STICS SOIL-CROP MODEL

Conceptual framework, equations and uses

N. Beaudoin, P. Lecharpentier, D. Ripoche-Wachter, L. Strullu, B. Mary, J. Léonard, M. Launay, É. Justes, editors

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Foreword

Peter Thorburn

Cropping systems are complicated non-linear biophysical systems, made complex by drivers that can't currently be predicted, namely climate and management actions executed in response to numerous socio-economic-political drivers. How do we, agricultural scientists, make sense of these systems and help land managers meet their goals and the goals of the societies in which they live? Models are tools used by agricultural scientists to make sense of these systems for over 100 years. This 2nd edition of the "STICS red book" represents an important milestone in the evolution of cropping systems models over that period.

Models have evolved from simple equations of plant growth in the early- and mid-1900's to today's sophisticated cropping systems models (Keating and Thorburn, 2018). An important part of this evolution was the "leap" from crop models, which coupled models of growth of a single crop to models of soil processes, to "cropping system" models in the 1990's. Cropping systems models allowed realistic representation of crop rotations and so reflected more closely the way farmers viewed and managed their fields. As these models developed descriptions of them were published: A landmark was papers by the major modelling groups around the world in 2003 Special Issue of the *European Journal of Agronomy* (Volume 18, Issues 3–4) followed by updates in a Thematic Issue of *Environmental Modelling and Software* in 2014 (Volume 62). Overviews of STICS were included in both (Bergez *et al.*, 2014; Brisson *et al.*, 2003). However, journal papers come with length restrictions and the "overviews" of complicated tools like cropping systems models in those papers are inadequate resources for new and experienced users alike. To me, the 1st edition of the "STICS red book" represented the commitment of the STICS team to support those users and expose the detail of the concepts, structures and approaches in the model to their modelling peers.

The 2nd edition of the "STICS red book" shows how comprehensive the STICS cropping systems model has become. Long gone are the days (for STICS and other models) when simulating a "crop-fallow-crop" rotation was challenging and novel. This is now one of the first tasks given to students learning cropping systems modelling. Developments since the 1st edition of the "STICS red book" include the capability to address contemporary issues such as climate change impacts and adaptation, greenhouse gas (GHG) emissions and abatement, organic agriculture, spatial application, and coupling with other models (e.g. of hydrology, pest and diseases, etc.).

Some of these applications have indirect or direct links with government policy. Modelling in this context raises new challenges for model development and application coming from the increased scrutiny to which the results will be subjected (Moore *et al.*, 2014). In agriculture, models started as tools of scientific enquiry. For example, CT de Wit's interest in modelling was sparked by the desire to know the potential yield of a crop (Keating and Thorburn, 2018). The scrutiny of such modelling was likely limited to scientific peers who likely understood and accepted the strengths and weaknesses of modelling [although the was not always the case; e.g. Passioura (1996)]. As models developed and modellers started using them to inform farmers how to improve their management, scrutiny expanded to include farmer stakeholders as well as scientific peers. However, in many farmer interactions the model (or simulation output) acted as a "boundary object" facilitating discussions between the modeller and farmer (Jakku and Thorburn, 2010). The modeller explaining to the farmer the simulation results and their meaning built trust in the farmer of the modeller (provided the explanations made sense to the farmer!). This was/is essentially a social process and the technicalities of the model application itself were not necessarily scrutinised – if the farmer trusted the modeller, she trusted the model. Further, the farmer was free to change farm management, or not, as a result of these interactions, and solely bore the consequences of any changes (whether positive or negative).

In public policy applications, the link between the modeller and (government) stakeholder is likely to be much less personal than between modellers and farmers or scientific peers. Further, the application of the policy will often create "winners" and "losers". It is natural for the "losers" to want to scrutinise the technical basis behind the policy impacting them. A recent example of this is the examination of modelling behind water quality policy for agricultural lands in New Zealand (Johnson *et al.*, 2021). The "losers", and other stakeholders, will likely ask questions about the quality of the science in the model, whether that is accurately implemented in the code (and for the specific version of the model used in the analysis) and whether the model was competently run. Publication in the peer reviewed literature is often the means of assuring the quality of the science. As a community, however, cropping systems modellers have less established methods of quality assurance for implementation and running models than some other communities. For example, just for calibration of phenology, an important but limited part of running a crop model, there is a huge diversity of approaches used by different modellers (Seidel *et al.*, 2018) and there will be benefits from having some consistency in the approach (Wallach *et al.*, 2021). Conversely, ensuring accurate implementation of science in model code, i.e. having good software development practices, has received less attention across cropping systems models (Holzworth *et al.*, 2015). It is therefore significant that this issue has been discussed in the 2nd edition of the "STICS red book".

