Available online at www.sciencedirect.com

ScienceDirect

Postharvest Biology and Technology 49 (2008) 135–139

Postharvest Biology and Technology

www.elsevier.com/locate/postharvbio

Ultralow oxygen treatment for postharvest control of western flower thrips, *Frankliniella occidentalis* (Thysanoptera: Thripidae), on iceberg lettuce II. Effects of pre-treatment storage on lettuce quality

Yong-Biao Liu *

USDA-ARS, 1636 E Alisal Street, Salinas, CA 93905, USA

Received 3 January 2008; accepted 3 January 2008

Abstract

Iceberg lettuce stored under normal atmosphere and controlled atmosphere (CA) with about 3% oxygen at low temperature for 1 week was compared with fresh lettuce for their response to 2 d ultralow oxygen (ULO) treatment with 0.003% oxygen at 10 °C for control of western flower thrips. Lettuce which had been stored for 1 week under normal or CA tolerated ULO treatment while over 30% of fresh lettuce sustained minor injury to heartleaves. Therefore, pre-treatment storage at low temperature enhanced tolerance of lettuce to the subsequent insecticidal ULO treatment. A sequential combination of CA storage and ULO treatment was demonstrated to be effective against western flower thrips and lettuce aphid and safe to all seven lettuce cultivars tested. The study indicated that ULO treatment can be made safer to lettuce through pre-treatment storage to increase lettuce tolerance.

Published by Elsevier B.V.

Keywords: Controlled atmosphere; Ultralow oxygen; Thrips; Aphid; Phytosanitary treatment; Lettuce; Storage; Postharvest quality

1. Introduction

Controlled atmosphere (CA) has been studied extensively as a potential alternative to methyl bromide fumigation for postharvest pest control on fresh commodities (Carpenter and Potter, 1994; Mitcham, 2001, 2003; Mitcham et al., 2001; Liu, 2003, 2005, 2007, 2008). Typical CA treatments for postharvest insect control use elevated carbon dioxide or/and reduced oxygen. Ultralow oxygen (ULO) refers oxygen levels below 1%. Recently, controlled atmosphere treatments with ultralow oxygen levels of 0.015–0.025% (ULO treatments thereafter) were demonstrated to be effective in controlling lettuce aphid, *Nasonovia ribisngri* (Mosley) (Homoptera: Aphididae), on iceberg lettuce without negative effects on lettuce quality (Liu, 2005). ULO treatment with 0.003% oxygen was demonstrated to be safe and effective in controlling western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), on broccoli (Liu, 2007). Western flower thrips is a common pest of lettuce and broccoli in the United States. However, it is quarantined in some overseas markets such as Taiwan. Complete control of western flower thrips on iceberg lettuce was also achieved with minor injury to heartleaves in certain lettuce cultivars (Liu, 2008).

CA research for postharvest pest control on fresh commodities including lettuce so far has very little success because of intolerance of commodities to insecticidal CA treatments (Zhou and Mitcham, 1998; Mitcham et al., 2001; Liu, 2003, 2005, 2007, 2008). Lettuce is very sensitive to carbon dioxide (Lipton et al., 1972; Brecht et al., 1973a,b,c; Stewart and Uota, 1976). CA storage with very low oxygen levels also causes injury to lettuce (Lipton, 1967, 1971; Lipton et al., 1972). Most CA studies focus on atmospheric composition, treatment time, and treatment duration to reduce injury to specific commodities and achieve effective pest control (Carpenter and Potter, 1994; Mitcham et al., 2001). There is a lack of studies on potential effects of postharvest handling and storage on responses of fresh products to insecticidal CA treatments. After harvest, fruits and vegetables undergo an acclimation process marked

* Tel.: +1 831 755 2825.
E-mail address: YongBiao.Liu@ars.usda.gov.

0925-5214/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.postharvbio.2008.01.007

by reduced respiration as they are stored at low temperatures (Kader and Saltveit, 2003). Respiration of broccoli shows a continuous decline in cold storage for over a week after harvest (Kasmire et al., 1974). The acclimation process may affect tolerance of fresh fruits and vegetables to insecticidal CA treatments.

