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Physiological and Quality Responses of 'Bartlett' Pears to Reduced O_2 and Enhanced CO_2 Levels and Storage Temperature

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Abstract. **'Bartlett' pears (Pyrus communis L.) tolerated up to 10 days of exposure to atmospheres containing 1.0%, 0.5%, or 0.25% O_2 at 0, 5, or 10C without any detrimental effects on their quality attributes. The fruits also tolerated 4 to 6 days of exposure to air enriched with 20%, 50%, or 80% CO_2 at the three temperatures. The beneficial effects of exposures to the O_2-reduced or CO_2-enriched atmospheres included reduction of respiration and ethylene production rates and retardation of skin yellowing and flesh softening. While 1.0% or 0.5% O_2 and 20% CO_2 did not increase ethanol and acetaldehyde contents, 0.25% O_2 slightly increased and 50% or 80% CO_2 dramatically increased the contents of these two volatiles in juice of the fruits. The effects of low O_2 or high CO_2 on the above attributes generally became more pronounced at the higher temperatures. The low O_2 or high CO_2 treatments did not significantly affect either soluble solids content or titratable acidity. Low O_2 did not influence, but high CO_2 slightly increased pH of the fruits.**

There have been many studies of controlled-atmosphere (CA) storage of fresh fruits and vegetables, but these have largely evaluated the responses of the commodities to moderately low O_2 (2% to 3%) and/or high CO_2 ($\leq$ 5%) levels over long-term storage. In recent years, there has been increased interest in studying the responses of fruits and vegetables to short-term exposure to O_2 levels $\leq$ 1% and CO_2 levels $\geq$ 20%. Such atmospheres may be effective as a quarantine treatment for insect control in fresh fruits and vegetables (Aharoni et al., 1979; Lidster et al., 1981, 1984; Soderstrom and Brandl, 1987; Soderstrom et al., 1986).

Exposure of 'Granny Smith' apples to O_2 levels $\leq$ 0.5% for 9 days has been reported to have beneficial effects in scald control and in delay of fruit softening and loss of greenness (Little et al., 1982). Nichols and Patterson (1987) showed that short-term storage of 'Delicious' apples to 0.5% or 0.75% O_2 maintained fruit firmness and increased ethanol content. Yoshida et al. (1986) reported that storage of 'Bartlett' pears in 1% O_2 for 4 months reduced ethylene production rate and retained higher levels of organic acids. Claypool (1969, 1973) showed that low-O_2 atmospheres (0.5% to 1%) prolonged storage life and caused no injury to 'Bartlett' pears. Long-term storage of 'd'Anjou' pears in 1.0% O_2 maintained higher dessert quality and higher contents of amino acids and organic acids than storage in air, and prevented scald disorder and internal brown core (Chen and Mellenthin, 1982, Chen et al., 1981; Mellenthin et al., 1980).

Couey and Wright (1977) reported that short-term exposure of 'd'Anjou' pears to 12% CO_2 for 14 days before storage reduced stem decay and scuffing, improved flavor retention, and retarded softening after either regular or CA storage. Similarly, prestorage high CO_2 (10% to 20%) treatments for 10 to 15 days retained higher firmness, acidity, and flavor scores of 'Golden Delicious' apples (Couey and Olsen, 1977) and retarded softening of 'McIntosh' apples (Bramlage, 1977). Recently, Kerbel et al. (1988) showed that 10% CO_2 reduced rates of respiration and ethylene production, contents of protein and fructose-1,6-bisphosphate, and activities of ATP:phosphofructokinase and PPi:phosphofructokinase. However, the high CO_2 treatment increased fructose-6-phosphate and fructose-2,6-bisphosphate levels. Frenkel and Patterson (1977) reported that elevated CO_2 (5% to 20%) decreased succinic dehydrogenase activity and caused disintegration of plastids, vacuoles, and cytoplasmic matrix in 'Bartlett' pears. Chen et al. (1985) reported that elevated CO_2 levels (up to 3%) reduced ethylene production rates and retained higher contents of organic acids in 'Bartlett' and 'Bose' pears. However, one of the major problems with the storage of pear fruits in elevated CO_2 atmospheres is the possible development of CO_2 injury (Blanpied, 1975; Hansen, 1957; Hansen and Mellenthin, 1962; Lau et al., 1977; Little and Peggie, 1987; Porritt and Meheriuk, 1977, 1982; Smock, 1979), which largely limits the use of these treatments in long-term storage of the fruits.

