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XXV CYCLE

PhD TESIS

Assessment of the cropping and farming system sustainability through simulation

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Contents

1 Introduction

1.1 Sustainability assessment

Sustainability is not easy to be assessed. In the Sixth Framework Programme (FP6) of the European Commission, lots of efforts were given to identify methods for assessing sustainability, to challenge climate change and reduce the EU's dependence on fossil fuels for its energy needs. During this program, about 55 million euros were designed to develop methods and instruments to measure sustainability (Sieber *et al.*, 2010; Bonari and Silvestri, 2012). The difficulties to evaluate sustainability have its base in the troubles to define sustainability, sustainable development, and related concepts (Costanza and Patten, 1995). The World Commission on Environment and Development (1987) defines sustainability as: “to meet the needs of the present without compromising the ability of future generations to meet their own needs”. This definition is clear and is based on long-term wellbeing and it related to the maintenance of the natural world and its natural resources. The U.S. National Research Council (1999) argued that there are important components of sustainable development: i) what is to be sustained, ii) what is to be developed and iii) the intergenerational component. Later Kasemir *et al*. (2003) describe the complex dynamic interactions between environmental, social and economic issues.

The sustainability assessment (SA) has been always associated with tools of impact assessment e.g. the environmental impact assessment and strategic environmental assessment (Ness *et al*. 2007). The definition of SA can be recognized with a tool that aims to help decision-makers to identify the actions to be taken or not in an attempt to make the society more sustainable (Devuyst *et al*. 2001). SA is also an important and necessary tool to support in the transition into sustainability farming production (Van Passel and Meulb, 2012).

Sustainable farming system is at the base of the agriculture policy of the European Union (Common Agricultural Policy - CAP), in fact, the CAP has been increasingly adapted for integrating environmental concerns and to serve best the sustainability purposes. This adjustment is based on a distinction between ensuring a sustainable way of farming (by avoiding environmentally damaging from agricultural activity) and providing incentives for environmentally beneficial public goods and services. For ensuring sustainable agricultural activities, farmers must respect rules and standards for preserving the environment and the landscape. (Silva and Marta-Costa, 2012). To provide a better environment, farmers have to voluntarily or compulsorily respect legislation, with appropriate incentives or with the who-pollute-pays principle (EU 2011).

Very different sustainability evaluation tools already exist such as monetary tools, biophysical models and sustainability indicators. Examples of monetary tools are i) Cost Benefit Analysis (e.g. Costanza *et al*., 1997), ii) Index of Sustainable Economic Welfare (Daly and Cobb, 1989) iii) Genuine Savings (Pearce and Atkinson, 1993). Examples of biophysical models are Emergy (Odum, 1996), Exergy (Bastianoni *et al*., 2005; Hoang and Rao, 2010) and the Ecological Footprint (Wackernagel and Rees, 1997). Examples of sustainability indicator has been set by the UN (United Nations, 2001), OECD (OECD, 2006) and the EU (European Commission, 2005). Furthermore, combinations of physical indicators with monetary evaluation can also be identified (Neumayer, 2003). An example of such hybrid approach is the sustainability gaps approach (Ekins and Simon, 1999). Interesting reviews of approaches for assessing the progress towards sustainability can be found in Neumayer (2003) and Gasparatos *et al*. (2008).

1.2 Method for measuring sustainability

There are different approaches for SA, which can be categorised depending on their factors or dimensions (Baumann and Cowell, 1999; Moberg, 1999; Wrisberg *et al*., 2002). Ness *et al*. (2007) suggest considering the following factors:

- <u>temporal characteristics</u>, this tool evaluates past development (*ex-post*), or it can be used for predicting future outcomes (*ex-ante*) such as a policy change or an improvement in a production process.
- <u>the focus</u>, if the aim of the evaluation is at product level or on a proposed change in policy.
- <u>integration of nature–society systems,</u> in what degree the tool fuses environmental, social and/or economic aspects.

Figure 1.1 shows some SA tools based on the sustainability assessment inventory from Ness *et al.* (2007). It consists of three suggested categorisation areas; i) indicators and indices, ii) product-related assessment tools, iii) integrated assessment. The explained tools are arranged on a time continuum based or if they look back in time (retrospective) or if they are forward looking (prospective, forecasting) tools.

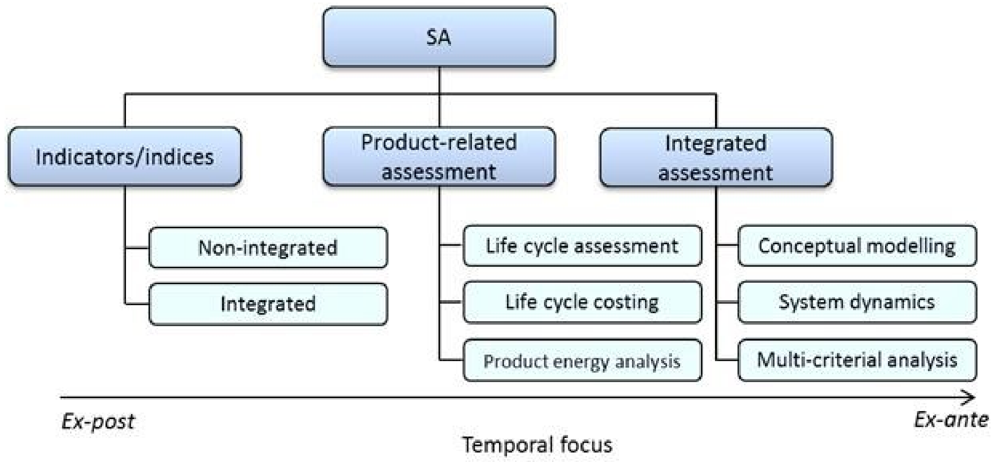

Figure 1.1 Scheme of sustainability assessment (SA) tools based on the inventory scheme from Ness *et al.* (2007)

1.2.1 Indicators

Indicators are simple, qualitative (but often expressed with numbers) instruments that represent a state of sustainability (economic, social and/or environmental). Usually indicators are defined for territorial level (district, region and nation - Ness *et al*. 2006). Indicators should be simple, with a wide aim, quantifiable, allowing trends to be determined, sensitive to change, and allow timely identification of trends (Harger and Meyer, 1996).

Indicators can be aggregated in different ways into indexes and they can be integrated or not. Some examples of non-integrated indicators are: the Environmental Pressure Indicators (EPIs) developed by Statistical Office of the European Communities Eurostat. The EPI consists of 60 indicators, six in each of the ten policy fields under the Fifth Environmental Action Programme (Lammers and Gilbert, 1999). Another example is the set of 58 national indicators used by the United Nations Commission on Sustainable Development (UNCSD).

More interesting are the integrated indicators (and indices), for which lot of effort has been made to move beyond the non-integrated and combine different nature–society dimensions in one indicator or index (Ness *et al.*, 2007). Well-known examples of integrated indicator are: i) the Ecological Footprint (Wackernagel and Rees, 1997) is an accounting tool that estimates the resource consumption and waste assimilation requirements of a given population or economy in terms of a corresponding land area;the Ecological Footprint has been applied to numerous countries and regions; and ii) the Environmental Sustainability Index (ESI) developed to measure "overall progress toward environmental sustainability" (Centre for International Earth Science Information Network, 2002); it consists of 68 indicators of five different categories: the state of environmental systems (air, water, soil, ecosystems, etc.), reducing stresses on environmental systems, reducing human vulnerability to environmental change, social and institutional capacity to cope with environmental challenges and the ability to comply with international standards and agreements (Centre for International Earth Science Information Network, 2002). Even if indicators are largely used and easy to understand, they give only a synthetic description of the system and do not explain the system, therefore it is not possible to identify critical points for optimization of the studied system (Confalonieri, 2012).

1.2.2 Product-related assessment

Product-related assessment tools are focused on flows in connection with production and consumption of goods and services and allow both retrospective and prospective assessments, which support decision-making. A good example and wide used or agricultural process (Brentrup *et al*. 2001) analysis is the Life cycle assessment (LCA) method. The LCA is the most established and well-developed tool of product related assessment; it has been used in varying forms in the last years to evaluate the environmental impact of a product or a service throughout its life cycle. It is an approach that analyses real and potential pressure that a product has on the environment during raw material acquisition, production process, use, and disposal of the product. The International Standards Organisation (ISO) has established guidelines and principles for LCA (Ness *et al.*, 2007). For this reason LCA has been used in agricultural research and thousands of papers have been written about the use of LCA in considering farm production (crops, milk, meat, biomass, energy, etc.) as the base for LCA analysis. Even if LCA is very used and the procedure is defined and recognised, it is important to remark that LCA does not directly consider some important factors of the farming system such as climatic variability, also in condition of climate change and biological interactions typical of the cropping systems.

1.2.3 Modelling and simulation

Modelling is often referred to a conceptual and simplified representation of reality (van Driel and Verloop, 1999.) and it often makes use of stock and flow diagrams, flow charts, causal loop diagrams, specific languages or programming. Conceptual modelling can be used for visualising and detecting where changes in a given system can be made for increasing sustainability or as the initial conceptualisation mechanism in a larger computer modelling approach (Ness *et al*., 2007). Modelling is a dynamic and simplified representation of reality, based on the description of variation’s causes rather than the description of phenomena themselves. It is able to make predictions on the evolution time of the system through numerical solutions of the model, called "simulation." The main obstacles to the practical use of simulation models are the difficulty of obtaining reliable estimates for the parameters and the large amount of detailed information required as input. Examples of models related to sustainability assessment include IIASA's air pollution model (RAINS), the IMAGE model created to analyse social, biosphere, and climate system dynamics, and the Wonderland model designed to illustrate economic–environmental interactions (Ness *et al*., 2007). Moreover other simulation models for the agricultural system sustainability have been developed (Thornton and Herrero, 2001; Zhang *et al*., 2002; Parsons *et al*., 2011; Sujithkumar *et al*., 2012). The strength of simulation models in the assessment of the sustainability of the agricultural system is the capability of considering most of the complexity that characterize the biological process, i.e. climatic variability, interaction of environmental factors with strategic decisions etc. Moreover, it allows also to assess scenario analysis of short- and long- term periods (i.e. economic, political or climatic change scenario, etc.). Sensitivity analysis and optimization of parameters can also be performed.

1.3 Farming systems and agro-energy production chains

The research was carried out within the framework of the research project: “Agroenergy production chains in *Friuli Venezia Giulia*: assessment of the economic, energetic and environmental sustainability at farm and territorial level". This project was aimed to find solutions related to the sustainable use of biomass, vegetable oils and biogas, useful to the partial or total energy self-sufficiency of farms in the region *Friuli Venezia Giulia* (North-East Italy).

The energy self-sufficiency can improve the farm competitiveness by reducing costs and facilitating the commercialization of farm products; this production model is called short chain, in which the farm (either individually or subsidiary) provides the raw material directly to the energy conversion, which ensures a return on the basis of supply agreements established between the parties. The advantage of this structure resides in the reduction of the steps chain and, therefore, the removal of the economic benefits to downstream, towards the farm. Moreover, it was considered important to have analytical tools for the rapid evaluation, planning, adaptation and optimization of the cropping systems and to choose the better farm management, oriented to the energy production in a sustainable way. In this sense, it was fundamental, in addition to the recovery and utilization of previously obtained regional, national and abroad research results, i) the implementation of crop and farm simulation models (Hammer *et al*., 2002) integrated with a LCA (Life Cycle Assessment; Brentrup *et al*., 2004) analysis and, ii) the development of a farm management model that can take into account the interactions in the bioenergy farming system, in relation to external factors and related to agronomic, weather/climate, environmental and economic constraints. All together, databases, crop and farm simulation models, LCA and farm management model have been the basis for the construction of a decisions support system (DSS), aimed to be used to optimize strategic decisions of bioenergy farm. It was also consider important to overcome the usual approach based on standard coefficients and tables, to identify a new methodology effective to deal with biological, climatic and operational variability. The approach of the dynamic simulation model representation is therefore particularly suited to properly address this issue.

As already mentioned, economic, environmental and energy sustainability assessment of the farm, that moves towards the energy production, is a critical parameter and it is important to understand the real potential applications of farm production.

The project was aimed to develop computer simulation models to quantify and compare the costs and benefits of alternative technologies and farm strategies and to analyse the organizational and technical feasibility, considering the economic, energetic and environmental sustainability of the farm. These models can analyse the trend of the farm behaviour through simulations, taking into account the possible economic scenarios (prices, public support, etc.), technological scenarios (variety, cultivation, processing techniques, power plants, etc.) and environmental scenarios (soil, climate, etc.). They can be used to improve planning decisions and can allow to develop farm configurations in alternative of those in progress, defined *a priori* on the base of the assumed changes in the market (changes in the international prices of agricultural commodities or oil), the European and Italian policies, such as the national definition of framework agreements, public incentives to bioenergy, biofuels tax exemption, variation of European common agricultural policy, technological innovation (improvement of efficiency of energy processes) and agronomy (improving the yield of crops).

1.4 Objectives and organisation of the research

The research has been developed in the above described background and was aimed in the development and implementation of tools able to assess the cropping and farming sustainability, considering the variability typical of the agronomic systems (climatic, economic, political, etc). These DSS tools will be useful for the planning and the optimization of the production process. In detail, the research was focused, at first instance, in the identification of the best method and instruments for the implementation of the sustainable assessment tool. The idea was to integrate LCA with biophysical modelling; in this way, it is possible to correctly consider the environmental, energetic and economic factors with crop production, bearing in mind also the climate variability. It was important to identify also the correct scale of model representation (crop, farm and territory).

For the implementation of the models it was necessary to identify a modelling language and framework able to treat dynamic biophysical models with a high level of complexity; it needs to consider simultaneously state based model (e.g. for crop and soil simulation), individual based models (e.g. for the cattle and fields simulation), deterministic and stochastic models (e.g. for climatic variability representation). Moreover, the possibility of dealing with event based models was fundamental for the implementation of the farm management and simulation of economic strategies. Furthermore, the simulation framework had to provide easy method for multiple simulation and automatic calibration.

The framework chosen has been SEMoLa (Simple, Easy to use, Modelling Language – Danuso, 2003) a simulation language and modelling environment developed at the Department of Agricultural and Environmental Sciences of the University of Udine. This software allows creating computer models for dynamic systems and managing different types of agro-environmental information. Moreover, the high level of complexity in managing and achieving the goals of the research, a continued development of conceptual instruments and algorithms has been necessary. In fact, it was developed new tools of SEMoLa. The developed version of this software (6.5.0) is described in Chapter 2, as an abstract of two papers already submitted for publication: *SEMoLa: a simple and easy to use modelling language* (Danuso and Rocca, submitted) and *The SEMoLa framework: a tool to manage complex system knowledge* (Danuso *et al.*, summited). Also in chapter 2 a rewee of the most important model evalution index has been explored, this because model evaluation is an essential step in the modelling process, infact allow to verify if the model reproducing the actual system.

After selecting the tools for modelling representation, the research was focused on identifying the best way to treat climate variability. Climate is one of the main factors which affect farm activities and all the ecological processes in the cropping system. The study of the climate statistical properties allows the development of climatic stochastic models (weather generators) for the generation of synthetic weather data (Birt *et al.*, 2010). For treat this type of variability, a new version of the Climak weather generator (Rocca *et al.*, 2012) has been developed; based on, the previous version developed in the early '90s (Danuso and Della Mea, 1994), that has provided significant results. In Chapter 3, a summary of the paper *Implementation and validation of Climak 3 weather generator* (Rocca *et al.*, 2012) is presented. In this research activity the implementation of the stochastic simulation model for the weather generation was develop, the model that has been later calibrated and validated.

For the crop simulation, CSS (Cropping System Simulator; Danuso *et al.*, 1999) has been used. This model considers the different components of the cropping system with an high level of detail; the biomass accumulation, crop yield and leaf area dynamics are based on SUCROS (van Laar *et al.*, 1997), a model based also on CO_2 fixation, crucial characteristic to obtain the whole crop carbon balance. CSS has a modular structure, which allows an easy development of new modules for the better representation of the cropping system. A new version for the phenological module and a new soil water module were developed. The soil water module was based on the previous version (Danuso *et al.*, 1992 – two dynamic layers cascade approach) but considering the water distribution into the layers instantaneously. A new soil organic matter module has been also developed, with an implementation of the RothC model (Coleman *et al*., 2008) crucial for the crop carbon balance of the whole system. Moreover, three complete new modules have been developed for assessing the economic, energetic and environmental factors (CSS-Economy, CSS-Energy and CSS-Environment). The energetic and environmental modules follow a LCA approach for the calculation. In Chapter 4 the CSS model will be described and a calibration case study, based on the paper *Jerusalem artichoke (Helianthus tuberosus L.) productivity in different Italian growing areas: a modelling approach* (Baldini *et al*. 2011) is be also presented.

In Chapter 4, X-crop software will be also presented; this application is, in fact, based on CSS model. X-crop allows the simulation of the cropping system with an easy-to-use graphical user interface. The simulation process is performed using CSS model as calculation engine.

It is well known that models are often strictly connected to academic and research contexts and have not wide-melted farmers and agricultural technicians, despite they are strongly encouraged to optimize the cropping activities. To avoid this limitation, MiniCSS has been developed: it is a software for the optimization of irrigation and nitrogen (N) fertilization by a simplified crop simulation model. This model is a generic crop model, with daily time step and has been kept deliberately simple in order to facilitate its practical application. This model integrated a user graphical interface that allows to set up the input data requested and to summarize the simulation results. Moreover, MiniCSS allows the optimization of irrigation and fertilization strategies by simulation experiments to create multi year averagesimulations. The model performs also simple economic and energy balances, able to compare the sustainability of different cropping scenarios. In Chapter 4 (presented in *MiniCSS: a software application to optimize crop irrigation and nitrogen fertilization strategies* - Rocca and Danuso, 2011) the model engine and the software, together with a calibration case study of the water module, are described.

To assess the sustainability of the farming system, the implementation of a whole farm simulation model (X-farm) has been considered as necessary. X-farm includes, not only crops production but also other aspects oriented to provide short- and long-term scenarios, and useful to improve the planning capability of the farm. Examples of the application of the simulation approach to the farming system simulation are the Whole-Farm Dynamic Model (GAMEDE; Vayssières *et al.*, 2009), Integrated Farm System Model (Rotz and Coiner, 2006), FARMSIM (Van Wijk *et al.*, 2006), SIPEAA (Donatelli., 2006) and X-farm (Danuso *et al.*, 2007). In general, increasing the complexity from the cropping system to the farming system involves many new fundamental representation difficulties. In particular, the concurrence of different farm activities in their requirements for farm resources (manpower, energy, machinery, time window for tillage, etc).

In Chapter 5 the X-farm model is presented. It is a farm dynamic simulation model to manage an "agro-energy farm" that takes into specific account the crop biomass production, net energy production, environmental and economic balances. This chapter is presented from the papers *Simulation of the Agro-Energy Farm with the X-farm Model: Calibration of the Crop Module for Sorghum Yield* (Danuso *et al.*, 2010) and *X-farm: Modelling Sustainable Farming Systems* (Rocca *et al.*, 2012).

