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To Yves Crozat

His understanding of agronomy, of the balance between experimentation and modelling, his scientific curiosity, his open-mindedness, his capacity for listening, his organizational skills and his extreme kindness…

we will miss greatly

Contributors to STICS formalisations

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Notations
The illustrations and equations are numbered by chapter. The variable names used in the equations are listed in annex 1. and the parameters are identifiable by indices: "T" for technical parameters, "S" for soil parameters, "C" for climate parameters, "P" for genotype-independent plant parameters, "V" for genotype-dependent plant parameters and "G" for general parameters. The index "I" is used for the initial status of the key variables. When used in the text those variables are written in capital letters. In the equations the variables (VAR) are referred to the current day, I, by writing them as VAR (I) while this reference is omitted in the text to lighten it. In a summation over time, the time daily variable is named J.

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Preface

What is a crop model? 'Snake oil' (Passioura 1996), i.e. an impossible (and moderately honest) challenge to fit the current scientific knowledge into a single framework? A mechanistic view of plant growth and development which represent causality between component processes and yield (Yin et al. 2004)? Robust empirical relations between plant behaviour and the main environmental variables (Passioura 1996)? A tool for analysing plant behaviour and its genetic variability which bypasses, but may help to increase the knowledge about underlying mechanisms (Tardieu 2003, Hammer 2006)? All these definitions are partly true, all are potentially misleading.

Considering the achievements of crop models is perhaps the best way to understand what they are. STICS and other crop models have profoundly changed the vision that the agronomic community had of the soil – plant – atmosphere system and of its interactions with cultivation techniques. It has also changed the way agronomists design experiments and test hypotheses. Important and legitimate questions such as "which is the best sowing density for a crop?", "is an early cultivar better than a late one?", "what is the best fertilisation strategy?" have been the subject of hundreds of experiments in the 60's and 70's. Nobody would now imagine answering them without a model because "try it and see" experiments may well be the worst method for answering them, due to experimental errors and to the variability of behaviour of each genotype in different environments. Although our current knowledge is often poor for detailed processes, the behaviour of soil-plant-atmosphere systems is surprisingly predictable in relation to what could be expected from the synthesis of all mechanisms involved in it (Tardieu 2003). STICS, like other crop models, can therefore help to answer the above questions for a wide range of conditions which could never be tested experimentally. The role of experiments has changed, and is now to check whether experimental results, obtained in a limited number of environmental conditions, are consistent with those of the model in a wide range of situations to verify the credibility of the model in the studied range of environments (Lyon et al. 2003, Corre Hellou et al. 2007). Lack of agreement between the model and the experiments may suggest ways for improving some aspects of the model.

Is this science or engineering (Passioura, 1996)? This lengthy debate has been largely fruitless. The same model can be used for good or unexciting science, for good or inappropriate engineering. The important point is that the user is able to be critical with the model, so that his/her judgement or decisions after using STICS will be the result of some personal input and understanding of the model. This is the objective, hopefully fulfilled, of this book.

Making it clear, that STICS is a tool for reasoning and not a magic wand for prediction, is one of the main aims of this book. The model is by no means an exact representation of all the processes involved in a virtual experiment. It is therefore essential that the user has access to its workings, i.e. its architecture, equations and parameters, and that the robustness of equations is discussed and compared with that of other models. The reader can find every single process used in the STICS model, with its equations and parameters, and with figures which explain the meaning of equations and their consequences on model outputs. This gives several possibilities to the user. Most skilled users can go into the detail of some processes, check the consistency of hypotheses with their own ideas, and interpret results according to this information ("I get this output with that hypothesis, would I get a different output with this other hypothesis? "). Less skilled users will use the book for understanding the reasoning which accompanies the equations of a particular module. For instance the observations of Figure 5.2 and 5.3 clearly suggest that the objective is not to compare the root systems of rape seed, corn and wheat, which vary widely between fields, but to investigate what happens if the characteristics of the root system change with the species or with the soil ("examples are given for 3 species. What would be the behaviour of my favourite species in my soil?").

STICS is based on simple processes, essentially the same as in other crop models, but with some appreciable differences in method. This book clearly presents the basis for computing the progression of phenological stages from temperature, the light interception by leaves following Monteith's equation, the transpiration following Penman Monteith's equation, and the water and nutrient uptakes following Gardner's pioneering work. To my knowledge, these fundamentals do not differ essentially from those of other models (Yin and Van Laar 2005, Keating et al. 2003) except that the equations used in STICS have been chosen in a more "physics-oriented" way than those of other models. In STICS, as in any other model, things become less straightforward for simulations of growth and of distribution of assimilates and responses to environmental stresses. The STICS group was successful in representing complex networks of interactions without generating scores of equations and parameters which can never be checked. Are the methods used in STICS better than those of other models? Another book could be written to compare the respective value of the algorithms used in different models. For most users, it is enough to know that methods and algorithms are coarse but useful representations of reality and that they can vary substantially between models, so it may be useful for some purposes to compare the output of STICS with those of other models.

