What is the correct carbon dioxide concentration?

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- There have been no recent breakthroughs in reliable methods to determine the acceptable CO_2 concentration, so one must rely on an indirect approach to choose the correct CO_2 concentration.

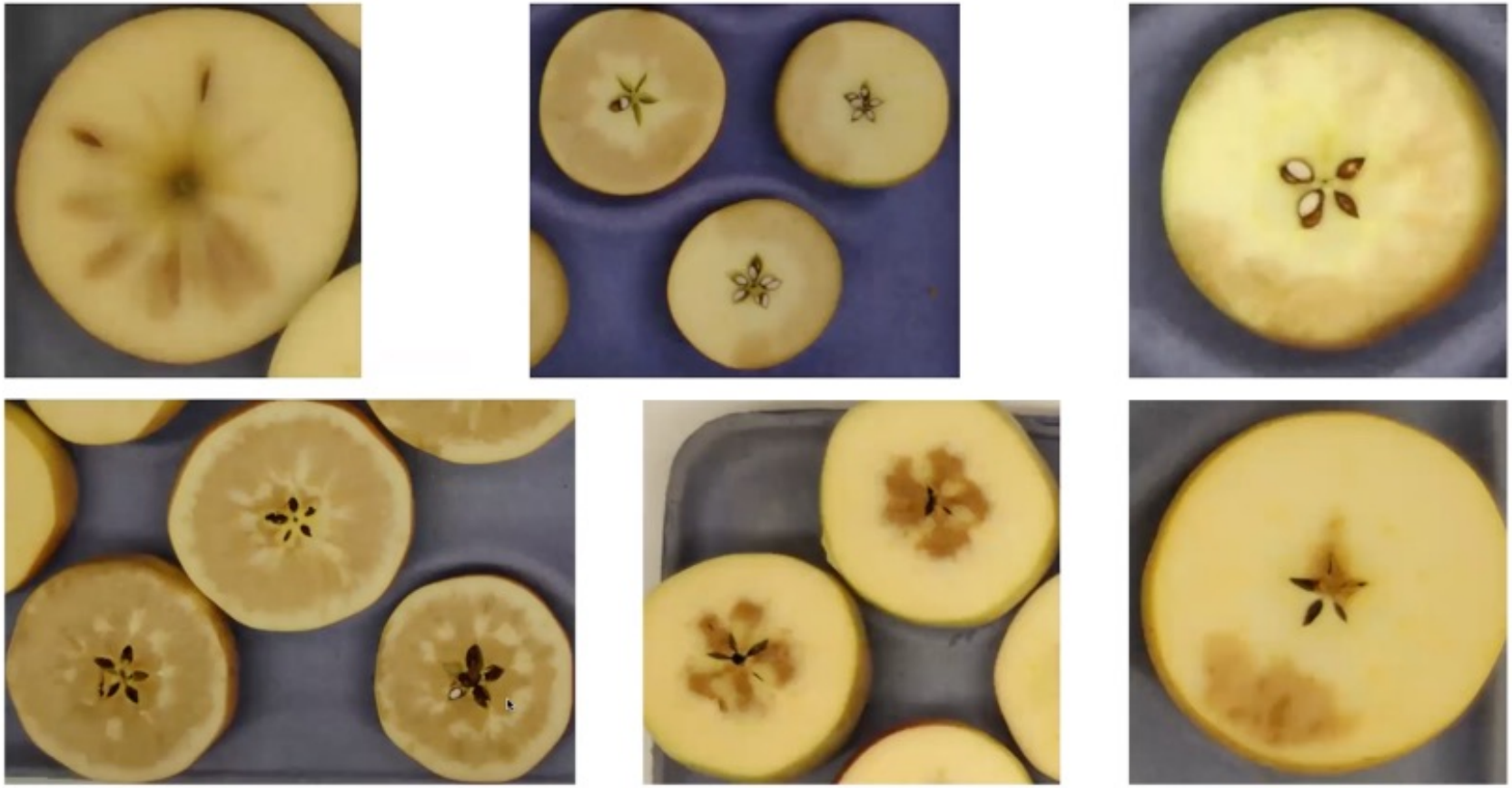
- This presentation examines the utility of selecting the CO_2 concentration in CA as a proportion of the recommended O_2 (as defined by global use), in other words, using a CO_2/O_2 ratio.

