

## Article

# Effect of Storage Conditions on Storability and Antioxidant Potential of Pears cv. ‘Conference’

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**Abstract:** Late pear cultivars, such as ‘Conference’, can be stored for a long period if kept in good storage conditions. A three-year study (2011–2013) compared the impact of six-month storage using four technologies—normal atmosphere, normal atmosphere + 1-methylcyclopropene (1-MCP), controlled atmosphere, and controlled atmosphere + 1-MCP—on the quality parameters of ‘Conference’ pears, such as mass loss, firmness, total soluble solids, acidity, antioxidant capacity, and the incidence of diseases and disorders. Additionally, the study analysed different storage conditions in terms of profitability, based on the market prices for pears in the seasons during which the pears were stored. The storage conditions had a very strong influence on the fruit quality parameters, and were found to affect most visibly the mass loss and the incidence of postharvest diseases and disorders. The 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 controlled atmosphere for the same period, no matter whether 1-MCP was applied or not.



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**Keywords:** rootstock; 1-MCP; cost-effectiveness of technology; controlled atmosphere; cold storage; ORAC; TSS; acidity; firmness

## 1. Introduction

Pears are the most cultivated pome species in the world after apples [1]. Pear cv. ‘Conference’ is the most important cultivars in Europe with a yearly production of around 1 million tonnes [2]. It is also one of the most commonly stored pear cultivars. The storability of pear, which is a typical climacteric species [3], depends on various factors [4], most notably, the optimal harvest date [5], the fruit cooling rate after harvest [6], the degree of pollination and rootstock [7], storage conditions [8], fertilization, and health [9]. For example, studies conducted on the influence of pollination on the quality properties of ‘Conference’ pears showed that the number of seeds was positively correlated with fruit mass and calcium content, but was negatively correlated with total soluble solids and firmness [7], and the initial TSS value and firmness are crucial for storability assessment.

Sometimes, however, as in the case of apples, other factors may contribute, such as the rootstock used, which, by affecting the nutrition of trees, can influence the properties of the stored fruit [10]. Temperature is a factor that crucially influences the rate of any reaction, in particular, of respiration-related reactions [11]. The optimal fruit storage temperature depends on the species, and sometimes on the cultivar [12]. Pears belong to the few fruit species which suffer no damage if stored at a temperature below zero. The optimal temperature is between  $-1$  and  $0$  °C, with a clear preference towards the negative temperature [13]. As early as 1964, Porrit found out that the storage life of ‘d’Anjou’ and ‘Bartlett’ pear was, respectively, 35% and 40% longer at  $-1$  °C than at  $0$  °C [14].

Controlled atmosphere (CA) storage significantly extends the storability of pears compared to normal atmosphere (NA) [4]. CA storage delays ripening and preserves fruit

quality [15], but it may cause a decrease in the production of aromatic compounds [16]. The very low oxygen content (ULO) commonly used for long-term storage of apples cannot be used for pears due to their greater susceptibility to damage due to oxygen deficiency [17]. Low oxygen levels trigger anaerobic respiration resulting in the accumulation of alcohol in pears, which is directly responsible for damage to the flesh [18]. This can be prevented by the monitoring of changes in the alcoholic respiration in the atmosphere [19]. However, in controlled atmosphere, it is the internal disorders, such as internal browning, which are a major limiting factor [20]. In addition, high carbon dioxide content may cause internal browning in many cultivars, and ‘Conference’ pears are considered to be sensitive to high levels of this gas [21].

Another method used in recent years to improve storability is to use substances that limit ethylene production in climacteric fruit species [22]. One such substance is 1-methylcyclopropene (1-MCP), which has been used for nearly two decades [23]. In both NA and CA cold storage, 1-MCP can be applied to maintain the quality attributes of fruit, especially firmness. 1-MCP, a gaseous ethylene binding inhibitor, has proven useful in preventing the formation of ethylene in fruit, thus increasing its shelf life after harvest and enabling greater flexibility in distribution and retailing [24]. However, it has been shown that, unlike in apples, low doses of 1-MCP do not completely inhibit ethylene production in pears. 1-MCP interacts with fruit in manifold ways. It can limit the development of fungal diseases. It can also reduce the occurrence of superficial scald [25], but it may also cause an unexpected increase in the incidence of this physiological disorder [26]. However, despite the risk of this negative effect, the benefits of 1-MCP application for other quality parameters and storability are significant and can be observed in all climacteric fruit species [24]. The most important of them include the limitation of the incidence of fungal diseases strictly associated with senescence, and the reduction in transpiration and respiration, which translates into lower storage costs, as the fruit produces less heat at the same temperature. Other important advantages of using 1-MCP include the limitation of: vitamin C losses during storage, the incidence of chilling disorders in tropical fruit species (avocado, mango, papaya) and unwanted changes in flesh structure, such as woolliness (mealiness) and internal breakdown in peaches and nectarines [24]. However, the occurrence of disease is specific to particular fruit species and the conditions in which they are grown and stored, and therefore more detailed studies are still needed in this area [24,27].

Pears have moderate antioxidant activity, but because of relatively high consumption of pears in Europe [1], they are an important source of health-promoting compounds [28]. Pears owe their antioxidant potential to such bioactive compounds as polyphenols, triterpenoids, carotenoids, and chlorophylls, and also have anti-inflammatory and anti-proliferative properties [29].

The antioxidant capacity of food, including fruit and vegetables, depends on the presence of complex bioactive compounds which differ considerably not only in terms of compound class and chemical makeup, but also bioavailability, due to the complex composition of food and the interaction between individual nutrients [30]. The literature provides ample information on the complex nature of the antioxidant activity of food products [31]. In this context, a distinction is often made between extractable and non-extractable antioxidants, the presence (or absence) of which determines how nutritional or healthy a food product is [31]. Residues left after the extraction of bioactive compounds from fruit still show antioxidant activity, so various complex extraction methods are applied to determine more precisely the total antioxidant capacity of food, including that of compounds linked by covalent or hydrogen bonds or forming hydrophobic interactions with other nutritional components such as carbohydrates or proteins. Antioxidant capacity is typically measured in water–alcohol or acidic extracts; however, in complex systems, such as food products, other hydrolysis and extraction methods are also needed to determine the total value of this parameter. A method commonly applied in science to determine the

antioxidant capacity of food is to measure the ABTS\* cation radical scavenging activity of 70% methanol extracts (*v/v*) from food samples [32].

The objective of this study was to assess (1) the impact of storage conditions on monthly qualitative changes in 'Conference' pears during six months of storage, (2) the effect of the rootstock on the storability of 'Conference' pears, (3) the impact of 1-MCP application on the storability of 'Conference' pears, and how all these factors translate into revenues from the sale of pears after storage.

## 2. Materials and Methods

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 planted in spring 2002 at spacing of 4 × 1.5 m. Pears were grafted on three different rootstocks: *Pyrus caucasica* Federov, Pyrodwarf, and Quince S1. There were 64 trees on each rootstock. The pear orchard was maintained according to the standard commercial practice for integrated fruit production.

### 2.1. Sampling

The experiment was carried out from autumn 2011 to spring 2014. The harvest occurred on dates determined as the optimum harvest dates (OHD), using the starch test [33] and the sum of active temperatures (growing degree units) method proposed by Łysiak [34]. The sum of active temperatures determined according to the latter method was 2580 degrees.

After harvest, pears intended for storage were graded to eliminate those not meeting the highest commercial quality standard applicable in OECD countries [35]. According to those standards, pears of superior quality ("extra"), have to be intact, sound, clean, and free of any damage. The experiment was carried out using 20 boxes of 15 kg of graded pears. Each box contained about 75 pears.

### 2.2. Storage Conditions

After harvesting and sorting, the fruit was put in the cold chamber for 48 h to stabilize the fruit temperature. Then half of the fruit (10 boxes) was inserted into a gas-tight chamber where 1-MCP was applied at a dose of 0.05 gm<sup>-3</sup> for 24 h. After the application, the fruit was placed in four experimental gas-tight chambers with a capacity of 1 m<sup>3</sup> each (5 boxes per each chamber). The following storage conditions were applied:

1. Normal atmosphere (NA), temp. −1 °C.
2. Normal atmosphere (NA), + 1-MCP, temp. −1 °C.
3. Controlled atmosphere (CA) 2% O<sub>2</sub> + 1% CO<sub>2</sub>, temp. −1 °C.
4. Controlled atmosphere (CA) 2% O<sub>2</sub> + 1% CO<sub>2</sub>, + 1-MCP, temp. −1 °C.

