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Modeling sugar content of pineapple under agro-climatic conditions on Reunion Island

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ABSTRACT

A process-based model simulating the change in total soluble solids (TSS (%)) in fruit flesh was developed to describe the effect of climatic conditions on the sugar content of 'Queen Victoria' pineapple at harvest on Reunion Island. Sugar content varies throughout fruit development according to three processes (the supply of carbohydrates to the fruit, fruit metabolism, and dilution) which are affected by environmental factors, mainly temperature, rainfall and fertilization. The ecophysiological model of soluble sugar accumulation was linked to SIMPIÑA, a crop model that accurately predicts the daily increases in flesh dry and fresh weight. When the process-based model and crop model were linked, the dry and fresh matter of the pineapple flesh, as affected by climatic conditions, could be used as inputs to predict the TSS (%) at harvest. The relative rate of transformation of carbon as sugars in the fruit flesh for the synthesis of compounds other than sugars was estimated during fruit growth. TSS (%) were compared for harvested fruit grown under eight agro-climatic conditions. In the flesh of fruit harvested close to maturity, i.e., at 1400 degree-days after flowering, TSS (%) were significantly related ($r^2 = 0.55$, $P < 0.001$) to total soluble sugar content. The variability of TSS (%) between the eight agro-climatic groups ranged from 16.9 for pineapples grown in dry locations irrigated, under N-deficit conditions to 19.4 for pineapples grown in dry locations, without irrigation and without N deficiency. The variability of TSS (%) was substantial within each of the eight agro-climatic groups: standard deviations ranged from 0.9 to 1.5 for pineapples grown in dry locations, irrigated, without N deficiency and in dry locations, without irrigation and without N deficiency, respectively. For data from 14 experiments conducted under different climatic conditions, N fertilization, and irrigation conditions, the model predicted the TSS (%) at harvest with an RRMSE of 0.04. By linking this sugar model to the SIMPIÑA crop model, the impact of environmental conditions and cultural practices on the growth and development of pineapple are taken into account to predict the gustatory quality of pineapple grown on Reunion Island. The model could have a practical application to manage fruit quality, plan harvest, and marketing.

1. Introduction

Fruit quality has become increasingly important in fruit production, and improving the quality of products is an economic, public health, and scientific concern. The gustatory quality of fruit can be highly variable and difficult to manage (Basile et al., 2007; Génard and Bruchou, 1992; Taylor et al., 2007). Therefore, understanding fruit growth and the accumulation of compounds affecting gustatory quality has been a challenge for researchers. Predicting how these compounds accumulate in fruit is difficult because their accumulation is affected by the environment and by management.

Sugar content greatly affects the gustatory quality of fruit (Vaysse et al., 2000). Sweetness depends on the concentration of sugar, which is synthesized and accumulated in the flesh during fruit growth (Leonard et al., 1953; Prudent et al., 2011; Robertson et al., 1992). Fruit growth determines fruit weight and volume at harvest, and larger fruit obviously require more sugar than smaller fruit to achieve the same concentration of sugar. The pathways by which sugars accumulate differ among fruit species (Hubbard et al.,

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1991). Sugar content, and more precisely the amount of carbon in sugars in the flesh, varies according to the supply of carbohydrates to the fruit; that supply depends on leaf photosynthesis and plant metabolism and is diluted by increases in fruit volume (Quilot et al., 2004). As fruit volume increases, carbon and water enter the fruit via the xylem and phloem and exit the fruit via respiration and transpiration (Fishman and Génard, 1998; Génard et al., 2003; Génard and Souty, 1996; Lescourret et al., 2001). Measurement of the percentage of TSS (%) is used extensively in commercial food manufacture to evaluate fruit sweetness. TSS (%) are strongly correlated with sugar content in the ripe fruit of various species, including peach (Grechi et al., 2008) and banana (Fernando et al., 2014).

Models of fruit quality range from simple equations that estimate fruit size and yield to a complex representation of respiration, photosynthesis, and assimilation of nutrients with the goal of predicting seasonal changes in concentrations of compounds involved in quality (Vazquez-Cruz et al., 2010). Although the latter ecophysiological models simulate how environment and plant metabolism affect fruit mass, fruit volume, and sugar content, they seldom consider how water and nitrogen (N) balances affect vegetative growth and fruit quality. At the same time, several crop models have been developed that assess carbon partitioning in fruit trees as affected by water stress but that do not assess fruit quality (Allen et al., 2005; Costes et al., 2008). Sansavini (1997) proposed the combined use of a crop model and a fruit growth model for fruit quality to understand how crop management affects processes underlying crop performance. Recently, the Qualitree model was developed to simulate the vegetative growth and the development of fruit quality as affected by physiological processes and crop management (Lescourret et al., 2011). This model has been used to evaluate the effect of water restrictions on fruit growth and also on sugar concentrations in peach fruit (Miras-Avalos et al., 2013). Process-based fruit growth models are useful for understanding how fruit quality is affected by climate and management (Dai et al., 2008), and their usefulness could probably be increased if they are linked to crop model simulates maize kernel moisture content. This kind of linkage should be useful for improving the quality, yield, and management of pineapple and other fruit crops.