What does the future hold for cropping systems models? That question has been addressed in a number of recent papers (Jones *et al.*, 2017; Keating and Thorburn, 2018; Silva and Giller, 2020) and their conclusions do not need repeating here. However, those authors agree that application of cropping systems models will be an important methodology in meeting the coming challenges faced by food and agricultural systems and the models will need to be further improved and developed. That development will necessitate increasing efforts in collecting data to underpin those developments.

Data availability has always been both a limitation and driver of model development: in many respects cropping systems models have been created to overcome the scarcity of data. As we enter the age of "big data", data will increasingly be available from remote and proximal sensors. That raises the questions of how those data will aid model development and/or application, and how will they affect the relevance of cropping systems modelling? An example of the first question is the potential use of multi-year high resolution data on crop growth and development to inversely parameterise models, e.g. soil water (He and Wang, 2019) or phenology (Araya *et al.*, 2016) parameters, aiding subsequent application. The implications of the second question are less clear. With rich data, possibly less biophysical detail is needed in a model if it is designed for use in conjunction with those data (e.g. Donohue *et al.*, 2018). Even further, there may be no role for a biophysical model at all. However, this "struggle" between models and data for prediction and understanding is not new. An example is the prediction of the optimum rates of nitrogen fertiliser in the mid-west corn-belt of USA. Large datasets have been gathered and developed into a tool for forecasting the Maximum Return to Nitrogen (Sawyer *et al.*, 2006; http://cnrc.agron.iastate.edu). However, recently developed approaches based on cropping systems modelling are showing promise in increasing accuracy of those forecasts (Puntel *et al.*, 2018). And, unlike purely data-driven approaches, the cause of a result from a cropping systems model can be tracked down and understood, enlightening the modeller and their stakeholders. Thus, it is unlikely there will be a single "winner" in the "struggle" between models and data for prediction. What is clear however, is that modelling systems (structure and software) will need to evolve to be easily applied with these new sources of data. The STICS model is well advanced down that development road and thus will remain relevant for a long time. I forecast there will be a 3rd edition of the "STICS Red Book" in the future!

Dedication

This book is dedicated to Nadine Brisson… Nadine Brisson was an ever-enthusiastic captain of the STICS ship and kept her sights set far ahead. With her intelligence, energy, insightfulness, determination and presence, she was always able to bring people on board with her who would remain ever faithful. Her vessel covered great distances, towards the shores of all the continents, sometimes facing storms along the way but continuing cheerfully and steadfastly onwards, committed to fulfilling her pledge: to give the scientific community a tool to help tackle food security, climate change, agroecological transition and other major challenges. She would have been so pleased with this new edition, which is available at zero cost (free numeric version), in keeping with the values of Open Science that she promoted before the movement had even emerged. Her life ended much too soon, but it was full of professional and personal adventures. She became fast friends with nearly everyone she met, and this is how we will forever remember her.

To Nadine

Au rendez-vous des bons copains
Y avait pas souvent de lapins
Quand l'un d'entre eux manquait a bord
C'est qu'il était mort
Oui, mais jamais, au grand jamais
Son trou dans l'eau n'se refermait
Cent ans après, coquin de sort
Il manquait encore

When to a rendezvous they'd go
Not often was there a no-show
If one of them was not on board,
it means he was no more
But never could their friendship dim
as the deep seas closed ever him
A hundred years after the peal,
they mourn him still

Source: LyricFind

Parolier : Georges Brassens (1964)

Preface

Nicolas Beaudoin, Patrice Lecharpentier and Dominique Ripoche-Wachter

⏩ The first book

In 2009, the initial project team produced the book *Conceptual Basis, Formalisations and Parameterization of the STICS Crop Model* (Brisson *et al.*, 2009), often referred as the 'STICS Red Book', published by Editions Quae.

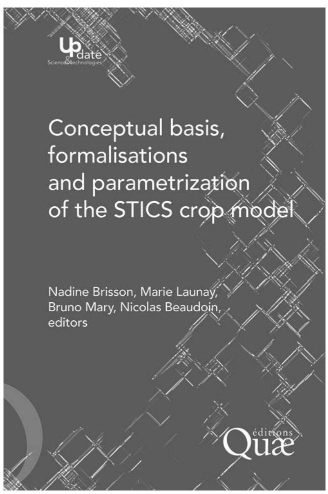

Figure 0.1. Cover of the first edition of the book.

