FINAL PROJECT REPORT

Project Title: At-harvest protocols for apple fruit disorder and quality management

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Notes: in-kind, GS-9 technician

Total Project Funding: $161,873

Budget History:

Item	2016	2017	2018
WTFRC expenses			
Salaries	$35,135	$35,239	$35,828
Benefits	$17,306	$17,716	$17,647
Wages			
Benefits			
Equipment			
Supplies	$1000	$1000	$1000
Travel			
Plot Fees			
Miscellaneous			
Total	$53,441	$53,956	$54,476

RECAP ORIGINAL OBJECTIVES

This project was developed based on previous work to identify factors influencing ‘Honeycrisp’ response in the postharvest environment. These included interactions among delayed cooling, rapid CA establishment, CA composition, and use of 1-MCP. The relative success in reducing risk of chilling disorder development (soft scald, soggy breakdown) using delayed cooling, reduced bitter pit from rapid CA and/or 1-MCP, and moderate CA O_2 concentration with low CO_2 showed the value for a postharvest management approach very different from that typically used for other varieties. Those results also suggested additional work to optimize and determine limits for the use of rapid CA for ‘Honeycrisp’ bitter pit management as well as to determine if similar practices influence disorders and fruit quality of other varieties. The increase in organic production and associated need for appropriate postharvest management strategies was another consideration for these studies. Disorders previously managed using DPA and/or 1-MCP require other control techniques, for chilling disorders the use of delayed cooling could be an option to reduce injury development. Delayed cooling increases the risk of fruit quality loss for varieties with softening as a primary concern during storage, but higher initial storage temperature can also reduce the risk of CO_2 injury. Establishing CA during conditioning was hypothesized to be a means to reduce the risk of quality loss but this strategy also posed risk for inducing other disorders due to the potential for low O2 injury at relatively warm temperatures. The studies were therefore designed to determine impacts of conditioning with or without CA on chilling and other disorders as well as fruit quality.

SIGNIFICANT FINDINGS

Objective 1 (Identify optimum controlled atmosphere conditions during ‘Honeycrisp’ conditioning) partially met, conditions under which CO_2 injury can occur not identified.
Objective 2 (Determine impacts of CA established during temperature conditioning on fruit quality and disorder development of ‘Gala’, ‘Fuji’, and ‘Granny Smith’ apples) fully met as positive and negative consequences of treatments were identified, potential for commercial use exists.
Objective 3 (Compare how 1-MCP and rapid CA establishment during temperature conditioning impact disorders and fruit quality) fully met, results consistent over 7 orchard years.

- ‘Honeycrisp’ bitter pit incidence is consistently reduced by one week in CA established during conditioning followed by storage in air.
- Bitter pit was reduced in some lots by treatment with 1-MCP alone or in combination with CA during conditioning.
- CA established during ‘Honeycrisp’ conditioning did not provoke development of internal or external disorders.
- No CO_2 disorders developed through 8 months storage of ‘Honeycrisp’ apples stored in CA with up to 4% CO_2 during conditioning.
- CA during conditioning of ‘Fuji’, ‘Gala’, and ‘Granny Smith’ has potential to reduce disorders without fruit quality loss.
- CA storage of ‘Gala’ at 31ºF increased internal browning and shrivel compared to fruit stored at 33ºF.
- CA oxygen concentration (0.5 or 1%) did not influence quality compared to storage temperature during ‘Gala’ CA storage.
- Conditioning ‘Fuji’ and ‘Granny Smith’ reduced development of core browning compared to fruit held continuously at 33ºF.

RESULTS & DISCUSSION

Optimum CA conditions during 'Honeycrisp' conditioning

Oxygen concentration during conditioning: The objective was to determine if bitter pit control is possible with relatively high oxygen concentration (5-15%) during conditioning. CA (all with 0.5% CO_2) was established 1 day after receipt and after 1-MCP treatment. Fruit were stored in air at 37°F after conditioning. There was some bitter pit reduction due to the CA treatments, but a clear trend was not established due to results for fruit held at 5% O_2 (Figure 1). Additional experiments would provide a better indication of the potential for this protocol.

