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Spatial and temporal variations in mango colour, acidity, and sweetness in relation to temperature and ethylene gradients within the fruit

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ABSTRACT

Managing fruit quality is complex because many different attributes have to be taken into account, which are themselves subjected to spatial and temporal variations. Heterogeneous fruit quality has been assumed to be partly related to temperature and maturity gradients within the fruit.

To test this assumption, we measured the spatial variability of certain mango fruit quality traits: colour of the peel and of the flesh, and sourness and sweetness, at different stages of fruit maturity using destructive methods as well as vis–NIR reflectance. The spatial variability of mango quality traits was compared to internal variations in thermal time, simulated by a physical model, and to internal variations in maturity, using ethylene content as an indicator.

All the fruit quality indicators analysed showed significant spatial and temporal variations, regardless of the measurement method used. The heterogeneity of internal fruit quality traits was not correlated with the marked internal temperature gradient we modelled.

However, variations in ethylene content revealed a strong internal maturity gradient which was correlated with the spatial variations in measured mango quality traits. Nonetheless, alone, the internal maturity gradient did not explain the variability of fruit quality traits, suggesting that other factors, such as gas, abscisic acid and water gradients, are also involved.

Introduction

Management of fruit quality is essential because it defines fruit grade and, by extension, its commercial value. However, fruit quality is a complex notion because it involves numerous attributes including external appearance, taste, and nutritional value (Abbott, 1999; Hewett, 2006; Léchaudel and Joas, 2007). Fruit quality traits depend on concentrations of primary metabolites including sugars, organic acids, and amino acids, as well as secondary metabolites such as pigments, vitamins and aromas. The concentrations of these compounds vary during the course of fruit development (Fishman and Génard, 1998; Gautier et al., 2008; Lechaudel et al., 2007) and in different parts of the fruit tissues (Biais et al., 2010; Moing et al., 2011; Pedreschi et al., 2009). Several studies have focused on the determinants of temporal changes in fruit quality, but less information is available on the causes of the spatial variation in fruit quality.

Variations in sugar and acid contents in fruit are linked to thermal time, i.e. degree days, as reported for several species including mango (Lechaudel et al., 2010), peach (Génard and Souty, 1996), and grapevine (Duchêne et al., 2012). It can thus be hypothesised that the marked temperature gradients caused by the heterogeneity of environmental factors at the fruit scale, measured (Léchaudel et al., 2012; Woolf et al., 1999) and modelled inside the fruit (Nordey et al., 2014b; Saudreau et al., 2007), could be involved in the spatial variability of fruit quality traits.

Variations in overall fruit quality during the fruit ripening process have been the focus of a number of studies. During this irreversible fruit development stage, fruit quality changes considerably, thereby rendering the fruit attractive to the consumer (Bapat et al., 2010; Lelièvre et al., 1997). Current knowledge emphasises the involvement of abscisic acid and ethylene, two phytohormones known to be involved in ripening, in the regulation of the biochemical and physiological changes which occur during fruit ripening (McAtee et al., 2013). Several authors reported that ethylene

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content varies considerably within fruits (Fernández-Otero et al., 2006; Hershkovitz et al., 2009; Mita et al., 1998). It can thus be hypothesised that the spatial variation in the primary and secondary metabolites involved in quality traits could be partly explained by variations in the production and diffusion of phytohormones within the fruit, as suggested by Moing et al. (2011).

The aim of this study was to investigate to what extent the spatial variability of fruit quality traits is related to variations in ripening and to thermal time within the fruit. Mango fruit was chosen because quality management of this climacteric fruit is a major limit to its sale (Tharanathan et al., 2006). This study focuses on the quality traits responsible for the external appearance of the fruit, using peel colour as the indicator, sweetness, assessed by total soluble solids (TSS), sourness, measured by titratable acidity, and the carotenoid content of the flesh, deduced from the flesh colour. To facilitate measurement of titratable acidity and TSS content, a method was developed based on visible and near-infrared (vis–NIR) reflectance. The spatial variability of mango quality traits was compared to variations in thermal time within the fruit during its development, simulated using a physical model (Nordey et al., 2014b), and to internal variations in maturity, using ethylene content as an indicator.

Our results advance our understanding of the processes involved in variations in quality traits within fruits and should help control fruit quality.

Materials and methods

Fruit samples

The study was carried out on mangoes of the Cogshall cultivar (Fig. 1A). Fruits were grown during the 2012–2013 production season in the CIRAD orchard in Reunion Island (20°52′48″ S, 55°31′48″ E), which is composed of 7-year-old trees grafted on a 'Maison Rouge' cultivar. The trees were well irrigated, spaced 5 × 6 m apart, and were approximately 3 m tall at the time of the study.