X-crop and X-farm are part of the more inclusive framework for bioenergy production sustainability assessment X-plan (Figure 1.2) that includes also X-land (not treated in this thesis - Ginaldi *et al.* 2012). X-plan has been developed by the Department of Agricultural and Environmental Science of University of Udine to give the possibilities to analyses the sustainability at three scales: crop level (X-crop), farm level (X-farm) and land level (Xland).

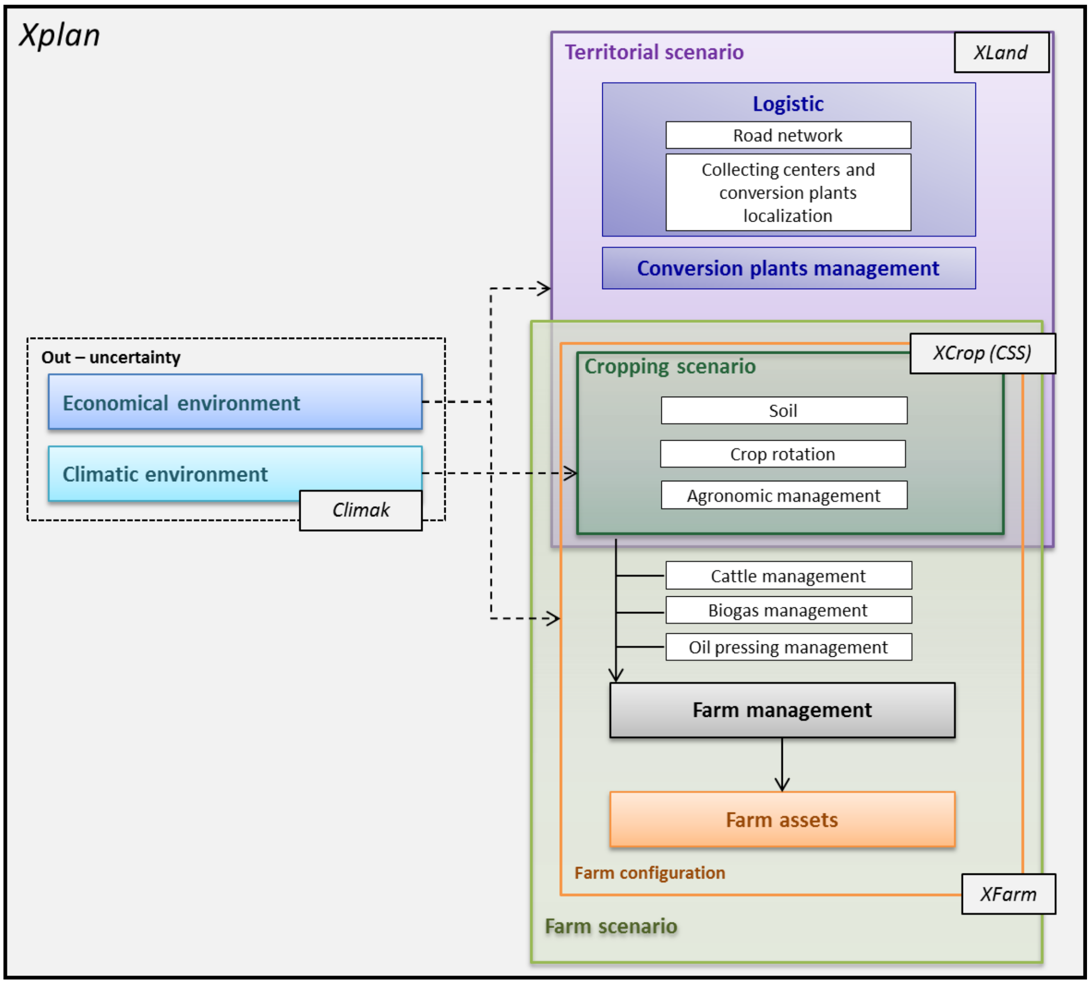

Figure 1.2 The X-plan framework for the sustainability assessment: the territorial scenario (Xland), assesses the sustainability of the bioenergy production chain considering the actual transport from the production areas to the collecting centres and then to the conversion plants, using the real road network; the cropping scenario (X-crop), perform simulation for cropping rotation with CSS model, considering different climatic conditions, soil characteristics and various agricultural practices, calculating economy, energy and environmental balances and indices of performance; the farm scenario (X-farm), performs simulation of the farming system considering more than one field, with different soil characteristics and diverse crop rotations, also representing other farm production, e.g., oil, biogas and milk.

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2 Development of modelling and simulation tools

Environmental management and the related decision support systems are become important topics in productivity activities. However, there is increasing request optimal tools to manage knowledge (Matthews, 2006). Since knowledge is a psychological result of perception it requires a conceptualization process to produce an abstract view of reality. Nevertheless, different types of knowledge exists (Table 2.1) and many tools should be used to collect and use information.

Table 2.1 Knowledge classification for the level of generality, representation and level of certainty (Danuso, 2010)

Generality level	
A priori	system structure, relationships, constants, rules
A posteriori	data, facts, model parameters, specific objects
Computer representation	
Euristic	rules bases in expert systems
Algorithmic	models, computing procedures
Declarative	databases, facts in expert systems
Certainty level	
True	Deterministic processes
Uncert	Random events, Markov processes

To well manage environmental systems, knowledge needs to be represented by means of a proper ontology. Ontology is an explicit formal specification of how to represent objects, concepts and their relationships existing in some area of interest. Nevertheless, ontological differences between disciplines slow down the model creation and confine modelling practices to an exclusive group of expert. By contrary, the complexity of reality and the increasing request for multi-dimensional assessment need modelling approaches based on knowledge integration (IMA). As reported by McCarthy *et al.*, (2001) an integrated approach of knowledge can be defined as the "combination, interpretation, and communication of knowledge from diverse scientific disciplines from the natural and social sciences to investigate and understand causal relationships within and between complicated (and complex) systems". Oriented to consider the interconnected nature between ecology, economy and societies it takes the reflexive relationship between disciplines into account (Argent, 2004; Argent, 2004a; Patterson *et al.*, 2007).

For these reasons, to well describe a complex reality, a plurality of knowledge should be considered and a language, able to consider the interconnected nature between them, should be developed.

One of the best tools for the knowledge management is the simulation model (Becchini and Stöckle, 2007). When people try to model some part of real world, often a common statement declared is: “we have not enough data to implement the model”. Actually, we do not want to implement data but knowledge and making models need knowledge and not simply data. So, the previous statement, probably, means: “we are not able to implement knowledge about the system. This often arises for the lacking of suitable computer tools to manage it or, even, because people have not learned how to use them (Danuso, 2010).

In recent years, an increasing number of software has been proposed, by individuals or institutions, to represent and manage knowledge. However, representational difficulties can arise from ontological differences between disciplines (Costanza and Ruth., 1998). According to Checkland (1981) “in ecological models, used to describe a complex reality, both methodology and formal language are important. They are conditioned by the framework on which they are based”. For this reason, model science needs new software to describe the complex reality and different methods of analysis should be integrated in order to approach the multi-dimensionality of reality (Villa and Costanza, 2000; Villacampa *et al*., 1999).

As reported in Figure 2.1 and Figure 2.2, different methods, generally used for managing different kind of knowledge and different levels of generality and uncertainties exist. Physical law, for example are characterized by high generality and high certainty, because based on knowledge *a priori*. On the contrary if we have low knowledge *a priori* but many data, we can use analytical models as neural networks or empirical models. Simulation models are useful to integrate many kind of knowledge: given that they use both a *priori* knowledge and *a posteriori* knowledge, they can be suitable to describe reality or to scenario analysis.

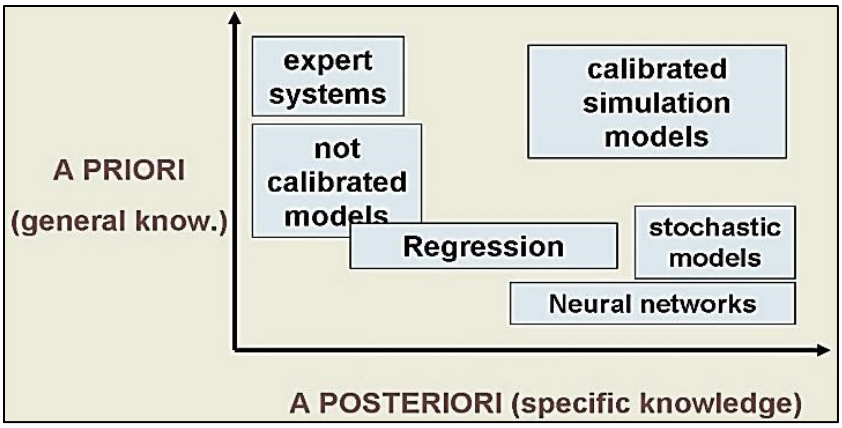


Figure 2.1 Tools applicability with relation to general or specific knowledge (da Zerbi *et al.*, 1997)

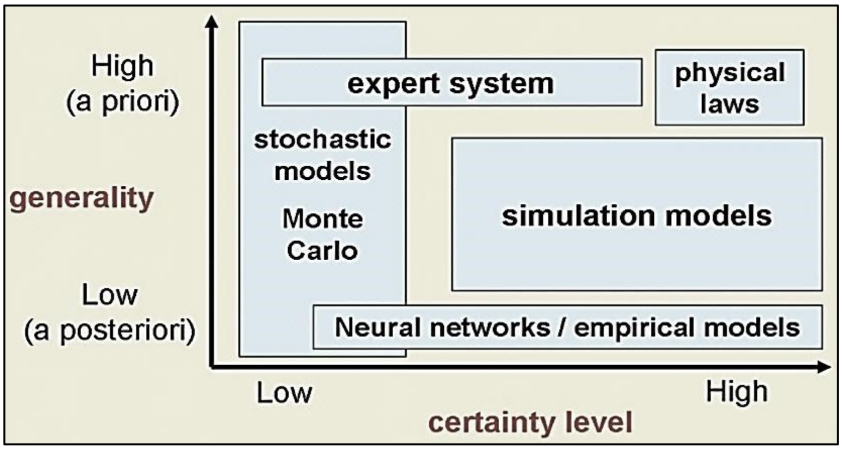


Figure 2.2 Tools applicability with relation to generality and certainty of knowledge (da Zerbi *et al.*, 1997)

In the field of agro-ecological modelling, many efforts have been devoted to design software oriented to manage information and to represent it in models (SIMILE, STELLA, Barkeley Madonna, GoldSim, Simulink and VenSim). However, they have a limited capacity to integrate knowledge, intended as capacity to manage data, provide regression analysis, neural networks, expert systems, Monte Carlo simulation, sensibility analysis, and other (Table 2.2). In order to improve the management of knowledge, this chapter the software SEMoLa will be describe. This framework allows making simulation models and managing data.

2.1 SEMoLa framework overview

SEMoLa (Simple, Easy to use, Modelling Language) is a simulation language endowed by a modelling environment developed at the Department of Agricultural and Environmental Sciences of the University of Udine (Italy) to create computer models for dynamic systems and manage different types of agro-environmental information. The software runs under Windows OS and is freely available from http://www.dpvta.uniud.it/~Danuso/ docs/Semola/homep.htm. SEMoLa language (Danuso, 2003) is based on the principles of system dynamics (Forrester, 1968; Zeigler, 1976; De Wit and Gaudriaan, 1978; Ferrari, 1978; Dent and Blackie, 1979; Jorgensen, 1995) and has been originated from non-procedural simulation languages like DYNAMO (Forrester, 1968; Richardson *et al*., 1981), CSMP (Brennan *et al*., 1970; IBM, 1972), PCSMP (Jansen *et al*., 1988), ACSL (ACSL, 1987), FSE (van Kraalingen, 1991). Used in simulation of complex environmental systems, the main fields of application are teaching, system analysis, research and for the construction of applicative models. SEMoLa is easy to use and has a modelling environment to interactively assist the modeller in developing, evaluate, calibrate, generating stand-alone models. Moreover, the declarative simulation language allows non mathematical and programming skilled users to create dynamic models by themselves.

In the following paragraphs the SEMola graphical user interface, the system ontology, the declarative language and the procedures for model development a simulation will be presented.

2.1.1 Graphical User Interface

Graphical User Interface is a set of interactive dialogs that allow the user to interact with the application by using keyboard and mouse. In SEMoLa the available dialogs are: the main dialog, a tabbed windows containing the model and file selection, the lists of model components, the variables of the current dataset, the SEMola functions and the procedural commands for the scripting (Figure 2.3).

Table 2.2 Comparative analyses of system ontologies and knowlage management.

Element	Forrester's DYNAMO	Matlab+simulink	SEMoLa	SIMILE	STELLA	Berkley Madonna
System ontology						
Conservative quantity	Material	Material	Material	Material	Material	Material
Non-conservative quantity	Information	Influence	Information	Influence	Action-connection	Action-connection
Element	-	Submodel	Element - Group	Submodel	Array	Array
Material in a state	State	Compartment	State	Compartment	Stock	Stock
Rate of material flux	Rate	Flow	Rate	Flow	Flow	Flow
Instantaneous change	-	Condition	Event	Condition	If, Then, Else	If, Then, Else
Constant during simulation	Parameter	Fixed parameter – Variable parameter	Parameter - Constant	Fixed parameter – Variable parameter	Converters	Converters
Info variable during simulation	Auxiliary variable	Auxiliary variable	Auxiliary variable	Intermediate variable	Converters	Converters
External information variable during simulation		Exogenous variable	Exogenous variable	Exogenous variable	Converters	Converters
Knowlage integartion						
Regression analysis	No	Yes	Yes	No	No	No
Neural networks	No	No	Yes	No	No	No
Expert systems	No	Yes	Yes	No	No	No
Simulation experimen	No	No	Yes	No	Yes	No
Expert systems	No	Yes	Yes	No	No	No
Monte Carlo simulation	No	Yes	Yes	No	Yes	No
Automatic sensibility analysis	No	No	Yes	No	No	No
Automatic calibration	No	No	Yes	No	No	No

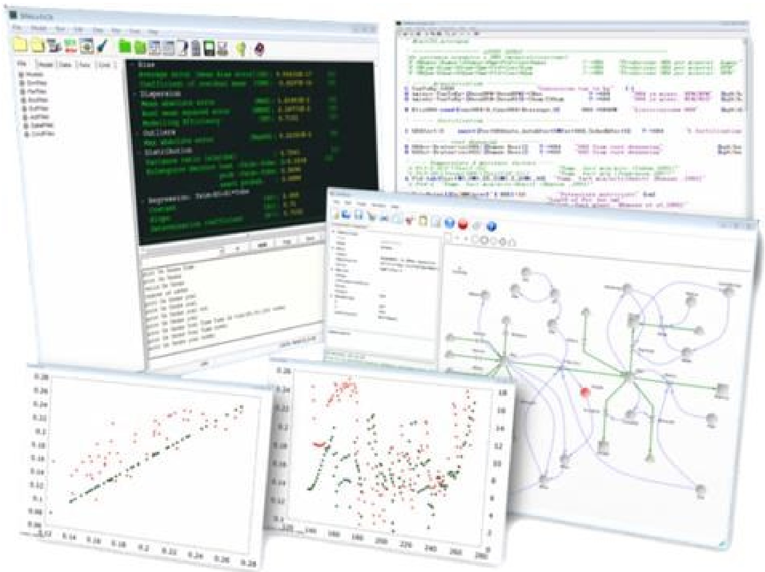


Figure 2.3 Shows the main screen of SEMoLa. It reports the main windows and features described above.

The SEMoLa frameworks works also by using commands. Commands are textual instruction give to the application requiring the execution of certain actions (e.g. document models, display simulation results, perform sensitivity analysis, statistical regression, data management, uncertainty analysis, etc.). It is possible to save lists of commands so creating command file (a "script"). A script is a list of commands that can perform a task autonomously, without the assistance of the user. Generally, they are used to automate the pre-processing of model input data or for the post-processing of the simulation results. The main advantages of the scripting, respect to the interactive use of commands or dialogs are: (*i*) the possibility to check later the whole procedure; (*ii*) the possibility to repeat the procedure for other tasks without repeating complex series of commands; (*iii*) the complete documentation of a procedure. However, contrary to the SEMoLa modelling language, a script is strictly procedural. Below, a script to calculate a day length variable is presented.

```
' Daylen.cmf
'    Daylength (hours) calculation from day of the year (DOY)
'    Ref: KEISLING T.C., 1982 (Agron.J.)
'    Aut: F.Danuso (20/11/95)

 scalar Lat=45.5                                       ' set latitude
 scalar h3=pi/180
 scalar LATR=Lat*h3                                    ' converts to radians
 scalar al=90*h3                                       ' zenithal distance (rad)
 gen M=(0.9856*Doy-3.251)*h3                           ' mean sun anomaly (rad)
 gen l6=M+h3*(1.916*SIN(M)+0.02*SIN(2*M)+282.565)
 gen dec=0.39779*SIN(l6)                               ' sine obliquity
 replace dec=ATN(dec/SQRT(1-dec*dec))                  ' declination (rad)
 gen zk=(SIN(LATR)/COS(LATR))*(SIN(dec)/COS(dec))
 gen fot=COS(al)/(COS(LATR)*COS(dec))-zk
 gen daylength=2/15*(-ATN(fot/SQRT(1-fot*fot))/h3+90)' Daylength (h)"
 drop M l6 dec zk fot
```

The command file is named *daylen.cmf* and uses latitude and the variable “day of the year” (*doy*) to calculate the variable *daylenght.* The script uses the variable *doy* (a column in the current dataset) containing the day of the year (1-365) and generates the variable *daylenght* with the astronomical photoperiod. Some working variable (*M, 16, dec, zk, fot*) are also generated and then erased at the end of the calculations, when no more needed. To use the script, the user has to set the latitude value and to prove that a variable with the day of the year (*doy*) exist.

2.1.2 System ontology and its representation in SEMoLa

The system ontology in SEMoLa uses the System Dynamics notation proposed by Forrester (1961) and widely used in describing continuously varying systems (Muetzelfeldt, 2003). Combining concepts of amount, flow and influence, it is useful to describe the complexity of reality and consider the interconnected nature between ecology, economy and society.

System Dynamics in SEMoLa is based on eight types of statement:

- Material (M): declares the quantity that follows the conservation law (conservative quantity). It is opposite to “information” which is not a conservative quantity. A system can have more than one material (e.g. water, biomass, nitrogen) and each material can be in one or more states.
- Group (G): it defines an “entity” composed by elements sharing a number of common properties (i.e. amount of materials, state, parameter). Each element can have

its own inputs and outputs and can interact within the same groups or with other groups. A group can be static or dynamic. Static if composed by a constant number of elements. Dynamic if the number of elements can change during the simulation, depending on events. It is composed by a set of elements sharing the same properties. Each element can be characterized by states and parameters and can interact or not with other elements or with the environment.