Too much CO_2 can cause external and internal damage.

External CO_2 damage

Golden Delicious, R. Prange

Internal CO_2 damage
(but would be given different disorder names)



- Symptoms vary with genotype making diagnosis difficult

(Rudell, 2023)

Avoiding CO_2 damage will depend on:

- Cultivar
- Oxygen concentration
- Stage in storage season
- Storage temperature
- Storage humidity
- Use of post-harvest chemicals – 1-MCP, DPA

Determining the effect of cultivar and O_2

The concept of CO_2/O_2 ratio concept has been accepted in a general sense but is not well-defined.

Example:

"In CO_2-intolerant cultivars, the CO_2 should remain well below the O_2 level at all times." (Kupferman, 2003)

Using my postharvest cultivar database, I have created 7 CO_2/O_2 ratio categories:

1) 1.5 or more (Very high CO_2 tolerance)

2) 1.25 to 1.49 (Moderately high CO_2 tolerance)

3) 1.00 to 1.24 (Slightly high CO_2 tolerance)

4) 0.75 to 0.99 (Medium CO_2 tolerance)

5) 0.50 to 0.74 (Slightly low CO_2 tolerance)

6) 0.25 to 0.49 (Moderately low CO_2 tolerance)

7) 0 to 0.24 (Very low CO_2 tolerance)

Mean CO_2/O_2 ratio for some major apple cultivars

1) CO_2/O_2 ratio = 1.5 or more (Very high CO_2 tolerance).

Cultivar	CO_2/O_2 ratio	Sample size
Jonagold*	1.83	35
Golden Delicious*#	1.58	44
McIntosh*	1.59	7
Elstar *	1.50	23

* = A delay in increasing CO_2 may be required

= High CO_2 may provide some benefit, e.g. greener, firmer, less Jonathan spot

Mean CO_2/O_2 ratio for some major apple cultivars

2) CO_2/O_2 ratio = 1.25 to 1.49 (Moderately high CO_2 tolerance).

Cultivar	CO_2/O_2 ratio	Sample size
Gala*	1.35	56
Rome (Morgenduft)	1.27	12
Delicious*	1.25	32
Idared#	1.24	28

* = A delay in increasing CO_2 may be required

= High CO_2 may provide some benefit, e.g. greener, firmer, less Jonathan spot

Mean CO_2/O_2 ratio for some major apple cultivars

4) CO_2/O_2 ratio = 0.75 to 0.99 (Medium CO_2 tolerance)

Cultivar	CO_2/O_2 ratio	Sample size
Granny Smith	0.90	24
Cripps Pink (Pink Lady) *	0.90	18
Fuji*	0.80	25
Nicoter (Kanzi) *	0.80	12
Cox's Orange Pippin *	0.78	8

* = A delay in increasing CO_2 may be required

= High CO_2 may provide some benefit, e.g. greener, firmer, less Jonathan spot

Mean CO_2/O_2 ratio for some major apple cultivars

5) CO_2/O_2 ratio = 0.50 to 0.74 (Slightly low CO_2 tolerance)

Cultivar	CO_2/O_2 ratio	Sample size
Honeycrisp *	0.65	18
Braeburn *	0.57	25

* = A delay in increasing CO_2 may be required
# = High CO_2 may provide some benefit, e.g. greener, firmer, less Jonathan spot

Mean CO_2/O_2 ratios for some major pear cultivars

Group 3) CO_2/O_2 ratio = 1.00 to 1.24 (Slightly high CO_2 tolerance)