Lettuce like many other vegetables has greatly reduced respiration under postharvest cold storage conditions (Lipton, 1967; Nunes and Emond, 2003). Stored lettuce and fresh lettuce also differ in chemical profile (Wang, 1990; Ke et al., 1993; Eriş et al., 1994; Smyth et al., 1998). It is interesting and important to know whether postharvest storage can affect responses of fresh commodities to ULO treatment. In the present study, effects of pre-treatment storage of lettuce on response of lettuce to ULO treatment were evaluated and a sequential combination of CA storage and ULO treatment was evaluated for control of western flower thrips and effects on postharvest quality of head lettuce.

2. Materials and methods

2.1. Insects

Western flower thrips were reared on lettuce plants in a greenhouse (Liu, 2008). Thrips (larvae and adults) were collected in plastic vials (2.5 cm diameter by 7 cm high) with lettuce leaf pieces using a vacuum powered aspirator (10–20 thrips per vial). The vials were sealed with screened lids lined with Kimwipe tissue to prevent escape of thrips. Whole lettuce plants with thrips from the thrips culture were also used in the large-scale treatments. Plants were cut above soil and put individually in plastic cups (12 cm diameter by 14 cm high). The cups were sealed with screened lids lined with paper towel.

Lettuce aphid colony was maintained on lettuce plants in screen cages (61 cm × 61 cm × 61 cm) in a greenhouse (Liu, 2005). The colony was originated from field collected lettuce aphid in 2001 in Salinas Valley, CA and field collected aphids were added in 2003. For ULO treatment, lettuce plants with lettuce aphid from the aphid colony were set up in plastic cups as described above. The cups were sealed with screened lids.

2.2. Effects of pre-treatment storage on responses of lettuce and insect to ULO treatment

Commercial iceberg lettuce was stored under CA with about 3% oxygen or under normal atmosphere for 7 d at 2 °C. The stored lettuce was then compared with fresh lettuce for responses to a 2 d ULO treatment with 0.003% oxygen at 10 °C in visual quality and susceptibility to ULO injury. Four treatment combinations were compared: (1) 7 d CA storage followed by 2 d ULO treatment; (2) 7 d normal cold storage followed by 2 d ULO treatment; (3) 2 d ULO treatment followed by 7 d CA storage; and (4) 2 d ULO treatment followed by normal cold storage. Effects of different treatment combinations on survival of western flower thrips were also evaluated. A total of 6–8 vials of thrips (10–20 thrips per vial) were added to each chamber to be treated. Each treatment combination was replicated three times.

Vacuum-cooled and wrapped commercial head lettuce was obtained from Tanimura & Antle Co. (Salinas, CA) on the day of harvest. Lettuce cultivars used were: “Corona”, “Diamond”, “Liberty”, “Sureshot”, “Telluride”, and “Trojan”. CA storage and ULO treatment were conducted in treatment chambers modified from plastic boxes (64 cm × 46 cm × 25 cm) in refrigerators which were equipped with external digital temperature controllers and circulation fans to maintain accurate and uniform temperature. The treatment chambers had circulation fans inside to circulate air constantly and ports for tubing connections. A dish of about 100 g sodasorb (Grace & Co., Atlanta, GA) was placed in each chamber to absorb CO_2. The chambers also had sleeves of vinyl film on the openings. Each chamber was sealed by covering the chamber with a lid that had upward lip to form a pool filled with water and then folding the sleeve and press the sleeves in the water to achieve an airtight seal with a second lid on the top.

