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RESEARCH REPORT

Evaluation of sweet cherry fruit quality after short-term storage in relation to the rootstock

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Abstract

Fruits of the sweet cherry cultivar 'Regina' collected from trees growing on seven rootstocks were stored in a cold room at 2 °C with a normal (NA) and controlled atmosphere (15% and 20% CO_2 and 5% O_2—CA1 and CA2) for 2 weeks. The rootstocks on which the trees grew and the storage conditions significantly affected all fruit parameters tested during both years of the experiment. Fruit from Damil rootstock exhibited higher mean firmness than fruit from Colt rootstock. The effect of rootstocks on the value of soluble solids content (SSC) varied, wherein the fruits from Tabel Edabriz and Damil were characterized by high SSC mean content. The organic acids content (TA) was significantly lower after storage than during harvest time. Fruits from Tabel Edabriz trees were characterized by faster ripening, as was evident by the higher SSC to TA ratio. The amount of mass lost depended significantly and only on the storage conditions—sweet cherries from both CA combinations had the lowest mass losses. The percentage of fruits showing disease symptoms was largely dependent on the weather conditions in the orchard the year before the fruit harvest, as well as atmosphere composition and RH during fruit storage. Cold storage conditions with a high (20%) CO_2 content are recommended for the short-term storage of sweet cherry fruits because they preserve fruit quality parameters: a low decrease in firmness, maintenance of a high SSC/TA ratio, a low percent of fungal infections, and good preservation of green color in the peduncle.

Keywords Controlled atmosphere · Firmness · Maintenance of green peduncle · Soluble solids content · Titratable acidity

1 Introduction

The world currently produces about 2.3 million tons of cherries. Most of these fruits come from Asia (43%), Europe (37%) and America (18%). The top ten producing countries supply more than 70% of cherries to the markets. Turkey (535,000 t), the USA (345,000 t) and China (220,000 t) are the largest producers. Polish production (according to USDA estimates) is about 50,000 t. Sweet cherry is a perishable fruit, characterized by a high water content in tissues, thin skin and high respiration intensity (Wang and Lang 2014). Harvest of non-climatic fruits (sweet cherries) usually occurs after full maturity, at the stage of consumption maturity, similarly to plum (Candan et al. 2011) and contrary to apple (Hărsan et al. 2006). Sweet cherry fruits are highly appreciated by consumers due to their excellent taste and high nutritional values, and they are consumed mainly as a dessert fresh fruit (Crisosto et al. 2003). Therefore, short cool storage technology is often applied to extend the fresh fruit supply to the market. However, sweet cherry fruits can be stored for a relatively short time (up to 8 weeks) under optimal storage conditions. Lately, studies concerning new storage technologies (modified atmosphere packaging, air and water precooling) have been conducted (Remón et al. 2000; Akbulut and Özcan 2008; Khorshidi et al. 2011; Giacalone and Chiabrando 2013). The rootstock used for growing fruit trees affects many traits of trees and fruits, such as tree vigor (Balmer 2008), flower bud induction and regular bearing (Koutinas et al. 2010), productivity index (Bielicki and Rozpara 2010), fruit mass (Gratacós et al. 2008), or cracking susceptibility (Brüggenwirth and Knoche 2016). Moreover, it also has an impact on such fruit characteristics as: size, firmness, soluble solids content, acidity, color (fruit, peduncle) and taste (Simon et al. 2004; Gratacós et al. 2008;

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Kankaya et al. 2008); rootstock can affect both harvest and postharvest periods. Trees of different vigor can produce sweet cherry fruits with different phenolic acid and flavonol contents. Sometimes, vitamin, polyphenol and anthocyanin contents in fruit can also be affected by the rootstock (Spinardi et al. 2005). Wild growing sweet cherry genotypes have different nutritional properties than light skin colored ones (Karlidag et al. 2009). The most often conducted experiments on the effect of rootstocks concern the evaluation of fruit quality characteristics during tree growth and development until fruit harvest (Kurlus 2008). However, the most frequent studies concern the effect of the rootstock on fruit quality characteristics during growth and development up to the time of harvest, while assessments of the effect of rootstock type on the properties of sweet cherry fruits during and after cool storage are rare and fragmented (Cavalheiro et al. 2005; Dziedzic et al. 2016, 2017). Therefore, we aimed to evaluate how the short-term storage of sweet cherry fruits relates to the effect of rootstocks, on which sweet cherry trees are cultivated in orchards. Over 2 years, we studied the effect of seven rootstocks (vigorous and dwarf) and two controlled atmosphere conditions (with high CO_2 concentration) on the quality of 'Regina' sweet cherry fruits after two-week cold storage. We also compared the present results with our earlier observations of the cultivar 'Regina' after storage in less favorable conditions.