Cultivar	CO_2/O_2 ratio	Sample size
Packham's Triumph	1.03	17

Group 4) CO_2/O_2 ratio = 0.75 to 0.99 (Medium CO_2 tolerance)

Forelle	0.83	9
Beurré Bosc	0.70	8

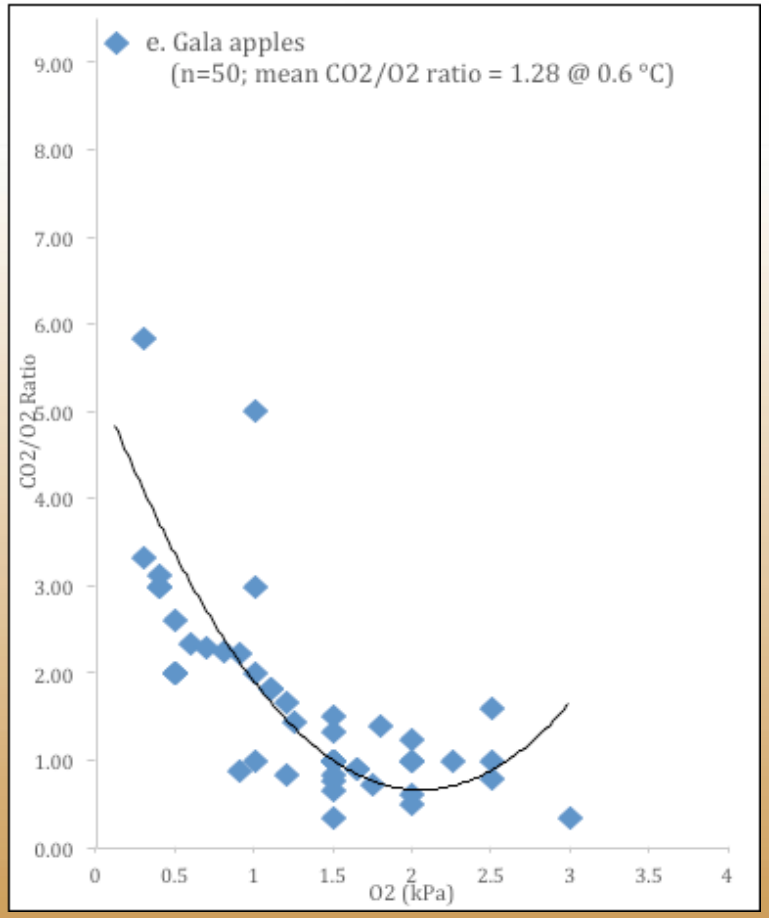
Group 5) CO_2/O_2 ratio = 0.50 to 0.74 (Slightly low CO_2 tolerance)

Williams (Bartlett)	0.73	13
Doyenné du Comice *	0.71	8
Beurré D'Anjou	0.51	2

Group 6) CO_2/O_2 ratio = 0.25 to 0.49 (Moderately low CO_2 tolerance)