The first edition of this book was written primarily by Nadine Brisson and was quite original in that synthesised scientific knowledge about cropping systems. The book covered the STICS model formalisms in an exhaustive way. But, more than ten years on, it was in need of a comprehensive update following the profound changes to the capabilities of the STICS model.

The following authors contributed to the original formalisations according to their affiliations:
– INRA (now INRAE): R. Antonioletti, N. Beaudoin, P. Bertuzzi, T. Boulard, N. Brisson, S. Buis, P. Burger, F. Bussière, Y.M. Cabidoche, P. Cellier, P. Debaeke,

F. Devienne-Barret, C. Durr, M. Duru, B. Gabrielle, I. García de Cortázar Atauri, C. Gary, F. Gastal, J.P. Gaudillère, S. Génermont, M. Guérif, G. Helloux, C. Hénault, B. Itier, M.H. Jeuffroy, E. Justes, M. Launay, S. Lebonvallet, G. Lemaire, B. Mary, T. Morvan, B. Nicolardot, B. Nicoullaud, H. Ozier-Lafontaine, L. Pagès, S. Recous, G. Richard, R. Roche, J. Roger-Estrade, F. Ruget, C. Salon, B. Seguin, J. Sierra, H. Sinoquet, R. Tournebize, C. Valancogne, A.S. Voisin
– ESA-Angers: Y. Crozat
– ARVALIS Institut du végétal: P. Gate
– CEMAGREF (now INRAE): B. Rebière, J. Tournebize, D. Zimmer
– CIRAD: F. Maraux

⏩ A new book based on an innovative approach

In 2019, ten years after the first book was published, the STICS project team decided to update it by integrating all the STICS skill extensions which have since been developed, evaluated and published. Several key changes deal with:
– the roles of carbon and nitrogen reserves in perennial crops,
– the biological destruction of mulch from crop residues,
– soil N_2O emissions,
– forage harvest management.

All of the STICS project team members worked together in a dynamic collaborative way to produce this new book.

Their work was supported by an innovative editorial approach, thanks to the involvement of Patrice Lecharpentier, who oversaw the feasibility study for the project, the design and finally the implementation of the writing workflow.

Another base part of the work is the bibliographic database management (under Zotero[1]) the workflow is depending on. The STICS database organisation and maintenance was possible thanks to the support of Christine Le Bas.

This dynamic workflow aims to maintain a close link between changes in model formalisms (including associated data) and the book content with regular updates (Figure 0.2).

The collaborative dimension is crucial and based on the experience of the project team. The use of reproducible science tools is of the utmost importance.

The project, named 'Open-STICS', was selected for the 2019 French National Fund for Open Science (FNSO) call for projects, which is aimed at supporting such kind of open science editorial projects.

The main objectives were to offer the STICS user community a written, open access resource in English, with content that can be updated regularly according to the standard versions of the model.

Specific tools were chosen to produce the book in order to easily incorporate updates, including making corrections, adding new formalisms, modifying settings, extending application domains and adding new plants species.

1. https://www.zotero.org/

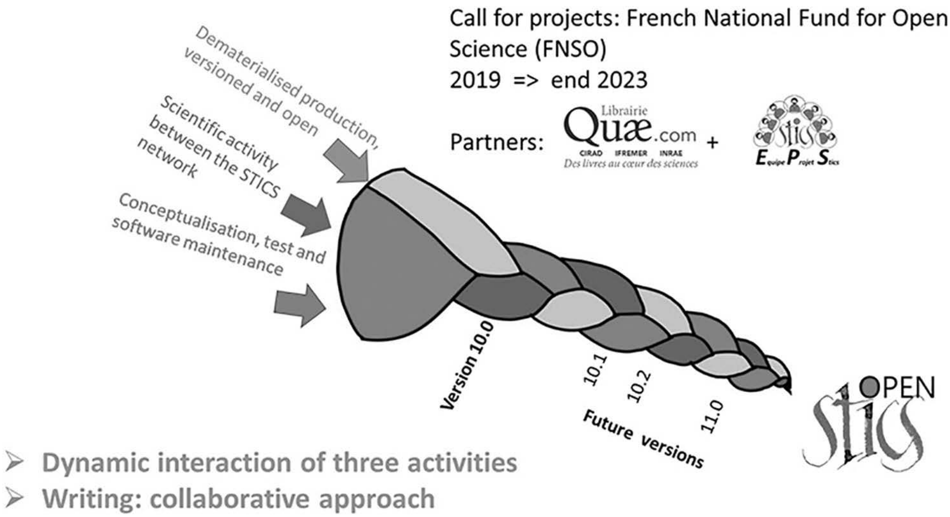

Figure 0.2. The workflow for the new book showing the dynamic interaction between the three activities of the STICS project team