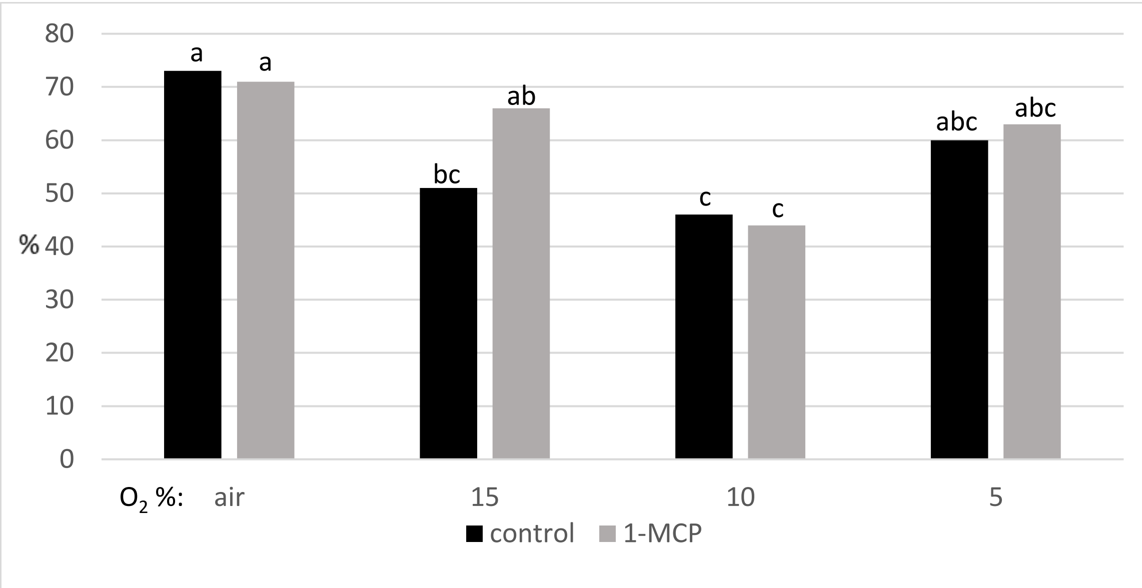

Figure 1. 'Honeycrisp' bitter pit incidence after 4 months cold storage plus 7 days at 68°F. Fruit were conditioned at 50°F for 7 days after receipt, 1-MCP applied day of receipt, CA established 1 day after receipt and held through a week, then fruit stored in air at 37°F for 4 months.

Carbon dioxide conditions during 'Honeycrisp' conditioning

'Honeycrisp' can be sensitive to CO_2 during storage. In the previous project CO_2 accumulation in air during conditioning did not provoke CO_2 injury (6 lots, 2 seasons). In the current project, fruit during conditioning were held in CA (2% O_2 throughout or 2 days at 3% then 2% O_2) with up to 4% CO_2. Exposing fruit to up to 2% CO_2 during conditioning, then storage in air (Table 1) or CA (2.5% O_2, 0.5% CO_2) (Table 2) after conditioning did not cause injury or reduce efficacy for bitter pit management. Each table contains means for 2 orchards. Use of 1-MCP did increase development of peel blotch and cavities for some treatments. This result for 1-MCP is different from our previous research where CO_2 exposure during conditioning was in air. Where DPA was applied prior to 1-MCP, no cavities developed. With the sample population to date, risk of injury from high CO_2 CA during conditioning is low where 1-MCP has not been used. While the results do not rule out CO_2 risk during conditioning, the cumulative lack of injury (experiments over 4 years, two years this project, two previous project) in work with 10 orchard lots not treated with 1-MCP suggests short CO_2 exposures at 50°F may not present a high risk for CO_2 injury.