2 Materials and methods

Trees of the sweet cherry (*Prunus avium* L) cultivar 'Regina' (late-season, large, dark red, firm, very resistant to rain cracking) were cultivated in the Experimental Station located near Krakow, 270 m above the sea level (50°09′ N, 19°56′ E). Trees were planted on seven rootstocks (Colt, Damil, Gisela 5, Mazzard F12.1, P - HL A, Tabel Edabriz and Weiroot 10) in 2003, in 5 × 2.5 m spacing. Weed control was maintained with herbicides in tree rows and with grass between rows. Flowers in the orchard were pollinated using pollen from the sweet cherry cv. 'Kordia'. Chemical protection of trees was carried out according to the recommendation for commercial orchards. Fruits were harvested on July 7th, 2014 and July 10th, 2015 during commercial maturity (stage). In 2015, there was no crop of sweet cherry fruits on trees growing on the 'Mazzard F12.1' rootstock. Immediately after harvest, fruits were transported to the laboratory (Department of Pomology and Apiculture) and subjected to a first assessment for firmness, soluble solids contents (SSC) and titratable acidity (TA). Random fruit samples (4 (replicates) × 500 g) from five trees from each rootstock combination were evaluated. Firmness was determining using a TA 500 Texture Analyzer (Lloyd Instruments Ltd., UK) equipped with an 8-mm tip and values were expressed in Newtons (N). Fruit SSC was determined by a digital refractometer (PR-101, Atago, Tokyo, Japan) at 20 °C and expressed as a percentage. Titratable acidity (TA) was determined by potentiometric titration to pH 8.1 with 0.1 N NaOH, up to pH 8.1 using 5 ml of diluted juice in 100 ml distilled H_2O, and the results were expressed as the percentage of malic acid. The color in the fruit peduncle was estimated visually, according to Royal Horticultural Society's Color Chart (RHS, UK). Fruit samples (replicates, 500 g each) from each treatment (3 storage combination × 7 rootstocks in 2014 and 3 storage combination × 6 rootstocks in 2015) were stored in plastic containers for 2 weeks, in three storage conditions: controlled atmosphere 1 (CA1) (15% CO_2 and 3% O_2, RH 90–92%, 2 °C (± 0.5 °C)), controlled atmosphere 2 (CA2) (20% CO_2 and 3% O_2, RH 90–92%, 2 °C (± 0.5 °C)), and normal atmosphere (NA) (RH 80%, 2 °C). After storage, the following fruit parameters were investigated: fruit firmness, SSC, TA and the SSC/TA ratio. The loss of fruit mass was recorded as a percentage by weighing fruit in each condition before and after the storage period. Moreover, maintenance of fungal decay and green color in the fruit peduncle was visually assessed and expressed as percentages. The greenness of the peduncle was assessed visually according to the Royal Horticultural Society's Color Chart (RHS, UK) as a percentage.

The average temperature and total precipitation were measured in May, June and July; during these months the average temperature was 13.6 °C, 13.8 °C and 20.2 °C, respectively, in 2014 and 12.9 °C 16.9 °C and 19.4 °C, respectively, in 2015. Total atmospheric precipitation was also recorded in May and June, and in July only until fruit harvest, and it amounted to 142.2 mm, 134.1 mm and 4.5 mm in 2014 and 141.4 mm, 92.7 mm and 35.6 mm in 2015, respectively.

2.1 Statistical analysis

The experiment was conducted over two seasons, with four replications for each combination. The data were analyzed using two-way analysis of variance (ANOVA) and Statistica software (StatSoft Inc., v.12, USA); calculations were conducted for each season separately. The values expressed as percentage were transformed according to the Bliss function ($y = \arcsin \sqrt{x}$). Tukey's HSD test was used to determine the significance of differences between mean values at the significance level of $p \leq 0.05$.

3 Results

3.1 Fruit quality at harvest

The analyses carried out after fruit harvest showed that the type of rootstock on which sweet cherry trees of the cultivar 'Regina' grew had a significant impact on all analyzed fruit quality parameters, except for fruit firmness, in both years of the experiment. Generally, the fruits had lower firmness in the first year (14.6 N) compared to the second year (18.4 N) of the experiment (Table 1). Each year, SSC and TA varied depending on the rootstock. The fruit from the Damil rootstock exhibited high SSC values in both the first and second year (16.0% and 18.7%, respectively) (Table 2). Fruit from the P- HL A rootstock exhibited higher titratable acidity (TA) in the first and the second year (0.69 mg 100 g^{-1} and 0.91 mg 100 g^{-1}, respectively), compared to fruits from the Damil (0.62·100 g^{-1} and 0.79 mg 100 g^{-1}, respectively) and Tabel-Edabriz rootstocks (0.60 mg 100 g^{-1} and 0.68 mg 100 g^{-1}, respectively) (Table 3). During both years, fruit from the Tabel-Edabriz rootstock had a high SSC to TA ratio (Table 4).

After 2 weeks of fruit storage, the studied factors—i.e., storage conditions and rootstocks on which 'Regina' sweet cherries trees grew—and the interaction between these factors significantly influenced the majority of the assessed fruit parameters.

Table 1 Fruit firmness (N) of 'Regina' sweet cherries directly after harvest and storage as affected by rootstocks and storage conditions

Year	Rootstock (A)	Harvest	Storage conditions (B)			Rootstock means
			NA	CA 1	CA 2	
2014	Colt	12.9 ± 2.94*	10.3 ± 2.42	12.4 ± 2.48	12.8 ± 1.88	12.1 ± 1.05
	Damil	15.9 ± 4.43	10.8 ± 2.03	13.8 ± 4.39	14.1 ± 3.05	13.7 ± 1.83
	Gisela 5	13.9 ± 2.42	11.3 ± 2.48	13.8 ± 2.08	13.8 ± 3.55	13.2 ± 1.10
	Mazzard F 12.1	13.2 ± 3.66	9.1 ± 2.42	12.0 ± 3.73	13.1 ± 3.49	11.9 ± 1.66
	P-HLA	14.6 ± 3.38	11.2 ± 2.49	14.3 ± 2.55	14.5 ± 2.68	13.7 ± 1.42
	Tabel-Edabriz	14.7 ± 3.60	11.8 ± 2.15	13.3 ± 2.86	14.2 ± 2.74	13.5 ± 1.11
	Weiroot 10	17.4 ± 5.25	10.6 ± 2.47	14.7 ± 4.44	15.0 ± 4.51	14.4 ± 2.44
Harvest/storage means		14.6 ± 1,46 b	10.7 ± 0.82 a	13.5 ± 0.91 b	13.9 ± 0.71 b	Rootstock means
2015	Colt	18.1 ± 2.98	14.5 ± 2.57	17.4 ± 3.55	17.0 ± 2.69	16.7 ± 1.36
	Damil	18.5 ± 2.62	17.4 ± 3.17	18.1 ± 3.54	18.1 ± 3.50	18.0 ± 0.40
	Gisela 5	19.1 ± 2.65	17.4 ± 2.97	18.7 ± 2.71	17.6 ± 3.17	18.2 ± 0.72
	P-HL A	17.5 ± 3.18	14.9 ± 2.07	17.0 ± 2.01	17.0 ± 2.78	16.6 ± 1.00
	Tabel-Edabriz	19.8 ± 4.51	15.5 ± 2.52	16.2 ± 3.04	16.3 ± 3.90	16.9 ± 1.67
	Weiroot 10	17.3 ± 3.11	13.7 ± 4.58	14.1 ± 3.96	16.3 ± 4.05	15.3 ± 1.50
Harvest/storage means		18.4 ± 0.87 b	15.6 ± 1.40 a	16.9 ± 1.49 ab	17.1 ± 0.65 ab	

