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Crop modelling in fruit crops: A review

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Abstract
Plant production systems are governed by site management and by biotic and abiotic factors. Studying and understanding the tree growth and development of fruit crops is a difficult endeavour. Crop models have long been powerful tools in unravelling physiological mechanisms that determine crop yield in relation to the environment. Models are used to estimate seasonal changes in quality traits as fruit size, dry matter, water content and the concentration of sugars and acids, which are very important for flavor and aroma. Different types of models are available which vary in parameters and precision. Use of crop models in fruit crops is relatively new. Available literature on fruit crop modelling has been reviewed here.

Keywords: Crop models, fruit crops, precision-farming

Introduction
Agriculture is the backbone of Indian economy accounting for 14 percent of the nation's Gross Domestic Product (GDP) and Horticulture accounts for about 30% of India's agricultural GDP from 13.08% of cropped area. Nearly about 65 percent of country's population still depends on agriculture for employment and livelihood. India has one of the largest and institutionally complex agricultural systems in the world. Studies on crop production are traditionally carried out by using conventional experience-based agronomic research, in which crop production functions are derived from statistical analysis without referring to the underlying biological or physical principles involved. The application of correlation and regression analysis has provided some qualitative understanding of the variables and their interactions that were involved in cropping systems and has contributed to the progress of agricultural science (Kumar and Chaturevdi, 2009) [35].

A number of approaches have been used to analyse the effects of environmental variables on crop growth. In statistical approaches regressions were obtained correlating environmental variables and yield (Reynolds and Acocx, 1985) [59].

The global climate is changing and agriculture will have to adapt to ensure sustainability and survival. Due to the complexity of both agricultural systems and climate change, crop models are often used to understand the impact of climate change on agriculture and to assist in the development of adaptation strategies. Climate change contributes to the evolution of agricultural landscapes and is also subject to a feedback loop as changes in land use, especially conversion to cropland, drives processes such as the global carbon cycle that have been linked to changes in climatic conditions. Variability in the biophysical processes in agricultural production has been found to be closely associated with climate.

Over the past decade or so the fruit growers experienced the most commonly encountered climatic conditions. Quality and yield of any crop is only possible through its optimum climatic requirements. The changed climatic parameters affect the crop physiology, biochemistry, floral biology, biotic stresses like disease-pest incidence, etc., and ultimately resulted to the reduction of yield and quality of fruit crops (Rajatiya *et al*., 2018) [58]. In recent years, fruit quality has become an increasingly important aspect of fruit production. Thus, a new field of science has been emerging that is loosely termed functional-structural plant modelling (Godin and Sinoquet, 2005) [22]. Research efforts directed toward understanding the effects of climate and management techniques on fruit quality are needed, and mathematical models are useful frameworks for these research efforts (Sansavini, 1997) [61]. Carbon balance models of plant growth have been used to identify environmental factors limiting plant growth (Loomis *et al*., 1979) [46]. Many detailed mechanistic models of photosynthetic processes within the plant canopy have been developed, but much less is known about the physiological processes involved in carbohydrate partitioning (Wardlaw, 1990) [73].

Modelling: Definition and Concepts

Modelling is the use of equations or sets of equations to represent the behaviour of a system. In effect crop models are computer programmes that mimic the growth and development of crops (USDA, 2007). Modelling represents a better way of synthesizing knowledge about different components of a system, summarizing data, and transferring research results to users (France & Thornley, 1984) [18]. Model simulates or imitates the behaviour of a real crop by predicting the growth of its components, such as leaves, roots, stems and grains. Thus, a crop growth simulation model not only predicts the final state of crop production or harvestable yield, but also contains quantitative information about major processes involved in the growth and development of the crop. Crop models can be used to understand the effects of climate change such as elevated carbon-dioxide changes in temperature and rainfall on crop development, growth and yield (Murthy, 2002) [47].

Two decades ago, it was not certain whether the complex physical, physiological and morphological processes involved in the growth of a plant could be described mathematically, except perhaps in some controlled environments. Thus, the relevance of crop growth simulation models in crop agronomy was challenged (Passioura, 1973) [54]. However, during the past 40 years, crop growth modelling has changed dramatically. In the sixties, the first attempt to model photosynthetic rates of crop canopies was made (De Wit, 1965) [13]. The results obtained from this model were used among others, to estimate potential food production for some areas of the world and to provide indications for crop management and breeding (De Wit, 1967; Linneman *et al.*, 1979) [14, 42].

