Water Loss in Horticultural Products - Modelling, Data Analysis and Theoretical Considerations

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Abstract

The water loss of individual fruit (melon, plum and mandarin) was analysed using the traditional diffusion based approach and a kinetic approach. Applying simple non linear regression, both approaches are the same, resulting in a quite acceptable analysis. However, by applying mixed effects non linear regression analysis, explicitly including the variation over the individuals, the kinetic approach was found to reflect the processes occurring during mass loss better than the diffusion approach. All the variation between the individuals in a batch could be attributed to the initial mass or size of the individuals. The fraction of the fruit mass that is available for transpiration is the key item in the water loss process, rather than the skin resistance and fruit area. Obtained explained parts are well over 99%.

INTRODUCTION

Water loss in horticultural products is still a major problem for growers, wholesalers and retailers (Banks et al., 2000). Research on water loss however, is nowadays very limited. The problem has been solved, hasn't it? Water diffuses through the skin into the environment which seems to be a simple and straightforward formulation and modelling using Fick's first law (De Smet et al., 2002; Díaz-Pérez, 1998; Maguire et al., 1999a, b, 2001). However, recently results have been found in the behaviour of water loss in different fruits (melons, plums and mandarins) that suggest a different mechanism is active. Non linear mixed effects regression analysis was applied to mass loss in monitored individual fruit. All the variation between the individuals in a batch could be attributed to the initial mass or size of the individuals. The rate constant of water loss (transpiration) was exactly the same for all individuals, even over different near-isogenic lines of melons with most probably large differences in skin thickness and water vapour resistance.

The amount of potential water loss is limited and certainly not equal to the total mass of the fruit. A fraction of the fruit mass is dry matter and will not be involved in water loss. Moreover, water will be less available for transpiration when bound to compounds like pectines, cellulose, sugars, etc., or occluded inside cells (cytosol). That forces us to rethink and remodel water loss.

The traditional approach is diffusion based and assumes that the rate of transpiration depends on the fruit area, size and resistance of the skin with respect to gases and water vapour. This approach has been used for several decades, however, to our knowledge never on individually monitored fruit. Since the size or mass vary over the individuals, this traditional approach inherently assumes that the biological variation will be in the overall rate constant of transpiration.

In this paper the water loss of melons, plums and mandarins, will be analysed using the same generic model based on a chemical equilibrium reaction as an approximation for the diffusive process of transpiration, assuming that the variation will be present in the amount of water that potentially can be transpired. By statistical analysis using non-linear mixed effects analysis, better results were obtained than with the traditional approach. All analyses achieved explained parts well over 99%.

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MATERIALS AND METHODS

Experimental Setup

1. Melons. In two successive seasons (2005 and 2006) near-isogenic lines (NILs) containing introgressions of different extent from the Korean accession 'Shongwan Charmi' PI 161375 (SC) on the linkage group III VII and X into the 'Piel de Sapo' (PS) genetic background (Eduardo et al., 2005) were grown in Torre Pacheco (Murcia, Spain) according the commonly used practise for melon cultivation. Fruit were stored covered by plastic liners (Plásticos del Segura, Murcia, Spain) at 21±1ºC and 66±6% RH (2005) and at 20.6±1.5ºC and 78±13% RH (2006). Fruit were individual labelled and monitored for mass during 22 and 24 d of storage respectively for both seasons. Details of the plant material used and the experimental setup have been reported in Fernández-Trujillo et al. (2008) and Tijskens et al. (2009).

2. Plums. 'Jubileum' plums were grown in 2006 and 2007 at the orchard of Planteforsk Ullensvang Research Center in Western Norway and harvested in September at commercial maturity. Plums were stored in storage rooms at 16ºC (2006) and 20ºC (2007) at about 60-70% RH. In each season, 60 fruit were individually labelled. The mass of these fruit was individually recorded during 5 d of storage.

3. Mandarins. 'Fortune' mandarins were grown at a commercial orchard in Cartagena (Spain) during 2007, harvested according commercial criteria and stored for 50 d at 5ºC and about 95% RH. During growth, mandarin trees were submitted to four RDI (Regulated Deficit Irrigation) treatments (see Fig. 1). Per water stress treatment 84 fruit were individually labelled and fruit mass was measured regularly during the storage period.

Model Development

The traditional approach in modelling water loss is based on Fick's first law of diffusion. Assuming an inner compartment (fruit tissue) separated from an outer compartment (storage room) by some membrane (skin), and assuming the outer volume is large compared to the amount of water loss, i.e., the outer conditions are unchanged by the process, and solving the differential equation for constant external conditions, we arrive at:

$$C_{in} = \left(C_{in,0} - C_{out} - C_{fix}\right) \cdot e^{k_t \cdot t} + \left(C_{out} + C_{fix}\right) \qquad (1)$$

where C is the concentration of water, k_t the rate constant of the process of water loss. The subscript *in* refers to the inner compartment (the fruit), *out* to the outer compartment (storage room), while *fix* refers to that part of fruit mass that is not available for transpiration (bound or occluded water).