*Means followed by the same small letter within a row and capital letter within a column, for each year, do not differ significantly at α = 0.05

NA normal atmosphere, *CA1* control atmosphere 15% CO_2 + 3% O_2, *CA2* control atmosphere 20% CO_2 + 3% O_2

Table 2 Soluble solids content (%) of 'Regina' sweet cherry directly after harvest and storage as affected by rootstock and storage conditions

Year	Rootstock (A)	Harvest	Storage conditions (B)			Rootstock means
			NA	CA 1	CA 2	
2014	Colt	15.7 ± 0.24 aCD*	15.9 ± 0.49 aC	15.5 ± 0.34 aBC	15.7 ± 0.52 aC	15.7 ± 0.14 c
	Damil	16.0 ± 0.63aD	16.1 ± 0.25 aC	16.5 ± 0.31 aD	16.6 ± 0.39 aD	16.3 ± 0.25 de
	Gisela 5	16.3 ± 0.24 aD	16.1 ± 0.62 aC	16.2 ± 0.31 aCD	15.6 ± 0.40 aC	16.1 ± 0.27 cd
	Mazzard F 12.1	11.4 ± 0.16 aA	11.9 ± 0.19 aA	11.2 ± 0.19 aA	11.5 ± 0.05 aA	11.5 ± 0.25 a
	P-HL A	15.0 ± 0.65 aC	15.0 ± 0.29 aB	15.5 ± 0.28 aBC	15.0 ± 0.16 aC	15.1 ± 0.22 b
	Tabel-Edabriz	16.0 ± 0.41 aD	17.2 ± 0.10 bD	16.9 ± 0.12 bD	16.7 ± 0.42 abD	16.7 ± 0.44 e
	Weiroot 10	13.9 ± 0.65 aB	15.6 ± 0.52cBC	15.0 ± 0.36 bcB	14.2 ± 0.16 abB	14.7 ± 0.67 b
Harvest/storage means		14.9 ± 1.71 a	15.4 ± 1.61 c	15.3 ± 1.80 bc	15.0 ± 1.71 ab	Rootstock means
2015	Colt	16.5 ± 0.41 aBC	17.6 ± 0.40 bB	17.6 ± 0.16 bC	17.1 ± 0.24 aC	17.2 ± 0.45 c
	Damil	18.7 ± 0.24 bD	18.4 ± 0.17 abC	17.9 ± 0.36 aC	18.3 ± 0.33 abD	18.3 ± 0.29 d
	Gisela 5	17.1 ± 0.73 aC	16.6 ± 0.26 aA	16.9 ± 0.54 aB	16.6 ± 0.28 aBC	16.8 ± 0.21 b
	P-HL A	15.8 ± 0.49 abA	16.3 ± 0.34 bA	15.7 ± 0.08 abA	15.4 ± 0.10 aA	15.8 ± 0.32 a
	Tabel-Edabriz	22.4 ± 0.62 abE	22.7 ± 0.12 abD	22.0 ± 0.16 aD	22.9 ± 0.22 bE	22.5 ± 0.34 e
	Weiroot 10	16.1 ± 0.16 aAB	15.9 ± 0.09 aA	16.2 ± 0.68 aA	16.0 ± 0.14 aAB	16.0 ± 0.11 a
Harvest/storage means		17.8 ± 2.27 a	17.9 ± 4.10 a	17.7 ± 3.49 a	17.7 ± 3.82 a	

*Means followed by the same small letter within a row and capital letter within a column, for each year, do not differ significantly at α = 0.05

3.2 Fruit quality after two-weeks of storage

3.2.1 Firmness

In both years the firmness of the sweet cherry fruit was lower after storage in the NA condition than at harvest time (Table 1). The controlled atmosphere (CA) conditions preserved the firmness of stored fruit at the same level as at harvest time. There was no difference in fruit firmness between two different atmosphere compositions—CA1 and CA2. The effect of rootstock type on the firmness value was not noted. Also, no significant interaction was found between studied experimental factors (rootstock and storage condition) and fruit firmness.

3.2.2 Soluble solids content (SSC)

The studied factors had a significant effect on SSC in fruits for both years, except for the storage condition in the second year (Table 2). In the first year, the increase of SSC in fruits from the NA and CA1 storage conditions in relation to the values measured at harvest time was noted. The effect

Table 3 Titratable Acidity (mg 100 g^{-1}) of 'Regina' Sweet Cherry Directly after Harvest and Storage as Affected by Rootstock and Storage Conditions