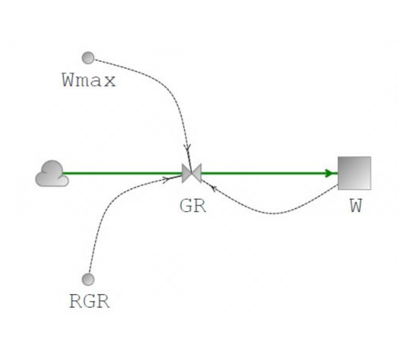
- State (S): is the amount of a conservative quantity (material) having specific properties (a state) and changes thanks to continuous flow rates or by event actions.
- Rate (R): is a variable that regulates the flow of materials from a state to another.
- Impulse (I) A action triggered by events that creates a sudden modification of states.
- Auxiliary (A): is an information obtained from the states of the systems, parameters and exogenous variables and used in the calculation of rates and events or to create useful output information.
- Exogenous variable (E): is an informative variable generated outside the system and not under the control of the system. It is able to affect the system itself.
- Parameter (P): is information of the system that remains constant during all the simulation steps. It is a static regulation of the system. In SEMoLa, parameters can be modified by action triggered by events. Parameters are inputs that the user can select.
- Constant (C): is information of the system that remains constant for all the possible simulation of the model (not only the time step of a simulation). Not modifiable by the user.
- Event (V): something happening that determines sudden actions changing state variables or parameter values. Events can be of different types: internal (conditional, periodical and standing conditional) or external (events that are regulated from outside the system).

The SEMoLa language has different components (the most important are illustrated in Table 2.3) to describe all the system aspects and behaviour. In Figure 2.4 and Table 2.4

the structure of the SEMoLa language and a simple model is reported (both in text, mathematical and in graphical implementation). Every line is identified by the first word of the line (line identifier, a single letter); then, the name of the component is to be declared, followed, generally, by the equal symbol and an expression, indicating how the component is to be calculated. For states (S) and parameters (P) the expression represent the initial value; in the other cases the expression is calculated for every step of the simulation loop. After the expression, there can be the definition of the component properties. In some cases they are required, in other are optional. Each statement can be labelled by a description and by a measure unit (as last part of the line) surrounded by parentheses. Description and measure units, besides their utility for code readability, are separately treated by the documentation commands, to build tables and other model documentations. The model code may be structured into logical sections. A section of the model is to be thought as a sub-system dealing with a particular material type of the system. The at-sign (@) declares a model section to be included in the current model.

Table 2.3 The symbols that constitute the SEMoLa diagramming language

State	Rate	Impulse	Auxiliary variable	Exogenous variable	Parameter	Constant	Internal event	External event	Out of system
S0	R0	I0	A0	E0	P0	C0	V0	V1	




```
S W=5           "Weight"                  (g)
R GR=RGR*W*(1-W/Wmax)      ?->W           (g/day)
P  RGR=0.1      "Specific growth rate"    (1/day)
P  Wmax=150     "Maximum weight"          (g)
```

$$GR = \frac{dW}{dt} = RGR \cdot W \cdot \left(1 - \frac{W}{Wmax}\right)$$

$$RGR = 0.1$$

$$Wmax = 150$$

Figure 2.4 Graphical, textual and mathematical representation of a simple sigmoidal growth model. The graphical representation has been obtained using the graphical editor SemDraw.

Being a no procedural language, SEMoLa allows representing a model in a conceptual rather than computational order by putting the statement in a free order on the listing. In general terms, a SEMoLa model is a text file in which every row completely describes a system component.

Table 2.4 Statements of the language

Material	M	material		options	label	
Group	G	gvar=#		options	label	
State	S	svar=#		options	label	(unit)
Auxiliary	A	avar=exp		options	label	(unit)
Rate	R	rvar=exp	source->sink	options	label	(unit)
Impulse	I	ivar	source->sink	options	label	(unit)
Exovar	E	evar		options	label	(unit)
Event	V	evtname=type		options	label	
Constant	C	cname=#		options	label	(unit)
Parameter	P	pname=#		options	label	(unit)
Option	$			option_list		
Section	@	sect_name		options	label	
Comment	`	text				

2.1.3 Model creation

The software SEMoLa allows creating a model by using a text file in which every row of diagram completely describes a system component or in a graphical editor (SemDraw). Once the SEMoLa source model has been written or drawn, the executable model is obtained through two steps, automatically performed: the translation of the SEMoLa code into Basic source code and the compilation of the source code into an executable by an external compiler. Model building, refereed also with the term "compilation", is the process to transform the SEMoLa code of the model (*model_name*.sem) into an executable file (*model_name*.exe); besides the executable, also some related input files (*simfile, parfile, exofile, evtfile, actfiles*) are created. The compilation translates the SEMoLa code into the source code (*model_name*.bas), then calls and run the Basic compiler to generate the executable form of the model (*model_name*.exe) and generate the template files for *simfile, parfile, exofile, evtfile, actfiles*. Template *exofile* is generated only if the model requires exogenous variables. *Evtfile* and *actfiles* are generated only if the model has external events.

2.1.4 Simulation

The simulation is a repeated calculation on a model in which the results of a calculation become the input of the next calculation process. The variations of the state variables are so calculated and accumulated to obtain a representation of the model behaviour in time (outputs or model solutions).

In SEMoLa the calculation processes are structured into a nested procedure in which a single calculation process is defined “step”. The simulations of continue dynamic systems is performed by numerical integration of ordinary differential equations (ODE). Figure 2.5 reports the simulation graphical interface.

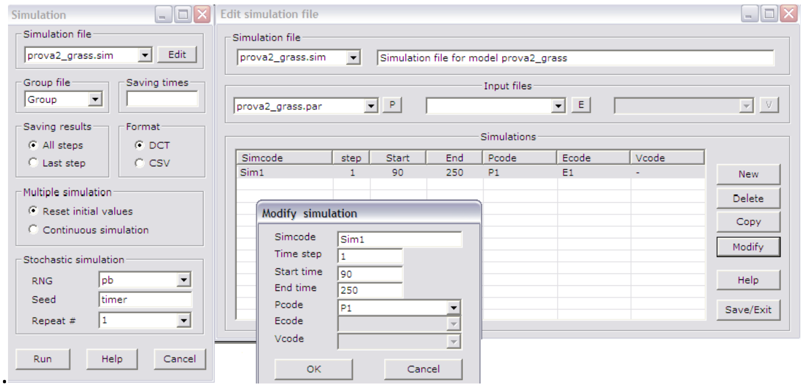


Figure 2.5 Simulation graphical interface

The software SEMoLa allows also 1) sensitivity analysis, 2) calibration of parameters and 3) stochastic model development and uncertainty analysis.

1. Sensitivity analysis: The sensitivity to the model prediction is computed as (∂Y/Y)/(∂P/P) where Y is the response (or output) variable of the model and P is a parameter. The sensitivity variables are computed, for all the declared parameters, with respect to the simulated variable indicated, for each time step. The sensitivity with respect to model predictions can be evaluated by the amount of change in a simulated variable (state or auxiliary) at a little change in a parameter. Sensitivity analysis allows evaluating the effect on some variables of the model of a variation in parameter values. Figure 2.6 shows the graphical interface for the sensitivity analysis, the model optimization/calibration and the validation

2. Calibration: Calibration is performed through the command *mrun* that allows the parameter estimation for dynamic model represented by sets ordinary differential

and algebraic equations, both linear and non-linear. The calibration routine (Danuso, 1991) uses an iterative procedure (Gauss-Newton linearization method; Beck and Arnold, 1977; Draper and Smith, 1981) which minimise the residual sum of square between observed and simulated values.

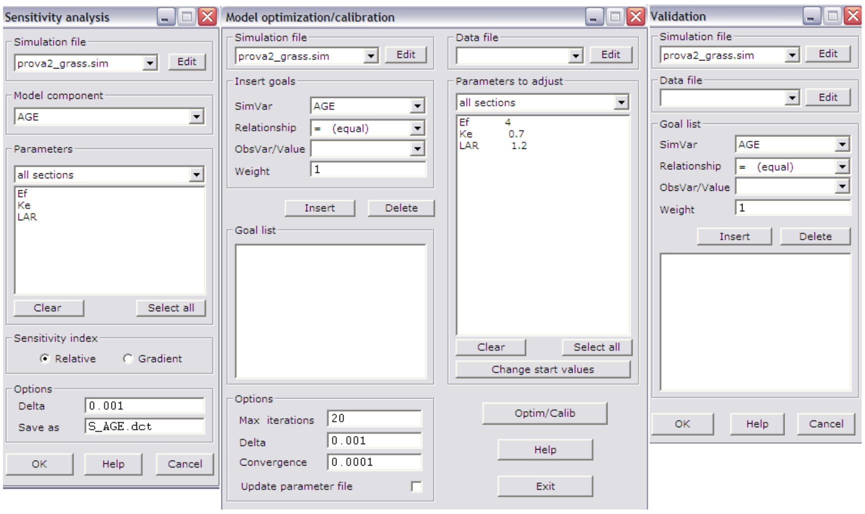


Figure 2.6 Graphical interface for the sensitivity analysis, the model optimization/calibration and the validation

3. Stochastic models and uncertainty analysis: In SEMoLa the uncertainty analysis can be applied to investigate the effect of three types of uncertainty due to the accuracy of parameters estimation and to natural variability (i.e., weather variability) and uncertainty in management parameters. In SEMoLa it is possible to represent uncertainty due to 1) uncertainty in the model parameters; 2) uncertainty in the rates; 3) stochastic input in deterministic model so performing Monte Carlo procedures. More details of stochastic model cam be read in chapter 3.

2.2 Model evaluation

Model evaluation is an essential step in the modelling process, this because allow to indicate if the implementation of the algorithm involved in representing the system and the level of accuracy of the model in reproducing the actual system (Huth and Holzworth, 2005). In fact model evaluation is one of the issues which mostly catalysed the attention of the modellers community in the last years (Bellochi et al., 2010). Many indices for quantifying the agreement between measured and simulated data was been proposed (Wallach, 2006; Moriasi et al., 2007), together with indices for assessing model complexity (Akaike, 1974, confalonieri et al., 2009), relevance, robustness, plasticity and (Confalonieri et al., 2012). The need of defining evaluation criteria accounting for different aspects of models behaviour led to the use of fuzzy-based procedures for aggregating different indices (Bellocchi et al., 2002) in order to allow multi-metric model evaluations (e.g., Confalonieri et al., 2009).

In this paragraph, some of the most used and common indicator for model evaluation will be presented.

2.2.1 Simple difference index

i) Mean bias error (MBE):

$$MBE = \frac{1}{n}\sum_{i=1}^{n} E_i - M_i$$

MBE or just bias (Addiscott and Whitmore, 1987) is the mean different between estimated and measured values, where n being the total number of data, E and M are the estimated and measured data respectively. Bias measures the average difference between measured and calculated values. If the model underpredicts, the bias is positive. When bias is negative the model overpredicts. Ad advantage of bias is that it is simple to implement and interpreted (Wallach, 2006). Bias alone is not sufficient for model evaluation. Bias near zero can be the consequence of very small model errors or alternatively of large positive and negative errors that cancel each other out (Wallach, 2006).

ii) Percent bias (PBIAS):

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(M_i - E_i) \cdot (100)}{\sum_{i=1}^{n}(M_i)}\right]$$

It measures the average tendency of the simulated data to be larger or smaller than their observed data. The optimal value of PBIAS is 0.0. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Moriasi et al., 2007). PBIAS has the ability to clearly indicate poor model performance (Gupta et al., 1999).

iii) Relative error (E): The relative error can result either positive or negative, being zero the optimal value.

$$E = \frac{100}{n} \cdot \sum_{i=1}^{n} \frac{E_i - M_i}{M_i}$$

iv) Coefficient of residual mass (CRM):

$$CRM = \frac{\sum_{i=1}^{n} M_i - \sum_{i=1}^{n} E_i}{\sum_{i=1}^{n} M_i}$$

CRM optimum value is zero but can result positive (under-estimation) and negative number (over-estimation). Intrinsic weakness is that CRM can result zero or near zero even without a good proximity between estimates and measurements but due to reciprocal compensation due to opposing sign differences.

v) Fractional bias (FB):

$$FB = 2 \cdot \frac{\overline{E} - \overline{M}}{\overline{E} + \overline{M}}$$

The Fractional Bias (FB) is a normalization of the mean bias (Kumar, 2000). It can be positive or negative from +2 to -2 , 0 being the optimum value. FB is dimensionless.

vi) Maximum error (MaxE) and maximum percent error (MaxE%): See Schaeffer (1980).

$$MaxE = Max(E_i - M_i) \qquad MaxE\% = \frac{100}{M_{max}} \cdot Max(E_i - M_i)$$

2.2.2 Absolute difference index

i) Maximum absolute error (ME):

$$ME = \max|E_i - M_i|$$

It is the maximum value of absolute value of the different between observed and estimated values (Loague and Green, 1991). A model is as better as ME tends to its lowest limit, equal to 0.

ii) Mean absolute error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|E_i - M_i|$$

Descrivet by Schaeffer (1980). MAE has the same unit of the data. Moreover, it does not overweight the large differences due to the squared differences between estimated and measured data.

iii) Relative mean absolute error (RMAE): See Mayer and Butler (1993).

$$RMAE = \frac{1}{n}\cdot\sum_{i=1}^{n}\frac{|M_i - E_i|}{|M_i|}$$

iv) Maximum absolute percent error (MA%E):

$$MA\%E = 100\cdot\sum_{i=1}^{n}\frac{|E_i - M_i|}{|M_i|}\cdot\frac{1}{n}$$

The model is good if the value of MA%E tends to 0 (Schaeffer, 1980). A potential problem exists with MA%E owing to the division by Mi, because MA%E is undefined when any measured value equals 0. Problems also occur with low values of Mi, as MA%E tends towards infinity as any Mi tends towards 0.

v) General absolute standard deviation (GASD): See Jørgensen et al.(1991).

$$GASD = MAE\cdot\frac{100}{\overline{M}}$$

vi) Modified modelling efficiency (EF_1):

$$EF_1 = 1 - \frac{\sum_{i=1}^{n}|E_i - M_i|}{\sum_{i=1}^{n}|M_i - \overline{M}|}$$

To overcome the problem of oversensitivity to outliers of EF (see below), the sum of squares of difference is replaced in EF1 with the sum of absolute differences (Yang et al., 2000). EF_1 is less sensitive to outliers than EF, given that $|EF_1|\leq EF$.

2.2.3 Square difference index

i) Simulation bias (SB):

$$SB = (\bar{E} - \bar{M})^2$$

Kobayashi and Salam (2000) declare that is an overall index of the bias of the estimates. It is simple to implement and to interpret. As it is based on squared differences, it tends to overweight large biases (Moriasi et al., 2007).

ii) Mean square error (MSE):

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(E_i - M_i)^2$$

A low MSE indicates a good performance of the model. MSE can be decomposed into separated contributions to identify the error sources. Willmott (1981) proposed decomposition based on a linear regression. $MSE=MSE_s+MSE_u$, where, $MSE_s=(1/N)\Sigma(E_i-M_i)^2$ and $MSE_u=(1/N)\ \Sigma(E_i-M_{cali})^2$. M_{cal} is the value of M calculated from the regression model. Moreover, Kobayashi and Salam (2000) show that MSE can be decomposed as; MSE=(SB)+SDSD+LCS. Where, SDSD = $(\sigma_M-\sigma_E)^2$ and LCS = 2 σMσE(1-r). SDSD is the different between the standard deviation of measured and calculated values. LCS is related to the correlation between observed and predicted values and depends in detail on how well the model simulates the observed variations. Gauch et al. (2003) suggest: MSE=(Bias)2+NU+LC, where, $NU=(1-b_{ME})^2\sigma E^2$ and $LC=(1-r^2)\ \sigma M^2$. The term bME is the regression of M on E. The NU term (nonunity slope) depends on how close the slope of regression of M on E is to 1. LC instead indicates how variations of M and E are correlated. See also Kobayashi (2004).

In general MSE, eliminates the problem of compensation between under and over- prediction (Wallach, 2006). MSE can be decomposed into separated contributions to identify the error sources (Wallach, 2006). It is overly sensitive to extreme values or large differences due to the squared differences (Legates and McCabe, 1999; Wallach, 2006; Moriasi et al. 2007).

iii) Root mean squared error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(E_i - M_i)^2}{n}}$$

It is the square root of MSE (Fox, 1981). The daily root-mean square (DRMS) is a specific application of the RMSE, which computes the standard deviation of the model prediction error. The smaller the DRMS value, the better the model performance (Gupta et al., 1999). RMSE has the same units as the data (estimated or measured) so its interpretation is easy. RMS had limited ability to clearly indicate poor-model performance (Moriasi et al. 2007).

iv) Root mean squared variation (RMSV):

$$RMSV = \sqrt{\frac{\sum_{i=1}^{n}\left[\left(E_i - \overline{E}\right) - \left(M_i - \overline{M}\right)\right]^2}{n}}$$

It is the square root of MSV (Kobayashi and Salam, 2000). MSV is the difference between the simulation and the measurement with respect to the deviation from the means. A bigger MSV indicates that the model failed to simulate the variability of the measurement around the mean.

v) General standard deviation (GSD): See Jørgensen et al. (1991).

$$GSD = RMSE \cdot \frac{100}{\overline{M}}$$

vi) Relative root mean squared error (RRMSE): See Robertson et al.(2002)

$$RRMSE = \frac{RMSE}{\overline{M}}$$

vii) Normalized mean squared error (NMSE):

$$NMSE = \frac{\sum_{i=1}^{n}(E_i - M_i)^2}{\sum_{i=1}^{n} E_i \cdot M_i}$$

viii) Modelling efficiency (EF) :

$$EF = 1 - \frac{\sum_{i=1}^{n}(E_i - M_i)^2}{\sum_{i=1}^{n}(M_i - \overline{M})^2}$$

It is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970; Greenwood et al., 1985, Loague and Green, 1991). If the model is perfect, then EF=1. A model with EF near to 0 is normally considered not to be a good model. EF<0 means that the model is a worse predictor than the average of measured data. (Moriasi et al., 2007). Moreover, Moriasi et al. (2007) suggest that a very good EF is higher than 0.75, a good one is from 0.65 to 0.75, a satisfactory EF is between 0.5 and 0.6 and an unsatisfactory EF is less than 0.5. EF was recommended for use by ASCE (1993) and Legates and McCabe (1999). It is also very commonly used because it provides extensive information on reported values. Sevat and Dezetter (1991) also found EF to be the best objective function for reflecting the overall fit of the model. EF is sensitive to outliers (Klepper and Rouse, 1991; Yang et al., 2000). Jain and Sudheer (2008) demonstrated that EF is not adequate in describing the performance of a model.

ix) Modelling percent efficiency (EF%): It is the complement to EF expressed in percentage (Greenwood et al., 1985).

$$EF\% = 100 \cdot (1 - EF)$$

x) Persistence model efficiency (PME):

$$PME = 1 - \frac{\sum_{i=1}^{n}(E_i - M_i)^2}{\sum_{i=1}^{n}(M_i - M_{i-1})^2}$$