CA	BP %	Peel blotch %	Lenticel breakdown %	Core browning %	Internal browning %	Cavities %
2% O_2, 0.5% CO_2	33b	0b	0b	3ns	3ns	1b
1-MCP	37ab	23a	7ab	0	3	12a
3/2% O_2, 0.5% CO_2	47ab	0b	0b	1	1	9ab
1-MCP	45ab	20a	6ab	4	4	15a
DPA, 1-MCP	25b	13ab	0b	0	3	0b
3/2% O_2, 1% CO_2	55a	0b	10a	1	3	4b
1-MCP	27b	24a	6ab	3	4	14a
3/2% O_2, 2% CO_2	52a	0b	4ab	3	8	8ab
1-MCP	32b	14a	10a	3	3	10ab

Means followed by different letters are significantly different, $p \leq 0.05$. ns: not significant

Table 1. 'Honeycrisp' fruit quality after 4 months in air plus 7 days at 68ºF. Fruit were held at 50ºF for 7 days then at 37ºF in air. 1-MCP applied the day fruit received, CA established the following day.

CA	BP %	Peel blotch %	Lenticel breakdown %	Core browning %	Internal browning %	Cavities %
air	53a	0ns	0ns	0ns	1ns	2ns
3/2% O_2, 0.5% CO_2	31b	3	2	0	2	6
3/2% O_2, 1% CO_2	26b	0	1	0	0	2
3/2% O_2, 2% CO_2	27b	1	1	0	2	4
3/2% O_2, 4% CO_2	29b	3	1	1	1	2

Means followed by different letters are significantly different, $p \leq 0.05$. ns: not significant

Table 2. 'Honeycrisp' fruit quality after 4 months in CA plus 7 days at 68ºF. Fruit were held at 50ºF for 7 days then at 37ºF. CA was established the following day. O_2 was held for 2 days at 3%, then reduced to 2%. After 7 days all CA treatments were 2% O_2 with 0.5% CO_2.

CA during conditioning of other varieties

'Gala' CA during conditioning

Over the two years with two orchards each year, CA during conditioning of 'Gala' provided similar results for quality management compared with CA begun 7 days after receipt for fruit held continuously at 33ºF (Tables 3,4). Delaying CA for conditioned fruit resulted in unacceptable firmness loss and more cavities in the first year and more cortex senescent browning in both years. Less senescent browning developed in CA and 1-MCP fruit supporting this is an aging-related disorder. Peel blotch occurred only in the second year and only in fruit held continuously at 33ºF supporting initial temperature as a factor in development of this disorder. The general conclusion is conditioning 'Gala' can reduce disorder development but CA is needed to avoid excessive firmness loss.

Initial Temp °F	Atm	MCP	Lbs	TA %	Senescent browning %
50	CA9d	No	12.7c	0.286d	8c
	CA1d	No	15.7b	0.302bc	0d
	Air	No	9.9e	0.193f	34a
	CA9d	Yes	17.1a	0.309ab	0d
	CA1d	Yes	17.4a	0.319a	1d
	Air	Yes	16.0b	0.295bcd	9c
33	CA9d	No	16.0b	0.292cd	3cd
	air	No	11.5d	0.203b	21b
	CA9d	Yes	17.3a	0.296bcd	1d
	Air	Yes	15.6b	0.262e	0d

Means followed by different letters are significantly different, $p \leq 0.05$.

Table 3. 'Gala' disorders and quality after 6 months plus 7days at 68°F, year 1, means of two orchard lots. Fruit were held at 50 (7 days) or 33°F at receipt, 1-MCP applied day of receipt. CA was 1% for both O_2 and CO_2, was established 1 or 9 days after receipt.

Initial Temp °F	Atm	MCP	Lbs	TA %	Stem end Browning %	Cavity %	Peel blotch %	Senescent browning %
50	CA9d	No	16.2c	0.303a	16ab	9a	0b	0b
	CA1d	No	16.9ab	0.310a	4cd	2bc	0b	0b
	Air	No	10.4d	0.203c	10bc	0c	0b	15a
	CA9d	Yes	16.6bc	0.310a	12ab	4b	0b	3b
	Air	Yes	16.9ab	0.303a	11ab	2bc	0b	0b
33	Air	Yes	17.0ab	0.284b	17a	3bc	6a	0b
	Cad1	Yes	17.2a	0.313a	1d	1c	4a	0b

Means followed by different letters are significantly different, $p \leq 0.05$.