Year	Rootstock (A)	Harvest	Storage conditions (B)			Rootstock means
			NA	CA 1	CA 2	
2014	Colt	0.63 ± 0.02 bAB*	0.51 ± 0.02 aC	0.54 ± 0.01 aBC	0.54 ± 0.01 aB	0.55 ± 0.05 c
	Damil	0.62 ± 0.02 cAB	0.47 ± 0.02 aAB	0.54 ± 0.00 bBC	0.53 ± 0.01 bAB	0.54 ± 0.05 bc
	Gisela 5	0.64 ± 0.03 bBC	0.48 ± 0.03 aBC	0.51 ± 0.00 abAB	0.50 ± 0.01 abA	0.53 ± 0.06 b
	Mazzard F 12.1	0.67 ± 0.03 bCD	0.51 ± 0.02 aC	0.54 ± 0.02 aBC	0.55 ± 0.01 aB	0.57 ± 0.06 d
	P-HL A	0.69 ± 0.02 cD	0.50 ± 0.04 aBC	0.56 ± 0.01 bC	0.55 ± 0.01 bB	0.57 ± 0.07 d
	Tabel-Edabriz	0.60 ± 0.01 cA	0.44 ± 0.02 aA	0.48 ± 0.01 abA	0.51 ± 0.00 bA	0.51 ± 0.06 a
	Weiroot 10	0.65 ± 0.03 cBC	0.48 ± 0.01 aBC	0.53 ± 0.01 bBC	0.53 ± 0.01 bAB	0.55 ± 0.06 c
Harvest/Storage means		0.64 ± 0.03 c	0.49 ± 0.03 a	0.53 ± 0.03 b	0.53 ± 0.02 b	Rootstock means
2015	Colt	0.75 ± 0.04 aB	0.72 ± 0.02 aB	0.74 ± 0,01 aBC	0.72 ± 0,01 aC	0.73 ± 0.01 c
	Damil	0.79 ± 0.02 aB	0.75 ± 0.02 aB	0.75 ± 0.04 aBC	0.81 ± 0.06 aD	0.78 ± 0.03 de
	Gisela 5	0.87 ± 0.02 bC	0.72 ± 0.03 aB	0.72 ± 0.01 aB	0.72 ± 0.02 aC	0.76 ± 0.06 d
	P-HL A	0.91 ± 0.03 cC	0.72 ± 0.02 aB	0.78 ± 0.06 abC	0.81 ± 0,01 bD	0.80 ± 0.07 e
	Tabel-Edabriz	0.68 ± 0.03 cA	0.51 ± 0.02 aA	0.56 ± 0.02 abA	0.61 ± 0.01 bB	0.59 ± 0.06 b
	Weiroot 10	0.63 ± 0.02 bA	0.49 ± 0.01 aA	0.51 ± 0.01 aA	0.51 ± 0.01 aA	0.53 ± 0.06 a
Harvest/Storage means		0.77 ± 0.10 c	0.65 ± 0.17 a	0.68 ± 0.15 b	0.70 ± 0.16 b	

*Means followed by the same small letter within a row and capital letter within a column, for each year, do not differ significantly at α = 0.05

Table 4 Soluble solids to acids ratio (SSC/TA) of 'Regina' sweet cherry directly after harvest and storage as affected by rootstock and storage conditions

Year	Rootstock (A)	Harvest	Storage conditions (B)			Rootstock means
			NA	CA 1	CA 2	
2014	Colt	24.9 ± 0.73 aC*	31.2 ± 1.33 bBC	29.0 ± 0.78 bBCD	28.8 ± 0.64 bBC	28.5 ± 2.27 c
	Damil	25.7 ± 0.24 aC	33.9 ± 1.29 bC	30.7 ± 0.81 bCD	31.3 ± 0.42 bCD	30.4 ± 2.97 d
	Gisela 5	25.4 ± 0.93 aC	34.0 ± 1.41 cC	31.9 ± 0.95 bcD	31.0 ± 1.21 bCD	30.6 ± 3.18 d
	Mazzard F 12.1	17.0 ± 0.82 aA	23.1 ± 1.34 bA	20.6 ± 1.08 bA	20.9 ± 0.61 bA	20.4 ± 2.19 a
	P-HL A	21.7 ± 0.65 aB	30.0 ± 2.68 bB	27.6 ± 1.23 bB	27.5 ± 0.66 bB	26.7 ± 3.06 b
	Tabel-Edabriz	26.7 ± 0.24 aC	39.0 ± 1.89 cD	35.0 ± 0.46 bE	33.0 ± 1.16 bD	33.4 ± 4.44 e
	Weiroot 10	21.4 ± 0.57 aB	30.5 ± 1.51 cB	28.4 ± 1.27 bcBC	26.9 ± 0.56 bB	26.8 ± 3.37 b
Harvest/Storage means		23.3 ± 3,17 a	31.6 ± 4.80 c	29.0 ± 4.26 b	28.5 ± 3.80 b	Rootstock means
2015	Colt	22.0 ± 0.22 aC	24.3 ± 0.40 bA	23.8 ± 0.29 abB	23.7 ± 0.50 abB	23.4 ± 0.87 bc
	Damil	23.7 ± 0.65 aCD	24.5 ± 0.31 aA	23.9 ± 1.65 aB	22.7 ± 1.72 aB	23.7 ± 0.65 c
	Gisela 5	19.7 ± 0.49 aB	23.1 ± 1.28 bA	23.4 ± 0.48 bB	22.9 ± 0.17 bB	22.3 ± 1.50 b
	P-HL A	17.3 ± 0.63 aA	22.6 ± 0.86 cA	20.3 ± 1.37 bA	19.0 ± 0.25 abA	19.8 ± 1.94 a
	Tabel-Edabriz	32.9 ± 0.69 aE	43.1 ± 1.73 cC	39.3 ± 1.34 bD	37.5 ± 0.85 bD	38.5 ± 4.08 e
	Weiroot 10	25.6 ± 0.82 aD	32.4 ± 0.39 bB	31.7 ± 1.84 bC	31.4 ± 0.57 bC	30.3 ± 2.72 d
Harvest/Storage means		23.5 ± 4,97 a	28.5 ± 8.97 c	27.1 ± 7.31 b	26.2 ± 7.30 b	

*Means followed by the same small letter within a row and capital letter within a column, for each year, do not differ significantly at α = 0.05

of rootstocks on the value of this parameter was diversified, whereby the fruits from the Tabel-Edabriz (16.7% and 22.5%, first and second year, respectively) and Damil (16.3% and 18.3%, respectively) rootstocks were characterized by high mean SSC. At harvest time and after the storage period in all storage conditions, the fruits from the Mazzard F12.1 rootstock in the first year and P-HL A rootstock in the second year were characterized by lower SSC values than other rootstocks. On the other hand, the fruits from the NA and CA1 conditions exhibited higher SSC in relation to harvest time on the Tabel-Edabriz and Weiroot 10 rootstocks in the first year, and on the Colt rootstock in the second year.