Diffusion Approach

In the traditional approach, used for the past decades, the overall rate constant is deduced (Fick's first law) to depend on skin thickness, fruit area and fruit volume according to Equation 2:

$$k_t = \frac{k_d \cdot A}{d \cdot V} \qquad (2)$$

where d represents the thickness of the membrane (here the skin), A the area of the fruit over which transpiration takes place, and V the volume of the fruit (inner compartment). k_d is the specific rate constant of the process (diffusion constant). Most of the time the factor C_{fix} is not explicitly taken into consideration in this approach. All concentrations are converted into pressures, including the RH of the outside (C_{out}).

All variation encountered in the data, almost exclusively mean values for a number of fruit, are considered to result from variation in area, volume and especially skin thickness. So, dealing with longitudinal data (repeated measurements of the same individuals), the variation is sought in the overall rate constant of the process (k_t).

Kinetic Approach

Based on a (very simple) chemical equilibrium system, shown in Equation 3, exactly the same analytical solution (Eq. 1) could be derived using the fundamental rules of chemical kinetics, assuming the rate constant of transport is the same in both directions.

$$\begin{aligned} &C_{in} \xrightarrow{k_t} C_{out} \\ &C_{out} \xrightarrow{k_t} C_{in} \\ &C_{fix} \rightarrow unchanged \end{aligned} \tag{3}$$

In this line of reasoning, however, the rate constant k_t is considered to be generic and the same for all fruit irrespective of size, area and skin thickness. All variation between the individual fruit is assumed to depend on the range of change. Since C_{out} depends exclusively on the temperature and the RH in the storage room, the variation is to be found in either the initial condition ($C_{in,0}$) or the fixed value (C_{fix}).

Conversion to Mass Loss

The conversion of the deduced model into actual mass loss is an algebraic transformation.

$$WL = 1 - \frac{W}{W_0} \tag{4}$$

Applying this transformation using mass W for concentration C to Equation 1, results in the equation, applied in all regression analyses:

$$\begin{aligned} WL &= \left(\frac{W_{fix} + W_{out}}{W_0} - 1 \right) \cdot \left(e^{k_t \cdot t} - 1 \right) \\ WL &= WL_r \cdot \left(e^{k_t \cdot t} - 1 \right) \end{aligned} \tag{5}$$

with W representing the measured mass, WL the mass loss. WL_r is the range in potential water loss, and actually represents that fraction of the fruit mass that can be lost by transpiration in the actual external condition together with those external conditions of temperature and RH. How to convert the external conditions into this line of reasoning is yet unknown. The factor WL_r will be estimated by regression analysis as one single parameter.

RESULTS AND DISCUSSION

The data on NILs of melons, plums and mandarins were analysed using both approaches using mixed effects non linear regression analysis, putting the variation (random effects) either on the initial condition (kinetic approach) or on the rate constant (diffusion approach). All other parameters were estimated in common (fixed effects). The data are also analysed using the standard non linear regression applied without taking variation over individuals into account. That actually makes both approaches the same. In Table 1 the results of the analyses are shown. The results of the analysis without taking variation over individuals into account are quite acceptable. The explained part (R^2_{adj}) is high, especially for the mandarins, and the standard errors (sterr) are low. However, by including variation over individuals, putting the variation over the rate constant (diffusion approach), the result show a large dichotomy: some series are much more reliable (high R^2_{adj}, low sterr) while other could not be estimated at all for whatever reason (shown in bold in Table 1). That indicates that the variation is not in the rate constant, and that this approach (diffusion approach) is in principle incorrect. In the kinetic approach the variation is put in the amount of water, available for transpiration (WL_r). All series analyse well, with extremely high R^2_{adj} and extremely low sterr. The one series in the upper part of Table 1 with a R^2_{adj} below 0.95 (Mandarin 1) and the series Plum 2006 showed a deviant value for the rate constant. In the actual conditions of storage for the different fruit tested, the rate of transpiration is so low that the exponential function is hardly defined by the data. One has to realise that the external conditions during storage (temperature and RH) are different for each series. The effect of this (W_{out}) is included in the range factor (WL_r) as deduced in Equation 5.

The results can graphically be presented by standardising the data using Equation 6.

$$\begin{aligned} & WL_{s\tan} = WL + WL_r = WL_{ref} \cdot e^{-k_t \cdot bt} \\ & with\ bt = t + \ln\left(\frac{WL_r}{WL_{ref}}\right) / k_t \end{aligned} \tag{6}$$

For melons of both seasons and mandarins RDI 4, the results of the diffusion approach and the kinetic approach are shown in Figure 2. For plums (2006), the diffusion approach did not work properly (Table 1) and only the result of the kinetic approach is shown.