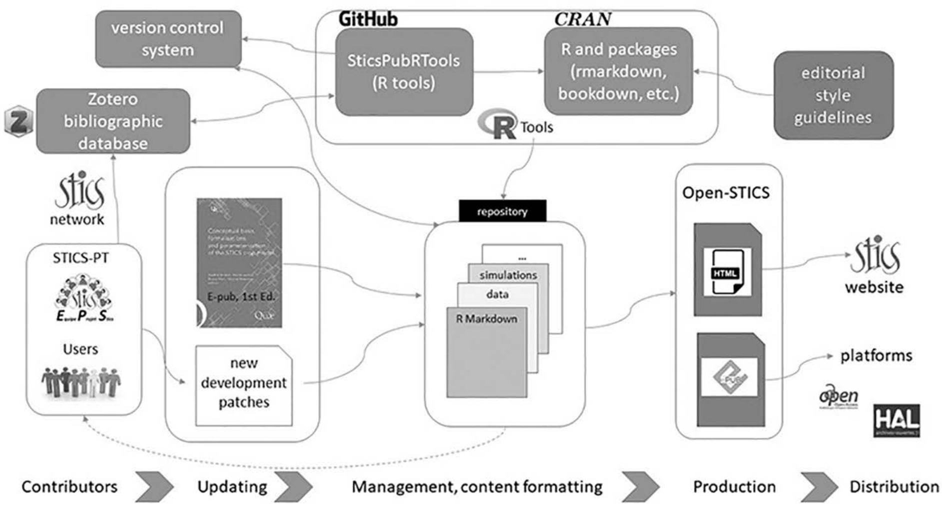

Figure 0.3. The technical workflow of the new book.

The book was produced using essentially R language (R Core Team, 2020) and a specific format for reproducible document writing, R Markdown (https://rmarkdown.rstudio.com/, Allaire *et al.*, 2021). The chosen configuration was based on the 'bookdown' package, which is designed for book or other document content formatting (https://bookdown.org/yihui/bookdown, ; Xie, 2016, 2021).

These packages are distributed under the GPLv3 licence and allow users to generate different output formats such as HTML, PDF, DOC, EPUB (Figure 0.3). The R Markdown format makes it easy to integrate lines of R code, for example, in order to generate illustrations (tables, graphs, etc.). Mathematical equations and literature references can be automatically formatted using specific syntaxes.

For a subset of these types of insertions and formatting, operations need additional R functions which have been developed separately from the packages used for this book (for equation implementation and plots), as well as data from simulations or observations, or which have been formatted in a specific way.

The book production is managed as a development project in the form of an RStudio project (RStudio Team, 2021, https://www.rstudio.com/). All necessary files (code, text and data) are managed using a version control system (Subversion, https://subversion.apache.org/) shared among all contributors (essentially STICS team members at the moment). This means that every author is able to maintain the content of the book project: they can save changes, get changes made by other authors, and finally produce the book or parts of it in different file formats. This package permits dynamic interaction between STICS book editions, scientific design activities and software maintenance (Figure 0.2).

⏩ Project funding

This project was funded with the support of:

- **the French National Fund for Open Science (FNSO)**,

- **CIRAD**, and

- **the Agroecosystems Division of INRAE**.

⏩ English revision

Teri Jones-Villeneuve (teri@jonesvilleneuve.com)

Throughout the revision process for the book, Teri offered helpful feedback by pointing out areas where additional clarity was needed and suggesting improvements. The entire STICS project team thanks her for her professionalism and are very grateful for this contribution to the book.

Chapter 1

Introduction

Dominique Ripoche-Wachter, Nicolas Beaudoin and Eric Justes

Reviewed by: Guillaume Jego and Patrice Lecharpentier

This introduction will outline the purpose and brief history of the STICS model, along with the general concepts. We will also discuss the collective dynamics of its development, evaluation and governance. Finally, we will introduce the different chapters of this book which describes the algorithms in the model. A list of user network services can be found at the end.

Some sections of this chapter come from the translation of the book chapter « Modélisation du fonctionnement des agro-écosystèmes: l'épopée STICS (Beaudoin *et al.* 2019), with the permission of QUAE Edition ».