Ii it’s a normalized model evaluation statistic that quantifies the relative magnitude of the residual variance (“noise”) to the variance of the errors obtained by the use of a simple persistence model (Gupta et al., 1999). PME ranges from 0 to 1, with PME=1 being the optimal value. PME values should be larger than 0.0 to indicate “minimally acceptable” model performance (Gupta et al., 1999). The power of PME is derived from its comparison of model performance with a simple persistence forecast model. According to Gupta et al. (1999), PME is capable of clearly indicating poor model performance. It has been used only occasionally in the literature, as a range of reported values is not available Moriasi et al. 2007).

xi) Pearson’s correlation coefficient (r):

$$r = \frac{\sum_{i=1}^{n}\left(E_i - \overline{M}\right) \cdot \left(M_i - \overline{M}\right)}{\sqrt{\sum_{i=1}^{n}\left(E_i - \overline{E}\right)^2 \cdot \sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2}}$$

Pearson’s correlation coefficient (r) describes the degree of correlation between simulated and measured data. It is an index of the degree of linear relationship between observed and simulated data ranging from −1 to 1, (Addiscott and Whitmore, 1987). If r=0, then no linear relationship exists. If r=1 or −1, a perfect positive or negative linear relationship exists (Moriasi et al., 2007). In a modelling context, only positive values are acceptable. Although r and CD (see below)) have been widely used for model evaluation, these statistics are oversensitive to high extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data (Moriasi et al., 2007).

xii) Coefficient of determination (CD)

$$CD = \frac{\sum_{i=1}^{n}\left(E_i - \overline{M}\right)^2}{\sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2}$$

The Coefficient of determination (CD) describes the proportion of the variance in measured data explained by the model. Tt is not the same of r^2, values being possible of CD greater than 1. CD=1 is the best, that is the deviation from the mean of measurements is the same for estimates and measurements. Values near to 1 indicate little error variance, and typically values greater than 0.5 are considered acceptable (Moriasi et al., 2007). EF and CD taken together help a better interpretation of RMSE when standard error of the measurements is unavailable (Smith et al., 1997).

xiii) Index of agreement (d):

$$d = 1 - \frac{\sum_{i=1}^{n}\left(E_i - \overline{M}\right)^2}{\sum_{i=1}^{n}\left(\left|E_i - \overline{M}\right| + \left|M_i - \overline{M}\right|\right)^2}$$

Developed by Willmott and Wicks (1980), it is a standardized measure of the degree of model prediction error. It varies between 0 (no agreement at all) and 1 (perfect agreement between the measured and estimated values). The index of agreement represents the ratio between the mean square error and the "potential" error. The index of agreement can detect additive and proportional differences in the observed and simulated means and variances. d is overly sensitive to extreme values due to the squared differences (Legates and McCabe, 1999). Legates and McCabe (1999) suggested a modified index of agreement (d1) that is less sensitive to high extreme values because errors and differences are given appropriate weighing by using the absolute value of the difference instead of using the squared differences. Although d1 has been proposed as an improved statistic, its use has been limited (Moriasi et al., 2007).

xiv) RMSE-observations standard deviation ratio (RSR:

$$RSR = \frac{RMSE}{\sqrt{\sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2}}$$

RSR is calculated as the ratio of the RMSE and standard deviation of measured data. RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. The lower the RSR is the lower the RMSE, and then the better the model simulation performance are. RSR is considered very good if it is less than 0.5, good if it is between 0.5 and 0.6, satisfactory if the value goes from 0.6 and 0.7 and unsatisfactory if it is higher than 0.7 (Moriasi et al., 2007). RSR incorporates the benefits of error index statistics and includes a scaling/normalization factor, so that the resulting statistic and reported values can apply to various constituents (Moriasi et al., 2007).

xv) Performance virtue statistic (PVk):

$$PVk = \sum_{i=1}^{n} \alpha_i[\omega_{i1}E_i^2 + \omega_{i2}(1 - |D_{vi}|) + \omega_{i3}(1 - R_{RRi})]$$

PVk is defined as the weighted average of the Nash-Sutcliffe coefficient, deviations of volume, and error functions across all of the evaluation stations (Wang and Melesse, 2005). It can range from -∞ to 1, the optimum value being 1. Negative PVk values indicate that the average of observed streamflow values is better than simulated streamflows (Wang and Melesse, 2005). PVk was developed for use in snow-fed watersheds; therefore, it may be necessary to make adjustments for rain-fed watersheds. PVk was only recently developed; thus, extensive information on value ranges is not available (Moriasi et al., 2007).

xvi) Prediction efficiency(Pe):

The prediction efficiency (Pe) indicates the model's ability to describe the probability distribution of the observed results (Santhi et al., 2001; Moriasi et al., 2007). However, it has not been frequently used to provide extensive information on ranges of values. In addition, it may not account for seasonal bias (Moriasi et al., 2007).

2.2.4 Non-Parametric indices

Non parametric indices are useful to evaluate the goodness-of-fit of the non-normally distributed variables (Zacharias et al. 1996; Chung et al., 1999).

i) Median absolute error (MdAE):

$$MdAE = median(|M_i - E_i|)$$

ii) Relative median absolute error (RMdAE):

$$RMdAE = median(|M_i - E_i|) \cdot \frac{100}{median(M_i)}$$

iii) Robust modelling efficiency (REF)

$$REF = \frac{median(|M_i - median(M_i)|) - median(|M_i - E_i|)}{median(|M_i - median(M_i)|)}$$

iv) Spearman's correlation coefficient (r_s): See Lehmann and D'Abrera (1998).

$$r_s = 1 - \frac{\sum_{i=1}^{n}(M_i - E_i)^2}{n \cdot (n^2 - 1)}$$

2.3 Model complexity

i) Parameter ratio (Rp): It is the ration of the relevant parameters (identify by sensitivity analysis) and all models parameters (Confalonieri et al., 2009). Rp can have values from 0 to 1. The best value is 0 and the worst is 1.

$$R_p = \frac{S}{T}$$

Where:
S = Number of relevant parameters in a model
T = Total number of parameters in a model

ii) Akaike information criterion (AIC) ratio (W_k): Wk is derived from the Akaike’s Information Criterion (AIC, Akaike, 1974). Wk can go from 0 (worst) to 1 (best), considering estimation accuracy and number of parameters (Confalonieri et al., 2009).

$$W_k = \frac{e^{-\frac{AIC_k}{2}}}{\sum_{k=1}^{p} e^{-\frac{AIC_k}{2}}}$$

$$AIC = n \cdot \log(MSE) + 2 \cdot T$$

T: number of parameters in a model.
n: number of E/M pairs.

2.4 Pattern indices

Model adequacy may be appreciated by plotting residuals against either an independent variable (e.g. a model input or a variable not considered in the model), model estimates, or measurements. The presence of patterns of residuals vs. a third variable by computing pattern indices is quantified via pattern indices (Donatelli al., 2004). Range-based pattern indices are computed by dividing the range of values of an external variable in 2, 3, 4, and 5 sub-ranges. Once the range of values of an external variable is divided into equal-length groups, a range-based index (PI) is the absolute value of the maximum difference between pairwise comparisons among average residuals of each group:

$$PI = max_{l.m=1,\ldots,p:l\neq m} \left| \frac{1}{q_l} \cdot \sum_{i_l=1}^{q_l} R_{i_l} - \frac{1}{q_m} \cdot \sum_{i_m=1}^{q_m} R_{i_m} \right|$$

Where:
R = model residual (E - M);
l, m = group index;
p = number of groups (ranging from two to five);
q_l, q_m = group size;
i_l, i_m = residual value inside group.

2.5 Robustness and plasticity

i) Model Robustness indicator (I_r):

$$I_r = \frac{\sigma EF}{\sigma V}$$

It measures the model reliability under different sets of experimental conditions (Confalonieri et al., 2010a). σ_{EF} is the standard deviation of the modelling efficiencies (EF, ranging from −∞ to +1; optimum=1). σ_V is the standard deviation of an indicator that describes the variability among datasets. For agro-meteorological models, the SAM indicator can be used (Confalonieri et al., 2010a):

$$SAM = \frac{Rain - ET_0}{Rain + ET_0}$$

in which *Rain* and ET_0 indicate annual values of rainfall and reference evapotranspiration (both in mm).

ii) Model plasticity (L):

$$L = TDCC \cdot e^{\sigma SAM^{-1}}$$

It Describes the model tendency to change its behaviour when applied to different conditions (Confalonieri et al., 2012). TDCC is the top-down concordance coefficient (Iman and Conover, 1987), ranging from 0 (no concordance) to +1 (perfect concordance).

2.6 Hypothesis tests

i) Paired t-test (mean difference): Student t-test performs a paired t-test to check whether the mean of the difference between estimates (Ei) and measurements (Mi) is zero. The null hypothesis is, therefore, that the population mean of the paired differences of Ei and Mi is zero. The null hypothesis is rejected when the associated p-value is smaller than or equal to the provided significance level.

ii) Kolmogorov-Smirnov test (distribution difference): Kolmogorov-Smirnov (K-S) test is a nonparametric test to estimate whether an underlying probability distribution of a given dataset differs from a selected distribution. The one-sample KS test compares the empirical cumulative distribution function (empirical CDF) with the cumulative distribution function specified by the null hypothesis. The null hypothesis for this test is that Ei and Mi are both sampled from the same continuous distribution.

2.7 Time mismatch index

The presence of mismatches in time histories generated by dynamic models can be detected, according to Donatelli et al. (2002). The time mismatch is identified by the time shift (forward or backward) at which the best value of evaluation statistics are reached.

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3 Development of a new version of the Climak weather generator

Climate variability and extreme events are a classic source of variability for agricultural crop production. During the cultivation, the possibility to manage variability in a dynamic way, through tactical action is linked to the ability of a quickly estimation of the risk level. Remote sensing instruments, combined with simulation models, can provide production forecasting and allow the identification of stress factors, designed to agricultural activities corrections also with a precision agriculture perspective (Cook and Bramley, 1998). The methodology commonly adopted utilizes climatic simulation models and weather generators. Great efforts have been devoted to weather forecasting investigations. The study of the climate statistical properties has allowed the development of climatic stochastic models (weather generators) for the generation of weather data (Jones *at al.*, 1970; Richardson, 1981; Larsen and Pense, 1982; Shu Geng *et al.*, 1985; Richardson and Nicks, 1990; Semenov *et al.*, 1998; Donatelli *et al.*, 2005; Donatelli *et al.*, 2009; Birt *et al.*, 2010).

Weather generators (*WG*) are stochastic models, which produce meteorological data of indefinite length, on the base of climatic parameters estimated from historical meteorological data series. Application of weather generators permits 1) Monte Carlo simulations to obtain probability distributions of agro-ecological variables related to climate, 2) spatial interpolation of the climate parameters (thus obtaining data for locations not covered by meteorological stations) and 3) assessment of environmental scenarios depending on climatic changes. The use of *WG* was considered of fundamental importance for the sustainability analysis of the cropping and farming systems; in fact, in this way it is possible to consider the climatic variability obtained from long term climatic series.

In this chapter *Climak* (Danuso and Della Mea, 1994; Danuso *et al*., 2011; Rocca *et al*. 2012) weather generator is presented. *Climak* was developed in the early '90s and provided significant results (Acutis *et al*. 1999; Danuso, 2002). The new version, named Climak 3, allows also the generation of wind speed data and has been developed and has been implemented using the SEMoLa language (Danuso, 2003). *Climak* has a structure similar to that of other weather generators; it generates daily total precipitations (*Prec*), daily minimum and maximum air temperatures (*Tmin, Tmax*), daily integral of solar radiation (*Rg*), evapotranspiration (*ETr*) and daily wind speed (*Winds*) (Table 3.1). For the evapotranspiration, this could be generated from real measured evapotranspiration or from calculated reference evapotranspiration (Allen *et al*., 1998).

The weather generation procedure consists of 1) estimation of climatic parameters from historical meteorological data, and 2) data generation based on the statistical parameters obtained (Figure 3.1).

Table 3.1 Meteorological variables considered by Climak

Meteorological variable	Abbreviation	Unit
Precipitations	Prec	mm
Minimum temperature	Tmin	°C
Maximum temperature	Tmax	°C
Solar radiation	Rg	$MJ/m^2/d$
Evapotranspiration	Etr	mm
Wind speed	Winds	m/s

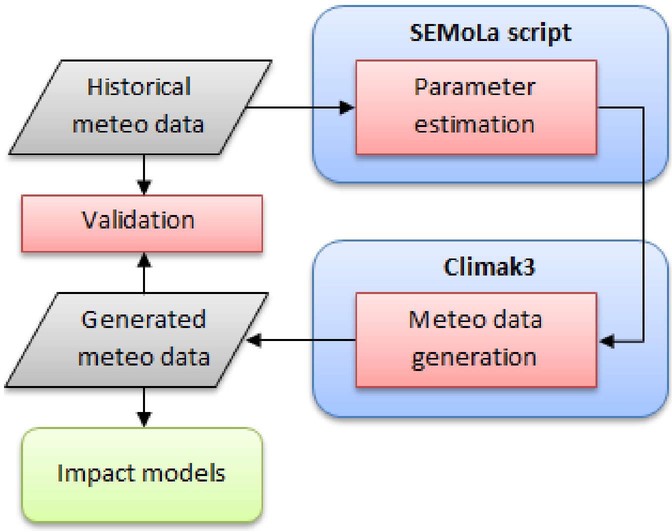

Figure 3.1 Application of the Climak weather generator

As a first step, *Climak* generates the occurrence of rainy or dry day and the rainfall amount, if the day is rainy. After rainfall generation, minimum and maximum air temperatures are generated, separately, for rainy and dry days. Solar radiation is obtained from the extra-terrestrial radiation or daylenth and from the daily thermal excursion.

The evapotranspiration is generated from the solar radiation data; if data of solar radiation are not available, evapotranspiration is obtained from daylenth and maximum temperature. In the end, wind speed values are generated (Figure 3.2).

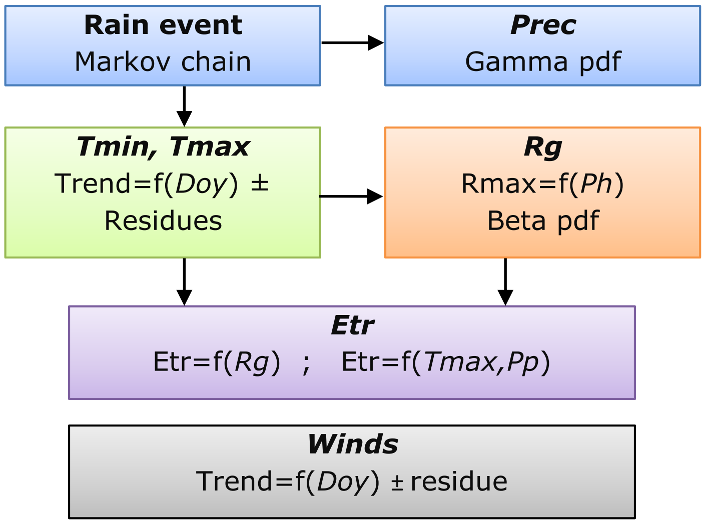

Figure 3.2 Procedure of generation of meteorological variables. Rain events are generated with a first degree Markov chain, will precipitation (prec) amount is sampled from a Gamma distribution. Temperature Tmax and Tmin) are generated sampling the residues from a normal distribution. Radiation (Rg) is simulated using a beta distribution. Evapotranspiration is generated as a function of Rg or Tmax and daylenth. Wind speed (winds) is generated sampling residues from a normal distribution. Most of parameters are specific for each month.

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4 Simulation of the cropping system

In this chapter the modelling approach for the simulation of the cropping system is described. For this aim, four steps were performed: 1) improvements and adaptation of the CSS model; 2) validation of CSS using previously obtained experimental data from a national project on topinambur: 3) development of a simplified version of CSS (MiniCSS) easy to use and endowed of a GUI (this was also the base for the development of the DSS software); 4) Case study for the calibration of MiniCSS; 5) development of the X-crop software (CSS improved model and a specific GUI and data management system).

4.1 CSS model description

CSS Cropping system simulator (Danuso *et al*. 2012) is a generic daily steep simulation model. CSS is developed using interconnected modules (Figure 4.1) that considers the whole cropping system, such us, crop and soil dynamics and their interactions with the environment, i.e. crop phenology, crop biomass production, reduction of potential yield depending on water and nitrogen deficiency and soil dynamics (water, nitrogen, phosphorous, organic matter, crop residues).

CSS requires daily data of air maximum and minimum temperature, water supply to the crop (precipitation and/or irrigation), evapotranspiration and radiation. The model has a parameter file containing soil and crop characteristics and management conditions.

The crop (*CSS-CropYield*) module constitutes the part of the cropping system responsible in simulating the crop growth dynamics using information from all modules. The model is generic so the same algorithms are used for the simulation of different crops (wheat, corn, soybean, etc.), in relation to the specific parameters adopted.

Similarly to most crop simulation models developed in the recent years (Ritchie *et al*., 1984; van Keulen and Seligman, 1987; Williams *et al*., 1989; Supit *et al*., 1994; Danuso *et al*., 1999; Porter *et al*., 2000; Stöckle *et al*., 2003; Brisson *et al*., 2003), the crop growth is linked to the evolution of phenological stages. The accurate quantification of the duration this stages, in fact, is particularly important since crop physiological processes change in relation on crop phenological age.

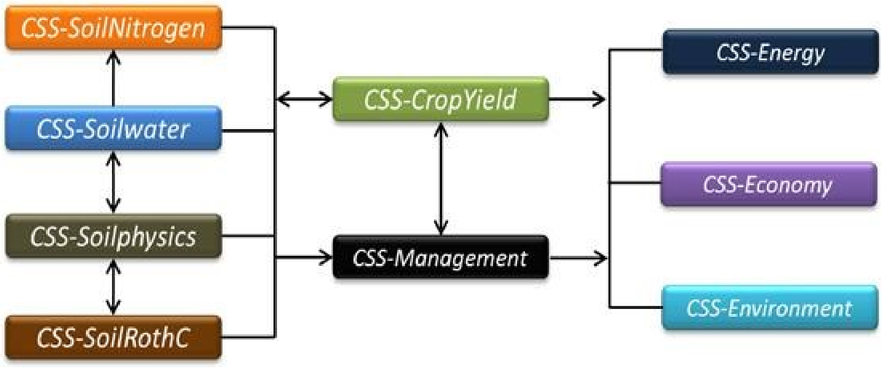

Figure 4.1 Modular composition of CSS each module use and give information from/to all the system. Four modules deals with soil dynamics (nitrogen, physics, water and carbon-RothC), two with crop production (crop yield, including phenology and biomass accumulation, and management) and three modules for the accounting (economic, energetic and environmental)**.**

The variable that most influences the phenological development, and the transition from one phase to another is air temperature. The most used approaches for the phenology simulation is based on the calculation of the growth degree day (GDD) expressed in °C·d or based on the phenological index (i.e. the fraction of time required to switch from one phenological state to another), also considering the temperature as the main driving force. In many models, correction factors related to water stress, photoperiod and vernalization have been introduced. The use of these factors makes the model sensitive to soil conditions (e.g. water stress) and the specific climate of each location (daylength, temperature). The module calculates phenology, for each simulation step, in two alternative ways: *i*) with the accumulated degree days (GDD, Growing Degree Days, °C·d) or *ii*) with the accumulation of a phenological index. The phenological stages are expressed as code number. In this model, each phenological stage is identified by an integer value (1 to 7), plus a code 0, indicating the absence of crop:

0 - absence of a crop

1 - emergence phase (from sowing or emergence to the beginning of the swelling of the buds sprouting)

2 - complete cover of the soil (from the emergence to the complete soil cover)

3 - vegetative stage (from the soil cover phase to flowering phase)

4 - flowering stage or set (from the beginning of flowering to the beginning of accumulation)

5 - accumulation phase (from the beginning of the accumulation phase to physiological maturity)

6 - maturation phase (from physiological maturity to the maturity of yield sinks)

7 – waiting for harvest (from full maturity to harvest).