### 2.3. Quality Measurements

1. Loss of fruit mass was measured in each stored box. Ten pears were numbered and weighed with an accuracy of 0.1 g before and after each month of storage. The mass loss is shown as a percentage of the initial mass.
2. Firmness was measured using a Fruit Tester 327 EFFEGI FT327 penetrometer (Facchini srl, Alfonsine, Italy), mounted on a stand. The maximum penetration force of a probe of 8 mm in length and 11 mm in diameter, applied to a small area with skin removed, on two opposite sides of the fruit, was recorded.
3. Total soluble solids (TSS) were determined using an ATAGO PAL-1 digital refractometer with automatic temperature compensation (Atago, Tokyo, Japan). The results were shown as an average of nine repetitions per sample and expressed as percentage values.
4. Titratable acidity (TA): titration with 1n NaOH to 8.1 pH, mval 100 mL<sup>-1</sup>; the results were expressed as mmol of malic acid per kg of fresh mass.

5. Starch pattern during harvest was determined with Lugol's iodine (measured according to a 10-point scale where 10 means no starch on the pear cross section) [36].
6. The Streif index is a combination of firmness (F), soluble solids content (R) and starch index (S) according the formula:

$$\text{Index} = F/RS$$

#### 2.4. Measurement of Antioxidant Capacity

Antioxidant capacity of methanol extracts was determined by means of spectrophotometric method using a cationic radical (ABTS+) [2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid)] [32]. The ABTS+ cation was generated by mixing 7 mM ABTS and 2.45 mM  $K_2S_2O_8$  (potassium persulfate or potassium peroxydisulfate) solutions at a ratio of 1:0.5. The ABTS+ cationic radical solution and 70% methanol extract (*v/v*) samples were diluted using Phosphate Buffer Solution (PBS) pH 7.4. Absorbance was measured at a wavelength of 734 nm on samples incubated for 6 min at 30 °C against PBS as a reference assay. Antioxidant capacity was determined based on the percentage reduction in absorbance of the ABTS+ cationic radical solution by the sample compared to the reducing power of Trolox (6-hydroxy-2,5,7,8-tetramethylchromate-2-carboxylic acid). The measurements were conducted using a Helios Alpha spectrophotometer (Thermo Electron Corporation Waltham, MA, USA) equipped with a water bath for the thermostating of samples. The results were expressed as an average of nine repetitions per sample and expressed in  $\mu\text{mol Trolox/g d.m.}$

#### 2.5. Incidence of Diseases and Disorders

Fruit was harvested in line with commercial quality standards and was free from diseases and disorders. After 6 months of storage, the pears were assessed for the presence of physiological disorders and fungal diseases. Fruit showing symptoms of, respectively, physiological diseases (internal browning and senescent scald) and fungal diseases was counted for each treatment. The identified fungal diseases included: gray mold caused by *Botrytis cinerea* Pers., blue mold caused by *Penicillium* spp., bitter rot caused by *Colletotrichum* spp., and brown rot caused by *Monilinia* spp. or *Sclerotinia fructigena*. Next, all pears were counted per box, and each box was treated as one repetition. The results were expressed as a percentage share of infected/damaged fruit in the total number of evaluated fruit.

#### 2.6. Economic Viability

Prices were obtained from "Fruga", a company trading on the Polish market in fruit produced in Poland and imported from other EU countries. The calculation was based on the average monthly prices received by the grower. Fruit mass losses measured each month were due to transpiration and differences in respiration of fruit undergoing the treatments. In addition, the losses identified after 6 months of storage included fruit mass loss due to fungal diseases and physiological disorders disqualifying the affected fruit as not meeting the highest commercial quality standard applicable in OECD countries [35].

#### 2.7. Statistical Analysis

The results were analysed by one-way and multiple-way ANOVA according to the experimental design, using Statistica 13.3 (TIBCO Software Inc., Palo Alto, CA, USA). The assumed sources of variation included the used rootstocks, the storage atmosphere (CA, NA) and the application of 1-MCP. The mean values were compared using Duncan's test at  $p \leq 0.05\%$ . The correlation coefficient analysis was carried out using Microsoft Office 365 Excel tools.

### 3. Results and Discussion

#### 3.1. Rootstock Effect

Fruit growers use different rootstocks to match the tree vigour to the climatic, soil and agricultural conditions [37]. In apples, the rootstock also influences the speed of fruit ripening and thus the date of harvest [38]. However, in this study, the ripening speed and the harvest date were hardly affected by the rootstock type (Table 1). The Streif index, which is considered a good indicator of harvest maturity [39,40], varied little in the discussed experiment. There were no index differences in 2013, and very small differences in the other two years. The starch index, which affects the Streif index most strongly, also showed only slight, although significant, differences. Differences in firmness between the fruit coming from trees grown on different rootstocks were very small as well. No firmness differences were found in two years (2011 and 2012), and a significant difference, although of only 2 N, was identified in 2013.

**Table 1.** The influence of rootstock on the quality parameters of pears at harvest in 2011–2013.

Rootstock	Streif Index		Starch Index		Firmness (N)		TSS (%)		TSS/TA		Total Acidity (% Malic Acid)	
2011												
Q S1	0.09	a <sup>1</sup>	6.6	b	63.7	a	12.9	a	62.3	a	0.21	b
PC	0.10	b	5.4	a	64.7	a	12.9	a	68.6	a	0.19	a
PD	0.10	b	5.8	ab	63.7	a	13.3	a	65.8	a	0.20	b
2012												
Q S1	0.08	a	6.5	b	60.8	a	12.0	a	57.9	ab	0.21	a
PC	0.09	ab	6.3	ab	61.8	a	12.4	b	61.6	b	0.20	a
PD	0.09	b	6.0	a	62.8	a	12.2	ab	57.0	a	0.21	b
2013												
Q S1	0.06	a	9.2	b	66.7	b	12.4	b	69.3	b	0.18	a
PC	0.07	a	8.6	a	66.7	b	11.9	a	66.1	a	0.18	a
PD	0.06	a	8.8	a	64.7	a	12.1	a	67.1	a	0.18	a
Mean												
Q S1	0.07	a	7.4	b	63.7	a	12.1	a	62.8	a	0.20	b
PC	0.08	a	6.8	a	64.7	a	12.4	a	65.4	a	0.19	a
PD	0.08	a	6.5	a	63.7	a	12.5	a	63.3	a	0.20	b

<sup>1</sup> One-way analyses of variance; data in the same column marked with the same letter, separately for each year of experiment, are not significantly different at  $\alpha = 0.05$  (Duncan's test). Q S1—Quince S1 rootstock; PC—*Pyrus caucasica* Federov rootstock; PD—Pyrodwarf rootstock.

A study assessing the influence of six rootstocks on the TSS of 'Forelle' pears found that the differences in TSS at harvest were very small and did not exceed 0.5° Brix within two years [10]. TSS differences were also small in our study. No differences were detected in the first year of the experiment, and even though they occurred in the two subsequent years, they were rather incidental and random. Total acidity followed a clearer pattern and was the lowest in fruit from trees growing on *Pyrus caucasica*. However, the TSS/TA ratio, which is crucial for the subjective perception of fruit taste [41], did not vary considerably between fruit from trees grown on different rootstocks.

As the present study did not show any significant and long-term influence of the rootstock on the basic quality features of pears, this factor was omitted in our further analyses regarding storage and storability, except for mass loss (Tables S1–S12).

#### 3.2. Mass Loss

Fruit mass loss during storage depends on a number of factors occurring both before and after harvest, such as the content of minerals (especially calcium) in fruit, fruit maturity at harvest, incidence of diseases and disorders, and storage conditions [11]. As all fruit analysed in the present study grew under the same conditions and was treated in the

same way at the time of harvest, and its selection was entirely random, in line with the experimental design, it can be assumed that the loss of fruit mass was influenced only by the experimental factors. All factors applied in this study affected the loss of fruit mass during storage (Tables 2–4). The rootstock may affect the quality parameters of fruit [42], as well as the speed and time of ripening [43]. In 2011, the effect of the rootstock type on the mass loss of stored fruit was significant from the first measurement until the 120th day of storage, but this factor became less and less significant with time. In the following year, no such effect was found, but it was observed that the interaction between rootstock and 1-MCP application had a very strong influence on transpiration. This interaction did not decrease with time, which means that 1-MCP application was the predominant factor. In 2013, the rootstock clearly affected the loss of fruit mass during the storage period, except the first month after 1-MCP treatment. The interaction between rootstock and 1-MCP application was weaker, such as in the first year, and was significant only in the middle of the storage period.

**Table 2.** Mass loss (%) of non-1-MCP-treated (control) and of 1-MCP-treated ‘Conference’ pears after storage in normal (NA) and controlled (CA) atmosphere in 2011.