3.2.3 Titratable acidity (TA)

During the experimental years, a significant effect was found between the studied factors and TA in fruits. In both years, the organic acids content was significantly lower after storage compared to at harvest time (Table 3). Also, in both years, the CA1 and CA2 conditions inhibited the disintegration of organic acids in stored fruits much more effectively than the NA condition. In the two years, fruits from the P-HL A rootstock were characterized by high organic acid content. Fruits from the Tabel-Edabriz rootstock (both years) and the Weiroot 10 rootstock (second year) exhibited the highest decrease in titratable acids content. Organic acids content measured at harvest time was generally significantly higher than after fruit storage, except for fruits from the Colt and Damil rootstocks in the second year.

3.2.4 SSC to TA ratio

The studied factors had a significant impact on the SSC/TA ratio in fruits over both experimental years. The SSC/TA ratio was higher after the storage period than at harvest time (Table 4). The SSC/TA ratio was highest in fruit stored under the NA condition. The composition of the controlled atmospheres (CA1 and CA2) did not affect the value of the discussed ratio. Rootstock type had a significant effect on the SSC/TA ratio in both years, and the ratio was highest on the Tabel-Edabriz rootstock (33.4 and 38.5, first and second year, respectively). A low SSC/TA ratio was found in fruits from the Mazzard F12.1 and P-HL A rootstocks in the first year and the P-HL A rootstock in the second year. Generally, this ratio was higher after storing than at harvest time, except for the Damil rootstock in the second year.

3.2.5 Natural weight losses

Fruit mass loss is one of the adverse effects of fruit storage (Fig. 1).

The value of this parameter was affected only by the storage conditions, whereas fruit weight was significantly higher after storage in the NA condition than in other two storage conditions. The composition of the controlled atmospheres did not affect fruit weight losses in either years.

3.2.6 Fungal decay

After storing, fungal decay caused by *Monilinia laxa* was observed (Table 5). Generally, the sweet cherry fruits were healthy after the storage period. Fungal decay in fruit depended on both storage conditions and rootstock type, and the interaction between the studied factors. The highest percentage of fruit with symptoms of fungal diseases was recorded in NA. In the first year, the most decayed fruits were found from the Mazzard F12.1 rootstock (4.1%). The degree of fruit infection from the Damil, Gisela 5, Tabel-Edabriz and Weiroot 10 rootstocks was low, less than 1% each. In the second year, fruits from the Weiroot 10 rootstock exhibited greater susceptibility to fungal diseases. Interactions between studied factors were also found, but the effect of these interaction depended on the year.

3.2.7 Maintenance of green peduncle

Sweet cherry fruits are harvested and stored together with the peduncle. After the storage period, their quality was assessed in terms of how well the green color was preserved in the peduncle. The influence of refrigeration conditions became apparent in the second year of research, while the type of rootstock had a significant impact on this trait in both years of the experiment (Fig. 2 and 3).

The high concentration of CO_2 under the cold conditions of CA1 and CA2 contributed to the preservation of the green color in the peduncle in up to 80% of the fruits. In regard to rootstocks, Colt, Gisela 5 and P-HL A in particular positively affected the preservation of peduncle color.

4 Discussion

Weather conditions during fruit ripening and fruit growth directly after harvesting have huge impacts on the quality characteristics of harvested fruits, as well as their quality after storage. In the present experiment, rootstock did not appear to affect fruit firmness, unlike in our previous research (Dziedzic et al. 2016, 2017). Over the two years of study, the weather parameters were measured until fruit harvesting, and weather conditions were found to be different between the two years. In second year, the mean temperature was slightly higher (1.6 °C), wherein the mean sum of precipitation was lower (11.1 mm) compared to the first year; hence, the second year was recognized as warmer and dryer. The discussed studies proved that after harvest the fruit exhibited better quality parameters—i.e., firmness