Conference *	0.38	11
Abaté Fetel *	0.25	4

Increasing CO_2/O_2 ratio with declining O_2



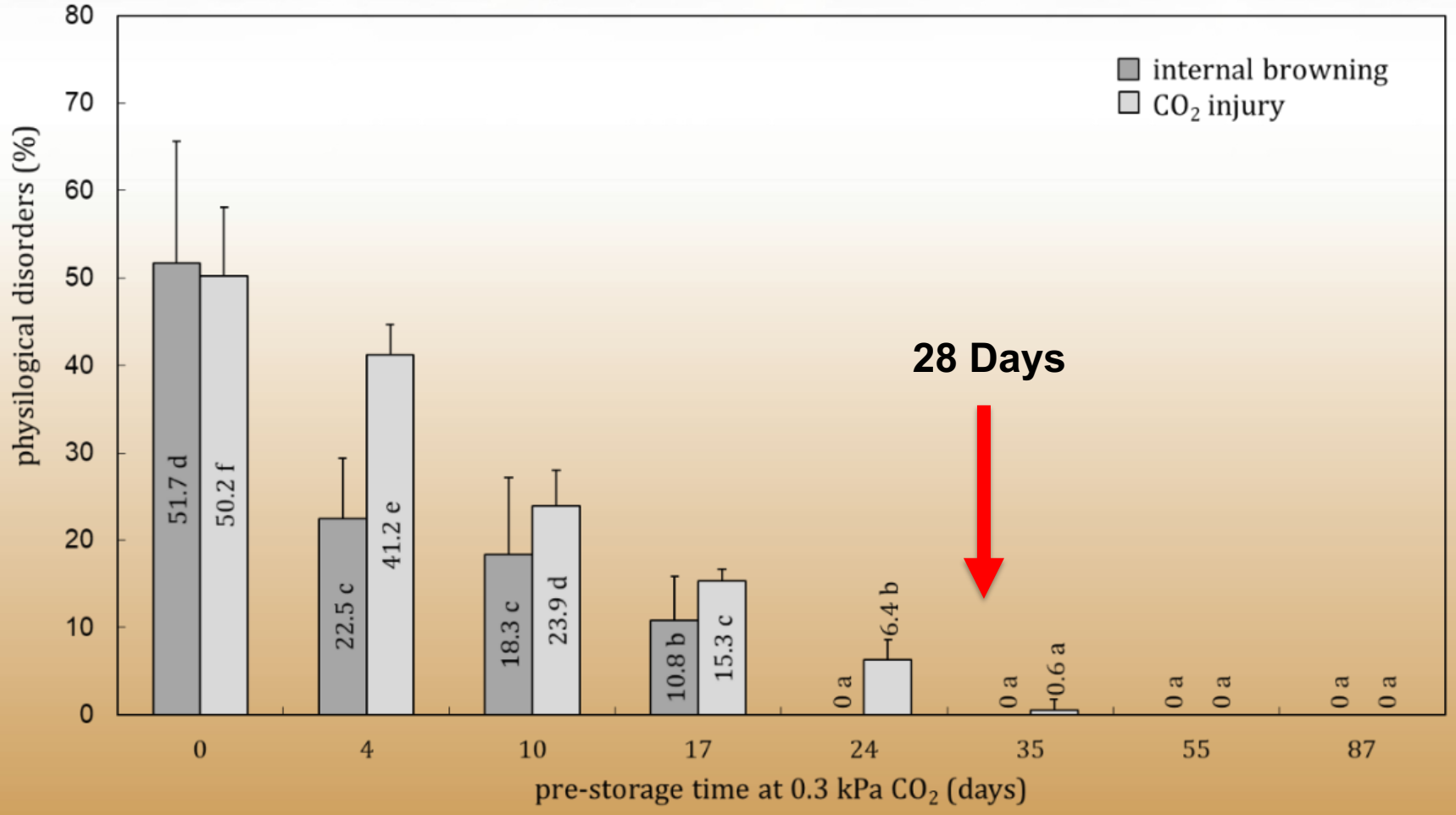
Appears to occur mainly below 1.0-2.0 kPa O_2 e.g., Gala

High CO_2 at the beginning of storage is more damaging than later in storage.