The stage of development is defined by the parameter Cstage that has an initial value 0, when the crop is not yet sown, while at the day of sowing its value becomes equal to 1. When the variable GDD (degree days cumulative) or the penological index (Iphen) reaches certain threshold values, established *a priori* and specific for each crop, the value of Cstage is changed by one unit through the phenological events listed below. The values of Cstage are numeric codes that indicate in which phenological state is the plant at any time of the simulation. Cstage is reset to 0, at the end of the growing season, at the moment of harvest. The threshold values of degree days accumulated, specific for each crop, are represented by the following parameters:

- GDD or Iphen for emergency
- GDD or Iphen for covering ground
- GDD or Iphen for end vegetative stage
- GDD or Iphen for start accumulation
- GDD or Iphen for physiological maturity
- GDD or Iphen for harvest maturity

The cumulate value of the degree-days (effective temperature), measured in ° C · d, is described by a state variable of the system. The increments are given by the difference between the mean daily air temperature and the temperature below which is considered that the crop remains in a state of standstill (base temperature, Tbase). If the mean temperature is less than the base temperature, the daily increase equal to zero. The value of the base temperature is specific for each crop. The phenological index, instead, is described as a state variable (Iphen) that through a daily rate accumulates the fraction of time needed to reach the next phenological stage. Both the accumulation of degree-days and the phenological index may be affected by water stress, acting in the simulation by a factor Pws, and subject to modification due to their sensitivity to photoperiod (for some crops only).

Water stress can change the speed of accumulation of degree-days through the variable Pws; since the effect of water stress is different in vegetative phase and during accumulation phase, making longer the first and reducing the duration of the second, so, two different modes of calculation are taken, according to the phenological stage in progress. This behavior is activated using an on-off parameter, if the phenology of the crop is sensitive to this phenomena.

The CSS model simulates the crop growth with an approach based on the assimilation of carbon dioxide. This approach is common among different models developed in the last decade (Supit *et al*., 1994; Porter *et al*., 2000). Moreover some other factors have been included for the reduction of growth rate in the presence of conditions far from the optimal: water stress, temperature and nitrogen deficiency. The module of the crop growth provides, for each simulation step, the value of the biomass of the crop (divided into leaves, stems, roots and accumulation organs).

In the model, the crop biomass accumulation is directly related to the assimilation of carbon dioxide and to the absorbed radiation. The photosynthetically active radiation incident (PARinc) is a fraction of the global radiation on the Earth's surface (Rg). Absorbed active Radiation is calculated as a fraction of the radiation incident active. The fraction of incident PAR that is reflected from the cover and the fraction absorbed by the ground are excluded. This is achieved by using an absorption coefficient (CoefAss). CoefAss is fucntion of albedo and is calculated us:

$$CoefAss = (1 - Albedo) \cdot (1 - \exp(-CoefEst \cdot LAI))$$

where *CoefEst* is a crop parameter thar rapresent the light extinction coefficient an can be a number from 0-1; and LAI is the leaf area index, calculated day by day in function of *Wleav* (mass of leaves).

The total biomass of the crop (Wcrop, $t \cdot ha^{-1}$) is given by the sum of four state variables: mass of leaves (*Wleav*), stems (*Wstem*), accumulation organs (*Wstor*) and roots (*Wroot*). The biomass of crop part is calculated through four distinct growth rates (GRLeav, GRstem, Grstor and GRroot, expressed as $t\ ha^{-1}\ d^{-1}$) which, only in the case with Cstage> 0, they assume values different than 0. The initial value of biomass is related to the amount of biomass of the sowed seeds. The harvest, biomass accumulated goes in part to the harvest and partly to the residue, and the amount collected is equal to the biomass accumulation of the organ chosen to be harvested. A specific rate (WstoHar) transfers the biomass accumulation in organs collected at the corresponding event (Harvest).

Each of the four rates - related to leaves, stems, roots and accumulation organs - is directly proportional to the absorption of CO_2 through a net carbon fixation coefficient (FissPar; for each mole of CO_2 absorbed, one mole of CH_2O is produced; therefore, using the molecular weights, 44 for the CO_2 and 30 for CH_2O, it is obtain 30/44 value). The amount of CH_2O is partitioned with the PartLeav, PaerStem, PartStor and PartRoot coefficient for leaves, stems, roots and storage organs, respectively. Moreover a specific factor (FCN), whose values are between 0 and 1 in relation to the amount of nitrogen in crop (Ncrop) and the theoretical optimum amount of nitrogen in crop (Nopt), allows to reduce the growth rate in the presence of nitrogen stress.

The root deepening (Dr, measured in mm) is obtained by integrating the actual rate of deepening (Drate, mm · d^{-1}), starting from an initial depth equal to the depth of sowing (Dsow). The actual root deepening rate (Drate, mm · d^{-1}) is obtained from the maximum rate (Rmax, specific for each crop), by applying a reduction factor related to phenology stage. Effects of water availability, mechanical resistance of the soil structure are not considered in this model.

$$Drate = Rmax * TstrFac * \left(\frac{1}{1 + \left(\frac{Iphen}{5}\right)^{20}} \right)$$

The soil water module is based on a modified version of the model Bidrico 2 (Danuso *et al.*, 1995). It is a cascade model which considers the soil divided into three compartments (surface, radical and deep layer), each of them which containing a reserve of water, that varies over time (Figure 4.2).

The first state is a dynamic surface water reserve (Rs), i.e. the water temporary stagnation. This is calculated dynamic according to the amount of daily rainfall o irrigation (Rain, Wirri), daily evaporation and IncRs.

$$RS = RS + dt \cdot (Rain + IncRs - EvapoRs)$$

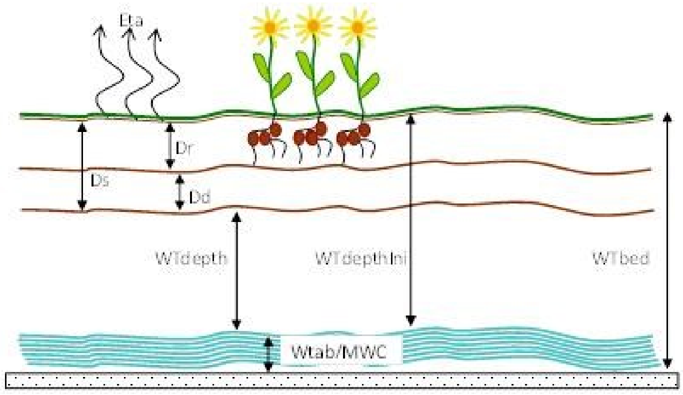

Figure 4.2 Soil layers as described by the CSS model.

IncRs is the increase of water reservoir and depends on the deficit (DefRs) of water that the surface of soil can support.

Below the surface there is root water reserve (Rr), i.e. the water contained in the root explored soil layer. The depth of this layer varies over time due to the root deepening.

$$Rr = Rr + dt \cdot (IncrRr + CRr - ETa)$$

IncrRr that is the daily increase of water in Rr, is calculated as the minimum between IncrRrVi and IncrRrDef which are respectively the increase limited to the intrinsic characteristics of the soil and moisture reached by the ground itself. CRr is the water that is added in Rr from capillary rise and Eta and the real evapotranspiration, which depends on reference evapotranspiration and the crop coefficients (Kc).

The deep water reserve (Rd) is the water contained in the layer of soil between the maximum depth reached by the roots and the maximum soil depth. This is calculated in a similar way to the previous one; however, the depth of the layer is reduced with the root growth.

The Economy module calculates the costs of resources (including variable and fixed costs) and revenues for specific crop production, after harvest crops are sale with a price establish as a crop parameter. The Energy modules compute both the energy inherent in the crop and the direct and indirect energy used by crops. The LCA approach based on trans-formation coefficients has been used (Pimentel, 2003; Venturi, 2003) in the energy crop module. The information obtained by the energy modules can be used for balance purposes or to estimate the farm EROI (ratio between energy output and input). The Environment module accounts for the direct and indirect inputs and outputs between farm and the environment for CO_2, nitrogen emission (using an implementation of the IPCC approach) and leaching. The complete SEMoLa code of the CSS model is reported in appendix I.

4.2 CSS validation on Jerusalem Artichoke *(Helianthus tuberosus* L.) in different Italian growing areas

Jerusalem artichoke can be considered as both a sugar and dietary fibre crop, as it accumulates linear polymers of fructose (fructans, also known as inulin) in its roots, tubers and stalks, with a highly variable degree of polymerization (4-150 DP), which affects their end-use. Fructans with low DP and fructose, obtained by hydrolysis of the fructans, are often used directly as dietary fibres or as low-calorie sweetening syrups, while inulin with high DP (10-30) is used entirely for industrial and non-food uses such as pharmaceuticals and cosmetics (Fuchs, 1993; Danuso, 2001).

One of the main problems of today's sugar processing industry is the need to extend the harvest season, in particular by anticipating it, with compensation given to farmers for the lower yield of earlier harvests. Jerusalem artichoke is today relegated to small areas mainly for the production of tubers for human or livestock consumption, so there could be interesting prospects for high earning potential with an early whole-plant harvest (stalks + tubers). This harvesting method has always produced higher yields than the traditional harvest of tubers alone, with the agronomic advantage of freeing the land earlier (Paolini *et al*., 1996; Baldini *et al*., 2004). The crop can be practised as i) an annual crop, with the harvest of stalks and tubers together or ii) a multiyear crop, harvesting only the aerial biomass each year (D'Egidio *et al*., 1998; Baldini *et al*., 2006).

The above-mentioned considerations and the current need to find new renewable energy sources, open new prospects for Jerusalem artichoke as a biomass crop for energy uses, particularly for liquid biofuel production (bioethanol - Curt *et al*., 2006), methane from anaerobic digestion (Lehtomaki *et al*., 2008) and gas from pyrolysis (Encinar *et al*., 2009).

In order to analyse the feasibility of these possible crop uses in different environments, the calibration of dynamic simulation models to forecast the plant growth, stalks and tubers biomass production depending on soil and climatic conditions, cropping techniques and genetic material, may result particularly useful (Meijer *et al*., 1993; Allirand *et al*., 1988; Spitters, 1988).

The aim of this work is application of the CSS model (Cropping System Simulator; Danuso *et al*., 1999) to the Jerusalem artichoke crop, using data obtained from experimental trials conducted in different Italian areas within the framework of the PRIN Project (MIUR), entitled "Colture per la produzione di inulina: modelli di risposta ambientale e strategie colturali".

4.2.1 Experimental trials

Trials on Jerusalem artichoke (*Helianthus tuberosus* L., "Violet de Rennes" variety) were conducted over the two years 1999-2000, by the Working Groups taking part in the PRIN project, in three areas of Italy: Udine, Policoro - Bari and Cadriano – Bologna (Table 4.1). In each environment the effects of two different production factors were evaluated: time of harvest; irrigation regime with two treatments: a) replacement of total evapotranspiration and b) dry regime (rain-fed crop with aid irrigation).

Table 4.1 Working groups and locations of the experimental sites

Working Groups	Locations	Altitude m a.s.l.	Latitude	Longitude
University of Udine	Udine (UD)	110	46° 03'N	13° 13'E
University of Bologna	Cadriano (BO)	33	44° 30'N	11° 20'E
University of Bari	Policoro (BA)	31	40° 20'N	16° 70'E

Tubers (average weight 50-70 g each) where manually planted at a depth of 3-4 cm, in rows 0.7 m apart and with a distance between plants on the row of 0.25 m (0.20 m in Bologna), giving a planting density of 5.7 tubers m-2 in Bari and Udine and 7 tubers m-2 in Bologna. The trial design was split-plot with 4 replications. The experimental unit was 5 rows of 12 metres in length in Bologna, giving an area of 42 m-2, and 8 rows, 8 metres long in Udine and Bari for an area of 44.8 m-2. Dry matter accumulation was evaluated collecting by hand five plants for each plot at different plant phonological phases covering the total growing season until the standing crop was naturally dried. In particular, the number of samplings varied from 6 to 11, depending from the different locations, with a time of about 10-15 days between two consecutive harvests. At each sampling, the fresh and dry weights of leaves, stems (with ramifications) and tubers (without stolons) were measured.

The code of the CSS model has been modified in order to improve its capacity to represent crops like Jerusalem artichoke or potato, in which the translocation of assimilates from stalks to tubers, at the end of the cycle, is relevant. This is a specific physiological process, not existing in grain crops like maize or wheat. The decreasing of leaves and stem weight at late growth stages due to senescence and translocation has been described in CSS through two interrelated aspects: i) no more biomass is allocated to leaves and stems after the physiological maturity stage; ii) part of their biomass is lost through senescence while the rest is translocate to tubers (Table 4.2).

Table 4.2 Code of the *CSS_CropYield* module introducing the late assimilates translocation to tubers (SEMoLa language).

```
' ==== CSS assimilates traslocation ====
P Tras=0      onevt(Planting,Crop("Tras",CropCode))                          (1=yes/0=no)

R TrasStem=cond(GDD>GDDpm&Tras=1&FrostCrop=0,Wstem*KtrasStem,0)  Wstem->Wstor  (tB/ha/d)
R TrasLeav=cond(GDD>GDDpm&Tras=1&FrostCrop=0,Wleav*KtrasLeav,0)  Wleav->Wstor  (tB/ha/d)

P KtrasStem=0.02   onevt(Planting,Crop("KtrasStem",CropCode))                      (1/d)
P KtrasLeav=0.008  onevt(Planting,Crop("KtrasLeav",CropCode))                      (1/d)
```

FrostCrop flag indicating the crop frozen by low temperatures (1/0); Cond(…) conditional function; Crop(…) function that returns crop parameters as a function of CropCode; CropCode identification code of the crop (1=maize, 2=soybean, …); GDD temperature summation accumulated by the crop (°C d); GDDpm GDD required by the crop to reach physiological maturity (°C d); KtrasLeav translocation coefficient Wleav-Wstor (0.008); KtrasStem translocation coefficient Wstem-Wstor (0.02); Planting planting event; Tras translocation parameter, depending on crop code (1=yes, 0=no); TrasLeav translocation from leaves to storage organs (t ha^{-1}·d); TrasStem translocation from stems to storage organs (t ha^{-1}·d).

In this study, CSS has been parameterized and calibrated for Jerusalem artichoke by a “trial and error” procedure and using the SEMoLa calibration algorithm, with measured soil, climatic data and crop parameters obtained from the PRIN project experimental trials conducted in the different locations (Table 4.1).

4.2.2 Input data for simulations

To perform simulations, CSS requires meteorological data, soil parameters, crop parameters and parameters for the cropping scenario to be represented. These data have to be organized in four types of input data files: *exofile,* containing exogenous variables (meteorological data), *parfile* with soil and crop parameters, *evtfile* declaring time, type and modality of every cropping practice (events), and *actfiles* (one for each event type), containing the “actions” or parameters of each application of cropping techniques. At run-time, and before the beginning of the simulation, parameters values of *parfile* are set and their values usually remain the same throughout the simulation; however, their values can be changed during the crop cycle by the event instances of the *evtfile*; these instances make reference to specific sets of parameter values in the corresponding *actfile* and then immediately modify the current parameter values. The modifications of the parameter values by events are considered the “actions” of the event; in this case parameters act in the system like “switches”. For example, the simulation can start with the crop parameters for “fallow”; when the event *Planting* occurs, all the crop parameters (for phenology, light interception, growth, etc.) are changed depending on the sown/planted crop. This allows the simulation of crop rotations with different types and amount of crop inputs. Every event type of the *evtfile* has a related *actfile*, with the same name of the event; for example, “*Planting.act*” is the *actfile* for the event *Planting* and contains different sets of parameters for the different application mode of the event.

The user can also change and increase the number of parameter sets in *actfiles*. In the case of organic fertilization, the event *OrgFert* has the *actfile* “*OrgFert.act*”, which contains parameter sets specifying the characteristics of different organic fertilizers like manure, straw, slurry, etc. *Exofiles*, *parfiles* and *evtfiles* can contain (as *actfile*) more than one dataset. These can be combined in any way to create the simulation file (*simfile*). Each row of the *simfile* specifies a distinct simulation with specific climatic, pedological and agronomic conditions. All the simulations of *simfile* are launched in the same run.

Table 4.3 Values of the soil parameters measured in the different sites and adopted to run the CSS model

Name	Soil parameter	Cadriano (BO)	Policoro (BA)	Udine (UD)
Gravel	Gravel volumetric content (%)	0	0	15
Sand	Sand content (%)	37	40	43
Clay	Clay content (%)	18	23	17
OM	Organic matter (%)	1.3	3.6	2.9
$CaCO_3$	Total carbonates (%)	1	6	3
Ds	Max exploitable soil depth by roots (mm)	3000	2500	500
MWC	Max water content fine fraction (mm/mm)	0.5	0.58	0.56
FC	Field capacity (mm/mm)	0.26	0.38	0.31
WP	Wilting point (mm/mm)	0.12	0.14	0.15
Dw	Soil working depth (mm)	400	400	400
Wtbed	Depth of the water table bed (mm)	20000	20000	60000
WtdeptIni	Initial depth of the water table (mm)	2500	2000	40000

Experimental data were used for the parameterization and calibration of the model. Values that could not be obtained from the experiment were obtained from the literature. A list of the soil and crop parameters resulting from the parameterization and used for the final simulations are reported in Table 4.3 and Table 4.4.

The main soil characteristics measured for each site and used for the simulations are given Table 4.3. The soil in Udine was very shallow (about 50 cm) and without groundwater useful for the crops, while in both Bologna and Bari the contribution of groundwater was important.

During simulation, the *cropchoice* event changes the crop parameters values according to the specific crop selected from the *actfile*. These parameters were adjusted considering a reasonable range of variation, as dictated by previous research, knowledge or experience Table 4.4 and Table 4.5).

The daily meteorological data required by the model are: minimum and maximum air temperatures (°C), precipitation ($mm \cdot d^{-1}$), reference evapotranspiration ($mm \cdot d^{-1}$) and global radiation ($MJ\ m^{-2}\ d^{-1}$). The trends of maximum and minimum temperature and rainfall reported in

Figure 4.3 show the meteorological conditions during the different trials.

The simulations for all the different environmental and agronomic conditions were obtained with the same calibrated crop parameter set and using the actual meteorological data, soil characteristics and cropping scenario. In this way the crop parameters found by calibration can be considered valid for all growing conditions.