All that information leads to the conclusion that the traditional approach is usually applicable, but does not reflect the real processes of mass loss. Based on the obtained results, the kinetic approach seems to reflect better what is going on. However, differences in skin thickness, surface area and volume do exist, especially in the melon NILs. The initial mass of individual melons ranged from 700 g to 3250 g per fruit. For plums, the initial mass ranged from 33 to 80 g per fruit. These large differences in initial mass, and hence fruit area, should affect the rate of water vapour transport over the skin into the outer atmosphere. A possible mechanism that could provide some explanation is that a thicker skin thickness induces a lower vapour pressure deficit (VPD) just inside the fruit. That lower VPD has far less force to release the loosely bound water for its anchorage. As a result less water is available for transpiration, reducing the actual value of WL_r. The phase change from liquid water to water vapour could well be the key issue in this process.

Since the process of water loss can be considered generic, i.e., the same model formulation and the same rate constant for all the individuals, the effect of storage condition (T & RH), treatment, NILs, seasons and other controlling circumstances not reported here such as skin roughness, lenticel density, structure of the peduncle, presence or absence of netting, cuticle structure, etc., has to be found in the variation in the potential water loss (WL_r). This is indicated in the last column of Table 1 (sd.WL_r). The meaning and interpretation of these results will be reported separately.

More dedicated research is needed to fully unravel the real mechanisms at work for different fruit types and for different conditions of temperature and RH in this long time ‘solved’ problem.

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Tables

Table 1. Results of the regression analyses of mass loss in different fruit at different storage conditions based on Equation 5.

Kinetic approach

Fruit type	Series	WL_r	k_t	R^2_{adj}	sterr.WL_r	sterr.k_t	N_{obs}	N_{gr}	sd.WL_r
Plum	2006	0.0300	0.3925	0.970	0.0014	0.0182	240	60	0.0088
Plum	2007	0.1653	0.1300	0.988	0.0104	0.0092	265	53	0.0310
Melon	2005	0.0704	0.0524	0.995	0.0025	0.0010	666	63	0.0180
Melon	2006	0.0597	0.0573	0.992	0.0012	0.0009	834	77	0.0094
Mandarin	1	0.1351	0.0022	0.903	0.2500	0.0043	84	12	0.0000
Mandarin	2	0.0195	0.0156	0.985	0.0018	0.0018	84	12	0.0020
Mandarin	3	0.0267	0.0122	0.986	0.0031	0.0017	84	12	0.0030
Mandarin	4	0.0328	0.0091	0.990	0.0042	0.0013	84	12	0.0028

Diffusion approach

Fruit type	Series	WL_r	k_t	R^2_{adj}	sterr.WL_r	sterr.k_t	N_{obs}	N_{gr}	sd.k_t
Plum	2006	**-5.8728**	**-0.0002**	**0.172**	**5561**	**0.2151**	240	60	0.0000
Plum	2007	**7539120**	**0.0000**	0.984	**78369**	**0.0000**	265	53	0.0000
Melon	2005	0.0891	0.0390	0.993	0.0015	0.0021	666	63	0.0147
Melon	2006	0.0657	0.0503	0.991	0.0007	0.0016	834	77	0.0117
Mandarin	1	**0.2454**	**0.000029**	**0.290**	**134.85**	**0.0162**	84	12	0.0000
Mandarin	2	0.0275	0.0099	0.983	0.0034	0.0015	84	12	0.0013
Mandarin	3	**0.0705**	**0.0022**	**0.432**	**0.1877**	**0.0060**	84	12	0.0000
Mandarin	4	**0.0328**	**0.0091**	**0.990**	**NA**	**0.0003**	84	12	0.0009

Without mixed effects (both models are the same)

Fruit type	Series	WL_r	k_t	R^2_{adj}	sterr.WL_r	sterr.k_t	N_{obs}
Plum	2006	0.0306	0.3789	0.769	0.0024	0.0540	240
Plum	2007	0.2121	0.0963	0.889	0.0585	0.0311	265
Melon	2005	0.0855	0.0408	0.883	0.0070	0.0045	666
Melon	2006	0.0587	0.0579	0.911	0.0019	0.0030	834
Mandarin	1	0.1351	0.0022	0.917	0.2500	0.0043	84
Mandarin	2	0.0216	0.0137	0.951	0.0042	0.0033	84
Mandarin	3	0.0333	0.0094	0.945	0.0106	0.0035	84
Mandarin	4	0.0419	0.0069	0.967	0.0143	0.0026	84