Examples of initial low CO_2 before increasing CO_2 for long-term CA

Cultivar	Atmosphere	Duration (days)	Comments
Apple:			
Braeburn	Air	21	
	Air	14-21	
	Air	21	
	Air	14-17	
Delicious	<1.0% CO_2	42	
Cripps Pink	Air	5	
	Air	21	
Fuji	Air	42	
	Air	60	
	Air	14	
Gala	Air	5	
	1.5% CO_2	28	
	2.5% CO_2	42	
	<1.0% CO_2	42	
Golden Delicious	1.5%+ 3.0%	28 + 28	
	1.5%	42	After temp. achieved
	Air	5	
Granny Smith	Air	30	If no DPA
	< 1% CO_2	-	Until CA is started (and scrub ethylene)
Nicoter (Kanzi)	Air	21	
Pear:			
Doyenné du Comice	Air	21	

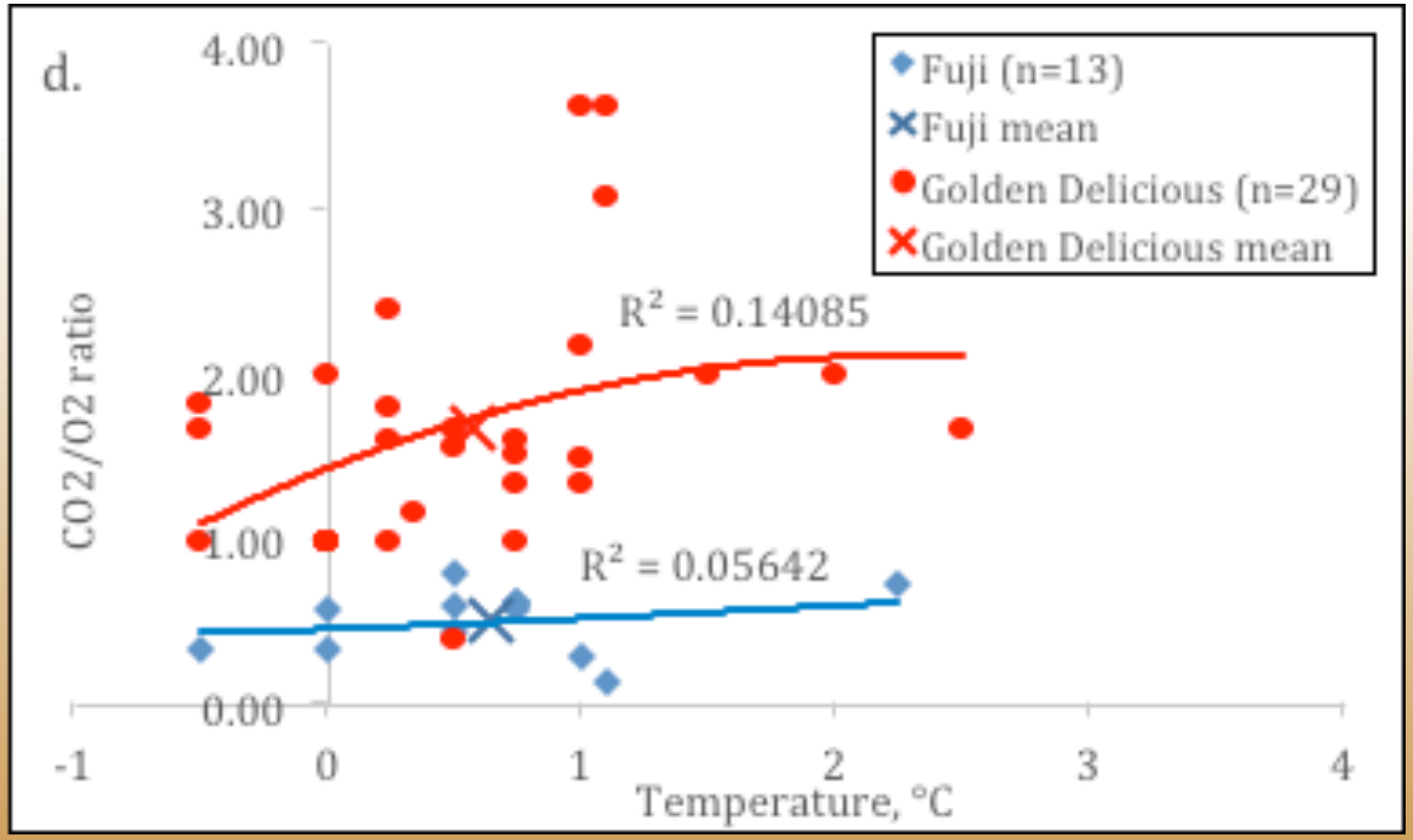
CO_2 injury and internal browning in Elstar apples after five months of CA storage as affected by CA-pre-storage time at 0.3% CO_2 and afterwards storage at 10% CO_2