We report here on the effects of short-term exposures to O_2 levels $\leq$ 1% or CO_2 levels $\geq$ 20% on postharvest physiology and quality attributes of 'Bartlett' pears as affected by temperature. This study was aimed at determining the tolerance of the fruits to very low O_2 or very high CO_2 stresses and the potential of using these treatments for postharvest insect control. CA treatments can be used for quarantine procedures only when they can effectively kill the insect of interest without detrimental effects on the quality attributes of the fruits.

Materials and Methods

Materials. For the determinations of quality attributes and volatile contents, mature-green fruits of 'Bartlett' pear were obtained from commercial packinghouses in Sacramento and Lake Counties, Calif., within 24 hr of harvest. Defective fruits were sorted out and the good fruits were matched by color. Ten selected fruits were put in a 4-liter glass jar as one replicate, with three replicates used per treatment. For the measurements of respiration and ethylene production rates, the fruits were stored at -1C until the beginning of the experiment, and there were four replicates consisting of eight fruits each in these measurements. The jars were then placed in a 0, 5, or 10C room and ventilated with humidified air or other gas mixtures at a contin-

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uous flow of 70, 140, or 280 ml·min^{-1}, respectively. Flow boards and capillary tubing were used for flow control.

Treatments. For one set of experiments, fruit samples were kept in air and in 1.0%, 0.5%, 0.25%, or 0.03% O_2 (balance was N); for another set of experiments, fruits were kept in air and in 20%, 50%, or 80% CO_2 (balance was air). The fruit samples were kept in the above atmospheres for 4, 6, 8, or 10 days at 0, 5, or 10C before evaluation (of one half of the fruits in each jar) and transfer to air at 20C for 1 to 6 days to permit fruit ripening before final examination (of the other one half of the fruits in each jar).

Gas analysis. The required O_2 or CO_2 concentrations of all gas mixtures were verified each day by taking a 10-ml gas sample and analyzing it using a Carle gas chromatograph (Model 111; Carle Instruments, Anaheim, Calif.) with a thermal conductivity detector. For measurement of respiration, CO_2 production rates of fruits kept under O_2-reduced atmospheres or air were measured each day by using a Horiba infrared CO_2 gas analyzer (Model SX-2; PIR-2000R; Horiba Instruments, Irvine, Calif.). Ethylene production rates were measured by detecting the ethylene concentration of the gas sample from each jar using a Carle gas chromatograph (Model 211) with a flame ionization detector.

Evaluation of quality attributes. Three initial samples of five fruits each were evaluated for skin color, flesh firmness, soluble solids content (SSC), pH, titratable acidity, and ethanol and acetaldehyde contents. Similar evaluations were also done after various durations of storage and after ripening at 20C. Skin color was measured with a Gardner XL-23 Tristimulus Colorimeter (Gardner Laboratory, Bethesda, Md.) using the "a" value in which a more-negative value indicates more greenness. Flesh firmness was measured as penetration force with a U.C. fruit firmness tester (Western Industrial Supply Co., San Francisco) using an 8-mm plunger tip. Fruit juice was made with a hand-press juice maker. Soluble solids content of the juice was measured by an Abbe refractometer, and pH and titratable acidity were determined by an automatic titrator with a PHM85 Precision pH meter (Radiometer, Copenhagen, Denmark), an ABU80 autoburette (Radiometer); a PRS12 Alpha printer (Radiometer), and a SAC80 sample changer (Radiometer). Ethanol and acetaldehyde contents were measured using a Hewlett Packard 5890A gas chromatograph with a flame ionization detector (at 250C) and a glass column (2 mm × 1.8 m) containing 5% Carbowax on 60/80 Carbopack as stationary phase (at 85C).

Estimation of CO_2 injury. The severity of CO_2-induced injury was estimated using a subjective scale from 1 to 5 according to the area of flesh browning: 1 = 0% browning, 2 = 1% to 25% browning, 3 = 26% to 50% browning, 4 = 51% to 75% browning, and 5 = 76% to 100% browning.

