Predicting Harvest Date and Quality of Mango (cv 'Cogshall') Fruit According to Environmental Factors

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Abstract
The effects of light environment, leaf-to-fruit ratio, and 'initial' fruit size on processes involved in mango fruit quality were investigated at the branch level, for a better understanding of the heterogeneity of mango fruit quality within a tree. This approach required analysing (i) the source/sink balance at the branch level, (ii) the water relations between branch and fruit, and (iii) the accumulation of sugars, organic acids and minerals in the flesh. Three models were derived from experimental data. They simulated fruit growth in water and dry matter content and storage of biochemical and mineral compounds in fruit flesh. The changes introduced in the original versions of these models are detailed. These models were integrated in a global model predicting individual fruit size and gustatory quality (i.e. sweetness and sourness). The global model of mango quality has been tested satisfactorily against experimental data of fruit size, sweetness and sourness. The global model at the branch level was then scaled up at the tree level. It predicted accurately the variability of mango quality observed within a tree by taking into account the fruit light environment, the 'initial' fruit size and the leaf-to-fruit ratio. The model was able to predict the distribution of fruit size and harvest date of a tree using as inputs the full bloom date of the orchard and distributions of 'initial' fruit size, light environment branches and competition for assimilate supply. These simulations showed that this model could have practical applications to manage fruit quality and plan harvest and marketing.

INTRODUCTION

Fruit size, sweetness and sourness are important components of fruit quality, both for fruit producers and consumers. These aspects of fruit quality are highly variable within a mango tree, because of variation in fruit water and dry matter content and in stage of maturity. Supply of water and assimilate depends on tree water status and carbohydrates production and allocation. Therefore, it is necessary to analyse factors affecting water and carbohydrates status in mango tree and their influence on fruit growth and maturity. This knowledge is a necessary step before suggesting cultural practices to control fruit quality and maturation.

Fruit taste is dependent on the balance between organic acids and soluble sugars, i.e. mostly citric acid and sucrose, respectively, in mango (Selvaraj et al., 1989). During mango fruit growth and maturation, the acidity of flesh increases and then decreases,

whereas total soluble sugar concentrations stay low and then increase rapidly before maturity (Ueda et al., 2001; Kudachikar et al., 2003).

Orchard management influence source-sink relationships involved in fruit growth, by manipulating light environment, source size, or sink size. The light environment of a fruiting branch influences fruit growth since it determines leaf photosynthesis (Génard and Baret, 1994; Urban et al., 2003). Its natural heterogeneity at the tree level is a source of variation of photosynthesis within the tree (Marini and Marini, 1983). Relationships between light environment and fruit quality have been reported for fruit size and total sugars content in apple (Morgan et al., 1984), pear (Kappel and Neilsen, 1994) and kiwifruit (Snelgar and Hopkirk, 1988). Controlling the leaf-to-fruit ratio is a way to manage the size of carbohydrates source per fruit. Low leaf-to-fruit ratios decrease mango fruit size (Chacko et al., 1982) due to a decrease of the fruit dry matter and water content (Léchaudel et al., 2002). For peach, a low leaf-to-fruit ratio reduces fruit size and sweetness (Souty et al., 1999). Final fruit size generally depends on the total number of cells in the fruit, as demonstrated for apple (Goffinet et al., 1995), tomato (Bertin et al., 2002) and mango (Léchaudel, 2004). The 'initial' fruit size, measured after cell division period, is an indicator of sink size and is related to final fruit size in conditions of potential growth in apple (Stanley et al., 2000). From a practical point of view, fruit thinning during early fruit growth affects sink size through an effect on fruit cell number (Westwood, 1967).

In previous papers, we presented two models simulating changes in water (Léchaudel, 2004) and dry (Léchaudel et al., 2005a) mass of mango at the branch level, according to climatic data, environmental factors, and 'initial' fruit size. In this study, we combined these models to obtain a global model predicting changes in fruit fresh mass and in flesh composition during fruit development at the branch level. We tested the ability of the model to reproduce the effects of leaf-to-fruit ratio, light environment, and 'initial' fruit size, on fruit growth and concentrations of citric acid and sucrose. These parameters were used to evaluate two main components of fruit quality: size and taste. Then, we tested the ability of the global model to predict the distribution of fruit size and harvest date at the tree level.