(Köpcke, 2024)

Declining CO_2/O_2 ratio with chilling temperature

Appears to occur mainly in high CO_2-tolerant cultivars e.g., Golden Delicious

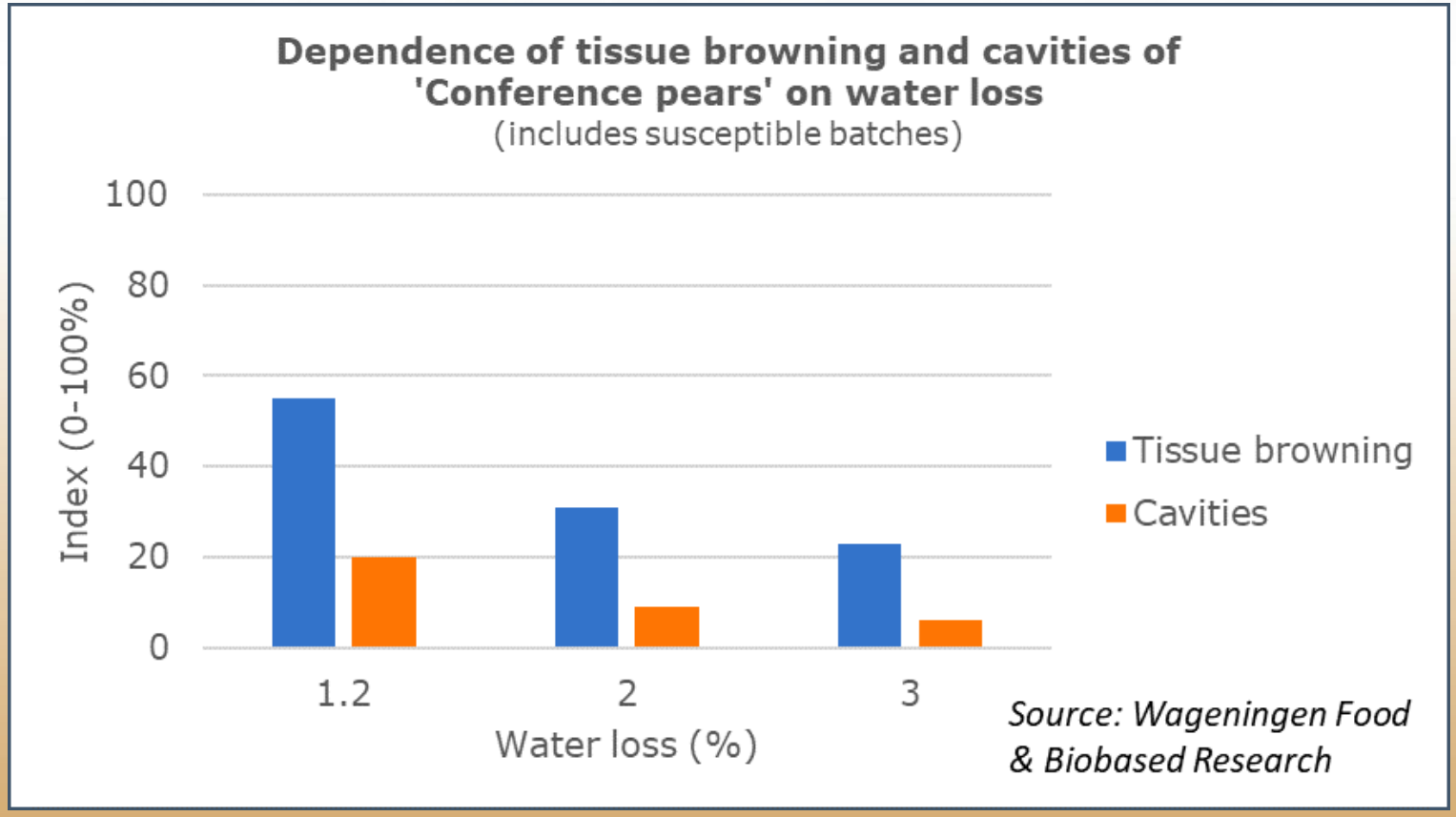


Lowering the temperature increases the respiration quotient (RQ) of apples

	RQ		
	Temperature (°C)		
Storage Atmosphere (O_2 + CO_2, kPa)	**0**	**3.3**	**7.2**
– CO_2 in headspace			
21 + 0	1.7	1.4	1.2
10 + 0	1.5	1.4	1.25
5 + 0	1.8	1.45	1.1
3 + 0	1.7	1.5	1.35
+ CO_2 in headspace			
10 + 10	1.2	0.95	0.75
16 + 5	1.3	1.2	0.95
5 + 5	1.0	1.1	0.95
3 + 5	1.1	1.1	0.9
1.5 + 5	1.2	1.15	1.1

(Fidler and North, 1967)

Lowering storage humidity can reduce CO_2 related disorders



Relation between tissue browning and cavities ('Brown-heart) and water loss after 9 months of storage

(De Wild, 2021)

Postharvest Chemicals

- 1-MCP
- DPA

The CO_2/O_2 ratio in CA is lower if 1-MCP is used.

The CO_2/O_2 ratio in CA is lower if 1-MCP is used.

Cultivar	CO_2/O_2 ratio		Final value (% of CA alone)
	CA alone	CA + 1-MCP	
Apple:			
Bramley's Seedling	1.56	0.10	6
Cortland	1.29	0.84	65
Delicious	1.25	0.53	42
Empire	0.81	0.38	47
Fuji	0.80	0.18	22
