Factors Affecting Mass Loss of Apples

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"We have not succeeded in answering all your problems. The answers we have found have only served to raise a whole set of new questions. In some ways we feel as confused as ever but we believe we are confused now on a higher level and about more important things."

Anon.

Executive Summary

Mass loss from harvested apples causes direct loss in returns to growers and marketers of fruit. This thesis characterises the process of mass loss in harvested apples, exploring the effects of various factors on water vapour permeance of the fruit, a measure of the ease with which water escapes from the fruit.

Values of permeance of 'Braeburn' and 'Pacific Rose'™ apples were roughly twice those of 'Cripps Pink' and 'Granny Smith'. Permeance of 'Braeburn' and Pacific Rose'™ apples increased with later harvest date whilst values for 'Cripps Pink' and 'Granny Smith' remained relatively constant. There were small differences in mean permeance of apples from different regions. Some growers produced more fruit with high water vapour permeances than others. There was no relationship between maturity indicators tested and the water vapour permeance of the fruit. Fruit from the inner regions of trees and with high numbers of fruit in contact had high permeances. Variation in water vapour permeance around the surface of the fruit had no pattern with respect to blush or sun/shade sides, nor was there any relationship with cuticular thickness. Rather, variation in water vapour permeance of fruit was linked to the extent of cuticular micro-cracking. A model was developed which explains the water vapour permeance based on the proportion of fruit surface which is cracked. Artificial stretch applied to pieces of fruit skin increased cracking and permeance. Strain in the cuticle during growth and development of the fruit created a reticulate crack network. Micro-cracking could be important in determining susceptibility to mass loss and shrivel after harvest. Permeance of 'Braeburn' apples decreased after harvest; the extent of this decrease was greater for low relative humidity and high temperature and for fruit with high initial levels of micro-cracking. Bruising caused by impact damage on

'Braeburn' apples increased water vapour permeance of fruit only very slightly.

A conceptual model is presented which summarises relationships between fruit attributes, environmental conditions and processes which contribute to overall mass loss of apples. A composite mathematical model from previous models developed in the thesis is presented which describes total water loss as determined by the level of micro-cracking in the fruit cuticle, time after harvest, relative humidity and temperature of the storage environment. A number of suggestions for minimised mass loss in the apple industry are presented based on three strategies: minimisation of permeance, reduction of driving force for water loss and segregation of lines of high risk and applying appropriate handling regimes. The composite model could be used to explore a range of alternative handling and marketing scenarios in terms of total mass loss.

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α_1	arc length of skin disc normal	m
α_2	arc length of skin disc under stress	m
a	non-linear regression parameter	
A	surface area of the fruit system	m^2
A^b	area of bruising of the fruit system	m^2
A^{ck}	area of cracking of the fruit system	m^2
A^{cut}	area of intact cuticle of the fruit system	m^2
A^{pores}	area of pores of the fruit system	m^2
A^{tot}	total area of the fruit system	m^2
a_w	water activity of fruit	%
b	non-linear regression parameter	
^{o}C	degrees Celsius	
c	non-linear regression parameter	
c.	approximately	
CO_2	carbon dioxide	
C^t	time conversion for days into seconds (86,400)	$s \cdot day^{-1}$
ΔM	total mass loss	kg
ΔM_{H_2O}	total water loss	kg
Δp_{H_2O}	difference in water vapour partial pressures between environment and inside of fruit	Pa
$\Delta p_{H_2O(1)}$	Δp_{H_2O} for the first set of postharvest conditions	Pa
$\Delta p_{H_2O(2)}$	Δp_{H_2O} for the second set of postharvest conditions	Pa
$\Delta p^{bl}_{H_2O}$	gradient of partial pressure of water vapour through boundary layer	Pa
$\Delta p^{ck}_{H_2O}$	gradient of partial pressure of water vapour through cracks	Pa
$\Delta p^{icut}_{H_2O}$	gradient of partial pressure of water vapour through the	Pa

	inner cuticle	
$\Delta p^{s}_{H_2O}$	gradient of partial pressure of water vapour through crack system	Pa
Δp_j	partial pressure difference for diffusion of species *j*	Pa
Δx	thickness of barrier	m
Δx^{b}	permanent deformation of bruise	m
Δx^{bl}	thickness of boundary layer	m
Δx^{ck}	thickness of cracks	m
Δx^{d}	deformation in centre of skin disc from stretching	m
Δx^{icut}	thickness of the inner cuticle	m
Δx^{flesh}	thickness of flesh at centre of a skin disc in side view	m
Δx^{m}	thickness of centre of a skin disc in side view	m
Δx^{s1}	thickness of side one of a skin disc in side view	m
Δx^{s2}	thickness of side two of a skin disc in side view	m
Δx^{skin}	thickness of visible skin at the centre of a skin disc in side view	m
d	day	
d^{b}	diameter of bruised area	m
d^{f}	diameter of fruit	m
df	degrees of freedom	
D_j	diffusivity of species j	$m^2 \cdot s^{-1}$
e	non-linear regression parameter	
ERH	Equilibrium relative humidity	%
γ	pyschrometric constant (equals 67 Pa · $^{o}C^{-1}$ at 20 ^{o}C)	Pa · $^{o}C^{-1}$
g	gram	
h	hour	
H_2O	water	
h^{b}	bruise depth	m
j	gaseous species	