Table 4. 'Gala' disorders and quality after 6 months plus 7days at 68°F, year 2, means of two orchard lots. Fruit were held at 50 (7 days) or 33°F at receipt, 1-MCP applied day of receipt. CA was 1% for both O_2 and CO_2, was established 1 or 9 days after receipt.

Temperature and O_2 optimization for 'Gala' CA storage. CA storage of organic 'Gala' has potential challenges for firmness management. We evaluated storage temperature (33 or 31°F) and CA O_2 concentration (1 or 0.5%, both with 0.5% CO_2), and CA establishment date (1 or 7 days after receipt, year 2 only) as factors that influence quality management. For two orchards in two production seasons, results showed temperature but not the O_2 concentrations used influenced fruit quality and disorders of fruit stored 6 months plus 7 days at 68°F (Tables 5,6). In both years fruit stored in 31°F had higher firmness but titratable acidity and soluble solids content (not shown) were not influenced consistently by temperature or CA O_2. Some disorders increased at the lower storage temperature including shrivel, stem-end browning, and senescent browning although the trends were not consistent across years for all disorders. Splitting incidence decreased with delayed CA establishment. The results indicate 'Gala' storage performance at 31°F and/or with 0.5% O_2 is not consistently enhanced compared to 33°F and 1% O_2, and that rapid CA may enhance splitting potential.

Temp °F	O_2 %	Lbs	Titr. Acid %	Shrivel %	Stem-end browning %
33	0.5	16.7b	0.307ns	0b	2b
	1.0	16.6b	0.300	0b	1b
31	0.5	17.3a	0.315	6a	10a
	1.0	17.5a	0.315	6a	6a

Means followed by different letters are significantly different, $p \leq 0.05$. ns: not significant

Table 5. 'Gala' quality (means for two lots) after CA storage at two temperatures and two O_2 concentrations, 2016 crop. CA CO_2 concentration was 0.5% for all treatments. CA was established one day after fruit were received. Fruit stored 6 months plus 7 days at 68°F.

Temp °F	O_2 %	Lbs	Titr. Acid %	Splitting %	Peel blotch %	Shrivel %	Senescent browning %
33	0.5 day1	16.7b	0.308a	7ab	1b	1b	0b
	1.0 day1	16.9ab	0.296a	9a	3ab	2b	0b
	0.5 day7	17.0ab	0.299a	1c	5ab	1b	1b
	1.0 day7	16.7ab	0.301a	1c	6ab	1b	0b
31	0.5	17.1ab	0..301a	6ab	9a	19a	0b
	1.0	17.3a	0.311a	5ab	6ab	19a	1b
33	air	11.6c	0.199b	3bc	1b	0b	13a

Means followed by different letters are significantly different, $p \leq 0.05$.

Table 6. 'Gala' quality (means for two lots) after CA storage at two temperatures and two O_2 concentrations, 2017 crop. CA CO_2 concentration was 0.5% for all treatments. CA was established one or seven days after fruit were received. Fruit stored 6 months plus 7 days at 68°F.

'Fuji' conditioning

Reducing the risk of CO_2 injury during CA from watercore at harvest can be accomplished by delaying establishment of CA for 'Fuji'. Delayed CA can result in some quality loss, particularly titratable acidity, that would be notable after long term storage. As DPA for internal browning control cannot be used with organic fruit, we evaluated conditioning at 50°F to reduce the risk of CO_2 injury when CA is imposed close to harvest. Fruit were held at 50°F for 7 days then 34°F, or at 34°F continuously. CA was established after 1 or 9 days. Fruit were held in CA after conditioning was completed through 8 months plus 7 days at 68°F. Watercore was present in year two (90% incidence, mean rating of 3.3 with a scale of 1-4, 4 being severe). Fruit with CA started 1 day after receipt during conditioning in both years had less core browning after 8 months compared to fruit held continuously at 34°F and CA established 1 day after receipt (Tables 7,8). However, delaying CA for fruit held continuously at 34°F resulted in core browning incidence like that of conditioned fruit with CA at day 1. Consistent impacts on SSC, TA, and firmness were not observed although values were higher after 8 months in year two for conditioned fruit (Table 8). While these results show conditioning and rapid CA provide similar disorder management to normal cooling and delayed CA, the question remains regarding how conditioning might impact fruit with a higher risk of CO_2 injury sensitivity at harvest compared with lots used in this study.