MATERIALS AND METHODS
Plant Material
The study was conducted on 12-year-old mango trees, cv. 'Cogshall' grafted onto 'Maison Rouge', in La Réunion Island (20°52'48''S, 55°31'48''E) during the 2001 and 2002 growing seasons. Trees were well irrigated, on a potential evapotranspiration basis. Six weeks after flowering, about ten to fifteen branches per tree were chosen. Branches were girdled after fruit drop, when fruit length was about 5 cm, by removing a 10-15 mm wide band of bark. Defruiting and defoliating were carried out, if needed, to reach 10 and 100 leaves per fruit. To keep the leaf-to-fruit ratio constant within each treatment, new emerging leaves were removed. Measurements of fruit growth and biochemical analysis, during the 2001 growing season, are described in Léchaudel et al. (2005b). During the 2002 growing season, fruit of 13 trees were harvested at full maturity and individually weighted in order to build the distribution of fruit mass and harvest dates for these trees.

Model Description
The global model was built by combining models simulating changes in water and dry masses of fruit and in biochemical composition of flesh, according to assimilate

supply, 'initial' fruit size and light environment at the branch level. The first model (Léchaudel et al., 2005a) computed, at a daily step, processes involved in leaves, branch and fruit: leaf photosynthesis, maintenance and growth respiration of the three organs, reserves storage and mobilisation in leaves and branch, fruit demand (as a function of 'initial' fruit mass) and fruit growth. The daily fruit dry mass was allocated to the three main components of mango, peel, pulp and stone, using empirical relationships (Léchaudel et al., 2002). The second model (Léchaudel, 2004) is based on the balance between water fluxes: the incoming flux, driven by the difference between branch and fruit water potential, and the outcoming flux due to transpiration. This model simulated, at an hourly step, changes in branch and fruit water relations (water potential, turgor and osmotic pressures), and changes in reversible and irreversible fruit growth under various assimilate supplies. A set of parameters was introduced for mango, as the elastic modulus, the cell wall extensibility and the yield threshold pressure which may change during the growth in mango. A third model of accumulation of biochemical (sucrose, fructose, glucose, citric and malic acids) and mineral (potassium, magnesium and calcium) compounds was linked to the previous model in order to predict the osmotic pressure, a component of fruit water status. It was necessary to change the time step of the second model, from hour to day, to combine these models. Thus, the state variables, like fruit transpiration, osmotic and turgor pressure of the flesh, were simulated daily. The total fruit fresh mass was calculated as the sum of simulated water mass stored in the flesh, the flesh dry mass and fresh mass of the stone.

The empirical model of biochemical compounds stored in the flesh (Léchaudel, 2004) was modified as follows. Firstly, we introduced the model of citrate concentration proposed by Lobit et al. (2003):

$$[\text{citrate}]_t = \frac{1}{FW_t} \cdot \int_{t_{ini}}^{t} \left(c_1 \cdot DW_{ini} \cdot \left(1 + c_2 \cdot (T_t - T_o)\right) \cdot \left(1 + c_3 \cdot (T_t - T_o) \cdot c_4 \frac{\text{Resp}_t}{DW_{ini}}\right)\right) \cdot dt$$

where $[\text{citrate}]_t$ is the citrate concentration (mol kg^{-1}) in fruit flesh, FW_t is the fresh mass of the fruit flesh (g), t is the date (in days after full bloom), DW_{ini} is the 'initial' fruit dry mass, t_{ini} is the date when the 'initial' fruit dry mass is measured (in days after full bloom), Resp_t is the respiration of fruit mesocarp, T_t is the temperature (°K), T_o is an arbitrary temperature (here T_o = 296 °K), c_1 (mol g^{-1} d^{-1}) and c_4 (g mol^{-1} d^{-1}) are coefficients, and c_2 and c_3 (°K^{-1}) are coefficients of response to temperature.

Secondly, we modified the model of sucrose by changing the empirical relationship (Léchaudel, 2004) by an exponential function:

$$[\text{sucrose}]_t = [\text{sucrose}]_{ini} + [\text{sucrose}]_{ini} \cdot \left(e^{\mu \cdot (t - t_{ini})}\right) \cdot \frac{DW_t - DW_{ini}}{\left(DW_{max} - DW_{ini}\right)}$$

where $[\text{sucrose}]_t$ and $[\text{sucrose}]_{ini}$, and DW_t and DW_{ini}, are the sucrose concentration (g g^{-1}) in fruit flesh, and the fruit dry mass (g), at a date t and when the 'initial' fruit dry mass is measured (in days after full bloom), DW_{max} is the 'maximal' fruit dry mass (g), calculated as in Léchaudel et al. (2005a), and μ (d^{-1}) a parameter.