Rootstock	Storage Atmosphere	1-MCP Dose	Days of Storage											
			30	60	90	120	150	180						
Q S1	NA	Control	1.82 <sup>1</sup>	(0.31)	3.72	(0.32)	5.13	(0.21)	6.14	(0.23)	7.10	(0.54)	7.50	(0.42)
		1-MCP	2.15	(0.29)	2.65	(0.44)	3.23	(0.59)	4.39	(0.97)	5.56	(1.32)	6.06	(1.47)
	CA	Control	1.49	(0.51)	1.97	(0.51)	2.52	(0.55)	3.00	(0.61)	3.48	(0.70)	4.11	(0.85)
		1-MCP	0.92	(0.19)	1.37	(0.29)	1.88	(0.42)	2.02	(0.37)	2.42	(0.38)	3.32	(0.61)
PC	NA	Control	1.52	(0.47)	2.69	(0.28)	4.74	(0.34)	5.60	(0.59)	6.24	(0.56)	6.77	(0.59)
		1-MCP	2.31	(0.79)	3.01	(1.00)	3.89	(1.43)	5.38	(1.80)	5.51	(1.58)	6.22	(1.86)
	CA	Control	1.01	(0.06)	2.02	(0.30)	3.05	(0.44)	3.46	(0.60)	4.32	(0.62)	5.18	(0.64)
		1-MCP	0.93	(0.13)	1.78	(0.15)	2.26	(0.46)	2.77	(0.41)	3.43	(0.44)	3.93	(0.47)
PD	NA	Control	1.41	(0.23)	2.82	(0.31)	4.52	(0.42)	5.41	(0.55)	6.30	(0.55)	6.64	(0.58)
		1-MCP	1.83	(0.25)	2.34	(0.28)	3.41	(0.51)	4.59	(1.01)	5.23	(1.12)	5.74	(1.29)
	CA	Control	1.07	(0.17)	1.98	(0.49)	2.56	(0.50)	3.08	(0.60)	3.59	(0.74)	4.44	(0.75)
		1-MCP	0.94	(0.19)	1.42	(0.28)	1.94	(0.39)	2.26	(0.45)	2.79	(0.56)	3.31	(0.68)
Main effects <sup>2</sup>														
Rootstock (A)			**	**	*	*	ns	ns						
Storage atmosphere (B)			***	***	***	***	***	***	***	***	***	***	***	***
1-MCP dose (C)			ns	***	***	***	***	***	***	***	***	***	***	
Interaction														
A × B			ns	**	ns	ns	ns	ns	**	*				
A × C			*	***	ns	*	ns	ns	ns	ns				
B × C			***	ns	**	ns	ns	ns	ns	ns				
A × B × C			ns	*	ns	ns	ns	ns	ns	ns				

<sup>1</sup> Numbers in parentheses are the standard deviation of the mean (n = 10). <sup>2</sup> p-value of F ratio: ns—not significantly different; \* p < 0.05; \*\* p < 0.01; \*\*\* p < 0.001. Q S1—Quince S1 rootstock; PC—Pyrus caucasica Federov rootstock; PD—Pyrodwarf rootstock. NA—normal atmosphere; CA—controlled atmosphere.

The use of 1-MCP reduces autocatalytic ethylene production and, thus, significantly slows down respiration [27]. The strongest impact of 1-MCP application was found in the last year of the research (Table 4), in which the reduction in fruit mass loss as compared to untreated pears had the highest level of significance in each month of testing. In 2011 and 2012, no differences between 1-MCP-treated and non-1-MCP-treated samples were identified after the first month of storage, whereas the differences were highly significant in the subsequent months.



Table 4. Cont.

Rootstock	Storage Atmosphere	1-MCP Dose	Days of Storage					
			30	60	90	120	150	180
Interaction								
	A × B		ns	ns	ns	ns	ns	ns
	A × C		ns	ns	ns	ns	ns	ns
	B × C		ns	ns	***	**	ns	ns
	A × B × C		*	ns	ns	ns	ns	ns

<sup>1</sup> Numbers in parentheses are the standard deviation of the mean (n = 10). <sup>2</sup> p-value of F ratio: ns—not significantly different; \* p < 0.05; \*\* p < 0.01; \*\*\* p < 0.001. Q S1—Quince S1 rootstock; PC—Pyrus caucasica Federov rootstock; PD—Pyrodwarf rootstock. NA—normal atmosphere; CA—controlled atmosphere.

However, it was the gaseous composition of the storage atmosphere which had by far the greatest impact on the mass loss during storage. During respiration, sugar and oxygen are combined to produce carbon dioxide and water, the excess of which is transpired into the environment, thus resulting in fruit mass loss [8,11]. The composition of gases in the storage atmosphere strongly influences the rate of fruit respiration [12]. Reducing the oxygen level and increasing the carbon dioxide level slow down respiration and, along with it, the consumption of respiration substrates. This study, during which the oxygen content was reduced to 2%, and the carbon dioxide content was increased to 1%, confirmed the beneficial effect of CA in each year and after each month of storage. This impact was highly significant in each year of the study. Of all the three main factors, the influence of the gaseous composition of the storage atmosphere on fruit mass loss had the highest level of statistical significance.

Mass loss during storage might also have been caused by parthenocarpy, and ‘Conference’ pear is known for producing a lot of parthenocarpic fruit in years of adverse weather conditions. It was observed in some earlier studies that parthenocarpy and the number of seeds produced in pears affected both their quality and storability [7].

### 3.3. Changes in Quality Parameters during Storage

Firmness is one of the most important quality criteria for traders and consumers alike [12]. Fruit starts to soften when still on the tree, about 4 weeks prior to the optimum harvest date [44]. After harvest, fruit continues to soften to finally reach edible firmness, and the softening rate depends on such factors as fertilization, harvest date and cultivar, but it is mostly influenced by the length and conditions of storage. The softening rate of late-maturing pear cultivars, such as ‘Conference’, was found to depend on the synthesis of two enzymes: acetyl-CoA synthase (ACS) and 1-aminocyclopropane carboxylic acid (ACC) [6]. In this study, both the softening rate and the total loss of firmness were clearly dependent on storage conditions (Tables 5–7). The initial firmness measured at harvest depends of many factors, which was visible in our study because it varied little between years, with the lowest value observed in 2012 and the highest in 2011. In addition, there were virtually no differences between years in the final firmness after 180 days of NA storage, and the total loss of firmness ranged from 34 to 40%. No clear regularity was revealed as regards firmness loss per month in individual years, but the firmness showed a tendency to decrease, as the greatest loss of firmness was noted in the last (sixth) month of NA storage in two years and in the next-to-last (fifth) month in one year of the study.

1-MCP application significantly reduces the softening rate of climacteric fruit and vegetables [24]. This study revealed that 1-MCP application visibly slows down the softening rate, particularly in the first months of storage—it reduced the total firmness loss by about 1/3 compared to the untreated fruit after six months of NA storage. Additionally, CA storage with the concentration of O<sub>2</sub> of 1.5–3% and CO<sub>2</sub> of 0.5–1.0% for ‘Conference’ slows down the softening rate [45]. Such CA storage conditions were applied in our study, and the CA-stored fruit softened significantly more slowly than the NA-stored fruit, but at an approximately equal rate as the NA-stored + 1-MCP-treated fruit. No differences were

observed after 180 days of storage in two years, whereas there was a significant difference in one year of the study, but it did not exceed 10%.

CA-stored + 1-MCP-treated pears had, by far, the highest firmness. Their average firmness loss within the three years of the study was only about 15% of the initial value, and such a difference does not affect consumer preferences [46]. During the first months of storage, the firmness loss was considerably higher in the non-1-MCP-treated fruit. 1-MCP application had a stronger influence on the softening rate than the gaseous composition of storage atmosphere during the first two months of storage, but the reverse was true (storage atmosphere more strongly reduced the softening rate than 1-MCP) at the end of the storage period. This could be explained by the way in which 1-MCP works: it slows down respiration by blocking ethylene receptors, but new non-blocked receptors are formed on the fruit skin with time [24], and the treated fruit becomes similar to untreated fruit.