Month	Initial Temp °F	Atm.	Core browning %	SSC %	TA %	Lbs
4	50/34	CA d9	6c	12.9bc	0.199a	13.2b
		CA d1	3c	12.7c	0.186ab	13.5b
		Air	30b	13.2ab	0.132c	10.9c
	34	CA d9	4c	12.5c	0.183b	13.4b
		CA d1	8c	13.5a	0.187ab	14.3a
		Air	87a	11.7d	0.109d	10.4c
8	50/34	CA d9	5b	13.2a	0.127b	13.2a
		CA d1	1d	12.8ab	0.135ab	12.8ab
		Air	82a	12.2c	0.062d	12.2c
	34	CA d9	3cd	12.5bc	0.133ab	12.5bc
		CA d1	12c	12.2c	0.144a	12.5bc
		Air	84a	10.9d	0.080c	10.9d

Means followed by different letters are significantly different, $p \leq 0.05$.

Table 7. 'Fuji' disorders and quality after storage plus 7days at 68°F, 2016 crop. Fruit were held at 50 (7 days) or 34°F at receipt. CA O_2 was 3% for 2 days then 1.5%, CO_2 was 0.5% throughout. CA was established 1 or 9 days after receipt.

Month	Initial Temp °F	Atm.	Core browning %	Cavities %	SSC %	TA %	Lbs
4	50/34	CA d9	0	6ns	15.2ab	0.323c	16.7b
		CA d1	0	6	16.2a	0.346b	17.3ab
		Air	0	1	15.2ab	0.250d	14.4c
	34	CA d9	0	8	15.8ab	0.379a	17.1ab
		CA d1	0	3	16.0ab	0.340bc	17.8a
		Air	0	1	15.1b	0.238d	15.1c
8	50/34	CA d9	0b	7ab	15.5b	0.317a	16.4c
		CA d1	0b	4ab	16.7a	0.310ab	17.4ab
		Air	39a	1b	15.6b	0.164d	13.6d
	34	CA d9	1b	10a	16.4a	0.298bc	18.1a
		CA d1	6b	4ab	15.2b	0.289c	16.7bc
		Air	39a	0b	15.1b	0.143e	14.2d

Means followed by different letters are significantly different, $p \leq 0.05$.

Table 8. 'Fuji' disorders and quality after storage plus 7days at 68°F, 2017 crop. Fruit were held at 50 (7 days) or 34°F at receipt. CA O_2 was 3% for 2 days then 1.5%, CO_2 was 0.5% throughout. CA was established 1 or 9 days after receipt.

'Granny Smith' CA during conditioning

Several factors influence superficial scald development on 'Granny Smith'. Most important in PNW fruit are storage duration, CA O_2 concentration, how long after harvest CA is established, and how long and under what temperature fruit are held after removal from CA. Scald is a chilling injury in that symptoms are unlikely to occur in fruit held at relatively warm temperature. Organic 'Granny Smith' storage relies on ultralow O_2 for superficial scald control. Core browning is another chilling injury that can be reduced by CA but may also respond to conditioning at harvest. In these experiments fruit were stored at 50ºF for 7 days then 33ºF or at 33ºF continuously. CA (1% O_2, 1% CO_2) was established 1 or 9 days after receipt (conditioned fruit where CA was established 9 days after receipt were lost due to cold room failure).
At 4 months conditioned fruit was like that held continuously at 33ºF except with statistically less but commercially unacceptable superficial scald on fruit stored in air (Table 9). After 8 months, quality of conditioned and control fruit was similar except that conditioned CA fruit had the highest acidity and much less core browning compared to fruit held continuously at 34ºF. However, superficial scald was not controlled by 1% O_2. A current study is repeating this experiment with the addition of a 0.5% O_2 CA treatment. Summary results will be submitted in summer, 2019.