Gala	1.35	0.95	70
Golden Delicious	1.58	0.64	40
Granny Smith	0.90	0.34	38
Honeycrisp	0.65	0.27	42
Idared	1.24	0.63	51
Jonagold	1.83	0.90	49
Jonathan	1.26	0.89	71
McIntosh	1.48	0.92	62
Nicogreen (Greenstar)	2.75	1.0	36
Northern Spy	1.42	0.80	56
Pinova	1.88	1.11	59
Pear			
Conference	0.36	0.20	55
Mean			48

This table is preliminary, based on a small number of CA recommendations that include a specific recommendation when using 1-MCP before CA starts.

Applying 1-MCP after CA is being adopted. This may alter the need to reduce the CO_2/O_2 ratio.

DPA is still allowed in some countries

Countries DPA is Banned

Country	Diphenylamine (ppm)	
	Apple	Pear
Argentina	3	3
Australia	10	7
Brazil	10	5
Canada	5	0.1
Chile	10	5
China	5	5
Egypt	10	5
European Union	0.05	0.05
Great Britain	0.05	0.05
Hong Kong	10	7
India	0.01	0.01
Indonesia	10	5
Israel	5	5
Japan	10	5
Korea	5	5
Malaysia	10	5
Morocco	10	5
New Zealand	10	5
Norway	0.05	0.05
Philippines	10	5
Russia[1]	-	-
Saudi Arabia	10	5
Singapore	5	5
South Africa	10	5
Taiwan	10	5
Thailand	10	5
Turkey	0.1	0.1
Ukraine	10	5
United States	10	5
Venezuela	10	5
Vietnam	10	5