**Table 5.** Effect of storage technology on the quality parameters of pears in 2011.

Storage Duration	Firmness					TSS (%)	TA		TSS/TA	ORAC $\mu\text{mol TE}/100\text{ g (d.m.)}$			
	(N)	Monthly Loss (%)	Total Loss (%)				(% Malic Acid)						
NA													
0	64.2 <sup>1</sup>	n	0			12.6	a	0.21	l	60.0	a	2858.8	d
30	62.2	mn	3.0	a	3.0	12.9	a–c	0.18	i	73.2	b		
60	55.9	g–i	10.1	c	12.8	13.3	b–d	0.15	ef	89.9	c–e		
90	52.2	f	6.8	b	18.7	14.6	g–i	0.11	c	134.5	g		
120	50.9	ef	2.4	a	20.7	14.9	i	0.11	c	135.5	g		
150	43.0	ab	15.5	d	32.9	14.6	g–i	0.10	b	154.0	h		
180	40.6	a	5.7	b	36.8	13.9	ef	0.06	a	231.7	i	2562.5	a
NA + 1-MCP													
0	64.2	n	0			12.6	a	0.21	l	60.0	a	2858.8	d
30	63.4	n	1.1	a	1.1	12.8	ab	0.19	i–l	67.8	ab		
60	58.1	i–k	8.4	c	9.5	12.9	a–c	0.19	i–k	69.3	ab		
90	53.5	fg	7.9	b	16.6	13.4	c–e	0.16	f–h	84.8	cd		
120	47.6	cd	11.0	e	25.8	14.3	f–i	0.16	e–h	92.1	c–e		
150	43.4	b	8.9	d	32.4	14.5	f–i	0.15	e	99.5	e		
180	42.9	ab	1.1	a	33.2	14.7	hi	0.10	bc	147.8	h	2782.5	b
CA													
0	64.2	n	0			12.6	a	0.21	l	60.0	a	2858.8	d
30	64.6	n	–0.7	a	–0.7	12.5	a	0.18	ij	69.0	ab		
60	62.3	mn	3.5	b	2.9	12.7	a	0.19	i–l	66.7	ab		
90	57.8	h–j	7.3	e	10.0	13.1	a–d	0.18	i	74.5	b		
120	54.8	g	5.1	c	14.6	14.1	fg	0.15	e–g	93.9	c–e		
150	48.6	de	11.3	f	24.2	14.5	g–i	0.15	e–h	95.1	de		
180	45.3	bc	6.7	d	29.3	14.8	i	0.12	d	123.7	f	2817.5	c
CA + 1-MCP													
0	64.2	n	0			12.6	a	0.21	l	60.0	a	2858.8	d
30	63.6	n	0.8	b	0.8	12.8	ab	0.21	m	60.6	a		
60	59.4	kl	6.7	f	7.4	12.6	a	0.20	kl	64.1	ab		
90	60.7	lm	–2.2	a	5.4	13.1	a–d	0.19	ij	71.0	ab		
120	59.1	jk	2.7	c	7.9	13.5	de	0.16	gh	84.0	c		
150	55.3	gh	6.4	e	13.8	13.9	ef	0.17	h	84.7	cd		
180	53.3	fg	3.5	d	16.9	14.3	f–i	0.16	e–h	89.4	c–e	2962.5	e

<sup>1</sup> One-way analyses of variance; data in the same column marked with the same letter are not significantly different within a year at  $\alpha = 0.05$  (Duncan's test). NA—normal atmosphere; NA + 1-MCP—normal atmosphere + 1-methylcyclopropene; CA—controlled atmosphere; CA + 1-MCP—controlled atmosphere + 1-methylcyclopropene.

**Table 6.** Effect of storage technology on the quality parameters of pears in 2012.

Storage Duration	Firmness				TSS (%)	TA (% Malic Acid)	TSS/TA (N)	ORAC $\mu\text{mol}$ TE/100 g (d.m.)					
	(N)	Monthly Loss (%)	Total Loss (%)										
NA													
0	60.6 <sup>1</sup>	l	0		12.2	a	0.23	m	53.0	a	2635.0	c	
30	56.4	hi	6.9	c	6.9	12.6	a–d	0.20	j–l	64.7	a–d		
60	53.5	fg	5.1	a	11.6	13.1	e–h	0.19	h–j	70.4	c–f		
90	50.5	de	5.6	b	16.6	13.5	f–i	0.17	f	79.4	gh		
120	46.9	c	7.1	d	22.6	14.0	j–l	0.15	e	93.3	i–k		
150	43.7	b	6.9	c	27.9	14.2	l	0.11	b–e	137.4	l		
180	39.8	a	8.9	e	34.3	13.6	k	0.07	a	194.3	m	2435.0	a
NA + 1-MCP													
0	60.6	l	0		12.2	a	0.23	m	53.0	a	2635.0	c	
30	58.9	jl	2.8	b	2.8	12.4	ab	0.19	i–k	66.5	b–e		
60	58.3	i–l	1.1	a	3.8	12.5	a–c	0.19	h–j	67.4	b–f		
90	56.3	hi	3.4	c	7.1	13.0	d–g	0.18	g–i	71.9	d–g		
120	52.0	ef	7.6	d	14.2	13.4	f–i	0.17	f	79.4	gh		
150	47.9	c	7.8	e	20.9	13.9	j–l	0.12	c	122.8	k		
180	44.2	b	7.8	e	27.1	14.3	l	0.11	bc	130.9	l	2537.5	b
CA													
0	64.2	m	0		12.2	a	0.23	m	53.0	a	2635.0	c	
30	60.4	l	5.9	d	5.9	12.2	a	0.20	lm	60.9	a–c		
60	58.6	i–l	2.9	b	8.7	12.5	a–c	0.19	j–l	65.3	a–d		
90	57.4	h–k	2.1	a	10.6	12.8	b–e	0.18	g–i	70.7	c–f		
120	55.7	h	2.8	b	13.1	13.2	f–i	0.18	fg	75.4	f–h		
150	53.1	fg	4.7	c	17.2	13.6	i–k	0.15	de	92.6	i–k		
180	48.9	cd	8.1	e	23.9	14.2	l	0.14	d–g	100.4	j–l	2627.5	c
CA + 1-MCP													
0	60.6	l	0		12.2	a	0.23	m	53.0	a	2635.0	c	
30	60.6	l	0.0	b	0.0	12.2	a	0.21	m	58.8	ab		
60	59.5	kl	1.8	c	1.8	12.3	ab	0.20	l	62.5	a–c		
90	58.3	i–l	2.0	d	3.8	12.7	b–e	0.20	j–l	65.5	a–d		
120	58.5	i–l	−0.4	a	3.3	12.9	c–f	0.18	f–h	72.7	d–g		
150	56.9	h–j	2.8	e	6.0	13.5	h–j	0.18	g–i	73.9	e–h		
180	55.2	gh	3.0	f	8.8	14.0	kl	0.17	fg	81.0	h–j	2777.5	d

<sup>1</sup> One-way analyses of variance; data in the same column marked with the same letter are not significantly different within a year at  $\alpha = 0.05$  (Duncan's test). NA—normal atmosphere; NA + 1-MCP—normal atmosphere + 1-methylcyclopropene; CA—controlled atmosphere; CA + 1-MCP—controlled atmosphere + 1-methylcyclopropene.

**Table 7.** Effect of storage technology on the quality parameters of pears in 2013.

Storage Duration	Firmness				TSS (%)	TA (% Malic Acid)	TSS/TA (N)	ORAC $\mu\text{mol}$ TE/100 g (d.m.)					
	(N)	Monthly Loss (%)	Total Loss (%)										
NA													
0	65.9 <sup>1</sup>	k	0		12.1	a	0.18	m	67.5	a	2975.0	c	
30	64.4	i–k	2.2	a	2.2	12.5	a–c	0.18	m	70.7	ab		
60	62.8	hi	2.5	b	4.7	12.7	b–d	0.15	h	87.6	cd		
90	56.1	f	10.6	d	14.8	13.6	f	0.13	fg	101.7	ef		
120	49.7	cd	11.4	e	24.6	14.3	gh	0.11	c	130.0	h		
150	45.4	b	8.6	c	31.0	14.8	jk	0.07	b	208.3	i		
180	39.9	a	12.3	f	39.5	13.7	f	0.06	a	228.3	j	2750.0	a

Table 7. Cont.