Types of models

There are different types of models that have been developed over the years, and they can be classified into various groups or types. A few of them are:

Empirical models: These are direct descriptions of observed data and are generally expressed as regression equations (with one or a few factors) and are used to estimate the final yield. This approach is primarily one of examining the data, deciding on an equation or set of equations and fitting them to data. These models give no information on the mechanisms that give rise to the response. Examples of such models include those used for such experiments as the response of crop yield to fertilizer application, the relationship between leaf area and leaf size in a given plant species and the relationship between stalk height alone or coupled with stalk number and/or diameter and final yield **(**Oteng-Darko *et al*., 2012) [51].

Mechanistic models: A mechanistic model is one that describes the behaviour of the system in terms of lower-level attributes. Hence, there is some mechanism, understanding or explanation at the lower levels (eg. Cell division). These models have the ability to mimic relevant physical, chemical or biological processes and to describe how and why a particular response occurs **(**Oteng-Darko *et al*., 2012) [51]. Mechanistic models, explain not only the relationship between weather parameters and yield, but also the mechanism of these models (explains the relationship of influencing dependent variables). These models are based on physical selection (Murthy, 2002) [47].

Stochastic models: In Stochastic models, a probability element is attached to each output. For each set of inputs different outputs are given along with probabilities (Murthy, 2002) [47]. These models define yield or state of dependent variable at a given rate. When variation and uncertainty reaches a high level, it becomes advisable to develop a stochastic model that gives an expected mean value as well as the associated variance **(**Oteng-Darko *et al*., 2012) [51].

Statistical models: These models express the relationship between yield or yield components and weather parameters. In these models relationships are measured in a system using statistical techniques. Statistical models of crop responses to climate change, based on historical datasets of crop and climate variables have recently been used (Lobell *et al*., 2008; Paeth *et al*., 2008; Schlenker and Roberts, 2009) [44, 52, 62] to address climatic change impacts on food security in developing countries.

Simulation models: These form a group of models that is designed for the purpose of imitating the behaviour of a system. Simulation models involve Computer models with a mathematical representation of a real world system. One of the main goals of crop simulation models is to estimate agricultural production as a function of weather and soil conditions as well as crop management. These models use one or more sets of differential equations, and calculate both rate and state variables over time, normally from planting until harvest maturity or final harvest (Murthy, 2002) [47].

Crop modelling in fruit crops

Among the horticultural crops, fruit crops are cultivated in an area of 6506.00 („000 ha) with production of 97358.00 („000 tons) (NHB data base, 2017-2018) [49]. Fruit crops play a significant role in the economic development, nutritional security, employment generation, and overall growth of the country. Fruit crops have climatic specificity and excellent fruits having delicacy, nutritive value, and good market acceptability are grown widely in temperate, tropical, and subtropical parts of the country. A large size of the population in India is engaged in fruit production, distribution and marketing (Yadav and Pandey, 2016) [79].

Fruit producers have, over the last decades, been adopting a wide variety of new technologies to meet increased market demands and environmental standards, to improve production quantity, to avoid losses, and to reduce maintenance costs. Increasing fruit quality and uniformity requirements are met by breeding, post-harvest technology, better management practices and more intensive monitoring (Ladaniya, 2007) [36]. In recent years, fruit quality has become an increasingly important aspect of fruit production. Thus, a new field of science has been emerging that is loosely termed functional-structural plant modelling (Godin and Sinoquet, 2005) [22]. Several authors (Behera and Panda, 2009; Bojacá *et al.*, 2009) [5, 6] have developed and used models that explain the effect meteorological variables have on the growth of different kinds of crops. As convincingly demonstrated by de Wit (1986), agricultural productivity depends primarily on the carbon assimilation and partitioning systems. Thus the backbone of crop models of this type involves modelling of plant photosynthesis, respiration and the allocation of the net photosynthate to the fruit or organs of interest. This includes, of course, annual crops as well as fruit tree crops.