To scale up the global model at the tree level in order to predict distributions of fruit sizes and harvest dates, we needed to take into account the variability of growth factors for each fruit. We assumed that each fruit was randomly located within tree canopy, and that input values of 'initial' dry mass, leaf-to-fruit ratio, light environment and date of flowering for each fruit could be randomly sampled in statistical distributions. At the tree level, fruiting branches were not girdled, and the leaf-to-fruit ratio was

considered as an indicator of local competition between fruit for carbohydrates. 'Initial' fruit dry mass and date of flowering were randomly sampled in two normal distributions, and leaf-to-fruit ratio and light environment of the fruit were randomly sampled in two uniform distributions. Distributions parameters were estimated from 2001 experimental data in order to be representative of the orchard conditions. Fruit growth simulation stopped when simulated sucrose concentration in the flesh reached the average value of sucrose concentration in mango flesh cv. Cogshall at maturity in Réunion Island. This global model at the tree level, whose parameters were estimated with the 2001 dataset, was confronted with the distributions of fruit sizes and harvest dates obtained in 2002 using a Monte-Carlo method to build the simulated distributions.

RESULTS

Parameters of the global model are presented in Table 1. The model correctly simulated changes in fruit fresh mass during fruit development, in the 2001 growing season, on the basis of light environment of the fruit, 'initial' fruit size and assimilate supply (Fig. 1a). The increase of fruit size with the leaf-to-fruit ratio was well predicted. Variability in fruit growth within each leaf-to-fruit ratio treatment, described by the standard deviation for mean fruit fresh mass, was large. The model correctly simulated this variability, regardless of the treatments (Fig. 1a). Simulated fruit sweetness, derived from sucrose, glucose and fructose concentrations in fruit flesh, were in the same range than actual data (Fig. 1b). The increase of fruit sweetness during fruit growth and with the leaf-to-fruit ratio treatment was correctly simulated by the model. Near maturity, fruit were larger and sweeter by increasing the leaf-to-fruit ratio. Simulated fruit sourness was in accordance with the pattern observed for two leaf-to-fruit ratio treatments (Fig. 1c). The model was able to reproduce the variability of fruit sourness, regardless of treatment.

The empirical distribution of fruit fresh mass at maturity was close to the model simulation, with a median about 450-500 g (Fig.2a). The model predicted satisfactorily distribution of harvest dates which occurred from 110 to 180 days after full bloom, with a peack at 140-150 days after full bloom (Fig. 2b). These empirical distributions presented for one tree were simulated with the same accuracy for the other twelve trees observed in 2002 (data not shown).

DISCUSSION

For a better understanding of the variability of fruit quality within a mango tree, we built a model integrating the effects of biological factors on the main physiological processes involved in fruit growth in water and dry matter. The model was able to simulate accurately the main components of individual fruit quality, i.e. size, sweetness and sourness, according to light environment of the fruit, assimilate supply, and 'initial' fruit dry mass. Simulations made with the global model confirmed the positive relationship between assimilate supply, fruit growth and fruit taste mentioned in several studies on mango (Chacko et al., 1982; Simmons et al., 1998; Léchaudel et al., 2005b). Thus near maturity, the simulated larger fruit had a higher sweetness, as already mentioned for sucrose in peach (Génard et al., 1999) and for soluble solids concentration in apple (Warrington et al., 1999). The pattern of simulated sourness, mainly due to changes in citric acid concentrations, was close to this observed in many fruit, including mango.

The global model of fruit quality estimated fresh mass and gustatory quality of individual fruit within a tree. It had therefore the advantage to predict fruit taste and to

account for variability between fruit, and did not only simulate an 'average' fruit in a tree (Buwalda, 1991; Grossman and Dejong, 1994). As a consequence, the global model can be used to predict the distributions of fruit sizes and harvest dates. The model robustness was confirmed on independent data obtained on thirteen trees during a different year than this used to estimate parameters and to calibrate the model. The main growth factors considered by the model, i.e. light environment of the fruit, leaf-to-fruit ratio and 'initial' fruit mass, may be manipulated by adequate cultural practices like pruning or thinning. The model is therefore expected to account for the effect of these practices on fruit growth and quality, as done for kiwifruit (Lescourret et al., 1999). This result is interesting for growers, as they can use this tool to predict the effect of cultural practices on the distribution of fruit quality at harvest, at the tree or orchard level. However, further validations of the model are needed, in particular for the effect of cultural practices. The accurate prediction of distributions of fruit sizes and harvest dates is useful to support decision with respect to crop management and marketing.