Storage Duration	Firmness				TSS (%)	TA (% Malic Acid)	TSS/TA (N)	ORAC $\mu\text{mol}$ TE/100 g (d.m.)				
	(N)	Monthly Loss (%)	Total Loss (%)									
NA + 1-MCP												
0	65.9	k	0		12.1	a	0.18	m	67.5	a	2975.0	c
30	64.4	i–k	2.2	b	2.2	12.4	ab	0.18	m	70.7	ab	
60	64.1	i–k	0.5	a	2.7	12.4	a–c	0.16	j–l	76.8	ab	
90	61.1	h	4.6	c	7.2	12.8	c–e	0.15	h	88.3	cd	
120	55.8	f	8.8	f	15.4	13.6	f	0.12	de	107.7	f	
150	51.4	de	7.9	e	22.0	14.6	ij	0.12	d	121.7	g	
180	47.6	bc	7.3	d	27.7	14.6	ij	0.11	c	132.7	h	2890.8 b
CA												
0	65.9	k	0		12.1	a	0.18	m	67.5	a	2975.0	c
30	66.2	k	–0.5	a	–0.5	12.3	ab	0.18	m	69.1	a	
60	63.3	h–j	4.4	c	4.0	12.4	ab	0.18	m	69.0	a	
90	62.0	hi	2.1	b	6.0	12.6	a–c	0.16	jk	80.4	bc	
120	57.7	fg	6.9	e	12.4	13.8	fg	0.15	h	93.4	de	
150	52.9	e	8.4	f	19.8	14.7	ij	0.14	g	107.9	f	
180	49.9	cd	5.6	d	24.2	15.1	k	0.13	ef	119.0	g	2990.0 c
CA + 1-MCP												
0	65.9	k	0		12.1	a	0.18	m	67.5	a	2975.0	c
30	66.3	k	–0.6	a	–0.6	12.2	a	0.18	m	68.9	a	
60	64.3	i–k	3.0	c	2.4	12.4	ab	0.17	l	73.9	ab	
90	63.3	h–k	1.5	b	3.9	12.5	a–c	0.16	kl	75.9	ab	
120	61.4	h	3.1	c	6.9	13.1	de	0.16	j–l	80.6	bc	
150	58.6	g	4.5	d	11.1	13.7	fg	0.16	ij	88.5	cd	
180	55.8	f	4.7	e	15.3	14.1	hi	0.15	hi	96.7	de	3107.5 d

<sup>1</sup> One-way analyses of variance; data in the same column marked with the same letter are not significantly different within a year at  $\alpha = 0.05$  (Duncan's test). NA—normal atmosphere; NA + 1-MCP—normal atmosphere + 1-methylcyclopropene; CA—controlled atmosphere; CA + 1-MCP—controlled atmosphere + 1-methylcyclopropene.

### 3.3.1. Total Soluble Solids, Total Acidity and TSS/TA Ratio

Two very important qualitative criteria are: TSS, which is the content of solids, notably sugars, in a liquid, and TA, which is the content of acids and is assessed as the sum of acids converted into malic acid [7,12]. The TSS value usually grows in the initial storage period, which is caused by the degradation of polysaccharides into monosaccharides, but may decrease later as the fruit uses stored energy for respiration [47]. The speed of changes depends on the storage time and storage conditions [11]. The TSS value at harvest was similar and ranged between 12.1 and 12.6% in all years of the study. The TSS value changed most rapidly in the NA-stored fruit: it increased relatively quickly to reach the maximum after four or five months. After six months of storage, the TSS content dropped but was still significantly higher than at harvest. In NA-stored 1-MCP-treated pears, the TSS content grew more slowly and reached its peak in the last 2–3 months of storage. CA storage considerably reduced the ripening speed expressed by TSS, regardless of whether 1-MCP was applied or not. 1-MCP application may have an inconsistent effect, both in CA and NA storage [48]. In this study, TSS in the CA-stored pears gradually grew and rose to the maximum value after the entire storage period. This suggests that after 180 days of CA storage the 'Conference' pears did not start yet the excessive consumption of sugars in the respiration process.

Total acidity in the stored fruit changed according to a clearer pattern than TSS. Monthly measurements showed a steady decrease in TA at a rate dependent on the storage conditions and 1-MCP treatment. This corresponds with the findings by Hedges et al. [23], who additionally pointed to the harvest date as a factor affecting TA as a harvest delay resulted in a visible decrease in the initial TA value. What deserves mentioning as regards

our study is the weather conditions prevailing during the growing season because the initial TA values measured at the optimal harvest date varied between years. The differences were not large, but were consistent with the findings from a study on apples harvested in the same year in three European countries characterized by different weather conditions [49]. In this study, TA declined during storage irrespective of storage conditions, but it reached the lowest values in the NA-stored fruit and amounted to about 1/3 of the initial value after storage in each year. The 1-MCP-treated pears had a significantly higher TA, which never fell below 50% of the initial value. CA storage slowed down the degradation of acids still further and the combination of CA and 1-MCP prevented TA from dropping below 20% of the initial value after six months. Such conditions were shown to be highly effective not only for 'Conference' pears, but also for another popular European pear cultivar, 'Alexander Lucas' [23].

Consumers' perception of fruit sweetness and acidity depends not only on the absolute TSS or TA values, but also on the TSS/TA ratio [50]. In our study, the TSS/TA ratio changed very rapidly in each of the three years and was strongly influenced by storage conditions. For example, whereas the TSS of NA-stored pears did not vary by more than 20% in any of the years, their TSS/TA ratio varied by at least 300%. This was the only quality parameter that was different in virtually every month, regardless of storage conditions and 1-MCP application.

### 3.3.2. Oxygen Radical Absorbance Capacity (ORAC)

Free radical scavenging activity is highly dependent on the species, cultivar, climatic conditions and harvest date [11]. During storage, it can remain unchanged, as was the case for 'Rocha' pears in Portugal [28], or it can grow, as shown by [51] for 'Golden Smoothee' apples. In our research, ORAC varied depending on storage conditions. Antioxidant capacity dropped considerably after NA storage, whereas the decrease was significantly smaller in the 1-MCP-treated sample. No changes were observed after CA storage, the ORAC value even rose after 1-MCP application. These differences can be explained by the differences in the ripening processes induced by increased respiration. Larrigaudiere et al. [52] found out that ripening may involve a noticeable decline in the content of ascorbic acid, which is one of the substances making up the antioxidant potential of fruit.

### 3.4. Revenue Differences Related to Differences in Storage Technology

Pome fruits, the most popular of which are apples and pears, are characterized by high storability [12]. As apples and pears can endure long-term storage, they can be supplied on the market all year round. The price of stored fruit is often similar to, and in some years even higher than, that of freshly harvested fruit [53]. In addition to market dependencies, including mainly the supply of fruit over a given period, the most important factor affecting the price is fruit quality [54]. For a grower who prepares fruit for sale it is important that it meets the parameters allowing its classification as top-class fruit for fresh consumption [55]. Fruit discarded after grading generates either no or very low revenue. This study compared the values of fruit stored in different conditions, taking into account the losses which arose during storage. Two types of loss were considered that could be measured based on the study results. Fruit mass loss caused by transpiration depends on relative humidity and respiration [12]. Assuming that the storage humidity was equal for all fruit, fruit mass loss resulted mainly from the rate of respiration. It has been shown in Section 3.2 that CA storage and 1-MCP application have a significant impact on respiration. The figures in Table 8 demonstrate that this translated directly in to the grower's revenue.

**Table 8.** Differences in revenues from the sale of the average pear yield in the EU at market prices in each year of the study, depending on storage conditions.

Storage Days	NA	NA 1-MCP	CA	CA 1-MCP	Price kg in (EUR)	NA	NA 1-MCP	CA	CA 1-MCP
	<b>2011/2012 (Av. Yield = 14.03 t·h<sup>-1</sup>)<sup>1</sup></b>								
	Transpiration (%)					Value after Storage (EUR)			
0	0.0	0.0	0.0	0.0	0.55 <sup>2</sup>	7723 <sup>3</sup>	7723	7723	7723
30	1.6	2.1	1.2	0.9	0.55	7600	7561	7631	7651
60	3.1	2.7	2.0	1.5	0.55	7485	7517	7569	7605
90	4.8	3.5	2.7	2.0	0.57	7659	7762	7827	7882
120	5.7	4.8	3.2	2.3	0.57	7585	7659	7789	7856
150	6.5	5.4	3.8	2.9	0.62	8119	8216	8358	8438
180	7.0	6.0	4.6	3.5	0.64	8382	8469	8598	8693
	Storage diseases (%)								
	16.0 ± 3.9 <sup>4</sup>	11.6 ± 3.5	9.1 ± 3.3	7.4 ± 3.5		6944	7424	7782	8026
	Value difference after storage					−779	−299	59	303
<b>2012/2013 (Av. Yield = 11.78 t·h<sup>-1</sup>)</b>									
	Transpiration (%)					Value after storage (EUR)			
0	0.0	0.0	0.0	0.0	0.58	6846	6846	6846	6846
30	2.2	1.9	1.1	1.2	0.58	6693	6714	6769	6763
60	4.0	2.7	1.9	1.6	0.65	7395	7490	7555	7579
90	5.3	3.8	2.6	1.9	0.73	8100	8230	8336	8395
120	6.1	4.5	3.0	2.5	0.82	9106	9260	9408	9456
150	6.9	5.2	3.8	3.1	0.99	10,892	11,082	11,247	11,332
180	7.8	6.1	4.7	4.1	1.14	12,361	12,583	12,778	12,858
	Storage diseases (%)								
	25.0 ± 3.7	19.9 ± 3.6	14.0 ± 2.7	9.9 ± 2.6		9004	9916	10,899	11,531
	Value difference after storage					3070	4053	4686	3070
<b>2013/2014 (Av. Yield = 18.85 t·h<sup>-1</sup>)</b>									
	Transpiration (%)					Value after storage (EUR)			
0	0.0	0.0	0.0	0.0	0.43	8122	8122	8122	8122
30	2.1	1.8	1.0	0.9	0.53	9719	9748	9824	9834
60	3.6	2.8	1.7	1.7	0.53	9567	9648	9756	9754
90	4.9	3.5	2.4	2.0	0.57	10,296	10,448	10,568	10,608
120	5.6	4.2	3.1	2.4	0.60	10,649	10,806	10,930	11,007
150	6.1	4.9	3.8	2.9	0.60	10,590	10,724	10,852	10,950
180	6.9	5.7	4.3	3.4	0.60	10,501	10,635	10,793	10,892
	Storage diseases (%)								
	29.2 ± 4.4	23.3 ± 3.1	17.9 ± 3.9	11.9 ± 1.8		7211	8006	8776	9550
	Value difference after storage					−911	−115	654	1428