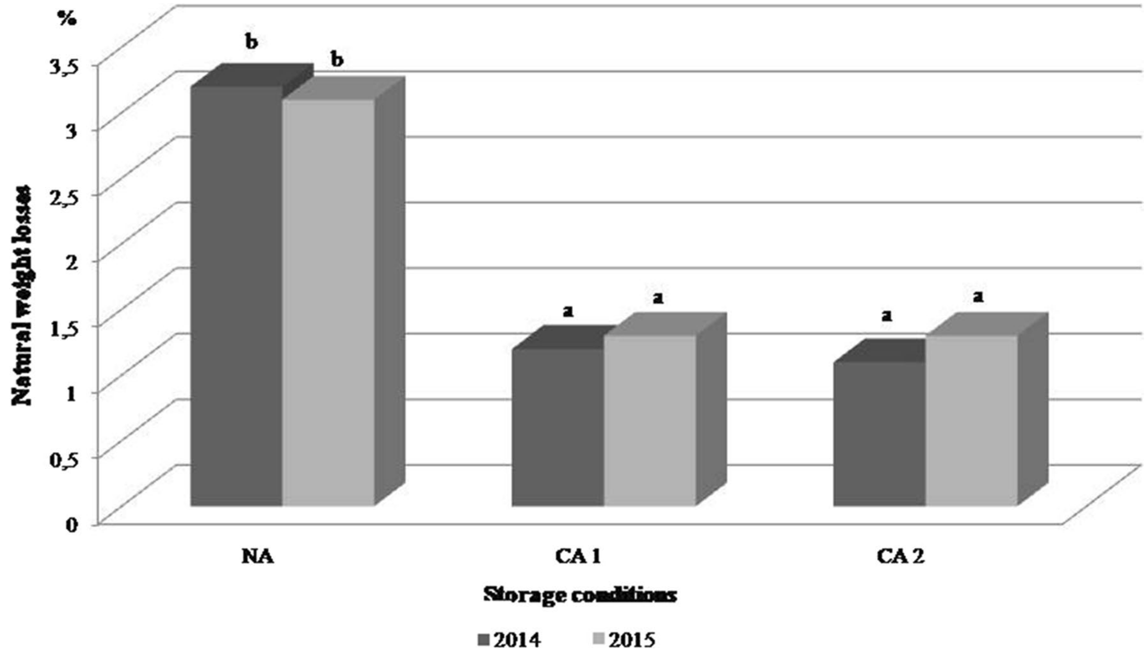

Fig. 1 Natural weight loss (%) of 'Regina' sweet cherry directly after storage as affected by storage conditions

Table 5 Percent of 'Regina' sweet cherry with brown rot symptoms directly after storage as affected by rootstock and storage conditions

Year	Rootstock (A)	Storage conditions (B)			Rootstock means
		NA	CA 1	CA 2	
2014	Colt	4.4 cC*	0.0 aA	1.8 bB	2.1 c
	Damil	1.0 bAB	0.0 aA	0.0 aA	0.3 a
	Gisela 5	1.1 bAB	0.5 bA	0.0 aA	0.5 ab
	Mazzard F 12.1	5.4 bC	4.3 bC	2.5 aB	4.1 d
	P-HL A	1.9 bB	2.4 bB	0.0 aA	1.4 bc
	Tabel-Edabriz	1.7 cAB	0.0 aA	0.5 bA	0.7 ab
	Weiroot 10	0.5 aA	0.5 aA	1.7 bB	0.9 ab
Storage means		2.3 b	1.0 a	1.0 a	Rootstock means
2015	Colt	3.3 bAB	3.1 bB	0.5 aA	2.3 a
	Damil	2.8 bA	2.7 bB	0.0 aA	1.8 a
	Gisela 5	4.5 cBC	2.6 bB	0.0 aA	2.4 a
	P-HL A	5.4 bCD	0.0 aA	0.3 aA	1.9 a
	Tabel-Edabriz	6.7 bDE	0.0 aA	0.0 aA	2.2 a
	Weiroot 10	7.5 cE	4.3 bC	0.0 aA	3.9 b
Storage means		5.0 c	2.1 b	0.1 a	

*Means followed by the same small letter within a row and capital letter within a column, for each year, do not differ significantly at $\alpha = 0.05$

and SSC—in the second year. Rootstocks can have different effects on the cultivars of sweet cherries grafted on them under different climatic and soil conditions (Hilsendegen 2004; Wociór 2008; Cantin et al. 2010) and can modify a wide range of fruit quality parameters (Gonçalves et al. 2005; Lugli and Sansavini 2008; Rozpara 2008; Kankaya et al. 2008). Our previous research (Dziedzic 2012; Dziedzic et al. 2016, 2017), as well as the current study, indicate that vigorous rootstocks, especially the Mazzard F12.1 clone, significantly affect the level of SSC in cherry fruits.

The SSC to TA ratio is often referred to as the 'ripening index', and it can be used to very precisely determine the optimal date for harvesting sweet cherries, as demonstrated by Çalhan et al. (2014). Index is also an indicator of the readiness of dessert fruits for consumption and has a great importance for measuring the taste perceived by consumers. In our previous studies (Dziedzic 2012; Dziedzic et al. 2016, 2017), the index was generally high, which was related to the relatively low content of organic acids. The highest rated fruits by consumers were also characterized by high values

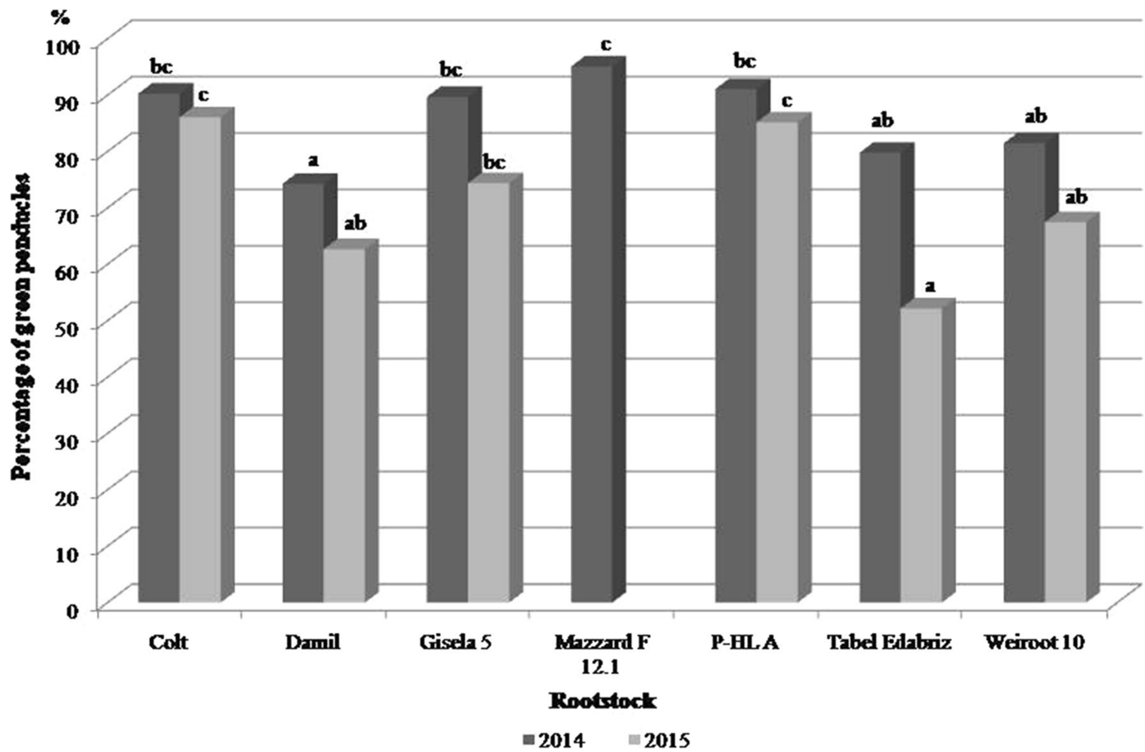

Fig. 2 Percentage of green peduncles in 'Regina' sweet cherry directly after storage as affected by rootstock