Fruit crop models have been developed beyond fruit dry mass accumulation but including fruit quality (Struik *et al*., 2005) [67]. Nowadays, the interest in mathematical modelling about the quality changes during fruit maturation has been increased (Wegehenkel and Mirschel, 2005) [74]. Fruit quality is a complex issue. It involves a set of traits such as fruit size, overall composition, taste, aroma, texture and proportion of edible tissue (Genard *et al*., 2007; Gruda, 2005) [19, 26]. The links between environmental control and quality traits have been extensively investigated (Wu *et al*., 2002; Challinor *et al*., 2004) [78, 11]. Even though every process involved in fruit physiology cannot be integrated into a model, a real degree of complexity is needed since fruit exchanges energy and mass with its environment and it is composed of a large number of diverse components (different sugars, acids, etc.) which interact with each other non-linearly (Genard *et al*., 2007) [19].Taste mainly results from the accumulation of sugars and acids in fruit cells. This accumulation can be controlled through the intensity of metabolic transformations. These processes are well known and have been extensively described in the literature (Ho, 1988; Wink, 1993) [28, 76]. On this basis, Genard *et al*. (2003) [20] designed a mechanistic model called SUGAR to predict changes in sugar composition during each fruit development. In this model, sugars are either directly stored in the cells, transformed into other sugars, or used to synthesize other compounds. Lobit *et al*. (2006) [45] designed two models predicting fruit acidity, the first one described citric acid production and degradation through the citrate cycle. In the second, malic acid content was modelled mainly on thermodynamic conditions of its transport from cytosol to vacuole.

Fruit tree crops share an important number of commonalities with annual crops (Goldschmidt & Lakso, 2005) [23] most processes occurring in annuals will occur in fruit tree crops. Therefore knowledge gathered on the modelling of annual crops provides a first basis to develop more advanced models for perennial fruit crops. Photosynthesis-driven models are also common for perennial fruit trees. Such photosynthesis-driven models have been developed for apples (Baumgaertner *et al*. 1984, Seem *et al*. 1986) [3, 64], grapes (Gutierrez *et al*., 1985) [27], kiwifruit (Buwalda, 1991) [10], olives (Abdel-Razik, 1989) [1] and peaches (Grossman and Dejong, 1994) [24-25]. Pioneering work of C.T. dewit (Van Ittersum *et al*., 2003) [72], most process-based fruit models have focused on carbon relationships leading to predictions of fruit growth in dry mass.

Some models have dealt with nitrogen content, representing nitrogen and carbon dynamics on a similar conceptual basis (sink-driven assimilation and allocation using priority rules (Wermelinger *et al.* 1991) [75]. A few models of fruit metabolism describing synthesis and degradation processes have been designed for sugar (Génard and Souty, 1996) [21] and citric acid accumulation (Lobit *et al*., 2003). The amount of carbohydrate supplied to tree fruits depends on the amount produced by leaf photosynthesis, which is related to leaf area and photosynthetic capacity and activity. The later is influenced by climatic conditions (Rosati *et al*., 1999; Le Roux *et al*., 2001) [60, 37-38] and can be affected by changes in source–sink relationships, as has been reported in many species, including apple (Palmer, 1992) [53], grapevine (Naor *et al*., 1997) [48] and mango (Urban *et al*., 2003) [70]. A central feature of crop models is the estimation of tree photosynthesis that provides the energy and carbon skeletons for biological productivity. There are a variety of approaches, primarily borrowed from earlier crop modelling, such as modifications of the annual crop growth model, SUCROS'86 (Grossman and DeJong, 1994) [24-25]. The light interception problem has also been addressed by separation of the total leaf area into sunlit and shaded components (Lescourret *et al*., 1998) [39]. Lloyd *et al.* (1995) [43] showed that whole tree gas exchange rates of macadamia and lychee trees could be accurately simulated by treating the tree surface as a hemisphere and calculating gas exchange characteristics separately for sunlit and shaded portions of the tree. This model has also been adopted for citrus (Syvertsen and Lloyd, 1994; Bustan *et al*., 1999) [68, 8].