Literature Cited

Bertin, N., Gautier, H., Roche, C., 2002. Number of cells in tomato fruit depending on fruit position and source-sink balance during plant development. Plant Growth Regul. 36:105-112.

Buwalda, J.G., 1991. A mathematical model of carbon acquisition and utilisation by kiwifruit vines. Ecol. Model. 57:43-64.

Chacko, E.K., Reddy, Y.T.N., Ananthanarayanan, T.V., 1982. Studies on the relationship between leaf number and area and development in mango (*Mangifera indica* L.). J. Hort. Sci. 57:483-492.

Génard, M., Baret, F., 1994. Spatial and temporal variation of light inside peach trees. J. Amer. Soc. Hort. Sci. 119:669-677.

Génard, M., Reich, M., Lobit, P., Besset, J., 1999. Correlations between sugar and acid content and peach growth. J. Hort. Sci. Bio. 74:772-776.

Goffinet, M.C., Robinson, T.L., Lakso, A.N., 1995. A comparison of 'Empire' apple fruit size and anatomy in unthinned and hand-thinned trees. J. Hort. Sci. 70:375-387.

Grossman, Y.L., Dejong, T.M., 1994. Peach: a simulation model of reproductive and vegetative growth in peach trees. Tree Physiol. 14:329-345.

Kappel, F., Neilsen, G.H., 1994. Relationship between light microclimate, fruit growth, fruit quality, specific leaf weight and N and P content of spur leaves of 'Bartlett' and 'Anjou' pear. Hortscience 59:187-196.

Kudachikar, V.B., Kulkarni, S.G., Aradhya, S.M., Aravinda Prasad, B., Ramana, K.V.R., 2003. Physico-chemical changes in mango (*Mangifera indica* L.) varieties 'Alphonso' and 'Raspuri' during fruit development and maturation. J. Food Sci. Tech. 40:285-289.

Léchaudel, M., Génard, M., Lescourret, F., Urban, L., Jannoyer, M., 2002. Leaf-to-fruit ratio affects water and dry-matter content of mango fruit. J. Hort. Sci. Bio. 77:773-777.

Léchaudel, M., 2004. Croissance et qualité organoleptique de la mangue (*Mangifera Indica*): analyse expérimentale et modélisation de l'effet de la disponibilité hydrique et carbonée. Doctoral thesis. Institut National Agronomique Paris-Grignon, Paris, pp. 147.

Léchaudel, M., Génard, M., Lescourret, F., Urban, L., Jannoyer, M., 2005a. Modeling effects of weather and source-sink relationships on mango fruit growth. Tree Physiol. 25:583-597.

Léchaudel, M., Joas, J., Caro, Y., Génard, M., Jannoyer, M., 2005b. Leaf:fruit ratio and irrigation supply affect seasonal changes in minerals, organic acids and sugars of mango fruit. J. Sci. Food Agri. 85:251-260.

Lescourret, F., Blecher, N., Habib, R., Chadoeuf, J., Agostini, D., Pailly, O., Vaissière, B., Poggi, I., 1999. Development of a simulation model for studying kiwi fruit orchard management. Agri. Sys. 59:215-239.

Lobit, P., Génard, M., Wu, B.-H., Soing, P., Habib, R., 2003. Modelling citrate metabolism in fruits: responses to growth and temperature. J. Exp. Bot. 54:2489-2501.

Marini, R.P., Marini, M.C., 1983. Seasonal changes in specific leaf weight, net photosynthesis, and chlorophyll content of peach leaves as affected by light penetration and canopy position. J. Amer. Soc. Hort. Sci. 108:600-605.

Morgan, D.C., Stanley, C.J., Volz, R., Warrington, I.J., 1984. Summer pruning of 'Gala' apple: The relationships between pruning time, radiation penetration, and fruit quality. J. Amer. Soc. Hort. Sci. 109:637-642.

Selvaraj, Y., Kumar, R., Pal, D.K., 1989. Changes in sugars, organic acids, amino acids, lipid constituents and aroma characteristics of ripening mango (*Mangifera indica* L.) fruit. J. Food Agri. 26:308-313.

Simmons, S.L., Hofman, P.J., Whiley, A.W., Hetherington, S.E., 1998. Effects of leaf:fruit ratios on fruit growth, mineral concentration and quality of mango (*Mangifera indica* L. cv. Kensington Pride). J. Hort. Sci. Bio. 73:367-374.