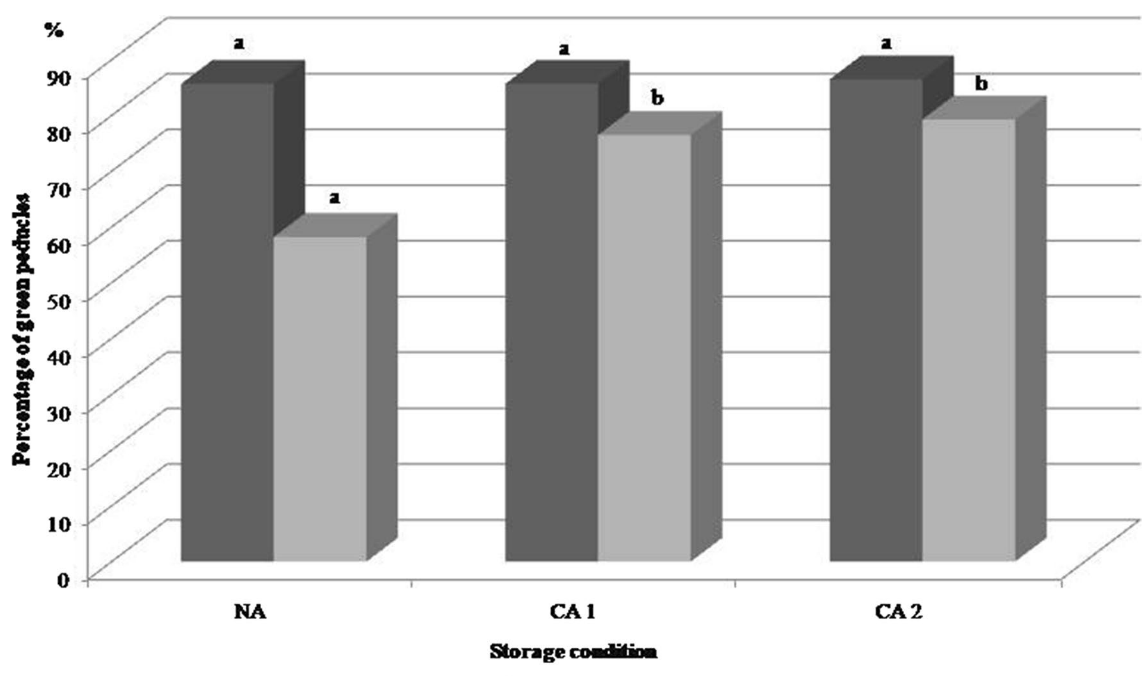

Fig. 3 Percentage of green peduncles in 'Regina' sweet cherry directly after storage as affected by storage conditions

of this coefficient (over 30) (Crisosto et al. 2003; Turner et al. 2008).

Sweet cherries can generally be stored for 1–4 weeks at 0 °C and 90% relative humidity (RH) (Esti et al. 2002). After fruit storage, we did not observe any injury from CO_2. According to the literature, the sweet cherry fruits are more resistant to high concentrations of CO_2, even 20%, than pome fruits are (Jiang et al. 2002; Goliaš et al. 2006). Maintaining satisfactory firmness of the flesh after fruit storage in a cold room is one of the most important goals, because sweet cherries belong to a group of perishable fruits harvested at the stage of consumption maturity. We noted that the use of high CO_2 concentrations (15% and 20% in CA1 and CA2, respectively) in the controlled atmosphere chambers influenced the preservation of firmness in comparison to the measurement directly after fruit harvest. In the present experiment, we found that only the storage conditions affected fruit firmness, while the effect of the rootstocks (on which the cherry trees were grown) was negligible, similar to our earlier studies (Dziedzic et al. 2016, 2017) and in contrast to Cavalhiero et al. (2005).

Our observations, indicating that high CO_2 concentration and low temperature favor preserving high fruit firmness, are consistent with the results in other experiments—e.g., for the cultivars 'Napoleon' (Jiang et al. 2002) and 'Vanda' and 'Van' (Goliáš et al. 2006). According to the latest observations, biochemical processes (associated with cell wall modification), resulting from enzymatic activity and dehydroascorbic acid content, are responsible for maintaining or decreasing fruit firmness after storage (Belge et al. 2015). Individual sweet cherry cultivars vary in the contents of these components, hence their different susceptibility to storage conditions.

There are several reasons for the changes in SSC content in fruits during storage. These changes are the result of metabolic changes during fruit ripening, sugar concentrations under low temperature, and dehydration of fruit tissue (Kappel et al. 2002; Cavalheiro et al. 2005; Horák et al. 2016). Wang and Vestrheim (2002) and Tian et al. (2004) reported that increasing the CO_2 content in the atmosphere during sweet cherry storage helped maintain high fruit quality. First of all, attention should be paid to preserve a high level of fruit SSC after storage, because it affects the taste assessment. Only the Damil, Gisela 5 and Tabel Edabriz rootstocks affected the fruit SSC level that is widely accepted by consumers, i.e., $\geq 16\%$ in both years of the experiment, in all tested storage combinations (Kappel et al. 1996). The study of Cavalheiro et al. (2005) confirmed the Tabel Edabriz rootstock contributed to the high SSC content in fruits after 42 days of storage.