An important side effect of the work of the STICS group has been to provide a common "meeting place" for scientists of several agronomic disciplines (plant science, soil science and cropping systems), for social scientists and for people working in extension services. This book should help to provide a bridge between scientific communities. It is a necessary tool for scientists who use the STICS model, for agronomists who are curious about the different topics which can be covered with crop models, and for modellers of different disciplines who wish to copy the methods of the STICS group. Will geneticists and molecular physiologists join the community of plant modellers? This is a major challenge for the years to come. Progress has been made (Hammer et al. 2006, Struik et al. 2007, Chenu et al. 2008), but these two groups seem reluctant to employ modelling methods (see e.g. Benfey and Mitchell-Olds 2008).

In conclusion, we have to be grateful to the authors, especially Nadine Brisson, for carrying out the huge and difficult task of explaining the detail of all that is involved in the STICS model.

François Tardieu

François Tardieu is a crop scientist and an ecophysiologist who works to fill the gap between agronomy and genetics. He was involved in projects in which crop modelling had an essential role. This, together with his role in scientific management in Inra (France) gives him a wide overview of the uses and concerns of crop modelling.

1 Introduction

1.1 Purpose

The aims of STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) are similar to those of a large number of existing models (Whisler *et al.*, 1986), while paying attention to cropping system diversity. It is a crop model with a daily time-step and input variables relating to climate, soil and the crop system. Its output variables relate to yield in terms of quantity and quality and to the environment in terms of drainage and nitrate leaching. The simulated object is the crop situation for which a physical medium and a crop management schedule can be determined. The main simulated processes are crop growth and development as well as the water and nitrogen balances. A full description of crop models with their fundamental concepts is available in Brisson *et al.* (2005).

STICS has been developed since 1996 at INRA (French National Institute for Agronomic Research) in collaboration with other research (CIRAD[1], CEMAGREF[2], École des Mines de Paris, ESA[3], LSCE[4]) or professional (ARVALIS[5], CETIOM[6], CTIFL[7], ITV[8], ITB[9], Agrotransferts[10], etc.) and teaching institutes. For more than 10 years STICS has been used and regularly improved thanks to a close link between development and application, involving scientists and technicians from various disciplines.

[1] Centre de coopération internationale en recherche agronomique pour le développement.
[2] Centre du machinisme agricole, du génie rural et des eaux et forêts.
[3] École supérieure d'agriculture d'Angers.
[4] Laboratoire des sciences du climat et de l'environnement.
[5] Arvalis, institut du végétal.
[6] Centre technique interprofessionnel des Oléagineux métropolitains.
[7] Centre technique interprofessionnel des fruits et légumes.
[8] Institut technique de la vigne.
[9] Institut technique de la betterave.
[10] Agrotransferts for the regions Poitou-Charentes and Picardie.

When STICS began to be developed, many well-known models were available (CERES: Ritchie and Otter, 1984; ARCWHEAT: Weir *et al.*, 1984; EPIC: Williams *et al.*, 1989; SUCROS: van Keulen and Seligman, 1987, etc.) that were developed from the pioneer works by de Wit (1978) or Duncan (1971 cited in Baker, 1980). However new models appear regularly in the literature (Amir and Sinclair, 1991a,b; Brisson *et al.*, 1992a; Hunt and Pararajasingham, 1995; Kanneganti and Fick, 1991; Maas, 1993; McMaster *et al.*, 1991; Teittinen *et al.*, 1994). As Sinclair and Seligman (1996) explained, this is because no one universal model can exist in the field of agricultural science and it is necessary to adapt system definitions, simulated processes and model formalisations to specific environments or to new problems (technical, genetic, environmental, etc.). These same authors emphasize the heuristic potential of modelling, a determining element in the development of STICS.

From a conceptual point of view, STICS is made up of a number of original parts compared with other crop models (e.g. simulation of crop temperature, simulation of many techniques) but most of the remaining parts are based on conventional formalisations or have been taken from existing models. Its strong points are the following:

– its “crop” generality: adaptability to various crops (wheat, maize, soybean, sorghum, flax, grassland, tomato, beetroot, sunflower, vineyard, pea, rapeseed, banana, sugarcane, carrot, lettuce, etc.)

– its robustness: ability to simulate various soil-climate conditions without too much error in the outputs (Brisson *et al.*, 2002a) and easy availability of its soil and technical inputs. Yet, this robusness can jeopardise accuracy on a local scale.

– its “conceptual” modularity: the possibility of adding new modules or complementing the system description (e.g.: ammonia volatilisation, symbiotic nitrogen fixation, plant mulch, stony soils, many organic residues, etc.). The purpose of such modularity is to facilitate subsequent development.