Results and Discussion

Effects of short-term exposures to O_2-reduced atmospheres. Exposure of 'Bartlett' pears to 0.5% or 0.25% O_2 at 0C significantly reduced respiration rates, compared to those of air control (Fig. 1). However, CO_2 production rates increased when O_2 level was further reduced to 0.03%; this increase was probably due to the occurrence of anaerobic respiration (Boersig et al., 1988). After the fruits were transferred to air at 20C, respiration rates dramatically increased in the fruits of all treatments. But in the first 3 days after the transfer, respiration rates of the fruits previously exposed to low O_2 were still lower than those of the fruits continuously exposed to air, indicating some residual effects of the low-O_2 treatments.

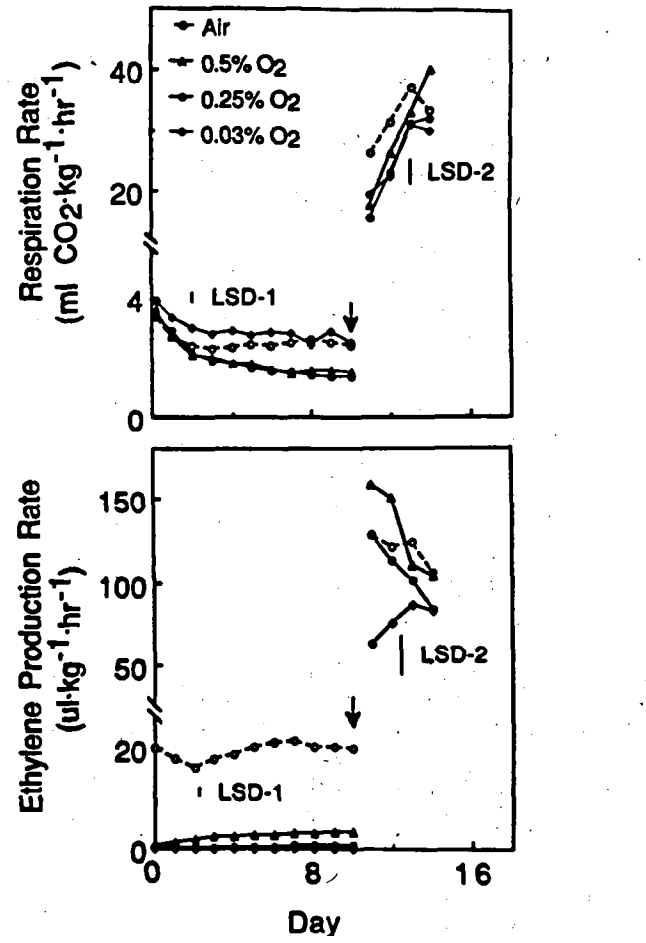

Fig. 1. Effects of low O_2 on respiration and ethylene production rates of 'Bartlett' pears kept at 0C for 10 days before transfer (indicated by arrow) to air to 20C for ripening.

Exposure to 0.5%, 0.25%, or 0.03% O_2 dramatically reduced ethylene production rates of the fruits (Fig. 1); the lower the O_2 concentration, the lower the ethylene production rate. Oxygen is required for the conversion of 1-aminocyclopropane-1-carboxylic acid to ethylene (Yang, 1985). After the fruits were transferred to air at 20C, ethylene production rates greatly increased in all treatments, but the rates of the fruits previously exposed to 0.03% O_2 were still lower than those of the other treatments. The reduction in respiration and ethylene production rates by low O_2 levels can be beneficial for extending the storage life of the fruits.

'Bartlett' pears tolerated 1.0%, 0.5%, or 0.25% O_2 at 0, 5, or 10C for up to 10 days without any detrimental effects on their quality attributes. The fruits also tolerated 0.03% O_2 at 0C for 10 days without any injury. The low-O_2 treatments did not significantly affect SSC, pH, and titratable acidity of the fruits (data not shown). The beneficial effect of keeping these fruits in the O_2-reduced atmospheres at 10C was the retardation of ripening, as indicated by delayed skin yellowing and flesh softening (Table 1) when compared to fruits continuously exposed to air. These effects were less pronounced or absent when the fruits were kept at 0 or 5C, and there were no appreciable differences among pears from the three low-O_2 treatments.

'Bartlett' pears kept in 1.0% or 0.5% O_2 had almost the same levels of ethanol content as the fruits continuously kept in air (Fig. 2), but the pears kept in 0.25% O_2 had a higher ethanol content. The effect of 0.25% O_2 was greater the higher the

Table 1. Effects of temperature and O_2 concentration on speed of degreening of the skin and softening of the flesh of 'Bartlett' pears kept at 0, 5, or 10C for 10 days before transfer to air at 20C for ripening.

