Scientia Horticulturae 204 (2016) 54–64

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

From fruitlet to harvest: Modelling and predicting size and its distributions for tomato, apple and pepper fruit

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A R T I C L E   I N F O

Article history:
Received 22 December 2015
Received in revised form 7 March 2016
Accepted 23 March 2016
Available online 6 April 2016

Keywords:
Diameter
Length
Volume
Size prediction
Biological variation
Apples (*Malus domesticus*, borkh)
Tomatoes (*Solanum lycopersicum* L.
Peppers (*Capsicum annuum* L.
Von bertalanffy growth model

A B S T R A C T

Size is an important property of all fruit as it determines, together with crop load, fruit yield. The aim of this study is to model the increase in fruit size during cell expansion based on diameter or length and to predict fruit size and volume, including the variation in size and volume, at harvest. The size of individual fruit during growth of fruit (four apple, two tomato and six pepper cultivars) was measured from early fruit set until harvest at several seasons. Size data were evaluated as diameter and length using the von Bertalanffy growth model, adapted to include the variation in size between individuals and the effect of growing temperature. The adapted von Bertalanffy model describes the increase in diameter and length and their variation. For any fruit type, size increased along the same generic growth model. A single stochastic variable, the biological shift factor, was sufficient to describe the variation in development time, initial size and maximum size. For all batches the percentage variation explained for were well over 93% with growth rate constants similar per species and only a minor effect of growing temperature.

Prediction of the maximum size distribution based on measurements half way the cell expansion period is explored and discussed. Size and its distribution can be predicted based on a single measuring point in time but with two or three points in time the prediction system becomes more robust.

1. Introduction

Fruit size is an important crop management focus as it determines, together with crop load, fruit yield. Fruit size can be manipulated by foliar fertilisation (Lovatt, 1999; Unuk et al., 2008), irrigation (Intrigliolo and Castel, 2006), crop load (Naor et al., 2000, 2008; Unuk et al., 2008) and weather conditions (Lötze and Bergh, 2004). Sorting on fruit size is applied to many different types of fruits in automated grading systems (Yom Din et al., 2003; Brosnan and Sun, 2004). Although fruit size is important for all actors in the horticultural supply chain, predictions of fruit size are not well established due to the complexity of the interacting factors mentioned above. Predictions of fruit size are, however, essential for optimizing supply chain strategies and marketability (Miranda et al., 2007; Naor et al., 2008). Traditionally, crop load and fruit yield from previous seasons are used as indicators. For instance, Lötze and Bergh (2004) applied a multi-regression approach to predict the apple and pear fruit size distribution at harvest based on fruit size at 42 days after full bloom and crop load; this approach accounted for 80% of observed variance. Stajnko et al. (2013) predicted fruit size based on accumulated heat (temperature sum) based on a modified Gompertz function. Zadravec et al. (2013) predicted final apples size based on the diameter measured over time during growth.

Potential fruit size is determined by the short period of cell division during the early post bloom fruit development while the actual size achieved at harvest is determined by the longer period of cell expansion (Al-Hinai and Roper, 2004a,b). The actually achieved size depends on the growth conditions (light interception, photosynthesis and temperature) during the cell expansion period (Austin et al., 1999). The increase in mass of fruits generally occurs in an asymmetrical sigmoidal fashion, often described by a Gompertz, Weibull or Richards curve (De Silva et al., 1997; Adams et al., 2001;

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http://dx.doi.org/10.1016/j.scienta.2016.03.036
0304-4238/

Avanza et al., 2008; Godoy et al., 2008). This sigmoidal behaviour can occur as emergent behaviour by combining biophysical processes like water fluxes, osmotic pressure and turgor pressure (Naor et al., 2000, 2008; Intrigliolo and Castel, 2006; Lechaudel et al., 2007; Bertin et al., 2010; Martre et al., 2011; Seginer and Gent, 2012; Hall et al., 2013). Another approach to describe the increase in size is based on the empirical von Bertalanffy individual growth model (von Bertalanffy 1938, 1948) which is widely used, especially in marine biology (Chen et al., 1992; He and Stewart, 2002; Shimose et al., 2009; Dumas et al., 2012) to describe growth in size. This growth model is now part of the Dynamic Energy Budget theory that describes body size scaling relationships based on uptake and use of energy and nutrients (Kooijman 1986, 1988).

Cope and Punt (2007) reported on the importance of including measuring error and individual variation in the analysis of fish length using von Bertalanffy's growth model. Zadravec et al. (2014) applied the von Bertalanffy model to the size of apples, however, without taking the variation into account.

In this paper the applicability of the von Bertalanffy growth model is explored as a means to describe the size of individual fruits during growth and to explore the possibilities of predicting the distribution of maximum size. To do this, the von Bertalanffy model is adapted to include the variation in size between individuals using the biological shift factor. The biological shift factor expresses the stage of development in time, relative to an arbitrarily chosen state of development, as the amount of time the growth curve for each individual fruit has to be shifted over the time axis to coincide with each other (Hertog et al., 2004; Tijskens et al., 2003, 2005, 2007, 2015). The general applicability of the adapted von Bertalanffy model is shown for apples (four cultivars during five seasons), tomatoes (two cultivars at two growing temperatures) and bell peppers (six cultivars and three growing temperatures). Prediction of the size distribution at harvest based on the size distribution halfway the growing season is explored and discussed.