Snelgar, W.P., Hopkirk, G., 1988. Effects of overhead shading on yield and fruit quality of kiwifruit (*Actinidia deliciosa*). J. Hort. Sci. 63:731-742.

Souty, M., Génard, M., Reich, M., Albagnac, G., 1999. Effect of assimilate supply on peach fruit maturation and quality. Can. J. Plant Sci. 79:259-268.

Stanley, C.J., Tustin, D.S., Lupton, G.B., McArtney, S., Cashmore, W.M., De Silva, H.N., 2000. Towards understanding the role of temperature in apple fruit growth responses in three geographical regions within New Zealand. J. Hort. Sci. Bio. 75:413-422.

Ueda, M., Sasaki, K., Utsunomiya, N., Shimabayashi, Y., 2001. Changes in properties during maturation and ripening of 'Chiin Hwang No. 1' mango fruit cultivated in a plastic greenhouse. Food Sci. Technol. Res. 7:207-213.

Urban, L., Le Roux, X., Sinoquet, H., Jaffuel, S., Jannoyer, M., 2003. A biochemical model of photosynthesis for mango leaves: evidence for the effect of fruit on photosynthetic capacity of nearby leaves. Tree Physiol. 23:289-300.

Warrington, I.J., Fulton, T.A., Halligan, E.A., De Silva, H.N., 1999. Apple fruit growth and maturity are affected by early season temperatures. J. Amer. Soc. Hort. Sci. 124:468-477.

Westwood, M.N., 1967. Cell size, cell number, and fruit density of apples as related to fruit size, position in cluster, and thinning method. Proc. Amer. Soc. Hort. Sci. 91:51-62.

Tables

Table 1: Parameter values (not previously published) for the global model of mango quality

| Parameter	Value (± s.e.)	Significance
Maintenance respiration		
MRR_{branch} (g C g^{-1} d^{-1})	$8.58\ 10^{-4}$	
MRR_{fruit} (g C g^{-1} d^{-1})	$1.15\ 10^{-3} \pm 1.1\ 10^{-4}$	Maintenance respiration rate of branch and fruit
Transpiration		
ρ (cm d^{-1})	5544.0 ± 141.6	Fruit surface conductance
Fruit plastic growth		
a.L (g cm^{-2} MPa^{-1} d^{-1})	0.3732	Product of the ratio between the composite membrane to the fruit area and the hydraulic conductivity of the fruit composite membrane for water transport
ϕ_{max} (MPa^{-1} d^{-1})	0.414	Coefficient of cell wall extensibility
Citric acid and sucrose models		
c_1 (mol g^{-1} d^{-1})	$1.05\ 10^{-5} \pm 0.75\ 10^{-6}$	Coefficients
c_2 ($°K^{-1}$)	-1.275 ± 0.369	
c_3 ($°K^{-1}$)	0.2927 ± 0.2772	Coefficients of response to temperature
c_4 (g mol^{-1} d^{-1})	7968 ± 9468	
μ (d^{-1})	0.0283 ± 0.0107	Coefficient of exponential increase in sucrose