CA with about 3% oxygen was established and maintained by releasing a mixture of nitrogen with about 0.2% oxygen from a nitrogen generator (Balston 75–7820, Parker Hannifin Co., Tewksbury, MA) and compressed air at a flow rate of 16.7 mL s^{-1} into each box chamber. The ULO treatment was established using the same procedures as described before (Liu, 2007, 2008). Treatment chambers were flushed with generated nitrogen initially followed by flushing with pure nitrogen from compressed cylinders. Pure nitrogen was released into each chamber at a constant flow rate of 16.7 mL s^{-1} once the desired oxygen level of 0.003% for ULO treatment was reached. Oxygen level in the chamber was monitored constantly over time using an oxygen analyzer with alarm relays (Series 800, Illinois Instruments, Inc., Johnsburg, IL). Generated nitrogen with about 0.2% oxygen was added to the nitrogen stream once the oxygen level in the chambers fell below the set limit of 0.003% triggered by the alarm relay of the oxygen analyzer to maintain a constant ULO level. A carbon dioxide analyzer (model 302 M, Nova Analytical Systems, Inc., Niagara Falls, NY) was used to monitor carbon dioxide levels in the treatment chambers and carbon dioxide levels were below 0.1% in all ULO treatments. The total length of time for completing a sequential combination of pre-treatment storage and ULO treatment was 10 d.

After ULO treatment, insects were kept overnight in an environmental chamber at 24 °C and 14:10 (L:D) photoperiod before being evaluated for mortality and lettuce heads were stored at 2 °C in a walk-in cooler for 2 weeks before being evaluated for postharvest quality. Insects that did not move or failed to respond to repeated probing with a soft brush were scored as dead. Lettuce quality was evaluated using the same procedures as described before (Liu, 2008). Visual quality of treated lettuce and the controls was scored using the method described by Kader et al. (1973). Weights of lettuce heads were measured individually. External abnormalities or injuries were recorded. Lettuce heads were then dissected to inspect for injury to heartleaf tissues. All heartleaves with injury were removed and weighed. A total of 1441 thrips and 142 lettuce heads from 6 cultivars were used.

Table 1
Mortality of western flower thrips in response to different combinations of low temperature storage and 2 d ultralow oxygen (ULO) treatment with 0.003% oxygen at 10 °C

Treatment combination	*N*	Mortality ± S.E. (%)
ULO–CA storage	315	99.5 ± 0.3 a
ULO–cold storage	322	99.6 ± 0.3 a
CA storage–ULO	320	100 a
Cold storage–ULO	322	100 a

Insect mortality rates in the four treatments were adjusted for 26.5% control mortality using Abbott's method. The mortality rates followed by the same letter were not significantly different (Tukey–Kramer multiple range test, $P > 0.05$ [SAS Institute, 2002]).

2.3. Effects of sequential CA–ULO combination treatment on insect mortality and lettuce quality

A sequential combination of 7 d CA storage with 3% oxygen at 2 °C and 2 d ULO treatment with 0.003% oxygen at 10 °C was conducted in large box chambers in a walk-in cooler to demonstrate its safety to lettuce and efficacy in controlling insects. The total length of time for completing the CA–ULO treatment was 10 d. The procedures for conducting CA storage and ULO treatment were the same as stated above but in larger box chambers (107 cm × 74 cm × 71 cm) (Liu, 2007, 2008). Vacuum-cooled and individually wrapped commercial iceberg lettuce heads were obtained from Tanimura & Antle Co. (Salinas, CA) on the day of harvest. Lettuce cultivars used were: "Corona", "Dallas", "Durango", "Oso Flaco", "Sniper", "Telluride", and "Victory". For each test, 2–4 cultivars (16–24 heads per cultivar) in three cartons were treated in one chamber. Specific cultivars used in each test varied depending on availability at the time of the test. A dish of about 100 g sodasorb was placed on top of a carton for absorbing CO_2. Thrips in plastic vials were placed in each carton. Plastic cups (12 cm diameter by 14 cm high) with lettuce plants infested with thrips were set on top of lettuce cartons. Plastic cups with lettuce plants infested with lettuce aphid were also set on top of lettuce cartons to be tested to confirm the efficacy of the CA–ULO treatment for control of lettuce aphid. A circulation fan was set on top of the cartons to circulate air in the treatment chambers constantly. The chambers were sealed by covering the chambers with lids which have lips inserted into water-filled troughs around the opening. In most tests, when the CA storage phase was terminated, some fresh lettuce heads were added before starting the ULO treatment phase to compare CA stored and fresh lettuce for response to the ULO treatment in the same treatment chamber.