Around 50 scientists of various disciplines participated in the STICS formalisations, most of them from INRA (Institut National de la Recherche Agronomique). Thus the model can be regarded as a synthesis of the French agronomic knowledge on the field and crop cycle scales, which motivated this book. It presents the formalisations of the STICS model (version 6.2), which can be considered as references used in the framework of crop sciences, helping professionals and students in the partitioning and understanding of the complex agronomic system. The book arrangement relies on the way the model designs the crop-soil system functioning, each chapter being devoted to one important function such as growth initiation, yield onset, water uptake, transformation of organic matter etc. One chapter is devoted to the cropping system and long term simulations and the final chapter is about the involvement of the user in terms of option choices and parameterization.

1.2 Overall description of the system with its components

1.2.1 The system

STICS simulates the behaviour of the soil-crop system, in one dimension, over one crop cycle or several successive cycles. The upper boundary of the system is the atmosphere, characterised by standard weather variables (radiation, minimum and maximum temperatures, rainfall, reference evapotranspiration and possibly wind and humidity) and the lower boundary corresponds to the soil/sub-soil interface.

Crops are generally perceived in terms of their above-ground biomass and nitrogen content, leaf area index, and the number and biomass (and nitrogen content) of harvested organs. Vegetative organs (leaves, stems, branches or tillers, roots) are functionally separated in terms of radiation, water and nutrient sensors or reservoir role. Soil is described as a sequence of horizontal layers, each of which is characterised in terms of its water content and mineral and organic nitrogen contents. Soil and crop interact via the roots, and these roots are defined in terms of root density distribution in the soil profile.

STICS can also simulate intercropping, i.e. two crops (annual or perennial) growing simultaneously as a mixture, each crop developing and growing with its own rhythm resulting from the resource partitioning. In this case the soil-plant-atmosphere system is divided into three sub-systems at the canopy level. There is the dominant canopy and the understorey canopy that is divided into two parts: a shaded part and a sunlit part, each of them being defined by a light microclimate that drives the different behaviour of the sub-systems.

1.2.2 Simulated processes

Crop growth is driven by the plant carbon accumulation (de Wit, 1978): solar radiation intercepted by the foliage and then transformed into aboveground biomass that is directed to the harvested organs during the final phase of the crop cycle. The crop nitrogen content depends on the carbon accumulation and on the nitrogen availability in the soil. According to the plant type, crop development is driven either by a thermal index (degree-days), a photothermal index or a photothermal index taking into account vernalisation. The development module is used to make the leaf area index and the roots evolve and define the harvested organ filling phase. Water stress and nitrogen stress, if any, reduce leaf growth and biomass accumulation. This reduction is based on stress indices that are calculated in water and nitrogen balance modules. Other stresses such as waterlogging and thermal stresses (frost or high temperatures) are also taken into account.

Particular emphasis is placed on the effect of crop management on the dynamics of the soil-crop-microclimate system, knowing that crop peculiarities influence both ecophysiology and crop management (e.g. accounting for the various forms of forage cutting, fertiliser composition, plastic or crop residue mulching, etc.).

1.2.3 Modules and options

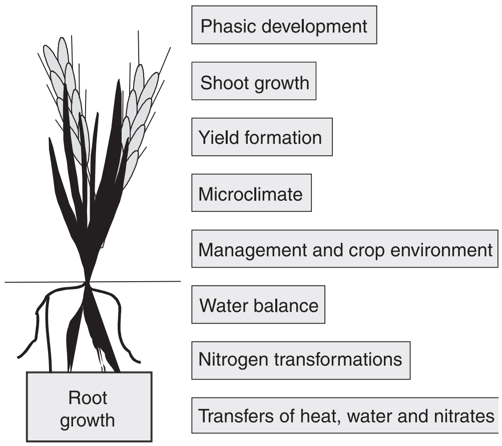

Figure 1.1. The main modules of the STICS crop model.

The STICS model is organised into modules (*Figure 1.1*), with each module composed of sub-modules dealing with specific mechanisms. A first set of three modules deals with the ecophysiology of above-ground plant parts (phenology, shoot growth, yield formation). A second set of four modules deals with how the soil responds in interaction with underground plant parts (root growth, water balance, nitrogen balance, soil transfers). The crop management module deals with the interactions between the applied techniques and the soil-crop system. The microclimate module simulates the combined effects of climate and water balance on the temperature and air humidity within the canopy.

Within each module, there are options that can be used to extend the scope with which STICS can be applied to various crop systems. These options relate to ecophysiology and to crop management, for example:
– competition for assimilate between vegetative organs and reserve organs (hereafter referred to as trophic competition);
– considering the geometry of the canopy when simulating radiation interception;
– the description of the root density profile;
– using a resistive approach to estimate the evaporative demand by plants;
– the mowing of forage crops;
– plant or plastic mulching under vegetation.

Certain options depend on data availability. For example, the use of a resistive model is based on availability of additional climatic driving variables: wind and air humidity.