[1] Personal communication, A. Ilinskiy

DPA can reduce CO_2 damage

Empire (US):

- If not DPA-treated: 1.5-2.0% CO_2 for first 30 days
- If DPA-treated: 2-3% CO_2 from day 0 in storage

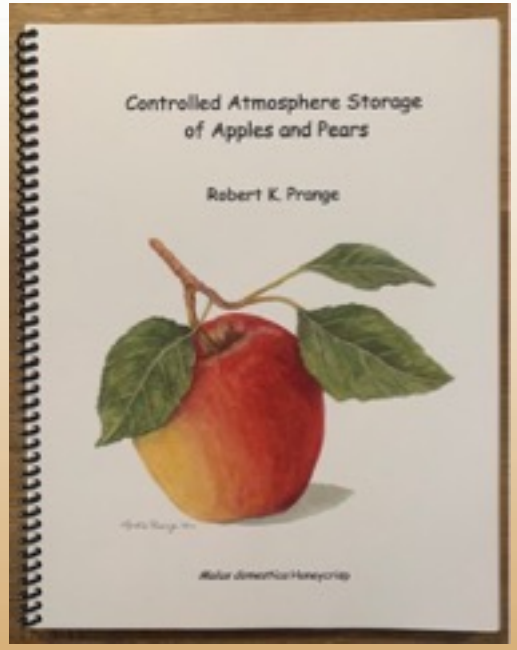
McIntosh – First 6 weeks

- CA alone – 2.5% CO_2 (US), 2.0% CO_2 (Canada)
- + 1-MCP – 0.5% CO_2 (US and Canada)
- + 1-MCP + DPA – 2.5% CO_2 (US), 2.0% CO_2 (Canada)

Acknowledgement

The material in this presentation was partly derived from:

Controlled Atmosphere Storage of Apples and Pears.
Robert K. Prange
116 pages. 36 Tables, 19 Figures, 14 watercolours.
ISBN 978-1-7776828-0-4



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CO_2 Final Thoughts

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- If no history of CO_2 damage – do not consider any changes.

CO_2 Final Thoughts

- **If there is a history of CO_2 damage, consider one or more of the following:**
  - Scrub CO_2 during loading and cooling, e.g., activated carbon and/or lime
  - Scrub CO_2 during O_2 pull-down.
  - In CA, control CO_2 levels according to the CO_2/O_2 ratio for a specific cultivar.
  - Consider scrubbing CO_2 for the first few weeks of CA. i.e. 4 weeks.
  - There is evidence that cultivars that tolerate high CO_2/O_2 ratios may lose their CO_2 tolerance at chilling temperatures, i.e., < 1.0 ºC.
  - In DCA (<1 kPa O_2), there is evidence that the CO_2/O_2 ratio can be higher.
  - If 1-MCP is applied at beginning of storage – reduce CO_2 by ca. 50%
  - If DPA is allowed – it may reduce risk of CO_2 damage

External CO_2 damage shown in Introduction

CO_2 damage on Golden Delicious

Store Room with disorder		Store Room with no disorder	
Temp (°C)	Ratio: CO_2/O_2	Temp (°C)	Ratio: CO_2/O_2
1.3	.01		
1.4	.01		
3.7	.01		
4.4	.02		
4.8	.02		
2.0	.03		
1.0	.10		
1.0	.20		
0.8	0.67		
0.8	1.57	2.6	0.2
0.8	**4.50**	0.5	0.8
0.8	1.33	-.9	.16
0.7	1.33	-.8	.19
0.9	1.33	-.8	.26
0.7	1.17	-.8	.36
0.8	1.17	-.9	.56
0.9	1.17	-.8	.87
0.9	1.17	-.7	.79
0.8	1.33	-.8	.65
0.8	1.33	-.8	.68
0.8	1.17	-.8	.67

3 Factors

1) Beginning of storage
2) Too cold too fast
3) Sudden increase in CO_2/O_2