After the CA–ULO treatment, insect mortality was scored using the same procedures as stated above and lettuce was stored at 2 °C in a walk-in cooler. Postharvest quality of treated lettuce and controls was evaluated after 7 and 14 d of post-treatment storage. The procedures for lettuce quality evaluation were the same as stated above using the method of Kader et al. (1973). The CA–ULO treatment was replicated six times. A total of 24 cartons (576 heads) of iceberg lettuce from 7 cultivars were used and 303 lettuce heads were scored for postharvest quality. A total of 2811 thrips and 9416 lettuce aphids were used.

2.4. Data analysis

Insect mortality from different treatments were adjusted for control mortality using Abbott's formula and transformed by arcsine$\sqrt{x}$ prior to analysis of variance. Tukey–Kramer's multiple range test was used to compared insect mortality using the standard least squares model of JMP Statistical Discovery software (SAS Institute, 2002). Data on visual quality scores, weights of lettuce, and weights of heartleaves with injury also were analyzed and compared using ANOVA and Tukey–Kramer multiple range test (SAS Institute, 2002).

3. Results

3.1. Effects of pre-treatment storage on responses of lettuce and insect to ULO treatment

In the comparison of the four combination treatments, two treatments resulted in 100% mortality of western flower thrips and the other treatments had only one survivor each (>99.6% mortality after adjusting for 26.5% control mortality). There were no significant differences among the four combination treatments in insect mortality (Table 1). There were, however, significant differences in lettuce susceptibility to injury by the ULO treatment. Cold-stored or CA-stored lettuce heads did not sustain any injury to heartleaves by the ULO treatment as compared with fresh lettuce. Fresh lettuce had about 32% and 42% of heads with heartleaf injury in the ULO–CA and ULO–cold storage combination treatments, respectively (Table 2). The average weights of injured heartleaves for each head with heartleaf injury were 1.8 and 2.3 g, respectively for the two treatments. There were no significant differences among the four treatments in visual quality or head weight. The visual quality ratings ranged

Table 2
Postharvest quality of head lettuce in responses to four storage and ultralow oxygen (ULO) treatment combinations after 14 d of post-treatment storage

Treatment combination	*N*	Visual quality (mean ± S.E.)	Head weight (mean ± S.E. (g))	Heads with injury (mean ± S.E. (%))	Weight of injured leaves (mean ± S.E. (g))
ULO–CA storage	37	7.2 ± 0.2 a	757.4 ± 34.2 a	32.4 ± 7.8 a	1.8 ± 0.6 a
ULO–cold storage	36	6.8 ± 0.3 a	747.0 ± 29.9 a	41.7 ± 8.3 a	2.3 ± 0.6 a
CA storage–ULO	36	7.6 ± 0.2 a	769.5 ± 33.9 a	0 b	–
Cold storage–ULO	33	7.1 ± 0.3 a	740.2 ± 33.6 a	0 b	–

The values in each column followed by the same letter were not significantly different (Tukey–Kramer multiple range test for more than two values and Student *t*-test for the two values of the last column, $P > 0.05$ [SAS Institute, 2002]).

Table 3
Mortality rates of western flower thrips and lettuce aphid in response to a sequential combination of 7 d controlled atmosphere storage at 2 °C and 2 d ultralow oxygen treatment with 0.003% oxygen at 10 °C (CA–ULO treatment)

Insect	Treatment	*N*	Mortality ± S.E. (%)
Western flower thrips	CA–ULO	2637	100
	Control	174	42.0 ± 5.0
Lettuce aphid	CA–ULO	5620	100
	Control	3796	4.1 ± 0.3

between 6.8 and 7.6, representing good quality with minor negligible defects. The average lettuce head weighed about 750 g (Table 2).

