1750	1047	454	64.0	12.6	8.3	0.94	0.195	65.4
2016	29.04	16.09	140	17.6	2487	2347	2205	2064	1782	1070	436	61..0	12.1	7.2	1.09	0.153	78.9
2017	18.04	22.09	157	15.7	2479	2322	2163	2003	1670	968	342	63.8	11.5	8.3	1.02	0.186	61.8
Mean	23.04	13.04	142.8	17.2	2469	2326	2182	2037	1746	1044	433	64.2	11.6	7.47	1.22	0.202	60.0
MD	13	19	24	2.93	68	75	82	90	155	205	185	12.8	1.8	2.5	0.75	0.130	42.2
SD	4.0	5.7	6.2	0.76	20	22	25	45	46	60	52	3.6	0.5	0,80	0.27	0.046	11.9

- F – date of full bloom, OHD – optimum harvest date, No – number of days from full bloom until OHD, AT-average air temperature during vegetation between full bloom and OHD, F - Firmness, TSS – total soluble solids, SDI- starch disintegration index, StI- Streiff index,TA- titratable acidity

2

3

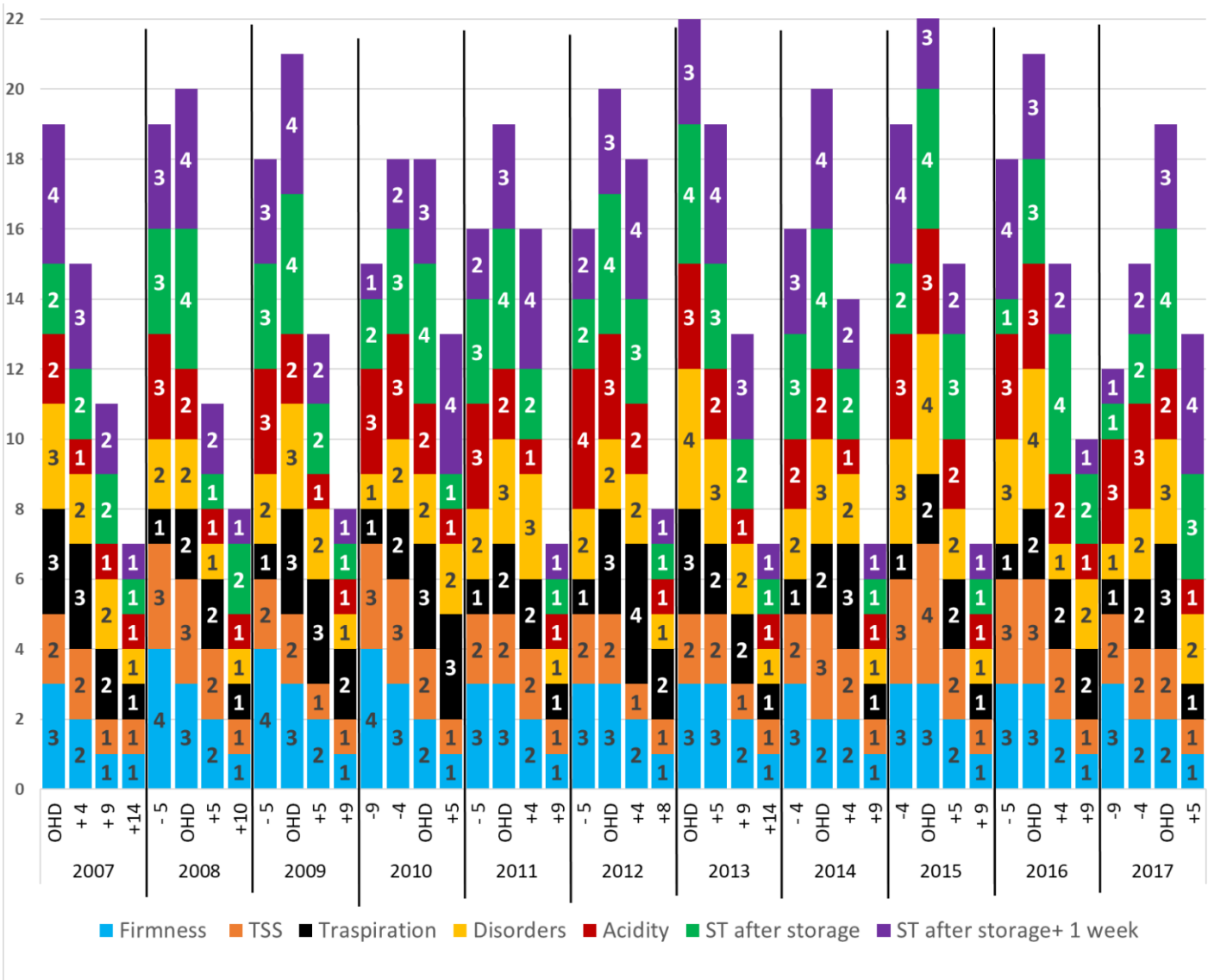


Figure 1. Assessment according to a point scale of the quality aspects of fruit samples harvested on the respective dates examined after storage in the years 1999–2006.