Treatment during first 10 days		Mean no. of days to reach	
Temp (°C)	% O_2	CDM[z] "a" value of −8	Firmness of 60 N
0	Air	13	12
	1.0	14	12
	0.5	14	12
	0.25	14	12
5	Air	13	12
	1.0	14	12
	0.5	14	12
	0.25	14	12
10	Air	11	9
	1.0	13	12
	0.5	13	12
	0.25	14	12

[z]CDM = color difference meter.

temperature. After the fruits were transferred from 0.25% O_2 at 10C to air at 20C for ripening, ethanol content dropped to only 37% of the previous value. Similarly, exposure to 0.25% O_2 slightly increased acetaldehyde content. However, these slight increases in ethanol and acetaldehyde contents by the low-O_2 treatments did not affect the flavor of 'Bartlett' pears. The fruits previously exposed to the low-O_2 atmospheres tasted as good, as judged in informal evaluations, as the fruits kept continuously in air when both were later ripened in air at 20C. While a large increase in acetaldehyde and ethanol contents could result in off-flavors, a small amount of these volatiles is essential for the development of characteristic flavor of many products (Lees and Jago, 1978), and the applications of these compounds at low concentrations may enhance fruits' sensory quality (Paz et al., 1981).

Effects of short-term exposures to CO,-enriched atmospheres. 'Bartlett' pears exposed to 20%, 50%, or 80% CO_2 (balance was air) at 5 or 10C showed delayed skin yellowing and flesh softening (Table 2). The higher the CO_2 concentration during holding at 5 or 10C, the longer it took for the fruits to ripen.

'Bartlett' pears previously kept in 20%, 50%, or 80% CO_2 had a slightly higher pH at the time of transfer to air at 20C for evaluation. For example, after 10 days at 0C, pH values were 3.98, 4.07, 4.09, and 4.20 in pears previously kept in air, 20%, 50%, and 80% CO_2, respectively. These treatments did not significantly affect either SSC (12.1% to 12.6%) or titratable acidity (0.18% to 0.24%) of the fruits.

While 20% CO_2 did not significantly influence ethanol and acetaldehyde contents, as compared with the air control, 50% or 80% CO_2 greatly increased the contents of these two volatiles in 'Bartlett' pears (Fig. 3). The effects of 80% CO_2 were greater than those of 50% CO_2, and the effects at 10C were the greatest. Ethanol content was 10 to 20 times higher than the corresponding acetaldehyde content. When the fruits were kept in 80% CO_2 for only 4 days, ethanol content dropped to ≈ 30% of the previous value during the subsequent 4 days of fruit ripening in air at 20C (410 to 440 $\mu l \cdot liter^{-1}$ at transfer and 70 to 150 $\mu l \cdot liter^{-1}$ at ripening). However, when the fruits were kept in 50% or 80% CO_2 for 10 days, ethanol content remained quite high, even after the fruits were transferred to air at 20C for ripening (Fig. 3). The persistently high ethanol and acetaldehyde contents in the juice of 'Bartlett' pears that were kept in 50% or 80% CO_2 for 10 days might have resulted in off-flavor development.

The tolerance of 'Bartlett' pears to high CO_2 levels depended on both temperature and CO_2 concentration. At 0 or 5C, CO_2 injury was observed after 6 days of exposure to 20%, 50%, or