A model of water import to the fruit has been designed (Bussieres, 1994) [7]. At the whole plant scale, recent studies tend to improve models of water balance, including its partitioning between transpiring and non-transpiring organs. Van Ieperen (1996) [71] studied the relations between the salinity of the nutrient solution and the dry matter content of fruits. Genard and Souty (1996) [21] went a step further on peach fruits. They designed a compartment model that simulated the time-courses of various carbohydrate contents among which were sucrose, glucose, fructose and sorbitol during fruit development. PEACH (Grossman & DeJong, 1994) [24-25] was an early sink driven, carbohydrate partitioning model for simulating reproductive and vegetative growth of fruit trees. The central focus of building L-PEACH was to model how carbon partitioning occurs in a growing tree. Carbohydrate partitioning has been a central problem of process-based models of tree growth because of the coupling between carbon partitioning, growth and architecture (Le Roux *et al*., 2001) [21]. However, as pointed out by Le Roux *et al*. (2001) [21], the PEACH model almost entirely ignored the interaction between tree architecture and carbon allocation (other than giving trunk and root growth lower priority for carbon allocation than crown organs such as fruit, leaves, stems, and branches). In addition, each organ type was treated collectively as a single compartment, and thus all organs of the same type grew at the average rate for that organ. Because of these limitations, there was no potential to simulate differences in organ size or quality as a function of location in the canopy. It was also impossible to use this model structure to simulate the function of individual organs, and capture the influence of their performance on patterns of carbon partitioning. Many of these limitations were possible to overcome with the development of L-systems (Lindenmayer, 1968; Prusinkiewicz and Lindemayer, 1990) [56, 41] as implemented in the latest version (4.0) of L-studio (Karwowski and Prusinkiewicz, 2003; Prusinkiewicz, 2004) [33, 55].

Limitations

As George E.P. Box Systems Science Professor reportedly said "All models are wrong. Some models are useful". It is important to acknowledge the first statement for complex systems like fruit trees, but to strive for usefulness. Crop models are not able to give accurate projections because of inadequate understanding of natural processes and computer power limitation. As a result, the assessments of possible effects of climate changes, in particular, are based on estimations. Moreover, most models are not able to provide reliable projections of changes in climate variability on local scale, or in frequency of exceptional events such as storms and droughts (Shewmake, 2008) [66]. A particular limitation for fruit tree crop models is the limited and incomplete database of good quantitative data for modelling. The best data and knowledge bases generally are for (1) phenology, (2) leaf photosynthesis (light and temperature responses), (3) shoot growth and leaf area development, and (4) fruit growth and respiration. Some of the major gaps are (1) root growth patterns, respiration, root turnover rates and its implications, (2) respiration rates in general – available data is almost all short term measurements; responses to temperature done in short term, not long-term, (3) the seasonal demands for carbon of different organs, and (4) detailed understanding of fruit abscission processes. Model performance is limited to the quality of input data. Model must accommodate the variability of the data that feed it, otherwise noises will disturb the resulting output, independent of data quality (Wisiol, 1987) [77]. That happens, for instance when the models are not prepared for processes in which response is delayed in relation to the input signal, and when feedback occurs. It is common in cropping systems to have large volumes of data relating to the above-ground crop growth and development. Most stimulation models require that meteorological data be reliable and complete. Finally, sampling errors also contribute to inaccuracies in the observed data (Murthy, 2002) [47]. An ultimate crop model would be one that physically and physiologically defines all relations between variables the model reproduces and universally real world behavior. However, such a model cannot be developed because the biological system is too complex and many processes involved in the system are not fully understood (Jame and Cutforth, 1996) [32].

Future aspects

Globalization of markets has increased competitiveness, highlighting the need for products of high quality (Dimokas *et al*., 2009) [16]. Fruit breeders must satisfy two requests concurrently: the production of high quality fruits and the use of sustainable practices (Li *et al*., 2009; Quilot *et al*., 2005; Kropff and Struik, 2002) [40, 34, 57]. Recent advances in genetics and molecular plant biology can play a key role in crop modelling by improving crop responses to environmental conditions and management factors (Bannayan *et al*., 2007) [2].

Conclusion

For the two last decades, crop modelling has become one of the major research tools in horticulture. As a research tool, model development and application can contribute to identifying gaps in our knowledge, thus enabling more efficient and targeted research planning. Concerning fruit quality, this new generation is really needed to accompany the advances in fruit genomics (Baxter *et al*., 2005). The adoption of standard units, formation of inputs and outputs, selection of variables, the production of proper documentation, limitations and the use of procedures of software quality assurance would increase the portability of models and lower the risk of error or misuse. An intensely calibrated and evaluated model can be used to effectively conduct research that would in the end save time and money and significantly contribute to developing sustainable agriculture that meets the world's needs for food.

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