Months	Initial ºF	Atm	SSC %	TA %	Lbs	Core Browning %	Superficial Scald %
4	50	CA day 1	12.2a	0.546a	17.7a	0b	0c
		Air	11.0d	0.431c	14.7c	61a	69b
	33	CA day 9	11.8b	0.536a	16.9b	0b	0c
		CA day 1	11.6c	0.533a	17.7a	0b	0c
		Air	11.4c	0.461b	14.8c	54a	92a
8	50	CA day 1	11.5a	0.513a	16.7a	3d	76c
		Air	11.0b	0.329d	10.4b	8d	82bc
	33	CA day 9	11.6a	0.447c	17.1a	60a	96a
		CA day 1	11.7a	0.485b	17.1a	31c	49d
		Air	9.5c	0.263e	10.5b	44b	90ab

Means followed by different letters are significantly different, $p \leq 0.05$.

Table 9. 'Granny Smith' fruit quality and disorders after 4 or 8 months plus 7 days at 68ºF. Fruit were held at 50ºF for 7 days after receipt then at 33ºF, or at 33ºF continuously. CA (1% O_2, 1% CO_2) was established 1 or 9 days after receipt (conditioned fruit where CA was established 9 days after receipt were lost due to cold room failure).

Bitter pit reduction from short-term CA established during 'Honeycrisp' conditioning

Work in the previous project showed CA established during 'Honeycrisp' conditioning and held through 4 months results in less bitter pit without increased development of internal disorders. The focus on the current project was to evaluate efficacy of short CA duration, CA during conditioning only or with an additional week after conditioning as fruit cooled. Results from 7 orchard years over

3 years consistently showed less bitter pit for fruit in CA for 1 week, with 2, 3, or 4 weeks (3 and 4 week results not shown) not significantly better than 1 week (Figure 2). Unlike previous results, 1-MCP did not enhance bitter pit reduction for CA fruit (Table 1). CA established during conditioning then storage in air did not enhance internal disorder development. Variation among lots existed in bitter pit incidence as well as the amount of reduction due to CA, but in most cases at least some bitter pit reduction was observed.

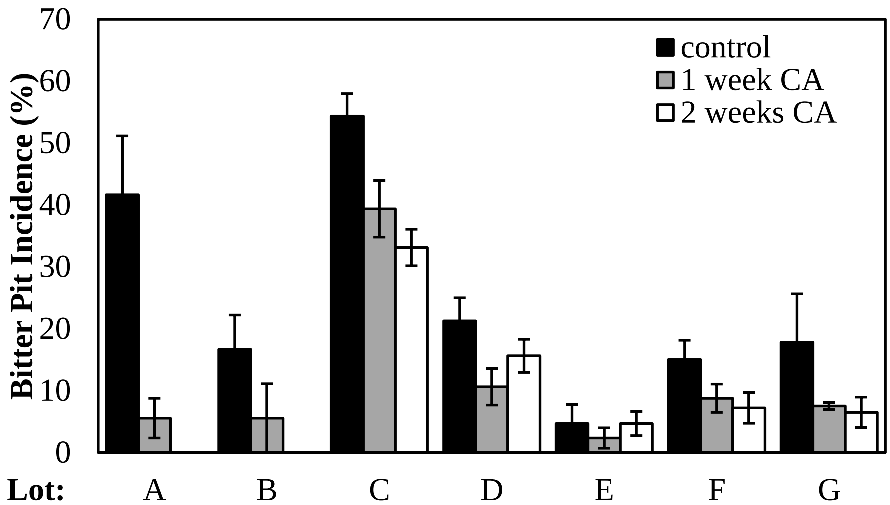

Figure 1. 'Honeycrisp' bitter pit incidence in 5 orchard lots over 3 seasons. Fruit were held at 50°F for 7 days then at 37°F. CA was established after one day in 50°F. O2 was initially All CA fruit held in air after removal from CA and stored for 4 months plus 7 days at 68°F.