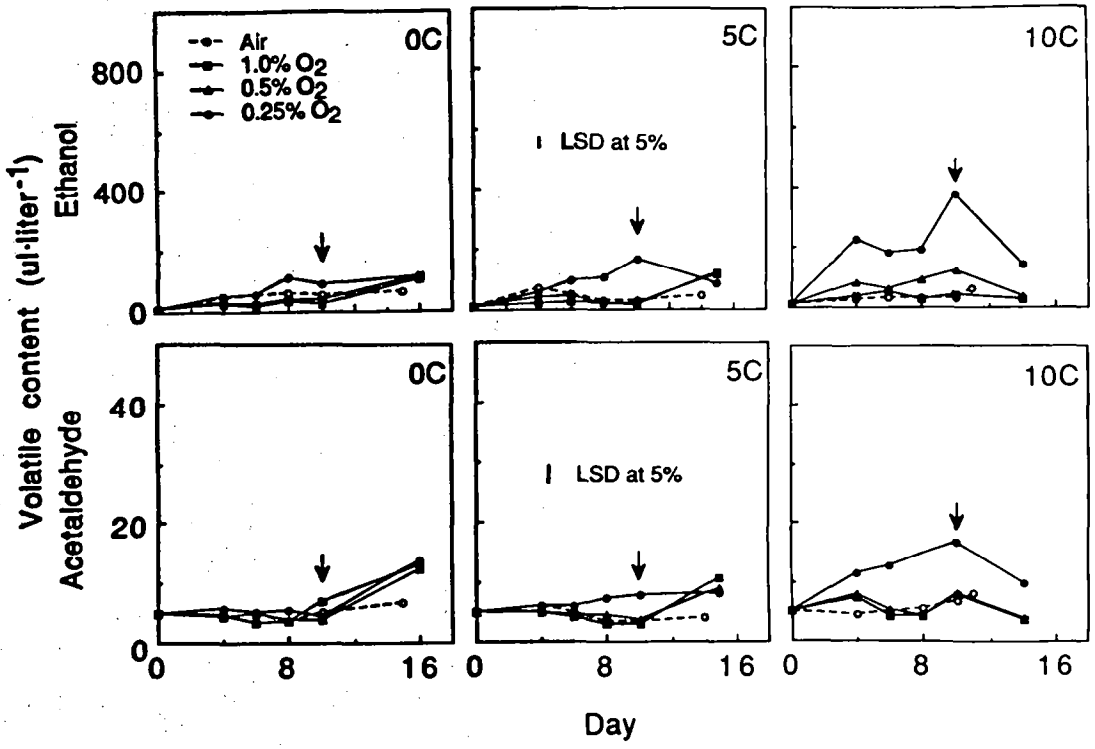

Fig. 2. Effects of reduced concentrations of O_2 on ethanol and acetaldehyde contents in juice of 'Bartlett' pears kept at 0, 5, or 10C for 10 days before transfer (indicated by arrow) to air at 20C for ripening.

Table 2. Effects of temperature and CO_2 concentration on speed of degreening of the skin and softening of the flesh and on severity of CO_2 injury (flesh browning) of 'Bartlett' pears kept at 0, 5, or 10C for 10 days before transfer to air at 20C for ripening.

Treatment during first 10 days		Mean no. of days to reach		Days to see CO_2 injury	Injury score[y] after 10 days of storage
Temp (°C)	% CO_2	CDM[z] "a" value of −8	Firmness of 60 N		
0	Air	12	11	NIO[x]	NIO
	20	12	12	6	1.1 b[w]
	50	12	12	6	1.3 b
	80	12	12	6	1.5 b
5	Air	10	10	NIO	NIO
	20	12	12	6	1.2 b
	50	12	12	6	1.5 b
	80	13	12	6	1.3 b
10	Air	5	5	NIO	NIO
	20	11	11	6	1.6 b
	50	12	12	4	3.1 a
	80	14	14	4	1.7 b

[z]CDM = color difference meter.
[y]Based on the area of brown flesh tissue: 1 = 0% browning, 2 = 1% to 25% browning, 3 = 26% to 50% browning, 4 = 51% to 75% browning, 5 = 76% to 100% browning.
[x]NIO = no injury observed during the experimental period.
[w]Mean separation among all temperature-CO_2 concentration combinations by LSD at $P = 0.05$.