<sup>1</sup> Average pear yield per 1 hectare in the EU countries where production exceeds 1000 ha. <sup>2</sup> Price of pears obtained by growers in the period. <sup>3</sup> Average pear yield per ha in the EU countries in which pear production exceeds 1000 ha × average pear price for growers.

<sup>4</sup> Standard deviation. NA—normal atmosphere; NA + 1-MCP—normal atmosphere + 1-methylcyclopropene; CA—controlled atmosphere; CA + 1-MCP—controlled atmosphere + 1-methylcyclopropene.

The difference between the highest and the lowest value of the yield that could be obtained per 1 ha did not exceed EUR 100 after the first month of storage (NA, NA + 1MCP, CA, CA + 1MCP), but it grew with each month. Even in the 2011/2012 season, in which the market prices were the most stable, this difference amounted to over EUR 350 after six-month storage. In the following season, during which the market prices rose much faster and the average yield was 2.5 t h<sup>-1</sup> lower, the difference was as much as about EUR 500. With the previous season's yield, the potential difference between revenues from the yield subjected to the simplest treatment (NA) and the most advanced treatment (CA + 1MCP) would have exceeded EUR 1500. In the last season, the difference decreased, but only to EUR 400, due to a high average yield.

The least advanced storage technologies give low protection against increased transpiration and the incidence of physiological disorders and fungal diseases [12,53]. The total losses caused by fungal diseases varied among individual years, because many of them originate in the orchard. The biggest difference was observed in the last year of the study—the revenues from the sale of the average pear yield in the EU after CA + 1-MCP treatment were over EUR 2300 higher than those calculated for the same yield after NA storage. CA + 1MCP-treated pears will be certainly easier to sell because also their other parameters are superior to those of the NA-stored pears. Since the costs of building a controlled atmosphere storage room, if properly designed, can be only about 5% higher than the costs of building a cold storage room [56], the financial advantages that can be achieved each year will surely more than make up for higher capital expenditures.

### 3.5. Incidence of Diseases and Disorders

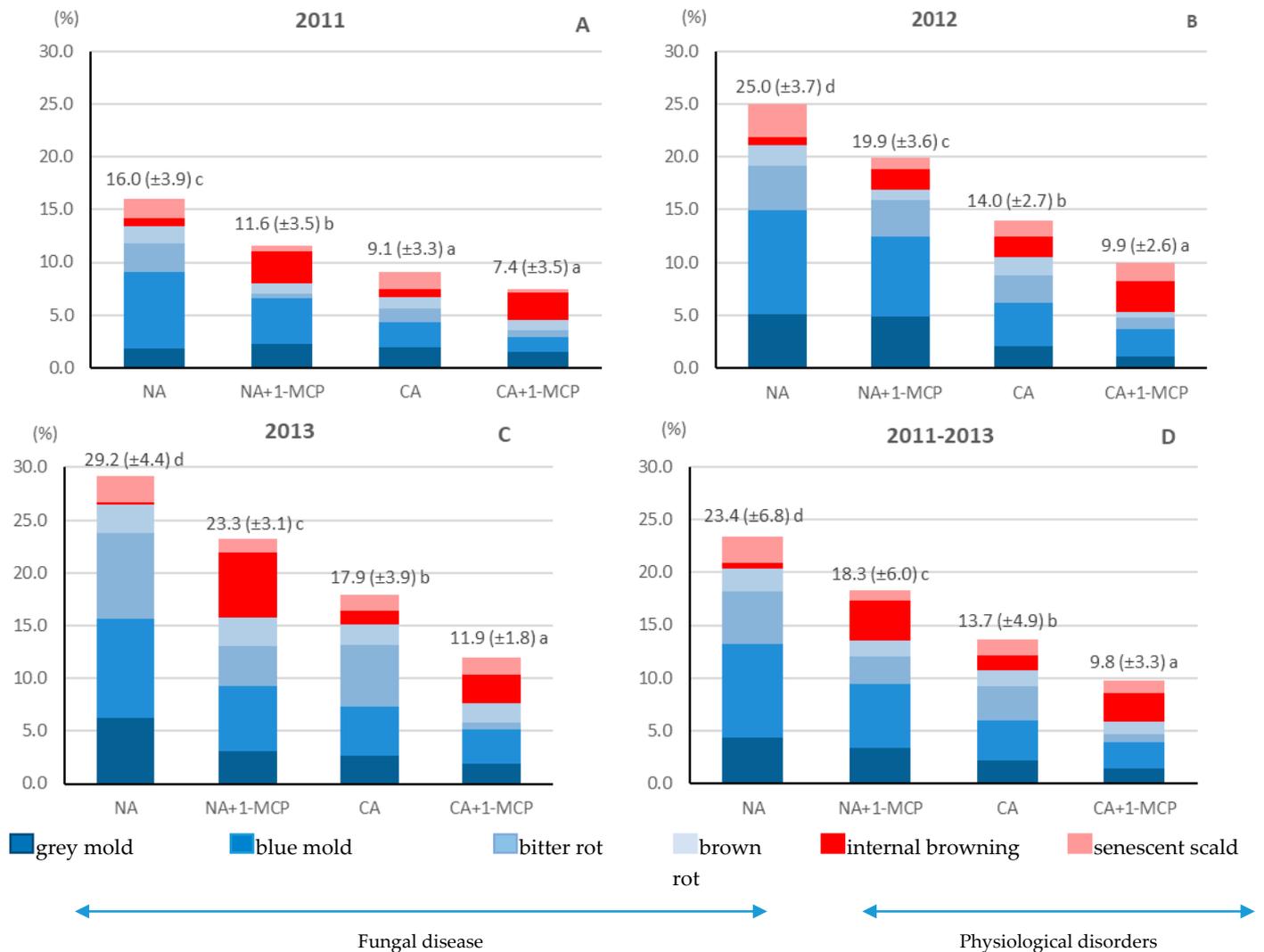
Postharvest diseases of pome fruit result in substantial economic losses during storage worldwide every year [9]. In this study, the occurrence of fungal diseases, physiological disorders and visible physical damage of fruit flesh changed every year but always depended on treatment (Figures 1 and 2). Fungal diseases occurred more often than physiological disorders—this tendency is stronger in pears than in apples [53]. The biggest total losses—of about 30%—were observed after six-month storage in 2013 (Figure 1C). The 1-MCP treatment of NA-stored pears reduced the total losses and visibly curbed the incidence of fungal diseases despite an increased incidence of internal browning. CA storage reduced the total losses by about half and the CA+ 1-MCP combination cut the incidence of diseases and disorders significantly. The smallest losses caused by diseases and disorders were noted in the first year of the study (Figure 1A), but 1-MCP application reduced the incidence of diseases and disorders only in the NA-stored fruit. In the second year, model results were obtained—starting from NA storage, each further treatment caused a drop in the total losses caused by diseases and disorder after six-month storage (Figure 1B). Other studies report different outcomes, though, which certainly depended on weather conditions in the orchard [23,57–59].