Table 4.4 General crop parameters of CSS. The values adopted and calibrated for the simulation of the Jerusalem artichoke crop are reported. The estimation method is indicated: from literature (L), calibrated against experimental results of crop biomass (C) and from common agricultural knowledge (A).

Parameter	Description	Value	Estimation
AEffCoef	Potential assimilation efficiency coefficient (gCO_2/MJ)	8	L (1)
AlloWS	Allowed water stress	0.2	L (1)
CNcrit	Critical N concentration in plant (kgN/t)	0.65	L (1)
CoefEst	Light extinction coefficient	0.8	C
ConvLeCo	Conversion of CH_2O to leaves biomass (t/tCH_2O)	0.59	L (1)
ConvRoCo	Conversion CH_2O to roots biomass (t/tCH_2O)	0.71	L (1)
ConvSmCo	Conversion CH_2O to stem biomass (t/tCH_2O)	0.75	L (1)
ConvSrCo	Conversion CH_2O to storage organs biomass (t/tCH_2O)	0.71	L (1)
CRnc	Nitrogen content in crop residue (kgN/kg)	0.004	L (1)
Dsow	Sowing depth (mm)	90	A
FracResDPM	Fraction of DPM in crop residues	0.6	L (2)
LAIc	Critical leaf area index for stress	3.5	C
MDRWat	Max leaves death rate for water stress	0.03	L/C
Qsow	Seed sowing amount (t ha^{-1}·d)	0.7	A
Rmax	Maximum root deepening rate (mm/°C/d)	1.3	L (2)
Sls	Specific leaf surface (haLeaf/t)	2.5	L (1)
Taef1	Minimum temperature for CO_2 assimilation (°C)	5	L/C
Taef2	Temperature for 25% opt. CO_2 assimilation (°C)	10	L/C
Taef3	Minimum optimal temper. for CO_2 assimilation (°C)	15	L/C
Taef4	Maximum optimal for CO_2 assimilation (°C)	38	L/C
Taef5	Maximum temperature for CO_2 assimilation (°C)	45	L/C
Tbase	Base temperature for development (°C)	9	L/C
Ync	N content in yield (kgN/kg)	0.005	A

(1) From SUCROS; (2) from CSS.

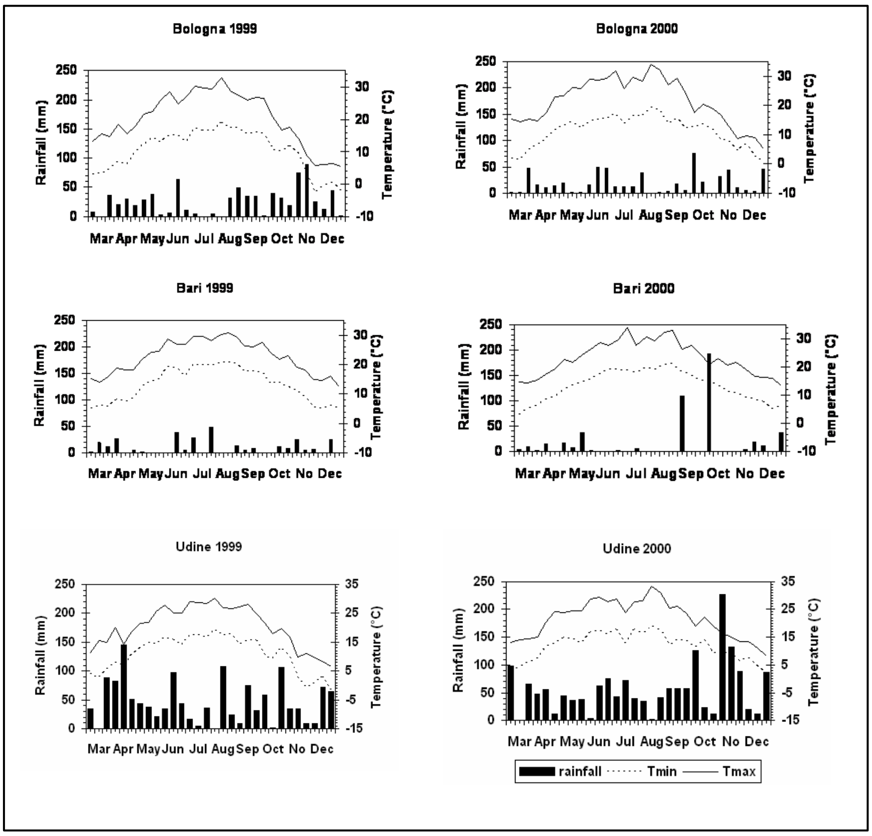

Figure 4.3 Ten-day total rainfall, and maximum and minimum temperature at experimental sites during 1999 and 2000.

In CSS the cropping techniques are considered as "events", i.e. as phenomena that happen and instantaneously modify parameters and states of the system. At present, the following events can be selected to build cropping scenarios: planting, organic and mineral fertilization, irrigation, harvesting, residue chopping, harrowing, hoeing, extirpation, chiselling, ploughing. The sequences of cropping techniques are saved in event files (*evtfiles*). The agronomic techniques adopted during experimental trials are inserted in the *evtfiles* to perform the simulation Table 4.6 and Table 4.7).

Table 4.5 Crop parameters of CSS related to the development stage of the crop. For each parameter, five values have to be inserted corresponding to the following stages: plant emergence from soil, complete soil covering, end of vegetative phase, start of accumulation in storage organs, physiological maturity and harvest maturity. During simulation, the current value for these parameters are obtained by linear interpolation among these values and as function of current value of accumulated GDD. The estimation method is indicated: from literature (L), calibrated against experimental results of crop biomass (C)

Parameter	Symbol	Emergence	Complete soil covering	End vegetative phase	Start accumulation	Physiological maturity	Harvest maturity	Estimation method
Growing Degree Days	GDD	90	490	900	1200	2400	3000	C
Crop coefficients for water use	Kc	0.35	0.6	1	1	0.35	-	L (1)
Optimal N concentration	No	20	20	12	10	8	-	L/C
Growth fraction leaves/shoot	LF	0.6	0.4	0.3	0.15	0.1	-	C
Growth fraction stem/shoot	SF	0.4	0.6	0.7	0.8	0.4	-	C
Total growth fraction root	RF	0.05	0.05	0.01	0.01	0	-	C

(1) from FAO (Allen *et al.*, 1998).

4.2.3 Results and discussions

Some simulation examples concerning biomass accumulation (t ha^{-1}·d dry matter) are presented below, in comparison with data obtained from the growth analysis experiments. The general capability of the model to represent different environmental situations appears to be good.

In Figure 4.4 and Figure 4.5 the biomass accumulation observed and simulated under rain-fed and irrigated conditions is distinctly reported for the different plant organs. A good corresponding between simulated and measured values can be remarked, particularly for biomass of tubers and leaves. About stalks, otherwise, the simulated accumulation trend turns out to be slightly in advance in comparison with those obtained experimentally. A not exact representation of the timing of assimilates storage by the stems and the further reallocation of the storage reserves to the tuber in rapid growing can be observed.

Table 4.6 Main cropping management techniques adopted for Jerusalem artichoke

	Bari 1999	Bari 2000	Bologna 1999	Bologna 2000	Udine 1999	Udine 2000
Soil tillage	ploughing at 40 cm, harrowing (2)	ploughing at 40 cm, harrowing (2)	ploughing at 30 cm, harrowing, pre-planting puckering	ploughing at 30 cm, harrowing, pre-planting puckering	ploughing at 40 cm, harrowing (2)	ploughing at 40 cm, harrowing (2)
Fertilization (kg/ha N, P_2O_5, K_2O)	pre-sowing + post-emergence 150-120-0	pre-sowing + post-emergence 150-120-0	pre-sowing + post-emergence 100-100-0	pre-sowing + post-emergence 100-100-0	pre-sowing 80-200-200	pre-sowing 80-0-125
Sowing time	12/4	27/03	12/04	14/04	25/03	21/03

Table 4.7 Natural and artificial water supply during the crop cycle for the different cropping scenarios.

Environment	Year	Thesis	Number of irrigations	Irrigation water (mm)	Rainfall (mm)(1)	Total water received by crops (mm)	Groundwater availability
Udine	1999	rain-fed	6	52	1145	1197	No
		irrigated	12	110	1145	1255	No
	2000	rain-fed	2	70	1104	1174	No
		irrigated	6	210	1104	1314	No
Bologna	1999	rain-fed	0	0	516	516	Yes
		irrigated	12	318	516	834	Yes
	2000	rain-fed	0	0	410	410	Yes
		irrigated	11	361	410	771	Yes
Bari	1999	rain-fed	14	143	237	380	Yes
		irrigated	14	570	237	807	Yes
	2000	rain-fed	11	115	403	518	Yes
		irrigated	11	451	403	854	Yes

(1) Rainfall is referred to the period March-October.

Differences observed between measured and simulated data for biomass accumulation in tubers during the last growing phase in Udine and Bologna 1999, could be explained with the quick physiological changes due to climatic variations; in fact, in October and November of the above-mentioned year, a sudden temperature decrease, in correspondence of the last harvest times, is observable (figure 4.6). This fact could have trigged off a translocation rate increase and a strong reduction of the remobilization of reserves from stalks to tubers period. This becomes more evident when the harvest has been delayed in Bologna during the first year. These results emphasize the difficulties found in survey methodology and model implementation to represent these particular physiological adaptations, suggesting shorter surveys intervals during this growing phase, when the translocation rate is increasing.

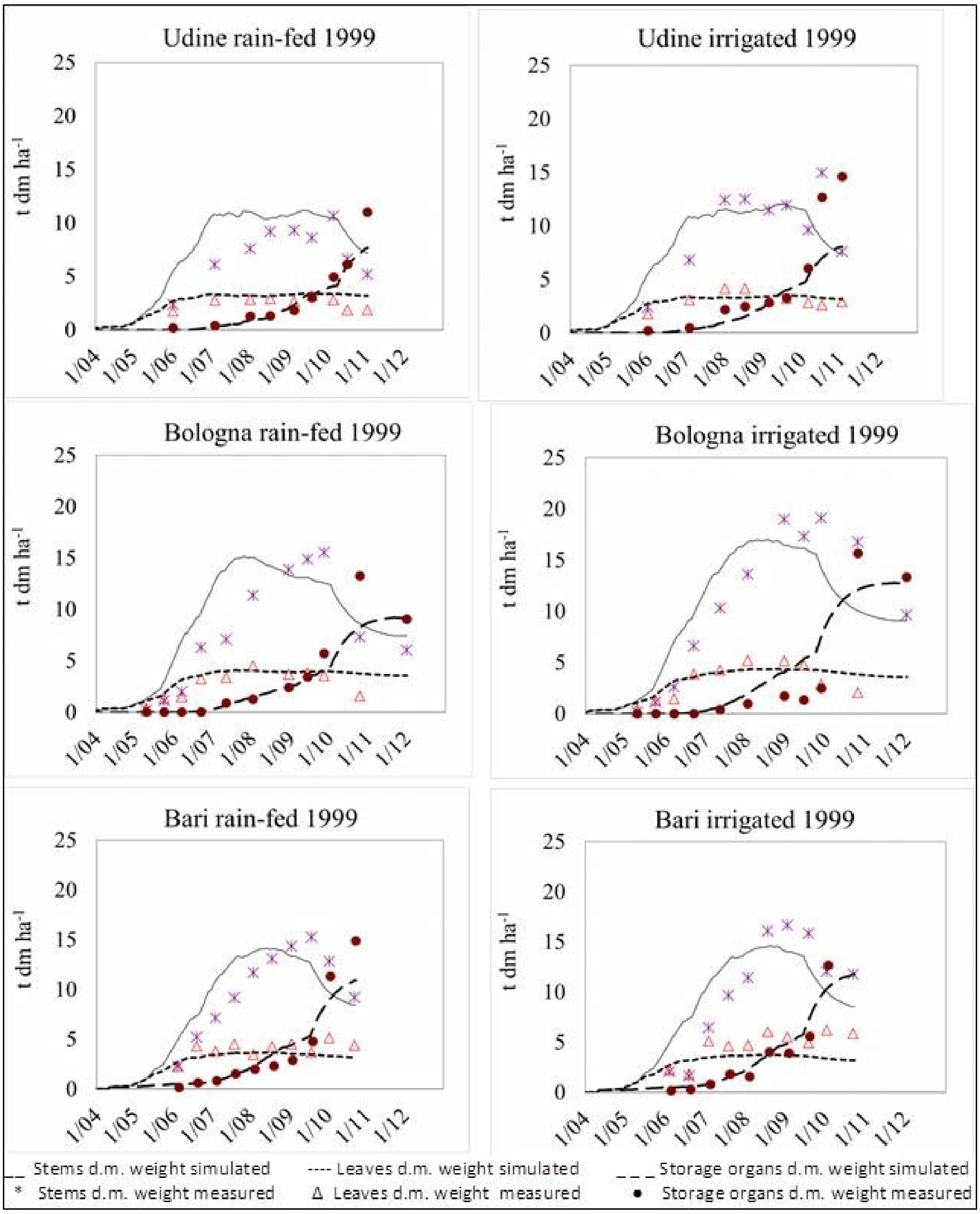

Figure 4.4 Leaves, stalks and storage organs biomass accumulation, as simulated by CSS, in comparison with the experimental growth data for the three locations and the two irrigation regimes (year 1999).

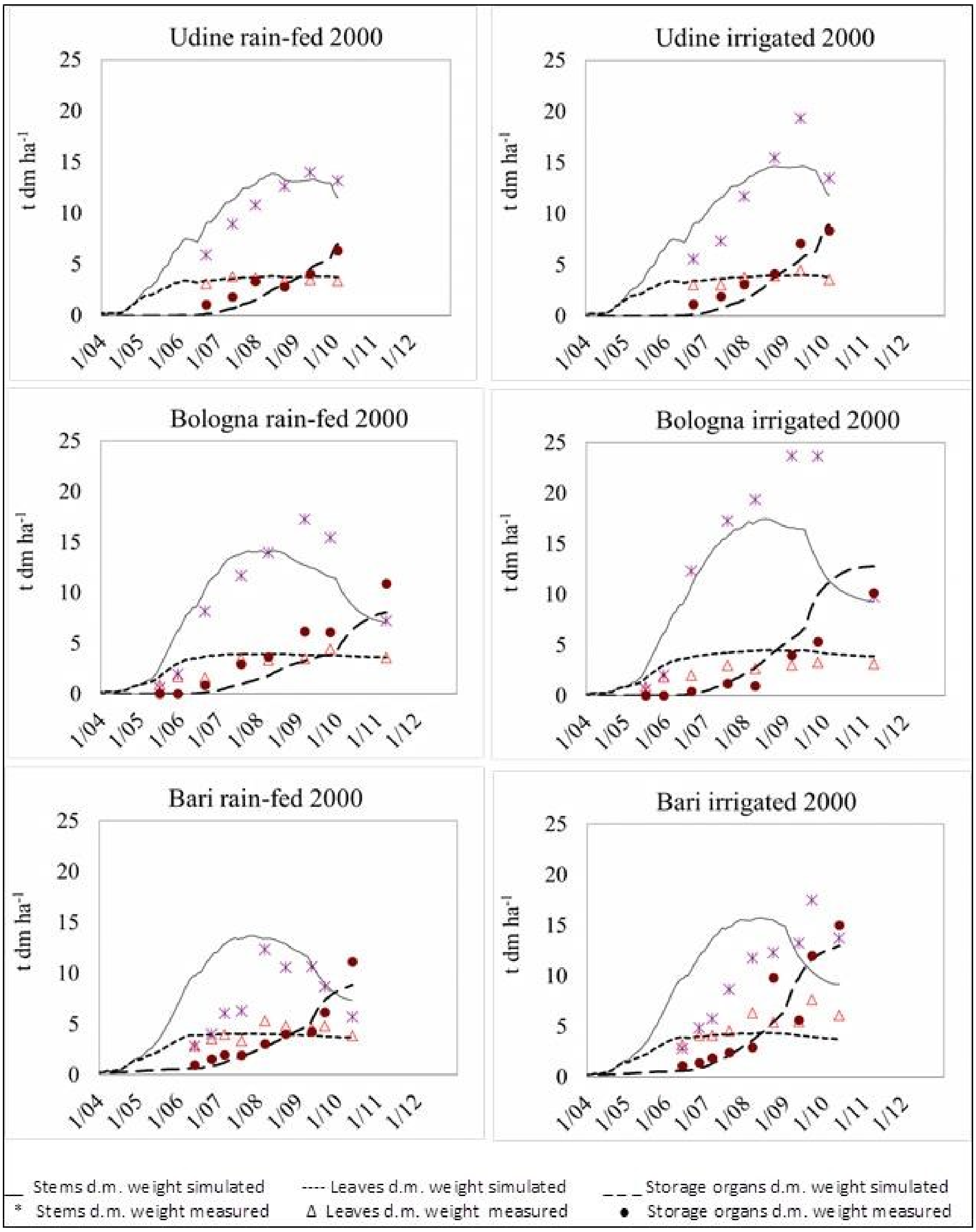

Figure 4.5 Leaves, stalks and storage organs biomass accumulation, as simulated by CSS, in comparison with the experimental growth data for the three locations and the two irrigation regimes (year 2000).

On the other hand, comparing the total biomass accumulation for Jerusalem artichoke in the different growing areas, during the same crop season and under rain-fed conditions (Figure 4.6), it is evidenced that the model is able to satisfactorily represent the maximum yields in biomass. In some cases the irrigation in the trials had a very limited effect on the biomass yield: this has also been well reproduced by the simulation. In these environments, in fact, the effect of the irrigation regime was very limited due to the favourable climatic conditions, good soil characteristics or shallow water table. Notwithstanding this, the model has also proved to be equally sensitive to these limited contributions.

Table 4.8 Model validation statistics of comparison of simulated and observed data for irrigated and rain-fed Jerusalem artichoke, at Udine, Bologna and Bari, for the two years (total biomass).

Environment	Year	Thesis	$RMSE_{(1)}$	$EF_{(2)}$	$CD_{(3)}$	$CRM_{(4)}$	$MaxAE_{(5)}$
Udine	1999	irrigated	4.88	0.52	0.25	0.06	10.87
		rain-fed	3.43	0.30	1.02	-0.22	5.66
	2000	irrigated	3.40	0.79	0.35	0.00	6.30
		rain-fed	1.54	0.87	0.69	-0.07	2.97
Bologna	1999	irrigated	3.62	0.87	0.76	-0.13	6.63
		rain-fed	4.18	0.74	0.71	-0.18	7.81
	2000	irrigated	3.43	0.90	0.60	-0.05	5.97
		rain-fed	4.46	0.76	0.35	0.01	6.69
Bari	1999	irrigated	9.35	0.48	0.19	0.11	26.26
		rain-fed	3.76	0.75	0.38	0.00	7.17
	2000	irrigated	5.25	0.45	0.66	-0.24	7.45
		rain-fed	4.92	0.13	0.55	-0.22	7.71

(1) RMSE=root mean square error
(2) EF=modelling efficiency
(3) CD=coefficient of determination
(4) CRM=coefficient residual mass
(5) MaxAE=maximum absolute error

In Table 4.8 is possible to notice some statistics (root mean square error, modelling efficiency, coefficient of determination, coefficient residual mass and maximum absolute) for the model validation (Janssen and Heuberger, 1995) for the different growing areas, thesis and crop seasons, obtained by the SEMoLa framework.