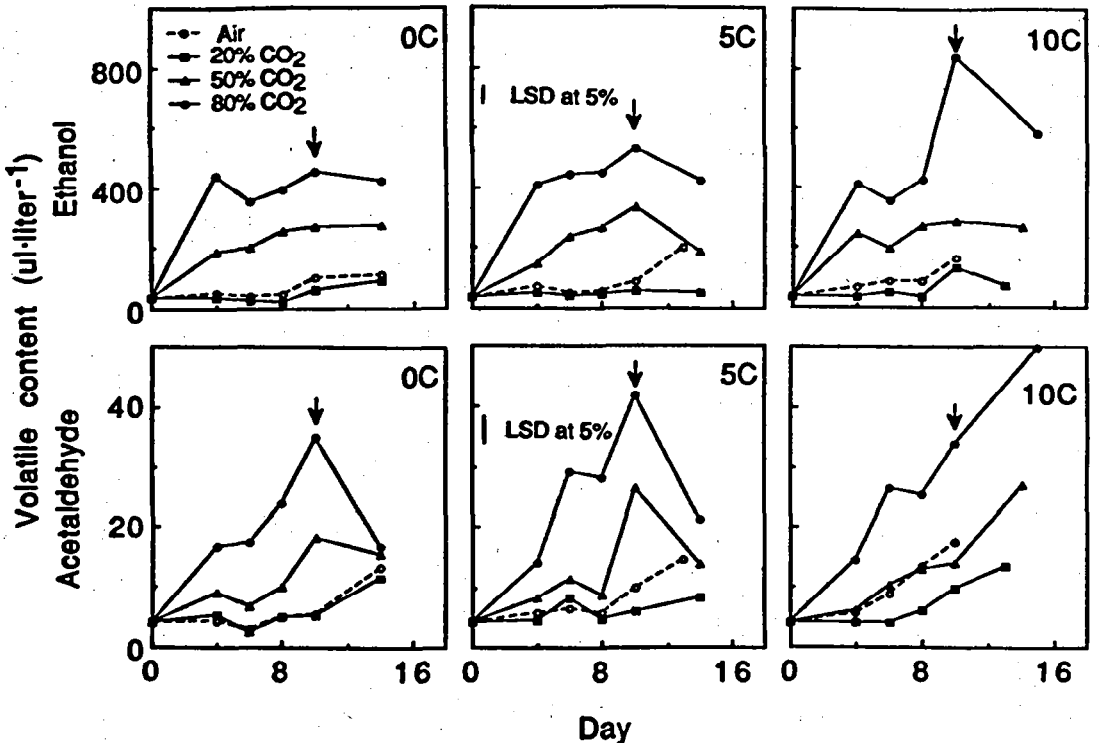

Fig. 3. Effects of elevated CO_2 levels on ethanol and acetaldehyde contents in juice of 'Bartlett' pears kept at 0, 5, or 10C for 10 days before transfer (indicated by arrow) to air at 20C for ripening.

80% CO_2 (Table 2). At 10C, CO_2 injury occurred after 6 days of exposure to 20% CO_2, while injury already was observed after only 4 days of treatment with 50% or 80% CO_2. Carbon dioxide injury started in the center of the fruits with a dark brown discoloration. The dark area increased as the injury became more severe. In extreme cases of injury, the whole flesh tissue became dark brown and soft and the skin of the fruit also became brown. These CO_2 injury symptoms were similar to those described by several other researchers in pears (Blanpied, 1975; Claypool, 1973; Hansen, 1957; Hansen and Mellenthin, 1962). There was a large variation in severity of CO_2 injury among fruits in each treatment. After 10 days of exposure, 50% CO_2 at 10C resulted in the highest injury score, whereas no significant differences in CO_2 injury scores were observed among

all the other CO_2 concentration/temperature combinations. The fact that 50% CO_2 resulted in a higher injury score (tissue browning) than 80% CO_2 at 10C may be due to the lower O_2 level in the latter treatment (≈ 4% O_2 vs. 10% O_2). Ong (1987) showed that 1.5% O_2 + 20% CO_2 resulted in a lower browning score than 20% CO_2 alone in 'Bartlett' pears. Similarly, Ke and Saltveit (1989) found that 1.5% O_2 could inhibit phenolic metabolism and tissue browning induced by 11% CO_2 in crisphead lettuce tissue.

Based on the data presented above, the following treatment combinations can be used on 'Bartlett' pears without detrimental effects on their quality attributes: up to 10 days exposure to 1.0%, 0.5%, or 0.25% O_2 at 0, 5, or 10C; up to 6 days exposure to 20%, 50%, or 80% CO_2 at 0 or 5C; 6 days in 20% CO_2 at 10C; or 4 days in 50% or 80% CO_2 at 10C. Once entomologists have determined which of these combinations can control specific insects, such treatments may be approved by quarantine authorities for commercial use. Accurate and sensitive monitoring techniques for O_2 and CO_2 concentrations and for temperature will be required to verify any approved treatment conditions to help protect the fruits against exposure to conditions that result in low O_2 and/or high CO_2 injuries.

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