Fungal pathogens are the main source of losses during the storage and sale of pears [53]. This finding is confirmed by the results of this study except the CA-stored + 1MCP-treated pears. In 2011–2012, the share of fruit with physiological disorders was similar to that of those with fungal diseases (Figure 2). It seems that it was because the treatments very strongly reduced the incidence of fungal diseases. The most important fungal pathogens causing losses due to rotting are *Penicillium expansum*, *Botrytis cinerea*, and *Mucor piriformis* [58]. Other etiological factors include *Phialophora malorum*, *Alternaria* spp., *Cladosporium herbarum*, and *Neofabrea* spp. [60]. Their spores are ubiquitous in the orchard and infect also other tree parts. Fungal diseases were found to be the main loss factor in each year of the study. In 2013, the year of increased incidence of fungal diseases during storage, the percentage of fruit infected with fungal diseases in NA storage was about 10 times higher than the percentage of fruit showing symptoms of physiological disorders. Pears suffer from physiological disorders more rarely than apples [12], which was also clearly apparent in the two other years of the study. In 2011 and 2013, no differences in the incidence of fungal diseases were found between the NA-stored + 1-MCP-treated pears and the CA-stored pears, but the combination of CA and 1-MCP treatment allowed a reduction in the incidence of fungal diseases by half (2013) or by one-third (2011). In 2012, the incidence of fungal diseases decreased gradually and significantly between samples from the level observed after NA storage to the level noted after CA +1-MCP treatment.

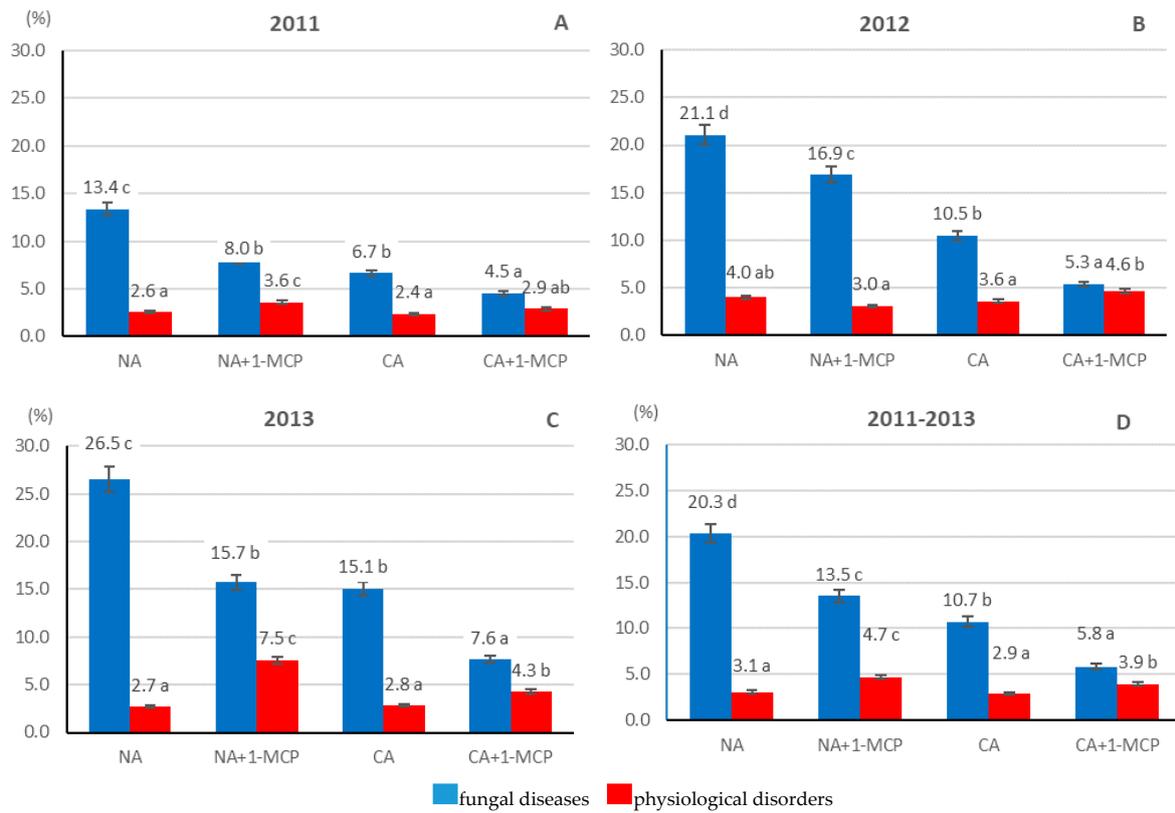
Even though physiological disorders occur more rarely compared to fungal diseases, they are more difficult to contain by changing the composition of the atmosphere or applying 1-MCP [61–63]. The share of fruit affected by physiological disorders varied considerably between treatments, but it did not exceed 7.5% in any of the samples, which shows that physiological disorders are a minor cause of losses during storage.

The share of individual diseases and disorders causing losses during storage varied between years (Figure 3). Blue mold led to the biggest losses in all years of the study. It is caused by *Penicillium expansum*, a fungus commonly found in orchards [64]. The study clearly shows that the best way to control the disease is to improve the storage conditions. Every method to enhance the storage conditions significantly reduced the infection rate so that the incidence of blue mold in the CA-stored + 1-MCP-treated fruit constituted 20–30% of that found in the NA-stored fruit. Blue mold control has not only economic relevance for growers, but it also makes it possible to limit the development and spread of strains that produce patulin, a mycotoxin that affects humans [64].

Grey mold, which is caused by *Botrytis cinerea*, was another fungal disease that was observed to infect the fruit in each year of the study. The lowest grey mold incidence rate was noted in 2011 and it is probably due to the low number of infected pears that the differences between the treatments were small and generally insignificant. In the two subsequent years, the differences were bigger and CA storage had a noticeable limiting effect on the disease. A controlled atmosphere is recommended for the storage of grapes that are very susceptible to grey mold for fresh consumption [65].

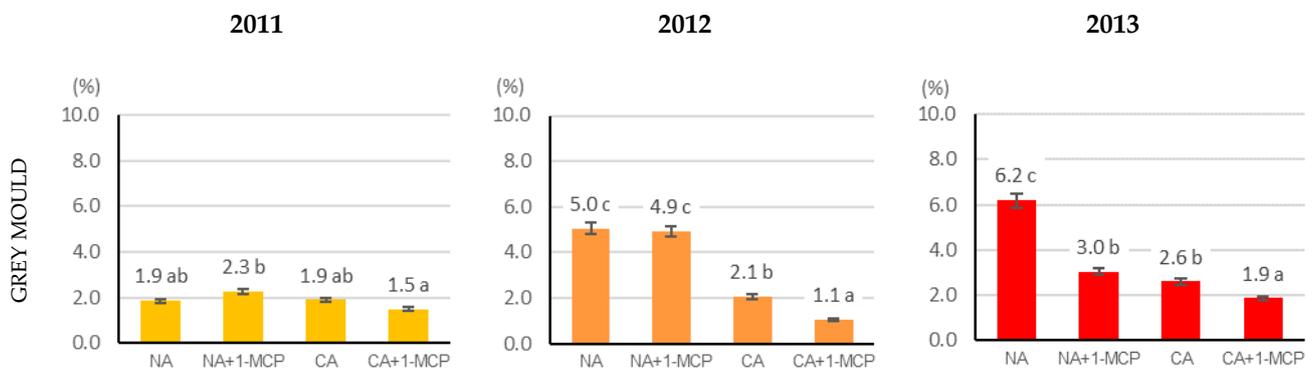


**Figure 1.** Total fruit losses caused by fungal diseases and physiological disorders. Numbers with different letters were significantly different at  $p = 0.05$  according to Duncan’s test. The data are expressed as mean  $\pm$  SD ( $n = 10$ ). NA—normal atmosphere; NA + 1-MCP—normal atmosphere + 1-methylcyclopropene; CA—controlled atmosphere; CA + 1-MCP—controlled atmosphere + 1-methylcyclopropene.