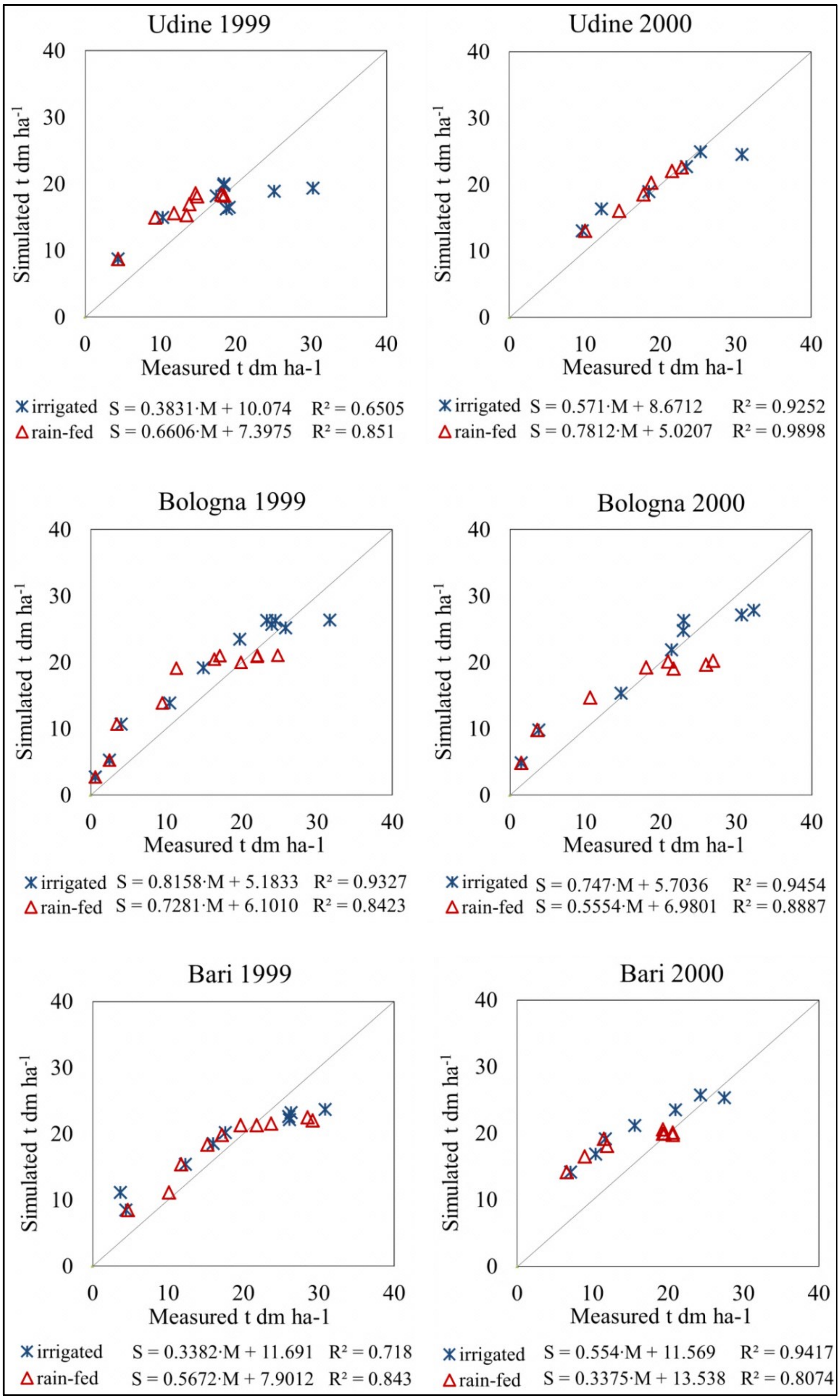

Figure 4.6 Total biomass accumulation obtained by simulations, in comparison with data measured for irrigated and rain-fed Jerusalem artichoke, at Udine, Bologna and Bari, for the two years.

The capability to well represent the experimental results on Jerusalem artichoke obtained in very different environmental and agronomic conditions (from northern to southern Italy) suggests the possible usefulness of the CSS model as a tool for the planning and risk evaluation of introducing Jerusalem artichoke as a crop for energy or inulin production. The model, despite a simplified description of some processes (for example, soil water dynamics) seems to be adequately responsive to the main environmental factors causing yield and biomass production variation among years and locations.

Indeed, the simulations confirm, at least for the yield in total biomass, the possibility of using the model to evaluate the different crop management techniques and Italian soil and climatic conditions, even if the model has been primarily developed to simulate annual herbaceous crops, yielding seeds and not tubers and stalks as in the case of Jerusalem artichoke. However, further model improvements are necessary in order to better represent phenology, partitioning and translocation of the assimilates among the plant organs. In particular, the “source-sink” relationship between stalk and tuber during the development phases of the plant and in different environments will have to be better clarified and modelled. In fact, the tubers grow both by current photosynthates and by remobilization of reserves from other plant parts, mainly from the stalk. The transfer from stalk to tuber is known to be up to 50% of final tuber dry weight, depending on many factors: temperatures, flowering time of the cultivar, aerial structural growth, tuber sink capacity, with complicated competing sinks, at plant level, with changing hierarchical relations during the crop cycle (Denoroy, 1996). Efforts have to be made to better understand the mechanism of assimilates distribution among aerial structures and tubers in order to identify the optimal period to obtain the maximum biomass yield adopting an integral or an aerial harvest, within the perspective of considering Jerusalem artichoke a crop for producing raw material for energy use at competitive prices.

In conclusion, CSS allows several aspects related to the cropping system to be simulated. However, it is necessary to calibrate the model for each specific crop. Moreover, the development of a more detailed crop parameter database is desirable for further evaluation and improvement of the model for crops with high translocation of assimilates.

4.3 MiniCSS: a software for the optimization of crop irrigation and nitrogen fertilization strategies

It is commonly recognized that water resources are limited and, at the same time, the agricultural input costs (in monetary and energetic terms) are steadily increasing. Furthermore, due to climatic changes, precipitation seems to be decreasing in amount or, at least, received in a more irregular manner than in the past. From the other hand, civil and industrial water demand is growing, especially in developing countries (Acutis *et al.*, 2010).

Correctly deciding the amount and time of irrigation and fertilization of agricultural crops is a difficult task, since the decider must simultaneously consider phenological and nutritional crop status, forecast the weather pattern during the irrigation season and take into account the economic and energy budgets of the farm. To be able to treat all these complexities in an integrate way the use of crop simulation models is particularly indicated. These can be used as decision support tools for the management of cropping system, for the optimization of the cultural practices and to take decisions like planting date, cultivar selection, fertilization, or water and pesticides usage (Steduto *et al.*, 2009) but also for strategic aims.

Several authors have proposed simulation models to optimize crop irrigation (f.i., Danuso *et al.*, 1995, Bergez *et al*., 2002; Acutis *et al*., 2010) and nitrogen fertilization (Makowski *et al*., 1999). Most of these models have a very complex structure and require specific skills and long training period for a correct use. Moreover, the typical crop model needs a long time for a good parameterization and calibration. Therefore, the use of many models is strictly connected to academic and research contexts and have not wide-melted farmers and agricultural technicians, despite farmers are strongly encouraged to optimize the use of water and fertilizer and technicians are called to assist farmers with the responsibility of protecting the environment.

This chapter presents MiniCSS, a software application for the optimization of irrigation and nitrogen fertilization by simulation, developed with the primary aim to avoid these drawbacks by reducing to a minimum the requests to the users. This goal has been pursued with a reduced number of input parameters and with a user friendly dialog window. As in other cases (Steduto *et al*., 2009), the intention was to maintain an equilibrium between accuracy, simplicity and robustness.

The MiniCSS application is formed by three components: 1) the crop model simulation engine CSSmini; 2) a database of crop and soil parameters that can be selected or updated by the user; 3) the graphical user interface of the application (MiniCSS itself).

The implementation methodology of MiniCSS (Figure 4.7) has been carried out by developing two different and parallel work plans: the simulation engine and the user application.

The first involved the creation of a simple but robust crop simulation model to be used as calculation engine (CSSmini). This is a generic, daily step crop simulation model derived from CSS (Cropping System Simulator - Danuso *et al*., 1999) and kept deliberately simple in order to facilitate its practical application.

The second task was the development of a simply to use graphical interface (MiniCSS), that allows the user to set up the input data requested by the model and to summarize the simulation results. Moreover, it allows the optimisation of irrigation and fertilization strategies by simulation experiments to create the dose-response curves. Parameters can be manually or automatically (with the Gauss-Newton algorithm) calibrated and simulated data can be graphically compared with the observed ones.

The model can use historical meteorological data or can generate synthetic meteorological series by the Climak (Danuso, 2002) weather generator, already implemented in the installation package. Meteorological data can be checked or rebuild by a proper procedure. MiniCSS runs CSSmini as a separate executable, preparing to it the input files; after the CSSmini simulation has been completed, reads and automatically post-processes its simulation results. This double way implementation allows an easy and independent updating of the CSSmini model, without modifying the main functions of MiniCSS, which remains with the same familiar graphical interface.

4.3.1 Model overview

CSSmini has been developed using SEMoLa (Simple, Easy to use, Modelling Language; Danuso, 2003), a software application for the development of simulation models and agro-ecological knowledge integration. SEMoLa allows the simulation of dynamic systems by the construction of deterministic and stochastic models, based on states (stock and flow) or on elements (Individual Based Modelling). The ontology of SEMola originated from the System Dynamics approach proposed by Forrester (1961) and widely used in describing continuous systems (Muetzelfeldt, 2003). A SEMoLa model is a text file, written with a declarative language, easy to understand and modify, that, after translation and compilation, becomes an executable file.

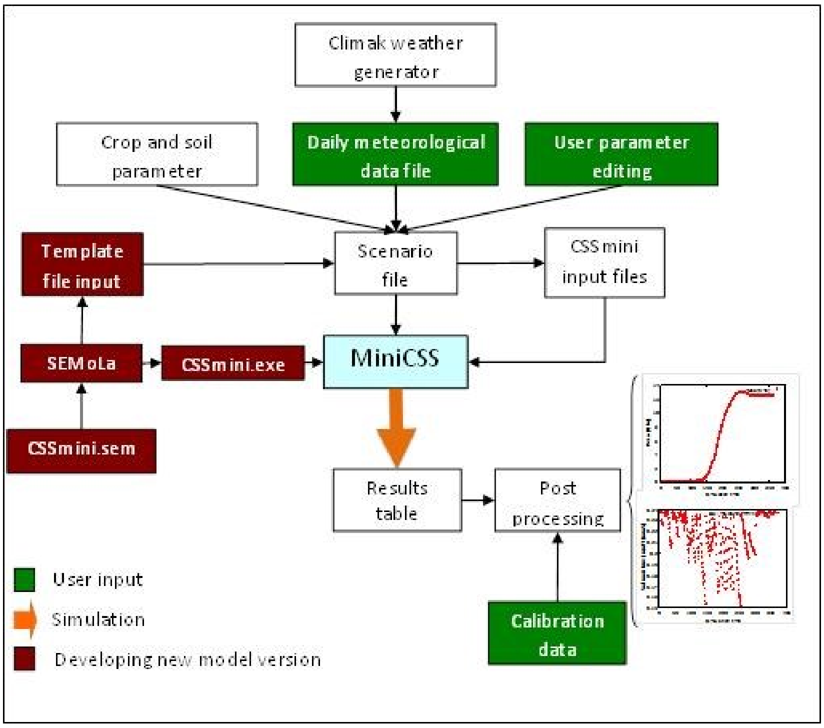

Figure 4.7 MiniCSS implementation methodology

CSSmini has a modular structure (Figure 4.8). Each module represents a different part of the cropping system. Besides the main module (*CSSmini*) connecting all the others, there are modules for phenology and crop growth (*CSSmini_crop*), soil dynamics (*CSSmini_soil*), water balance (*CSSmini_water*), soil organic matter dynamics (*CSSmini_som*), soil nitrogen (*CSSmini_nitrogen*) and the cropping practices (*CSSmini_manag*). Furthermore, an economic budget module have been developed (*CSSmini_economy*), that consider yield, market prices of products and costs for irrigation and fertilization.

CSSmini_soil, describes the physical characteristics of the soil such as water field capacity, wilting point and maximum water capacity; all this parameter are corrected for the gravel percentage of the soil. In addition, the module simulates the increase of soil depth as a function of the root deepening, synchronized to the epigeal development.

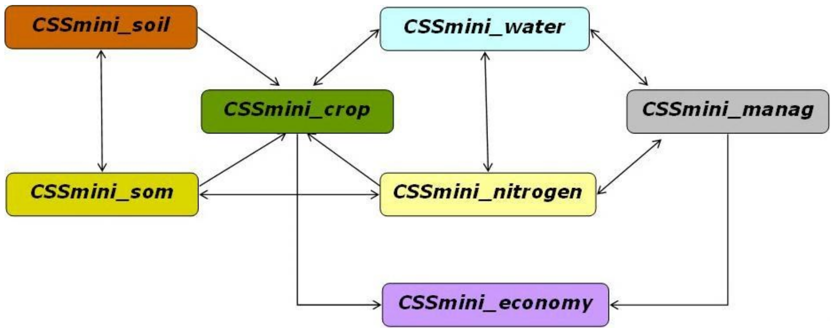

Figure 4.8 CSSmini modular structure

CSSmini_water, carries out, with a mono-layer cascade approach, the simulation of soil water content, considering maximum (*ETm*) and actual (*ETa*) evapotranspiration, runoff, infiltration, percolation and drainage into groundwater. ETa depends on the actual volumetric soil moisture (*Us*). The soil water reserve, increase with rainfall and irrigation. The maximum evapotranspiration (*ETm*) is calculated as $ETm=Kc \cdot ETr$, where *Kc* is the crop coefficient for the loss of water, according to the phenological stage (Allen *et al*. 1998) and *ETr* is the reference evapotranspiration.

CSSmini_som, simulates the dynamics of soil organic matter with an implementation of the RothC model (Coleman *et al*., 2008). This module divides soil organic matter into easily decomposable residues, resistant to decomposition residues, humus and microbial biomass, with specific mineralization coefficients.

CSSmini_nitrogen, simulates the nitrogen dynamics of soil, considering the fractions of nitrogen as nitrate (NO_3) and ammonium (NH_4). Ammonium is considered as NH_4 in solution and adsorbed on soil colloids. In the nitrification process, only the NH_4 in solution is involved. The nitrate is absorbed by plants or leached to groundwater. The concentration of NH_4 in the soil can increase due to the mineralization of soil organic matter or to nitrogen fertilizations.

CSSmini_crop, simulates the phenological development by the Growing Degree Days (*GDD*), calculated as the difference between the mean daily air temperature and the base temperature. This module also simulates the biomass accumulation and crop yield using the radiation use efficiency (*RUE*) approach. Moreover, the model considers the reduction of the maximum rate of growth in the presence of stress conditions (non-optimal temperature stress, water shortage stress and lack of nitrogen).

The water stress factor (*Fws*) is set to zero for soil moisture (Us) lesser than wilting point (*WP*), 1 for *Us* higher than the critical soil moisture (*Uz*) and *Fws*=(*Us*-*WP*)/(*Uz*-*WP*) for intermediate values, where:

Uz is the critical soil moisture for beginning of drought stress, calculated as:

$$Uz = WP + (FC - WP) \cdot (1 - Z)$$

WP soil moisture at wilting point, corrected for the amount of gravel;

FC soil moisture at field capacity, corrected for the amount of gravel;

Z critical fraction of available water for stress, obtained with an empirical equation (Danuso *et al.*, 1992) as a function of ETm. The equation interpolates the tabular values reported by Doorembos and Kassam (1986) for different crop groups (*C1*, *C2* and *C3* are empirical parameters):

$$Z = 1 - \left(\frac{C1}{1 + C2 \cdot e^{-c3 \cdot ETm}} \right)$$

The correction factor for the nitrogen stress on growth rate for (*FN*) is a linear function that depends on the nitrogen content of the crop. *FN* is 1 (no stress) when nitrogen concentration in crop is at his optimum and decreases linearly till to zero (maximum stress).

The total crop yield (grain or other useful products) is determined by the harvest index parameter (*HI*), applied to the total biomass production.

*CSSmini_manag; t*his module simulates the cropping practices (sowing, irrigation, fertilization) as events that can be automatically generated using a decisional strategy or scheduled by the user.

The scheduled cropping practices (sowing, irrigations and nitrogen fertilizations) have to be inserted by the user indicating their dates and amount. For the automatic practices, instead, the module uses information from other modules (temperature, phenological stage, water and nutritional stress index, etc.) for the decisions. Automatic sowing is based on mean air temperature values: when the daily mean temperature is greater than the base temperature for the crop for more than 3 consecutive days, the crop will be sown.

For the automatic irrigation, a parameter of allowed stress level (*Kdw*) is used, in order to calculate the critical soil moisture for irrigation (*Uirri*). When the actual soil moisture (*Us)* is smaller than *Uirri* the irrigation will be performed.

$$Uirri = WP + (Uz - WP) \cdot (1 - Kw)$$

Increasing *Kdw* determines a smaller *Uirri* so less irrigation events will be applied.

The irrigation water volume is calculated as the amount of water needed to bring the soil moisture to field capacity for the current soil rooting depth.

The automatic nitrogen fertilization uses the same criteria of the automatic irrigation: it is used a parameter of allowed nutritional stress (*Kdn*). When *FN* is smaller than *Kdn* the automatic fertilization will be performed. The amount of nitrogen fertilizer is defined by a parameter inserted by the user.

Both automatic irrigation and fertilization allow the crop to growth without stress, providing the maximum biomass accumulation, depending on temperature and radiation regimes.

*CSSmini_economy; t*his module simulates the crop economic budget, considering the fixed cost for each irrigation and variable costs depending on the amount of water applied; the costs of the fertilizer unit and for each application were also considered.

The incomes are obtained from the simulated yield, the market price of the product and, possibly, the monetary subsides.

4.3.2 Application description

MiniCss (Figure 4.9) is a software application with a graphical interface; its main aim is to make easy the use of the crop simulation model CSSmini. It can perform the optimization of irrigation and nutrition strategies throughout dynamic simulation. In this case, optimization is intended as the determination of times and amounts of water and nitrogen distributions, finalized to the maximization of crop responses, according to productive and economic criteria.

The calculation engine (*CSSmini.exe*) can be easily modified, improved, rebuilt and tested using the SEMoLa framework (Figure 4.8); calculation algorithms can be changed without the need to create a new graphical interface. This feature can be important for the on-line update of the model. At present, MiniCSS may perform annual or multi-annual simulations but not for crop rotation. By screen choices the user can create the "cropping scenario”, which contains all the needed information for the calculation procedures. The scenario is tailored by selecting standard crop and soil parameters, meteorological data files and from other screen choices made by the user.