Figures

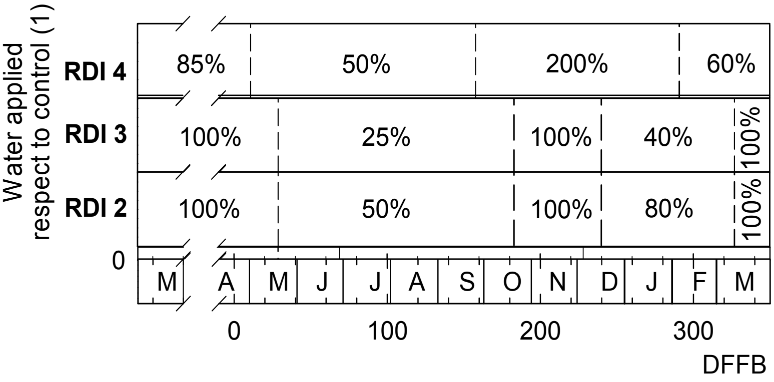

Fig. 1. Detailed schedule for the irrigation treatments of mandarin trees as a function of the days from full bloom (DFFB), relative to control irrigation, set at 130 ETc (crop evapotranspiration) using water with electrical conductivity of 4.2 dS m^{-1}. RDI 4 is an irrigation treatment scheduled by the farmer.

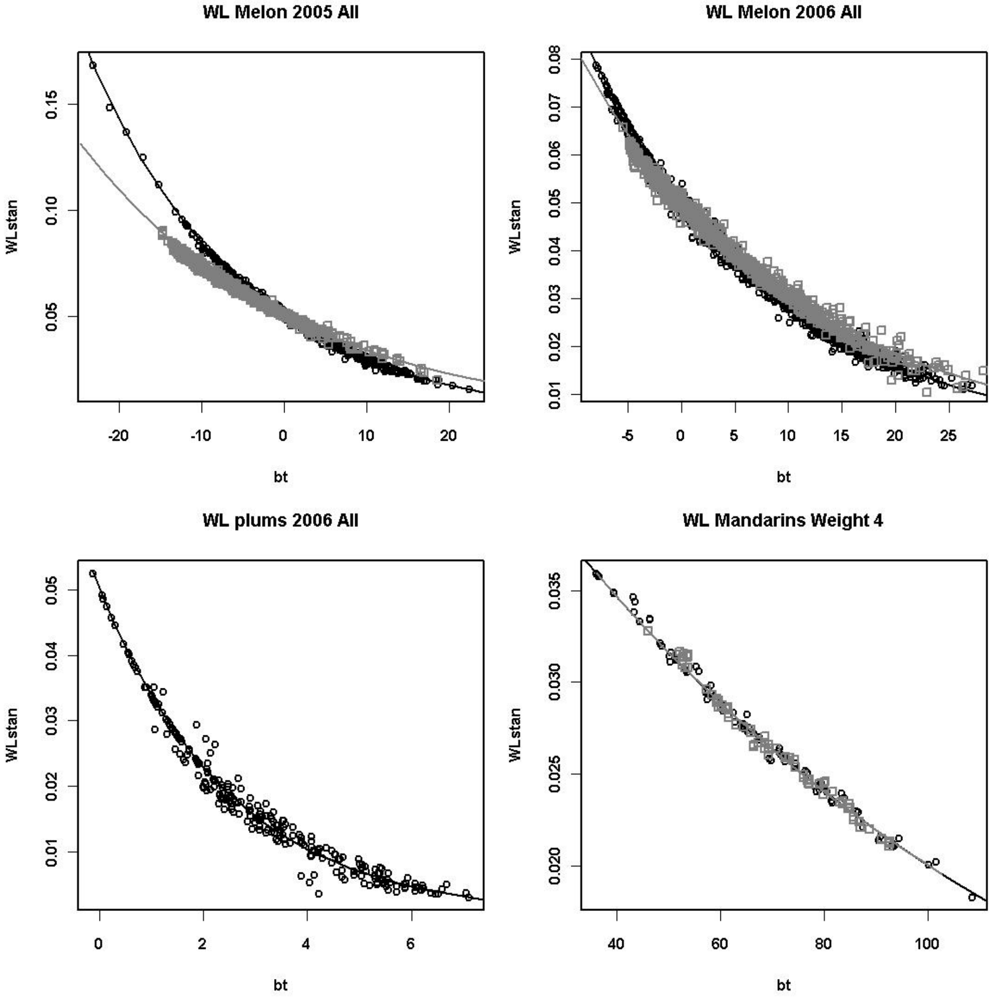

Fig. 2. Standardised mass loss versus biological time based on Equation 6 for different fruit at different conditions. Black = kinetic approach, gray = diffusion approach.