3.2. Effects of sequential CA–ULO combination treatment on insect mortality and lettuce quality

The sequential CA–ULO combination treatment achieved complete control of western flower thrips and lettuce aphid and caused no injury to lettuce (Tables 3 and 4). Visual quality rating of lettuce from controls was slight but significantly higher than the CA–ULO combination treatment. The quality for controls was 8.3 as compared with 7.3–7.6 for pre-stored or fresh lettuce subjected to the ULO treatment. There were also no significant differences in visual quality between 7 and 14 d post-treatment storage, indicating that treated lettuce retained good visual quality 24 d after harvest. The head weights of lettuce were similar across all treatments and controls with the average head weight ranged between 890 and 940 g. Lettuce heads subjected to both the CA storage and the ULO treatment had no injury to heartleaves. In comparison, fresh lettuce heads which was included only in the ULO phase of the treatment without prior CA storage had significantly higher percentages of heads with heartleaf injury (17% and 29% for 7 and 14 d post-treatment evaluations). The CA–ULO treatment was effective in controlling both lettuce aphid and western flower thrips and safe to head lettuce. For fresh lettuce, the percentage of heads with heartleaf injury and the average weight of injured heartleaves were not significantly different between the 7 and 14 d post-treatment evaluations due to large variation (Table 4).

4. Discussion

The effects of pre-treatment storage of lettuce in preventing injury to lettuce heartleaves by the subsequent ULO treatment has important implications for developing practical ULO treatment for insect control on lettuce and other fresh commodities. There has been extensive research on controlled atmosphere treatment for postharvest pest control in the last two decades with little success (Mitcham et al., 2001; Mitcham, 2001, 2003). Most studies focus on finding effective insecticidal treatments with little emphasis on enhancing tolerance of the subject commodities to the treatments. The enhanced tolerance of lettuce through pre-treatment storage demonstrated in this study suggests that lettuce susceptibility to ULO treatment can be modified significantly. It is likely that many other fresh commodities also exhibit similar characteristics of increased tolerance to extreme CA conditions including ULO after a certain length of acclimation to postharvest storage. The successful outcome of the present study points to a new direction of modifying postharvest physiology of the fresh products in developing CA-based postharvest pest control technology.

Previously, ULO treatments alone were reported to control lettuce aphid without effecting lettuce quality (Liu, 2005). The lettuce used in the study was obtained from supermarkets with postharvest storage experience and therefore was likely to have developed tolerance to ULO treatment before being tested. In light of the current finding of enhanced tolerance to ULO treatment by pre-treatment storage, it becomes questionable whether the ULO treatment for control of lettuce aphid can be safely performed with fresh lettuce even though the treatment was milder than the current ULO treatment for control of both western flower thrips and lettuce aphid.

The reason for the increased lettuce tolerance to the ULO treatment after pre-treatment storage was likely due to acclimation to postharvest storage. It has been suggested that acclimation plays important roles in fruit tolerance to low oxygen or low temperature. Fruits may better tolerate extreme low oxygen or temperature conditions by an acclimation process of pre-exposure to moderately low oxygen or low temperature (Chervin et al., 1996). The tolerance to low oxygen in CA storage by fresh commodities is also expected to increase

Table 4
Effects of 7 d pre-treatment controlled atmosphere storage at 2 °C on response of iceberg lettuce to the subsequent 2 d insecticidal ultralow oxygen treatment with 0.003% oxygen at 10 °C

Pre-ULO status	Post-ULO storage (d)	Time from harvest (d)	*N*	Visual quality	Head weight (mean ± S.E. (g))	Heads with injury (mean ± S.E. (%))	Weight of injured (mean ± S.E. (g)[a])
CA stored	7	17	84	7.5 ± 0.1 b	935.2 ± 19.0 a	0 b	–
	14	24	104	7.3 ± 0.2 b	897.5 ± 18.2 a	0 b	–
Fresh[b]	7	10	29	7.6 ± 0.3 ab	911.7 ± 37.0 a	17.2 ± 7.1 a	1.9 ± 6.3 a
	14	17	38	7.4 ± 0.2 b	891.1 ± 25.9 a	28.9 ± 7.4 a	14.8 ± 4.3 a
Control		17	48	8.3 ± 0.1 a	907.1 ± 23.9 a	0 b	–