A first set of fruit was used to destructively analyse variability of peel colour, TSS content, titratable acidity, and the colour of the fruit flesh, in the bottom, middle, and top parts of the fruit, and between the shaded and sunny sides. Fifty-two fruits were harvested at four commercial maturity stages: green mature, turning, yellow point (YPS) (Léchaudel and Joas, 2006), and ripe, corresponding to 90, 110, 120, and 130 days after full bloom, respectively. Between 12 and 15 fruits were analysed for each maturity stage. Titratable acidity was only measured on fruits at the green mature and ripe stages, without taking exposure to sunlight into account.

A second set of 50 fruits was used to calibrate the partial least square (PLS) regressions required to predict TSS content and titratable acidity using vis–NIR reflectance. Each fruit was randomly divided into three samples of flesh (Fig. 1B). For each sample, reflectance spectra were monitored before destructive measurements of TSS content and titratable acidity.

A third set of fruit was used to analyse spatial variability of TSS contents, titratable acidity and flesh colour from the inner to the outer flesh, and from the bottom to the top of the fruit, measured by vis–NIR reflectance (Fig. 1C). A total of 33, 13, and 21 fruits were harvested at the green mature, turning and yellow point stages, respectively.

A fourth set of fruits was used to evaluate variability of ethylene from the bottom to the top of the fruit, and from the surface to the seed of the fruit. A total of 5, 5, 5 and 6 fruits were harvested at the green mature, turning, yellow point and ripe stages, respectively.

Sampling and analysis of mango quality traits

After harvesting the first set of fruits, the colour of the peel of each fruit was measured with a Minolta Chroma meter CR300 (Konica Minolta, Osaka, Japan). The CIELAB coordinates (L^*, a^*, b^*) were measured on three areas of the fruit peel: the middle of the sunny side, the middle of the shaded side, and the bottom of the fruit. As suggested by Ayala-Silva et al. (2005) and Kang et al. (2008), peel colour is described using the hue angle as the criterion (Eq. (1)).

$$h_{ab} = \arctan\left(\frac{b*}{a*}\right) \quad (1)$$

The fruits were then divided into two "sides" according to their exposure to sunlight. Each side was divided into three sections from the top to the bottom of the fruit in order to obtain three samples of equal length (Fig. 1B). The colour of each flesh sample was measured with a Minolta Chroma meter CR300 (Konica Minolta, Osaka, Japan) and described using the hue angle criterion (Eq. (1)), as proposed by Vasquez-Caicedo et al. (2005). Flesh samples were then ground in a Grindomix blender (Retsch, Haan, Germany) to obtain fresh juice to measure TSS content using a refractometer ATC-1E (Atago, Tokyo, Japan) and titratable acidity. Titratable acidity, expressed as milli-equivalents of acid per 100 g fresh mass (Meq 100 gFM^{-1}), was measured by colorimetric titration with phenolphthalein and 0.05 mol L^{-1} NaOH solution.

Flesh samples from the second set of fruits used for model calibrations were prepared for analysis of their TSS content and titratable acidity in the same way as the first set of fruits.

Vis–NIR spectrophotometric measurements and partial least square regressions

For each sample of flesh from the second and the third sets of fruits, reflectance spectra were monitored from 350 to 2500 nm with a portable spectrometer (LABSPEC 2500, Analytical Spectral Devices, Inc., Boulder, CO, USA). Reflectance measurements in the second dataset were then used to calibrate the partial least square (PLS) regressions of TSS content and titratable acidity. To increase the accuracy of the predictions and the robustness of the model, the wavelengths used in PLS regressions were selected, as recommended by Andersen and Bro (2010) for reflectance data. Interval partial least square (IPLS) regressions associated with the stepwise method were performed to identify the best windows of wavelengths for the prediction of TSS content and of titratable acidity of the flesh. In addition, the number of latent variables in PLS regressions was selected to reduce the prediction error by cross validation using the leave-one-out method. The PLS package procedure (Mevik and Wehrens, 2007) developed in R software (Team, 2012) and fully described by Cornillon (2010) was followed.

The model prediction error was evaluated using the root mean square error (RMSE) as an indicator. Calculation of the RMSE is described in Eq. (2), where y_t is the tth observed or reference value, $\hat{y}_t$ is the tth simulated value, and n is the number of observed or simulated values. The root mean square error of the model (RMSEM) was calculated with the data used for model calibration, whereas the root mean square error of cross validation (RMSECV) was calculated with an independent set of data which was not used for model calibration.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{t=1}^{n}(y_t - \hat{y}_t)^2}{n}} \quad (2)$$

After the models were established, they were used to predict the TSS contents and the titratable acidity of flesh samples from the third dataset using their vis–NIR reflectance measurements. Spectrophotometric measurements were made at the surface of