⏩ 1.1 History

The model design started with a first meeting held in France in 1996, where the foundations of the key model principles were laid out. The aim was to create "a single model for different crops that integrated both specialist and generalist knowledge in order to be general, robust, simple, operational and flexible." (Beaudoin *et al.*, 2019)

The specifications of STICS were co-developed by researchers and engineers from various disciplines in the fields of agronomy (*sensu lato*) and modelling, who recommended four main characteristics:
– A balance between the different compartments and interacting processes in the soil-plant-atmosphere system, in order to produce a generic soil-crop model, applicable to a wide variety of themes and contexts.
– Genericity of the plant functioning description, based on general ecophysiological concepts, guiding to the definition of a single model. The same basis applies to the simulation of soil functioning processes.
– Simple and uncomplicated input data, with easily accessible parameters that are not very sensitive to change of scale, which facilitates the model's operational use in real agricultural situations.
– Robustness of formalisms and their parameterisation, which ensures realism in a wide range of agro-environmental conditions, and including management practices.

An additional characteristic scalability has emerged over time. The original strategy was to work together to design a dynamic, functional, one-dimensional model, with a strong agro-environmental aim. This soil-crop model can perform simulations either at a plot scale (the model's aim) or at a macro-regional scale, but only in conjunction with other models or tools (e.g. software platforms).

STICS was developed at INRAE (formed following the merger of INRA and IRSTEA) in collaboration with other research and educational institutes such as the French agricultural research and cooperation organization CIRAD, the Graduate School-Ecole des Mines de Paris and the Laboratory for Sciences of Climate and Environment – LSCE, along with French professional institutes (ARVALIS, Terres Inovia, CTIFL, ITV, ITB, Agrotransfert), and few other partners.

The STICS model is open source (Licence CeCiILL C, v2.1, the French equivalent of a lesser general public license, or LGPL). Its code has been filed with the Agency for the Protection of Programs (APP), the European organisation for the protection of authors and publishers of digital creations, under the reference number: IDDN.FR.001.360007.000.S.C.2021.000.10000.

In the early STICS development stages, many well-known models were available (CERES: Ritchie and Otter (1985), ARCWHEAT: Weir *et al.* (1984), EPIC: Williams *et al.* (1989), SUCROS: van Keulen and Seligman (1987), among others) that were

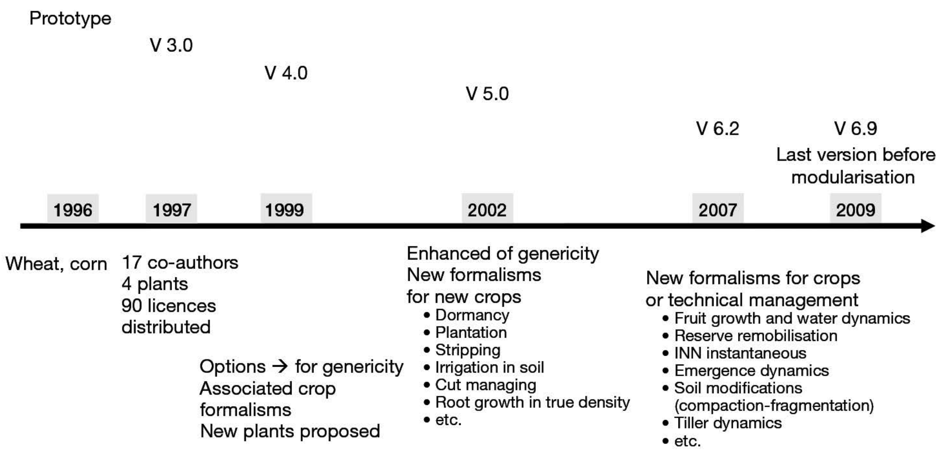

Figure 1.1. STICS versions before modularisation.

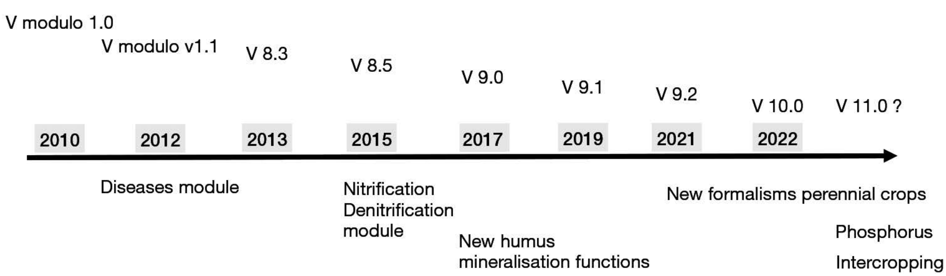

Figure 1.2. STICS versions since modularisation.