The values in each column followed by the same letter were not significantly different (Tukey–Kramer multiple range test, $P > 0.05$ [SAS Institute, 2002]).
[a] Student *t*-test, $P > 0.05$ (SAS Institute, 2002).
[b] For fresh lettuce, there was no significant different in proportion of lettuce heads with heartleaf injury between post-ULO storage time of 7 and 14 d based on contingency analysis (likelihood ratio $\chi^2 = 0.545$, $P = 0.136$, SAS Institute, 2002).

with increasing storage time (Saltveit, 2003). In the present study, both cold storage and controlled atmosphere storage resulted in prevention of heartleaf injury by the subsequent ULO treatment at a higher temperature than the temperature of pre-treatment storage. Therefore, it is likely that acclimation to cold storage increased tolerance of lettuce to the ULO treatment.

Sequential CA treatments were studied for control of Pacific spider mites on table grapes (Zhou and Mitcham, 1998). The sequential CA treatments consist of a short extreme treatment followed by a mild long term CA treatment. The rationale is that the extreme treatment causes injury to the mites and the subsequent mild CA treatment prevents repair of the injury and thereby results in the death of the pest (Zhou and Mitcham, 1998). In contrast, the sequential CA–ULO treatment, in the present study, focused on reducing susceptibility of lettuce to the potential injury by the subsequent ULO treatment.

The implication of the need to store lettuce for a certain length of time before ULO treatment is that ULO treatment is better suited for in-transit treatment in CA shipping containers or after lettuce reaches its destinations to minimize delay for lettuce to reach overseas markets. The 7 d CA storage time used in the present study would make it practical to complete the sequential CA–ULO combination treatment within the 10–14 d transit time from major U.S. west coast ports to major overseas markets in Asia. The 7 d pre-ULO storage allows enough time to establish ULO treatment condition. However, it is possible that shorter pre-ULO treatment storage may also be effective in preventing heartleaf injury by the subsequent ULO treatment. Further studies should be directed in this area to determine the minimum pre-treatment storage time for preventing injury by the subsequent ULO treatment and feasibility of pre-shipping ULO treatment for controlling western flower thrips and lettuce aphid on head lettuce.

Acknowledgments

I thank G. Gretz, M. Houston, G. Martinez, L. Tschumperlin, A. Obad, and J. Wasson for technical assistance and Tanimura & Antle Co. for providing lettuce used in the study. I also thank Drs. P.A. Follett, T.-X. Liu, J.D. McCreight, and two anonymous reviewers for comments and suggestions to an earlier version of this paper. This study was supported in part by funding from U.S. Department of Agriculture, Foreign Agricultural Service and California and Arizona Lettuce Export Council.

References

Brecht, P.E., Morris, L.L., Chesey, C., Janecke, D., 1973a. Brown stain susceptibility of selected lettuce cultivars under controlled atmospheres and temperatures. J. Am. Soc. Hortic. Sci. 98, 261–264.

Brecht, P.E., Kader, A.A., Morris, L.L., 1973b. Influence of postharvest temperature on brown stain of lettuce. J. Am. Soc. Hortic. Sci. 98, 399–402.

Brecht, P.E., Kader, A.A., Morris, L.L., 1973c. The effect of composition of atmosphere and duration of exposure on brown stain of lettuce. J. Am. Soc. Hortic. Sci. 98, 536–538.

Carpenter, A., Potter, M.A., 1994. Controlled atmospheres. In: Sharp, J.L., Hallman, G.J. (Eds.), Quarantine Treatments for Pests of Food Plants. Boulder, CO, Westview, pp. 171–198.

Chervin, C., Brady, C.J., Patterson, B.D., Faragher, J.D., 1996. Could studies on cell responses to low oxygen levels provide improved options for fruit storage and disinfestations? Postharvest Biol. Technol. 7, 289–299.

Eriş, A., Özgür, M., Özer, M.H., Çopur, H., Henze, J., 1994. A research on the controlled atmosphere (CA) storage of lettuce. Acta Hortic. 368, 786–792.

Kader, A.A., Saltveit, M.E., 2003. Respiration and gas exchange. In: Bartz, Brecht (Eds.), Postharvest Physiology and Pathology of Vegetables, 2nd edition. Marcel Dekker, Inc., New York, NY.