	1-MCP			Control		
Weeks CA	0	1	2	0	1	2
Bitter pit	20.4ab	14.5b	12.6b	27.9a	12.5b	11.9b
Soft scald	0.3ns	0.3	0.5	0.2	0.6	0.6
Soggy breakdown	0.3ns	0.1	0.3	0.6	0.4	0.7
Cavities	0.5ns	0.8	1.1	0.2	0.4	2.4

Means followed by different letters are significantly different, $p \leq 0.05$. ns: not significant

Table 1. Physiological disorders in 'Honeycrisp' apples after 4 months storage, means for 7 lots. 1-MCP (1 ppm) applied the day fruit were received.

The results suggest a brief period after harvest in CA can be sufficient to reduce bitter pit development without enhancing internal disorder risk. While this pattern was consistent throughout this study, situations where orchard factors including maturity, and postharvest factors including cooling and CA dynamics may increase disorder development risk cannot be ruled out. What the results from this and previous work may indicate is that bitter pit management from CA may be most likely the sooner CA is established after harvest. What remains to be determined are factors and situations, if any, that enhance risk of internal disorder development from CA established during conditioning.

EXECUTIVE SUMMARY

Meeting the postharvest challenges of ‘Honeycrisp’ has expanded the technical expertise of Washington apple industry and research personnel. ‘Honeycrisp’s’ sensitivity to chilling and susceptibility to bitter pit have been addressed through management practices that had not been considered for other varieties. Delayed cooling is commercially usable due in part to the lack of the need to manage ‘Honeycrisp’ texture, a primary postharvest objective for most legacy apple varieties. The efficacy of delayed cooling to reduce ‘Honeycrisp’ chilling susceptibility exacerbates bitter pit development, while establishing CA during conditioning reduces bitter pit. While CA is known to impact the disorder in other bitter pit prone varieties, the short duration (1 week) of CA needed to reduce ‘Honeycrisp’ identified in this project has not been widely recognized. This finding is the most significant outcome of this project. Adopting non-standard postharvest conditions for a high value, new variety pushed the comfort of some postharvest personnel, applying those concepts to other varieties could be equally as challenging.

Lessons from ‘Honeycrisp’ postharvest management, temperature conditioning, CA during conditioning, were the basis for this project. High volume, existing varieties with established postharvest systems are being challenged to adapt to organic production. The low O_2 CA fruit sensing technologies, efficient CA generation equipment, tight rooms and high capacity refrigeration systems provide the pieces to accomplish chemical-free apple storage management. What is needed is how to integrate their use to meet the specific needs of varieties with different objectives for postharvest management. The general conclusion of this project is that CA during temperature conditioning reduces the negative impacts of delayed cooling on fruit quality and can benefit disorder management for all the varieties we evaluated in some way. ‘Honeycrisp’ bitter pit, ‘Gala’ peel blotch, ‘Fuji’ and ‘Granny Smith’ core browning all were reduced by conditioning. Also notable is the lack of disorders induced by CA during conditioning. The lack of CA induced disorders is likely due to lowered CO_2 sensitivity at higher temperatures, and no fermentation at the O_2 settings evaluated.

A question considering all the results is whether the benefits of this protocol are sufficient in relation to established practices for changes in standard methods to be considered. We also recognize the commercial challenges of filling rooms rapidly. Note that none of the experiments with ‘Gala’, ‘Fuji’, or ‘Granny Smith’ have been pilot tested. The specific temperature, CA settings, and timing combinations evaluated may be useful to consider incremental changes in established practices as well as potential areas for further research. For example, ‘Gala’ peel blotch developed more on fruit held initially at a lower temperature. Humidity, rate of temperature decrease, and use of other temperatures between 33 and 50ºF were not evaluated leaving a question as to other ways to reduce this disorder based on how refrigeration is managed. Another positive is all this work was conducted with existing equipment in our facility. For industry that could mean changes in postharvest protocols rather than facility upgrades are what is needed to implement new procedures. Additional research that builds on results for each variety may be appropriate based on the degree to which specific disorders continue to be a management challenge for organic as well as conventional production. That work now has at least some path suggested that does not rely on identification of new technology or new chemistries.