Changes related to organic acid content occur in parallel to SSC changes in fruits, because organic acids, like sugars, are the basic substrates in the process of fruit respiration (Wang and Lang 2014; Wani et al. 2014). Studies indicate that sweet cherries are characterized by high respiration intensity, which adversely affects internal and external changes in fruit quality (Akbudak et al. 2008, 2009). The beneficial effect of high CO_2 concentration in reducing the decrease in organic acid contents demonstrated in the present experiment is consistent with other studies (Esti et al. 2002; Tian et al. 2004). Acids content is associated with pH values, and as pH increases, the color of anthocyanins changes (Gonçalves et al. 2007). We emphasize that changes in fruit TA content after storage are strongly influenced by rapid cooling (with air or water) of fruits directly after harvest, preferably up to 4 h (Bernalte et al. 2003; Akbulut et al. 2008). Our evaluation of the impact of several rootstocks on the TA level after fruit storage is a novelty of our research. In our experiment, low TA values were recorded for fruits from the Tabel Edabriz rootstock, just like in Cavalheiro et al. (2005) under the same CA conditions, i.e., 15% and 20% CO_2 concentrations.

As already mentioned above, the ratio of SSC to TA is a very important parameter of fruit quality assessment. The high value of this coefficient in the present study in fruits after storage is in accordance with our expectations and confirmed by our previous observations (Dziedzic et al. 2016, 2017). According to Crisosto et al. (2003) and Kalyoncu et al. (2009), the higher this coefficient, the better consumers judge a fruit to be. The index has an impact on consumer taste impressions; for sweet cherries, which are mainly dessert fruits, it should be higher than 20 (Kader 1999). The level of this coefficient is influenced by all changes in SSC content and TA, and these variables are known to depend on the impact of storage conditions and rootstocks.

The observed decreases in fruit weight after storage are mainly due to the loss of water through the fruit and peduncle, resulting in fruit skin wrinkling and wilting, and even drying of the peduncle, with the peduncle showing eight times higher water losses compared to the fruit (Linke et al. 2010). Sweet cherry fruits are characterized by low resistance to diffusion through the skin and a higher surface area vs. volume than other fruits (Wani et al. 2014). Our study recorded weight losses only in relation to the storage conditions (three times higher in NA than in both CA combinations), and many other authors have observed the same trend in other sweet cherry cultivars (Szymczak et al. 2003; Padilla-Zakour et al. 2004; Goliáš et al. 2007). Loss of fruit mass during storage affects the shelf-life and deteriorates fruit quality after storage (Serrano et al. 2005).

High sensitivity to fungal diseases in sweet cherry fruits is one of the factors preventing them from being stored longer. In temperate climate conditions during the cherry harvest period, precipitation often occurs and reduces the value of fruit with delicate flesh and thin skin. In our research, such a relationship was observed in 2015, when there was an increased rainfall before the fruit harvest. After storage, the percentage of fruits showing fungal decay was greater in this year, especially in the NA condition. A higher percentage of fruit fungal diseases from individual rootstocks was also observed that year.

Only cold storage with higher CO_2 concentration (20%) effectively reduced fungal fruit infections. The presented results are consistent with our previous observations (Dziedzic et al. 2017), where we showed that atmosphere composition (increased CO_2 concentration) had a more favorable effect on reducing diseases compared to low temperature; they are also in line with the results obtained by Tian et al. (2004). DeVries-Patterson et al. (1991) showed that high CO_2 concentration reduced the risk of fungal fruit infection during storage, and sweet cherries tolerate such atmospheric gas composition particularly well (Wang and Vestrheim 2002).

Increasingly, attention is also being paid to the appearance of the fruit peduncle, which is an important element affecting the assessment of fruit quality. Sweet cherries, as typical dessert fruits, are collected and stored together with peduncles, which prevents juice leaking from the flesh of the fruits. Currently, consumers prefer new sweet cherry cultivars with a short peduncle (Gjamovski et al. 2016) over the local cultivars characterized by a long peduncle, and this significantly hampers the harvest (Perez-Sanchez et al. 2010). However, the presence of oxygen in the air and high temperature cause that the peduncle to quickly release water and the chlorophyll in its tissues to degrade after the harvest (Sen et al. 2014); therefore, the preservation of green color in the peduncle is one of the determinants for assessing good fruit quality after storage. Atmosphere composition (Drake and Elfving 2002) as well as humidity and temperature (Goliaš et al. 2006, 2007) are factors that play a major role in maintaining the green peduncle. The present results in the second year indicate that the controlled atmosphere has a beneficial effect on a high percentage of fruits with a green peduncle. In our previous studies (Dziedzic et al. 2016, 2017), we also noted a high percentage of green in peduncles under CA conditions, despite the lower CO_2 content compared to the current experiment. Different rootstocks were also observed to have different effects on the greenness of the peduncle; in particular, the Gisela 5 and P-HL A and Colt rootstocks showed a satisfactory effect on this trait, as in other studies (Cavalheiro et al. 2005; Dziedzic et al. 2016, 2017).

5 Conclusions

The weather conditions prevailing in a given year have a significant impact on fruit quality during harvest and after storage. Cold storage in a controlled atmosphere with a high CO_2 content is recommended for the short-term storage of sweet cherry fruits because it preserved several fruit quality parameters: the maintenance of fruit firmness and titratable acidity at a good level, high SSC to TA ratio, low fruit weight losses, low percent of fungal infections caused by *Monilinia laxa,* good preservation of green color in the peduncle. The rootstocks on which the trees grew affected not only fruit quality parameters during harvest, but also their preservation after the storage period, except the fruit firmness.

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Author contribution ED and JB performed the experiments, analyzed the data and wrote the paper.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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