Kader, A.A., Lipton, W.J., Morris, L.L., 1973. Systems for scoring quality of harvested lettuce. HortScience 8, 408–409.

Kasmire, R.F., Kader, A.A., Klaustermeyer, J., 1974. Broccoli shipping odors caused by poor air circulation and low oxygen levels. Cal. Agric. 28 (6), 14.

Ke, D., Mateos, M., Siriphanich, J., Li, C., Kader, A.A., 1993. Carbon dioxide action on metabolism of organic and amino acids in crisphead lettuce. Postharvest Biol. Technol. 3, 235–247.

Lipton, W.J., 1967. Market quality and rate of respiration of head lettuce held in low oxygen atmosphere. USDA Market Res. Rep. No. 777, Washington, DC, p. 8.

Lipton, W.J., 1971. Controlled Atmosphere Effects on Lettuce Quality in Simulated Export Shipments, 51–45. USDA, ARS, Washington, DC, p. 14.

Lipton, W.J., Stewart, J.K., Whitaker, T.W., 1972. An illustrated guide to the identification of some market disorders of head lettuce. USDA, ARS, Marketing Research Report No. 950, p. 7, pl. 19.

Liu, Y.-B., 2003. Effects of vacuum and controlled atmosphere treatments on insect mortality and lettuce quality. J. Econ. Entomol. 96, 1100–1107.

Liu, Y.-B., 2005. Ultralow oxygen treatment for postharvest control of *Nasonovia ribisnigri* (Homoptera: Aphididae) on iceberg lettuce. J. Econ. Entomol. 98, 1899–1904.

Liu, Y.-B., 2007. Ultralow oxygen treatment for postharvest control of western flower thrips, *Frankliniella occidentalis*, on broccoli. J. Econ. Entomol. 100, 717–722.

Liu, Y.-B., 2008. Ultralow oxygen treatment for postharvest control of western flower thrips, *Frankliniella occidentalis* (Thysanoptera: Thripidae), on iceberg lettuce. I. Effects of temperature, time, and oxygen level on insect mortality and lettuce quality. Postharvest Biol. Technol. 49, 129–134.

Mitcham, E.J., 2001. Quarantine issues in 2000. Acta Hortic. 533, 451–455.

Mitcham, E.J., 2003. Controlled atmospheres for insect and mite control in perishable commodities. Acta Hortic. 600, 137–142.

Mitcham, E.J., Zhou, S., Kader, A.A., 2001. Potential of CA for postharvest insect control in fresh horticultural perishables: an update of summary tables compiled by Ke and Kader 1992. Department of Pomology, University of California, Davis, CA.

Nunes, M.C., Emond, J.P., 2003. Storage temperature. In: Bartz, Brecht (Eds.), Postharvest Physiology and Pathology of Vegetables, 2nd edition. Marcel Dekker, Inc., New York, NY.

Saltveit, M.E., 2003. Is it possible to find an optimal controlled atmosphere? Postharvest Biol. Technol. 27, 3–13.

SAS Institute, 2002. JMP Statistics and Graphics Guide, Version 5. SAS Institute, Cary, NC.

Smyth, A.B., Song, J., Cameron, A.C., 1998. Modified atmosphere packaged cut iceberg lettuce: effect of temperature and O_2 partial pressure on respiration and quality. J. Agric. Food Chem. 46, 4556–4562.

Stewart, J.K., Uota, M., 1976. Postharvest effects of modified levels of carbon monoxide, carbon dioxide and oxygen on disorders and appearance of head lettuce. J. Am. Soc. Hortic. Sci. 101, 282–284.

Wang, C.Y., 1990. Physiological and biochemical effects of controlled atmosphere on fruits and vegetables. In: Calderon, M., Barkai-Nolan, R. (Eds.), Food Preservation by Modified Atmospheres. CRC Press, Bona Raton, FL, pp. 197–223.

Zhou, S., Mitcham, E.J., 1998. Sequential controlled atmospheres treatments for quarantine control of Pacific spider mites (Acari: Tetranychidae). J. Econ. Entomol. 91, 1427–1432.