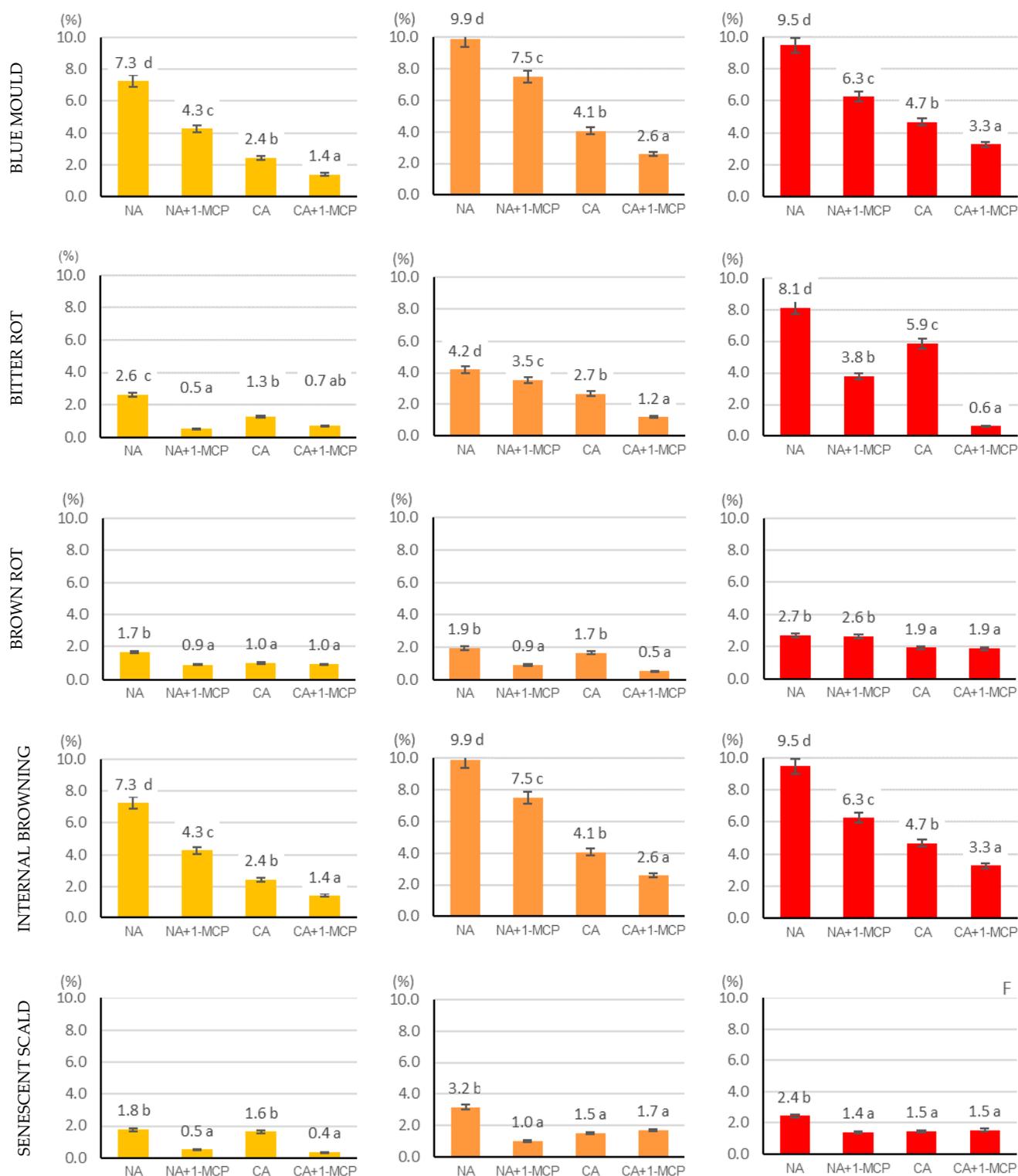


**Figure 2.** Fungal diseases and physiological disorders after storage in different conditions. Numbers with different letters were significantly different at  $p = 0.05$  according to Duncan’s test. The data are expressed as mean  $\pm$  SD ( $n = 10$ ). NA—normal atmosphere; NA + 1-MCP—normal atmosphere + 1-methylcyclopropene; CA—controlled atmosphere; CA + 1-MCP—controlled atmosphere + 1-methylcyclopropene.

Postharvest pathogens with economic importance for stored fruit also include bitter rot caused by *Colletotrichum* spp. [9]. In this study, the application of 1-MCP was much more effective in controlling this disease than the modification of storage atmosphere. Such a positive outcome of 1-MCP treatment was observed during the storage of apples [66]. Brown rot occurred in less fruit compared to the other fungal diseases. The differences in the incidence of bitter rot between treatments were small, although significant in some cases. In 2011, the highest number of infected pears was found in the samples stored in NA for six months. The other samples showed no differences. In 2012, 1-MCP had a beneficial effect on both NA- and CA-stored fruit, whereas, in 2013, a difference was noted only between the NA- and CA-stored samples, regardless of 1-MCP treatment.



**Figure 3.** Cont.



**Figure 3.** Impact of storage technology on the incidence of postharvest diseases and disorders in 2011–2013. Numbers with different letters were significantly different at  $p = 0.05$  according to Duncan's test. The data are expressed as mean  $\pm$  SD ( $n = 10$ ). NA—normal atmosphere; NA + 1-MCP—normal atmosphere + 1-methylcyclopropene; CA—controlled atmosphere; CA + 1-MCP—controlled atmosphere + 1-methylcyclopropene.

Physiological disorders caused much smaller losses than fungal diseases, which confirms the findings usually reported after the storage of pears [7,11]. The differences between individual treatments appeared to be random and there was even a growth in the number of fruit showing the symptoms of physiological diseases after the application

of 1-MCP. ‘Conference’ pears are prone to internal browning, the incidence of which may increase during CA storage [67,68]. This study only partially supported those findings and the 1-MCP treatment seemed to more strongly promote the development of internal browning, which agreed with the observations already made by Hendges et al. [63] during and after the storage of ‘Alexander Lucas’ pears. The possible reason for this is the loss of the antioxidant capacity and/or energy deficit caused by a reduction in the respiratory activity of fruit stored under CA. It has also been suggested that the inhibition of ethylene production may induce a stress response and thereby cause cell damage [69]. In our study, the significant increase in the incidence of internal browning was noted in 2011 and 2013 in both NA- and CA-stored fruit.

Senescent scald was a second physiological disorder observed in our study. It manifests itself with skin decolourization [12]. 1-MCP effectively reduces senescent scald in apples, but it is not clear how successfully it helps to control this disorder in pears [70]. Our study did not yield a clear result either; however, much more often than not, 1-MCP limited the occurrence of senescent scald. In 2011, the positive impact of 1-MCP was found after both NA and CA storage. In the following years, the difference was significant for NA-stored fruit. This suggests that the period of 6 months is too long for the storage of ‘Conference’ pears under NA conditions. The same conclusions were presented in an Italian study assessing the influence of 1-MCP on ‘Abbé Fétel’ stored in normal atmosphere [57].

#### 4. Conclusions

A three-year study showed that the rootstock type, storage atmosphere, and 1-MCP application affected the storability of ‘Conference’ pears. This is the first study that presents a simultaneous assessment of the influence of the above factors on the quality parameters, the losses caused by diseases and disorders, the antioxidant capacity, and of the economic profitability of long-term storage of an important European pear cultivar.

Rootstock had the weakest influence on storability, and its effects were identified only when determining the fruit mass loss caused by transpiration and respiration.

Antioxidant capacity, just like various other quality parameters, was strongly affected by storage conditions. It grew during six-month CA storage after applying 1-MCP, whereas it stayed at the same level or declined in other storage conditions. This is an important fact that may enable the promotion of the consumption of ‘Conference’ pear long after harvest.

Most of the results obtained in the study on how six-month storage affects fruit quality and proceeds from its sale show that ‘Conference’ pears should not be stored in NA for so long. The high incidence of fungal diseases and physiological disorders after such a long storage period and the resulting losses cannot be compensated by the benefits of long-term storage. The economic analysis has revealed that it pays off much more to sell the fruit directly after harvest than after six months of NA storage. The application of 1-MCP alleviates the above-mentioned drawbacks, but does not fully make up for the expenditures. The best solution is to keep the fruit under CA and to additionally apply 1-MCP. This technology is recommended as it allows the preservation of firmness, an appropriate proportion between sugars and acids, and a high content of antioxidant substances.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/article/10.3390/agriculture11060545/s1>, Table S1–S3: Firmness (N) of untreated (control) and 1-MCP treated ‘Conference’ pears analysis after storage in normal (NA) and controlled (CA) atmospheres at 2011–2013 year, Table S4–S6: Soluble solid content (%) of untreated (control) and 1-MCP treated ‘Conference’ pears analysis after storage in normal (NA) and controlled (CA) atmospheres at 2011–2013 year, Table S7–S9: Acidity of untreated (control) and 1-MCP treated ‘Conference’ pears analysis after storage in normal (NA) and controlled (CA) atmospheres at 2011–2013 year. Table S10–S12: Impact of storage technology on the incidence of postharvest diseases and disorders in 2011–2013.

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