Figures
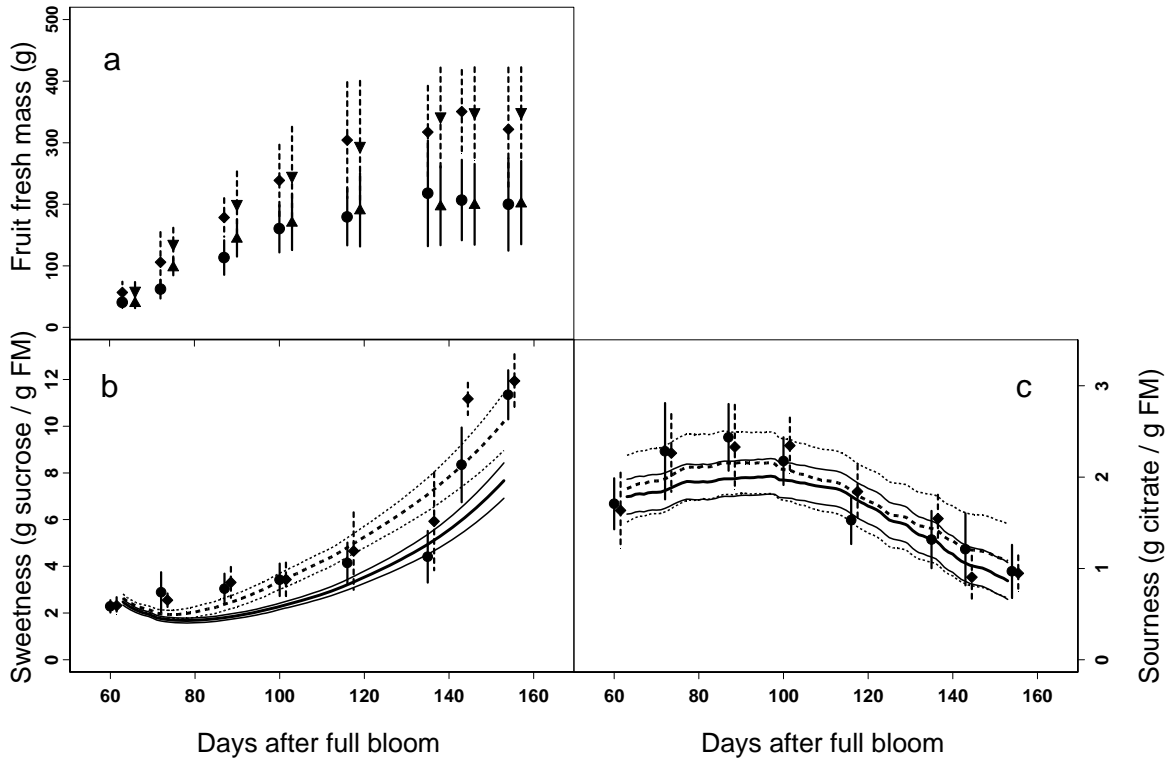
Fig. 1: Mean and standard deviation of actual mango fruit fresh mass (a), for the 10 (● and full line) and 100 (◆ and dotted line) leaf-to-fruit ratio treatments in 2001, and for the fresh mass simulated for the 10 (▲ and full line) and 100 (▼ and dotted line) leaf-to-fruit ratio treatments. Simulated data are offset by 3 DAB to ensure readability. For sweetness (b) and sourness (c), actual data for the 10 (●) and 100 (◆) leaf-to-fruit ratio treatments are compared to the model outputs (mean and standard deviation) simulated with leaf-to-fruit ratio of 10 (large and thin full line) and 100 (large and thin dotted line).
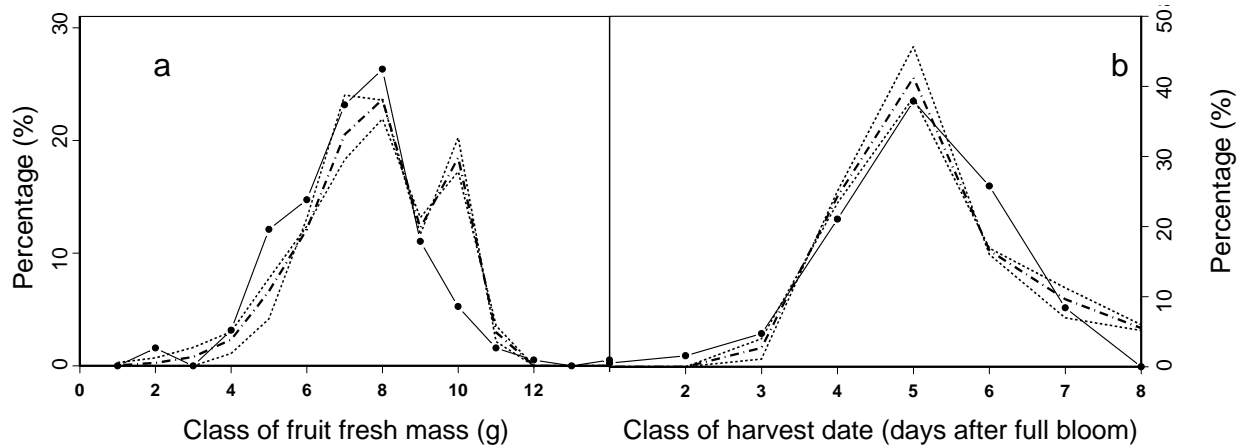

Fig. 2: Empirical and simulated distributions of fruit fresh mass (a) and harvest dates (b) for 190 fruit harvested on a mango tree in 2002. Twelve simulations of these 190 fruit were performed with a Monte-Carlo method to sample values of growth factors for each fruit. Classes are every 50g from 50 to 750 g, and every 10 from 100 to 180 days after full bloom, for fruit fresh mass and harvest date, respectively. For each class, mean and 5% confidence region are presented.