J	joule	
k	proportion of cracking	
K	kelvin	
L	radius of skin disc	m
L	litre	
m	metre	
M	mass of fruit	kg
min	minute	
mol	mole	
$\% M_{H_2O}$	water loss as a percentage of total mass	%
n	amount of gas	mol
N_{H_2O}	mole fraction of water in the solution	
P	probability and statistical significance of F or T test	
Pa	pascal	
p^{tot}	total pressure in a system	Pa
$P_0^{'}$	initial water vapour permeance of fruit	$mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
$P_{H_2O}^{'}$	water vapour permeance of fruit surface	$mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
$P_{H_2O}^{'ck}$	water vapour permeance of cracks	$mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
$P_{H_2O}^{'cut}$	water vapour permeance of undamaged cuticle	$mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
$P_{H_2O}^{'pores}$	water vapour permeance of pores or lenticels	$mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
$P_{H_2O}^{'s}$	water vapour permeance of crack system	$mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
$P_{H_2O}^{air}$	effective permeability of air to water vapour	$mol \cdot m \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
$p_{H_2O}^{e}$	partial pressure of water vapour in air	Pa
$p_{H_2O}^{f}$	partial pressure of water vapour in fruit	Pa
$P_{H_2O}^{icut}$	permeability of the inner cuticle to water vapour	$mol \cdot m \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
$p_{H_2O}^{sat}$	saturated partial pressure of pure water	Pa
$p_{H_2O}^{sat}(T)$	saturated partial pressure of water vapour at temperature (T)	Pa

$p^{sat}_{H_2O}(T_e)$	saturated partial pressure of water vapour at T_e	Pa
$p^{sat}_{H_2O}(T_f)$	saturated partial pressure of water vapour at T_f	Pa
$p^{sat}_{H_2O}(T_w)$	saturated partial pressure of water vapour at T_w	Pa
$p^{soln.}_{H_2O}$	partial pressure of water in steady state with the solution	Pa
P'_j	permeance of a barrier to gas species *j*	$mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
P_j	permeability of a material to species j	$mol \cdot m \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
P'_t	water vapour permeance of fruit at time *t*	$mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
P'_{t_1}	water vapour permeance at the end of the first set of postharvest conditions	$mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
P'_{t_2}	water vapour permeance at the end of the second set of postharvest conditions	$mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$
R	gas constant = 8.314	$m^3 \cdot Pa \cdot mol^{-1} \cdot K^{-1}$
R^2	proportion of total variation explained by regression	%
r_{CO_2}	specific rate of respiration	$mol \cdot kg^{-1} \cdot s^{-1}$
RH	relative humidity	%
r'_{H_2O}	rate of water loss in a system	$mol \cdot s^{-1}$
$r'^{bl}_{H_2O}$	rate of transfer of water vapour through the boundary layer	$mol \cdot s^{-1}$
$r'^{ck}_{H_2O}$	rate of transfer of water vapour through the cracks	$mol \cdot s^{-1}$
$r'^{icut}_{H_2O}$	rate of transfer of water vapour through the inner cuticle	$mol \cdot s^{-1}$
$r'^{s}_{H_2O}$	rate of transfer of water vapour through the crack system	$mol \cdot s^{-1}$
r'_j	rate of gas transfer of species *j* in a system	$mol \cdot s^{-1}$
r'_{mass}	rate of mass loss in a system	$kg^{-1} \cdot s^{-1}$

$rr\%$	respiration as a percentage of total mass loss	%
s	strain in skin	
s	seconds	
SED	standard error of the difference	
S_j	solubility of gaseous species within a fluid	$mol \cdot m^{-3} \cdot Pa^{-1}$
θ_1	angle required for calculating arc lengths of skin disc with no strain	
θ_2	angle required for calculating arc lengths of skin disc when strained	
t	time	d
T	temperature	^oC
t_0	time at beginning of the first set of conditions	d
t_1	time at end of the first set of conditions	d
$T_{(1)}$	temperature during the first set of conditions	^oC
t_2	time at end of second set of conditions	d
$T_{(2)}$	temperature during the second set of conditions	^oC
T_e	temperature of environment or air	^oC
T_f	temperature of fruit	^oC
™	trade mark	
T_w	temperature of wet bulb	^oC
v	velocity of air	$m \cdot s^{-1}$
V	volume	m^3
V^b	volume of bruised flesh	m^3
w/w	weight per weight	