2. Material and methods

2.1. Materials

2.1.1. Apple

Four apple (*Malus domesticus*, Borkh.) cultivars ('Golden Delicious Reinders', 'Gala Brookfield', 'Fuji Kiku 8′ and 'Kanzi') were grown at the orchard of the Fruit Growing Centre Gačnik near Maribor, Slovenia in the seasons 2006–2010. The trees were planted in 2003, except the 'Kanzi' trees that were planted in 2004, on M9-EMLA rootstocks at a density of approximately 4000 trees per hectare. The orchard was drip irrigated and the trees were covered with a black hail net. Standard chemical thinning with 6-benzyladenine (BA) was carried out at a fruit diameter of approximately 11 mm. A crop density of four to five fruit per trunk cross-sectional area was ascertained by hand thinning directly before the first measurements. The first size measurements were carried out at about 30–40 days after full bloom (DAFB), at the T-stage when cell division becomes less important than cell expansion. T-stage has been described as the phase when the underside of the fruit and stalk form the letter T (Blanke and Kunz, 2009). For each cultivar 40 apples from four trees were randomly selected. All apples were individually labelled. From the T-stage of fruit development, the diameter of the apples was measured with a digital calliper at regular intervals at the widest diameter at the equator.

2.1.2. Tomato

For model calibration purposes tomatoes (*Solanum esculentum)* Brioso RZ (cocktail type) and Cappricia RZ (intermediate sized tomato) were grown in a greenhouse at Unifarm, Wageningen, the Netherlands, in the spring of 2011. Two temperature treatments (21.4 ± 0.8 and 27.1 ± 1.5 °C) were applied to one truss per plant. Fruit diameter at the equator was measured at eight different stages between anthesis and breaker stage (fruit just starts to change coloration) using a digital calliper. Time was expressed as DAFB. Since the tomatoes were also used for chemical analyses, every measuring time a new set of tomatoes were taken. The location within the truss of the measured tomatoes was always the same. Experimental details can be found in Okello et al. (2015).

For size distribution prediction purposes tomatoes (cv 'Brilliant') were grown during March 2015 in a commercial greenhouse (Venlo type, 19.5 °C, 90% RH) in eastern Slovenia. Fifteen days after full bloom, the diameter of the third tomato of 200 randomly selected trusses was measured using a calliper. At commercial harvest time, 32 days later, the diameter of the same tomatoes was measured again. However, 26 tomatoes did drop off before harvest could take place.

2.1.3. Pepper and bell pepper

Pepper and bell pepper plants (*Capsicum annuum*) were grown in 2007 in a Venlo-type glasshouse in Wageningen, the Netherlands. Two experiments were carried out, one with a focus on fruit growth using six cultivars ('cultivar experiment') and one with a focus on one cultivar growing at three growing temperatures ('temperature experiment'). The cultivar experiment consisted of plants of six *Capsicum annuum* cultivars that produce fruit of different fresh weights, varying from about 20 g for 'Medina DR' (hot pepper type), up to 205 g for 'Funky DR' (sweet pepper type). Average temperature was 21.6 ± 2.0 °C and average daily global outside radiation was 16.3 ± 5.6 MJ m^{-2} d^{-1} (Wubs et al., 2009). Plants of the *Capsicum annuum* 'Mazurka RZ' were grown for the temperature experiment at three temperature regimes: 18.3 ± 0.5 °C, 20.3 ± 0.35 °C and 23.3 ± 0.31 °C. The average daily global outside radiation was 15.5 ± 2.9 MJ m^{-2} d^{-1} (Wubs et al., 2012). Flowers were tagged at anthesis. Plants were pruned to one or two fruits per plant. Other fruits and flowers from those plants were removed, and new flowers were removed weekly. Twice a week, length and diameter or circumference of the tagged fruit were measured. In the temperature experiment, a tape measure was used to measure length and circumference. In the cultivar experiment a digital calliper was used to measure length and diameter, except for fruits of cultivar 'Gepetto DR' in the second half of the growth period, where a tape measure was used to measure circumference due to irregular fruit shape. Diameter or circumference was measured at mid-fruit. The measurements were done from 5 to 7 days after anthesis until harvest. Fruits were harvested when completely red, well beyond the commercial harvest stage.

2.2. Model development

2.2.1. The von Bertalanffy growth model

The size of all growing fruits increases towards a maximum (e.g. Fig. 1). von Bertalanffy (1938, 1948) proposed a model (Eq. (1)) that, when solved for constant external conditions, results in an equation showing an exponential increase towards a maximum size (Eq. (1)).

$$\frac{\delta L(t)}{\delta t} = r_B \times (L_\infty - L(t))$$
$$L(t) = L_\infty - (L_\infty - L_0) \times e^{-r_B \times t} \quad (1)$$

with t the time, L(t) the length at time t, L_0 the initial length at the start of the experiment, L_∞ the maximum size (at infinite time) and r_B the von Bertalanffy growth rate constant. Von Bertalanffy