The highest bar in every year indicates the best storability according to the harvest date, OHD-optimum harvest date, TSS-total soluble solids, ST-sensory test carried out on the day after storage, ST after storage + one week shelf life in room temperature. Data for assessment are in Supplementary Material - SM1.

Fruit ripening is an irreversible, genetically programmed and enzymatically guided process leading to the development of a soft and edible ripe fruit with desirable quality attributes through a series of physiological, biochemical and organoleptic changes [7,8]. Ripeness is usually considered readiness for harvest. Numerous changes such as seed maturation, change in colour, abscission from the parent plant, texture softening, production of flavour volatiles, wax development on the skin, tissue permeability, and change in carbohydrate composition are measurable and many of them were considered in the decision about harvest [44,45,46,47]. However, due to a large number of variables, the end result is unpredictable for such fruits as pears intended for long-term storage. In the research conducted for 11 years, 4 harvests were conducted annually in the period which according to the indicators discussed above was the right time for harvesting (Figure 1).

Analysing the assessments presented on the chart prepared to present which of the harvest dates in the autumn was optimal, we can conclude that it was not easy to unambiguously determine the optimal harvest date in each year. In some years, the differences between individual harvests were very large and in some years small, and in principle this applies to each of the examined features and assessments. Firmness, which is considered one of the most important criteria (although in pears it is less important than in apples), was found to significantly vary between samples after storage only in 3 years of the experiment (2009-2011). TSS, which in pears is more important than firmness, varied even less and only fruit harvested in 2015 significantly differed after storage in terms of TSS, depending on the harvest date. A very interesting criterion is fruit loss as a result of transpiration and respiration during cold storage. Since pears have less wax bloom than apples or stone fruits, they lose water during storage much more easily [48,49]. This is especially the case when pears are harvested too early. The evaluation of fruit after storage allowed in 10 out of 11 years to determine definitely which harvest date was the best. Unclear results were obtained only in one year, because, taking into account fruit physiology, the optimal harvest date was exactly between those that were rated the highest. This also confirms the assumption that OHD is not limited to only one day but rather refers to a period of at least five days [12].

Measurements and observations made in autumn after harvest mainly focused on determining the first harvest date which may be optimal for long storage of pears. After six months of storage, all measurements and observations focused on determining which of the 4 dates was optimal and associated with the greatest economic and consumer success. Autumn and winter pear cultivars can be stored in cold storage for longer than the period during which they grow on the tree. In Table 2, the second and third columns show the key dates related to fruit development. The date of full bloom depends on the beginning of vegetation and the course of the weather in spring. The difference between the earliest and the last flowering date was 13 days. The optimal harvest date between years varied even more and amounted to 19 days. The fourth column indicates how long the fruit grew; however, although calculated on the basis of the two previous columns, it is more related to the conditions in which the fruit grew, which are presented in the fifth column. The average temperature of the period from flowering to harvest clearly indicates that this factor was crucial for the length of fruit development. A two-degree difference in the daily average between the growing seasons in 2007 and 2008 translated into a difference of as much as 2 weeks in the period of fruit growth and development on the tree. The length of the growth period, i.e. the period between full bloom and harvest, is one of the larger variables presented in this table. The maximum difference in the length of the period needed for the proper development of fruit is 24 days. The data clearly show that temperature is the basic factor affecting the length of fruit development. It affects the rate of all processes occurring in nature. According to van't Hoff's law, a temperature increase by 10°C leads to a 2- to 4-time increase in the rate of chemical reactions [50]. Thus, the sum of active temperatures must be a good OHD indicator. In the conducted studies, SAT was determined on the basis of data from 11 years.

SAT is calculated by summing the degrees above the base temperature in the period from flowering to harvest. The literature gives very different, in some cases even negative, base temperatures [26]. Most often, the base temperature is between zero and ten

degree Celsius. To determine the harvest date for 'Conference' pears, meteorological data were recalculated in relation to different base temperatures most often found in the literature. The result characterized by a smaller standard deviation of only 20 was obtained by calculating the sum of active temperatures for base temperatures equal to zero degrees. Using a higher base temperature in the calculation led each time to a much stronger variation of the result between individual years, as reflected by the increasing standard deviation. The presented research found that the sum of active temperatures allowing one to determine the optimal harvest date for 'Conference' pears is 2469 degree days.

5. Conclusions

'Conference' is a European pear cultivar characterized by high storability. Fruit collected at an optimal point in time can be stored without loss in a controlled atmosphere for half a year. A system for determining the optimal harvest date can be relatively easily developed by any producer. Using the sum of active temperatures to determine the optimum harvest date for 'Conference' ensures great accuracy. The calculations carried out as part of the research presented in this paper show that a harvest that will be carried out after the SAT has achieved the value of 2469 degrees will be optimal, with the possible error of only one day. Active temperatures were calculated most accurately using a base temperature of 0 °. The length of harvest window is minimum 5 days. The application of this method is relatively simple and requires only access to meteorological data. Automated metrological stations which are often installed in orchards are the only devices needed to determine the optimum harvest date.

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