Pineapple (*Ananas comosus*) is an economically important crop in tropical and subtropical areas, and fruit sweetness is a major factor determining the quality of pineapple fruit (Py et al., 1984). Fruit sweetness gradually increases during the later stages of fruit growth (Bartholomew and Paull, 1986). Variation in pineapple fruit sugar content is associated with fruit maturation and growing conditions (Bartolome et al., 1995; Py et al., 1984; Singleton and Gortner, 1965). Pineapple development depends on temperature and heat unit models were developed on various cultivars in many areas to predict the date of harvest (Fleisch and Bartholomew, 1987; Malezieux et al., 1994; Fournier et al., 2010). Pineapple ('Queen Victoria' cultivar) was the first fruit to be produced on Réunion Island, which is an island in the Indian Ocean, east of Madagascar. Pineapple is grown under a wide range of conditions in Réunion Island, where the elevation ranges from 50 m to 900 m a.s.l. and annual rainfall ranges from 500 to 5000 mm. The large variability in fruit size and quality makes it difficult to predict sugar content based on crop growth.

The objectives of this study were to analyze the effect of agroclimatic conditions on the total soluble solids of pineapple (TSS (%)) at harvest and to develop a sub-model (SIMPIÑA—Sugar) of the SIMPIÑA crop model (Dorey et al., 2015) capable of predicting pineapple TSS (%) at harvest. The sugar model developed in this study was partly based on the peach model of Quilot et al. (2004), which in turn was derived from the process-based SUGAR model developed for peach by Génard and Souty (1996) and Génard et al. (2003), and which was recently revised by Grechi et al. (2008).

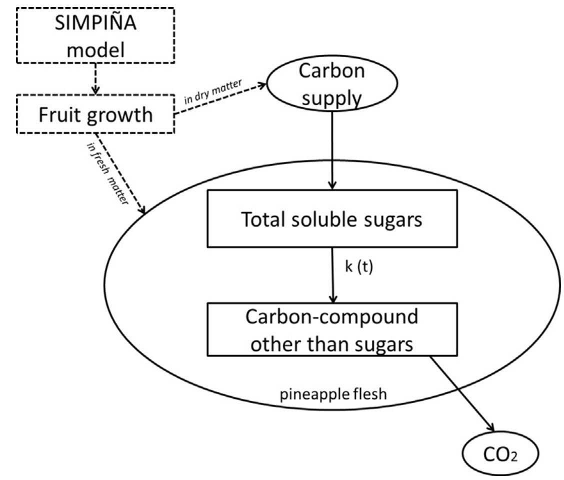

Fig. 1. Scheme of the SIMPIÑA—Sugar model (adapted from Wu Dai et al. 2009). Arrows and boxes represent carbon fluxes and carbon components, respectively. The two ellipses represent carbon supply and losses by respiration. $k(t)$ is the relative rate of synthesis of non-sugar carbon compounds from soluble sugars. Dashed boxes and dashed arrows represent processes developed in the SIMPIÑA crop model.

We first characterized the rate at which sugars are transformed into other compounds in pineapple flesh. Next, we calibrated the k parameter, which corresponds to the relative rate at which carbon in the sugars of fruit are used to synthesize compounds other than sugars. Then we evaluated the accuracy of the model by comparing TSS (%) simulations with data from 14 independent data sets covering a broad range of climatic and cultural conditions. Finally, we analyzed the simulation of TSS (%) at harvest for eight cropping systems representing different climatic and cultural conditions.

2. Materials and methods

2.1. Model description

2.1.1. SIMPIÑA model

Pineapple growth and fruit development in the field and as affected by daily changes in soil N and soil water were simulated. The growth of pineapple is based on radiation interception, conversion to dry biomass, and partitioning of dry biomass into compartments: roots, leaves, stem, peduncle, inflorescence, fruit, crown, and suckers. Fruit demand is calculated as the demand per fruitlet multiplied by the number of fruitlets per fruit. Fruitlet demand is simulated by a potential sigmoidal curve as proposed for other fruits (Léchaudel et al., 2005; Lescourret et al., 1998). Dry matter of each organ was converted to fresh matter by adding a volume of water, which depended on the newly formed dry matter per organ and the specific water content per organ. Fruit water content varied as a function of the sum of degree days (dd) after flowering. Dry matter and fresh matter of fruit were accurately simulated by the SIMPIÑA model, regardless of location, levels of irrigation and fertilization, and planting density (Dorey et al., 2015).

2.1.2. SIMPIÑA-Sugar model

The model predicts the daily change in total sugar content in pineapple flesh during the fruit growth period and the TSS (%) at the end of fruit growth, corresponding to harvest at a ripe stage. The model is based on one proposed for peach by Quilot et al. (2004), which is a simplified version of the process-based SUGAR model developed by Génard and Souty (1996) and Génard et al. (2003), that predicts the partitioning of carbon into sucrose, sorbitol, glucose and fructose in the flesh.