4.3.2.1 The cropping scenario

The scenario is a text file that set up the simulation: the program, by interacting directly with the screen choices, meteorological data, crop and soil parameters, automatically generates a simulation file (*simfile*) that specifies the simulation type (simple or multiple). In this way it is possible to create different complex simulations combining crop and soil parameters, meteorological data and cultural practices.

The scenario file is created by integrating four different types of information:

i) Meteorological daily data; the daily meteorological data required are mean temperature (°C), rainfall (mm/d), solar radiation (MJ/m2), reference evapotranspiration (mm/d). A meteorological data file can have one or more years of data, in fact the program can perform one or multiple year simulation. The number of dataset in the meteorological file determines the number of simulations to be run. In this way the program will set up, automatically, a simple or a multi-annual simulation. Meteorological data can be prepared by the user in different formats: SEMola database dctfile (dct), Dbase (dbf) or comma separated value (csv). The last two, can be directly created also from a spreadsheet application. MiniCSS has many options for the check and the rebuilding of data in meteorological files: it assists the user in the creation of correct meteorological data file by automatic correction of the names of variables, changes the date format, and rebuild missing data. It also advises when the file is not correct for missing days, wrong time order and data out of range.

ii) <u>Data from crop parameter database</u>; selecting a crop (maize, soybean, sunflower, wheat, etc.) all the crop parameters are set. The most sensitive parameters are displayed on the screen to be customized by the user. The other crop parameters not displayed on the main window of the application, can be also edited or used to create custom sets of crop parameters for new crops or for specific uses (for example, to modify crop parameters for existing crop, after calibration).

iii) <u>Data from soil parameter database</u>; in the same way as the crop parameters, by selecting a soil type, all its parameters are set, again showing the most sensitive to be edited. To be able to modify also the "less-important" soil parameter a specific window has to be open.

iv) <u>Crop management choices</u>: automatic or manual sowing; automatic, scheduling or fixed-date irrigation; automatic or scheduling fertilization; sowing, irrigation and fertilization dates and amount.

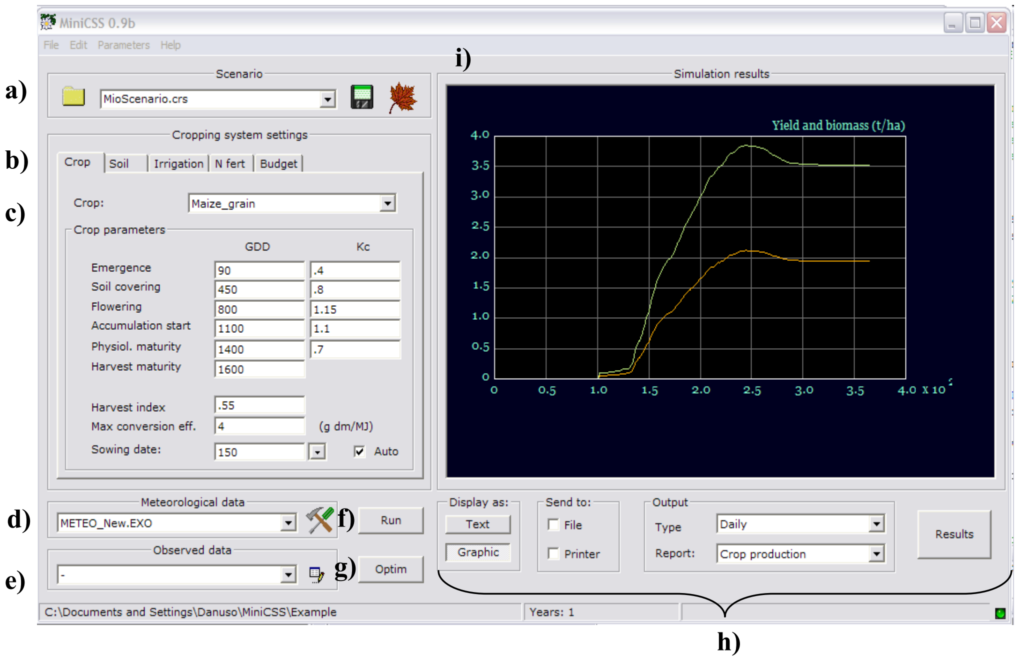

Figure 4.9 The MiniCss application: a) sets, saves and deletes scenario files; b) selects the type of information to set (crop, soil, irrigation, fertilization and budget); c) sets crop and loads crop parameters; d) sets, loads, edits, fixes and generates meteorological data file; e) sets and loads calibration data file; f) run simulation; g) run optimization; h) automatic calibration; i) run all scenarios for comparison; j) defines how to display results (text or graphic), the result type (daily, annual, cumulated probability, response curves) and the specific report. Text or graphic results can be sent also to printer or saved; k) result window switching between text and graphic format.

4.3.2.2 The simulation

The main uses of MiniCSS are the annual/multi-annual simulation, the definition of the irrigation and fertilization intensity (automatic or manual), the calibration of parameters and the optimization of the crop practices.

i) Annual and multi-annual simulation; depending on the meteorological data file selected, the simulation can be annual (Figure 4.10) or multi-annual (Figure 4.11). If the meteorological data file contains more than one data set (one for each year) the simulation will be multi-annual. This kind of simulation permits the estimation of the not-exceeding probability curve for the irrigation volume requirement, depending on climate variability.

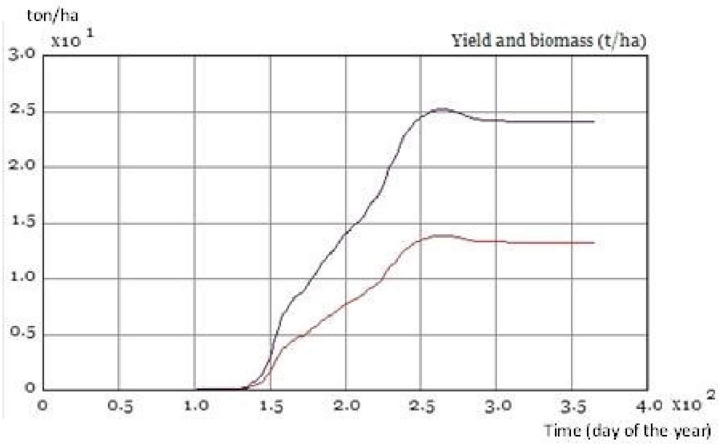

Figure 4.10 Crop yield and biomass result from an annual simulation

ii) Automatic and manual setting of cropping practices; the simulation can be set up with automatic or manual irrigation and/or fertilization. Automatic application is used to maintain the crop yield production to the maximum, so it is possible to obtain information about irrigation and nitrogen needs of the crop. Using the automatic cropping practices and a multi-annual simulation it is possible to probabilistically calculate the length of the irrigation season, irrigation water volume and nutritional crop requirements. The second approach of simulation provides a method for scheduling irrigation and nitrogen fertilization, in specific dates and amount of water and nitrogen. This approach can be useful to apply a scenario analysis, in order to verify the behaviour of crops with real or hypothetical scenarios, or even with just the natural contributions.

The manual setting of irrigation and fertilization is used also for parameter calibration, in order to compare the simulated results with the experimental data, considering the actual cropping practices.

iii) Parameter calibration; this procedure, consists in a graphical comparison of the simulation result with the experimental ones and the parameter adjustment. New runs are repeated till to the reaching of the best fitting. Moreover it is possible to perform automatic calibration. The dataset used for calibration can be in the “dct” or “csv” format and must contain the “time” variable plus the observed variables. These have to have the same name of the simulated variables.

iv) Optimization; the optimization is performed by the execution of simulation experiments to obtain dose-response curves for annual irrigation water. The simulation is set to automatic sowing, irrigation and nitrogen fertilization. The model will perform a multiple simulation, generating different level of seasonal irrigation water by changing, for each simulation, the parameter of allowed water stress Kdw, ranging from 1 (maximum stress allowed) to 0 (no stress allowed). The same approach is adopted for nitrogen fertilization.

4.3.2.3 The simulation result

After simulation, MiniCSS generates a file containing the main simulated variables (yield, soil moisture, soil nitrogen, economic balance, total water and nitrogen distributed, etc.) reported as daily values, annual averages, and cumulative probability or dose-response curves. The results can be shown in a graphical or textual form, saved to a file or printed.

Cumulative probability curve is calculated from the multi-annual simulation results; the simulation, performed on different years, reflects the climatic variation effect on crop yield (Figure 4.12), irrigation and nitrogen requirement, and crop budget.

From the cumulative curve it is possible to determine the beginning and the end of the crop period in which irrigation is required (irrigation season), its duration, both as average value or probability to exceed values.

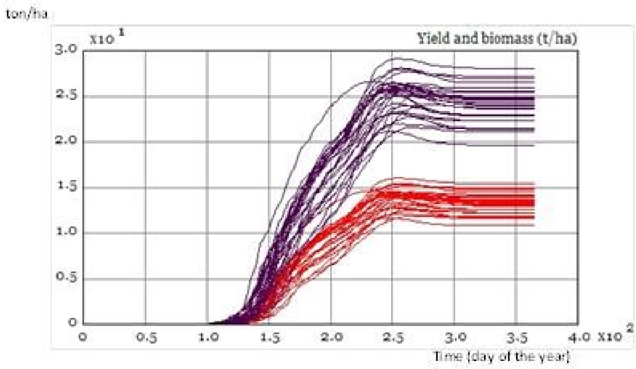

Figure 4.11 Crop yield and biomass result for a multi-annual simulation

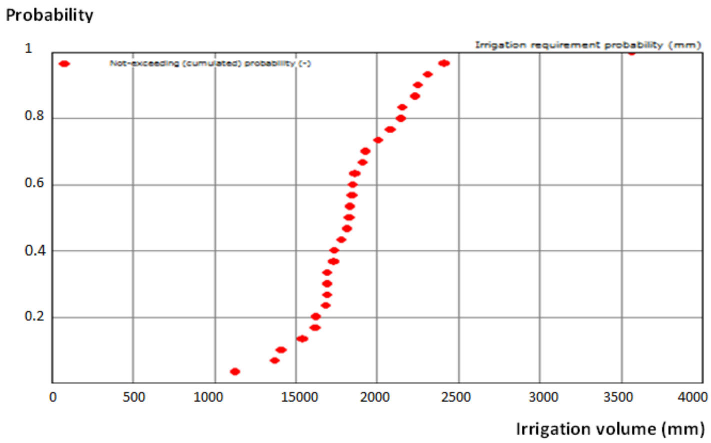

Figure 4.12 Irrigation requirement probability – Not-exceeding (cumulated) probability

Dose-response curve to irrigation volume are obtained performing a simulation experiment in which irrigation is applied with relation to the acceptable water stress (*Kdw*). MiniCSS makes twelve simulations, using different values of *Kdw*, ranging from 0 to 1, so obtaining different levels of seasonal irrigation volume to create the dose-response curve. The dose-response curve can be obtained for the yield (Figure 4.13), but also for the total crop net profit; Figure 4.14 it is possible to notice an example of dose-response curve for the crop incomes in a typical configuration of crop costs and revenues. Curve in Figure 4.13 and Figure 4.14 are not monotonic, because of the interaction between the procedure for automatic irrigation and natural rainfall.

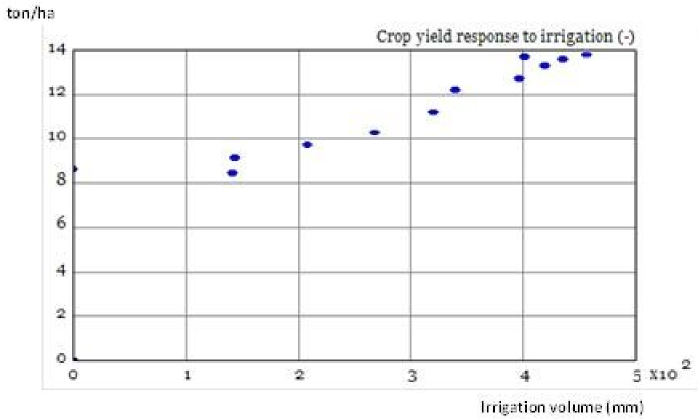

Figure 4.13 Dose-response curve to the seasonal irrigation volume for yield.

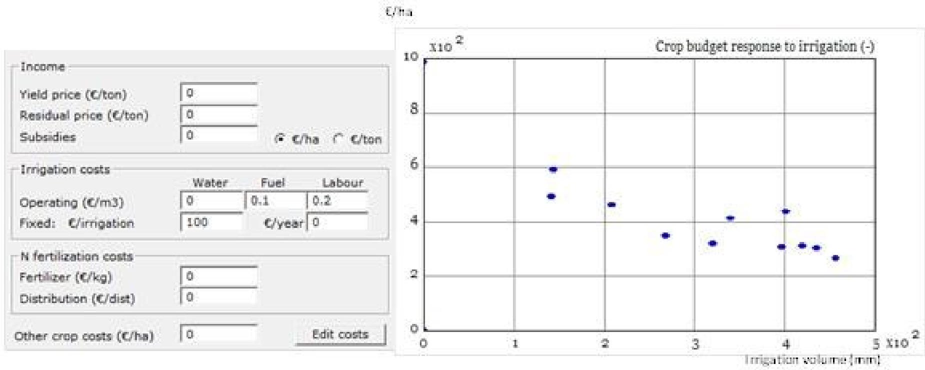

Figure 4.14 Crop budget configuration and dose-response curve for economic budget

4.3.3 MiniCSS calibration for sunflower in different agricultural conditions

In this work, CSSmini model has been parameterized and calibrated for sunflower (Helianthus annum L.) by a “trial and error” procedure and using the MiniCSS automatic calibration routine that uses an iterative procedure (Gauss-Newton linearization method; Beck and Arnold, 1977; Draper and Smith, 1981) for the minimisation of the residual sum of square between observed and simulated values. As a calibration example, soil, climatic data and measured results for soil moisture, leaf area index and yield obtained from experimental trials conducted at Udine have been used.

The experiment trials were carried out in 1987 at the Experimental Farm of the University of Udine (Udine, Italy, Lat. 46 ° 2 '49'' N, Long. 13 ° 13' 20'' E) at an altitude of 110 m above sea level. The soil was medium-textured and with about 10% of gravel (Table 4.9).

Table 4.9 Soil characteristics of the two year trials

Soil maximum depth	m	0.40
Soil moisture at field capacity	%	25.5
Soil moisture at wilting point	%	10.5
Maximum soil water content	%	50
Sand	%	42
Clay	%	18
Gravel	%	10.5
Soil organic matter	%	2.39

The meteorological data were collected from the meteorological station of the farm. The experimental test was carried out using the hybrid sunflower *Florom 305* and with two irrigation schemes. The sunflower crop was preceded by maize. Agricultural practices were focused on the soil preparation with an autumn ploughing and a harrowing before planting. The sowing was carried out with a distance of 0.70 m between rows and 0.28 m between plants on the row. The sowing date was 11/03/1987. Fertilization was done in two different periods: a pre-sowing fertilization with 60 kg/ha of nitrogen and 120 kg/ha P_2O_5 and K_2O and a second fertilization in coverage, with 80 kg/ha of nitrogen (urea). The irrigation events and the water volumes for the irrigated treatments are shown in Table 4.10. Weekly measurements were made on soil moisture (with the gravimetric method, taking samples of 5 cm of soil at 25 cm depth) and on leaf area index (LAI). The final grain yield (t/ha) was also observed.

The model calibration for sunflower has been carried out using MiniCSS, starting with the parameters suggested by the software and setting sowing day, irrigation and fertilization as in the trials. As first, the soil parameters have been calibrated against the soil moisture (Figure 4.15), obtaining the best fit with the values reported in Table 4.11. After calibrating soil parameters, crop parameters for the leaf index area have been calibrated (Figure 4.16). The obtained values are reported in Table 4.12.

In figure 4.18 the soil moisture observed and simulated under rain-fed and irrigated conditions are reported. Graphically it is possible to notice a good corresponding between simulated and measured values; it can be remarked that the fitting was better in the rain fed treatments.

Table 4.10 Irrigation events and water volumes for the irrigated treatments.

date	volume
03-07-87	40 mm
03-07-87	35 mm
24-07-87	25 mm
27-07-87	25 mm
13-08-87	25 mm
17-08-87	25 mm
21-08-87	25 mm

The leaf area index (Figure 4.16), notwithstanding the simplicity of the model, has been simulated quite satisfactorily. Furthermore, this good behaviour indicates a correct representation of crop phenology and crop biomass accumulation, confirmed also by the simulation of the crop yield (Figure 4.17).

Table 4.11 Calibrated soil parameters (for soil moisture).

Parameter	Description	Value after calibration	Unit (1)
Sand	Soil sand content	65	%
Clay	Soil clay content	12	%
MWC	maximum water capacity	0.45	mmW/mmS
FC	water at field capacity	0.25	mmW/mmS
WP	water at wilting point	0.13	mmW/mmS
Ks	Saturated conductivity	600	mmW/d
Gravel	soil gravel amount	10.5	%
Dsmax	Maximum soil depth	400	mmS
OM	soil organic matter	2.5	%

(1) mmW = mm of water; mmS = mm of soil

In Table 4.13, the most important statistics (root mean square error, modelling efficiency, coefficient of determination, coefficient residual mass, maximum absolute, etc.) (Janssen and Heuberger, 1995) for the fitting of the calibrated model are reported. This table is automatically generated by MiniCSS after the calibration run.

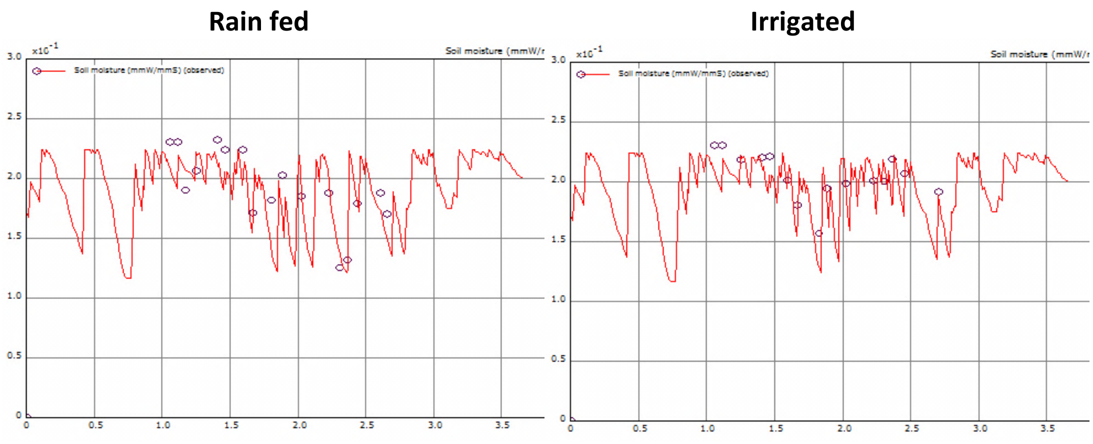

Figure 4.15 Soil moisture (*mmW/mmS*). Solid line represent simulated result, dots represents measured results.

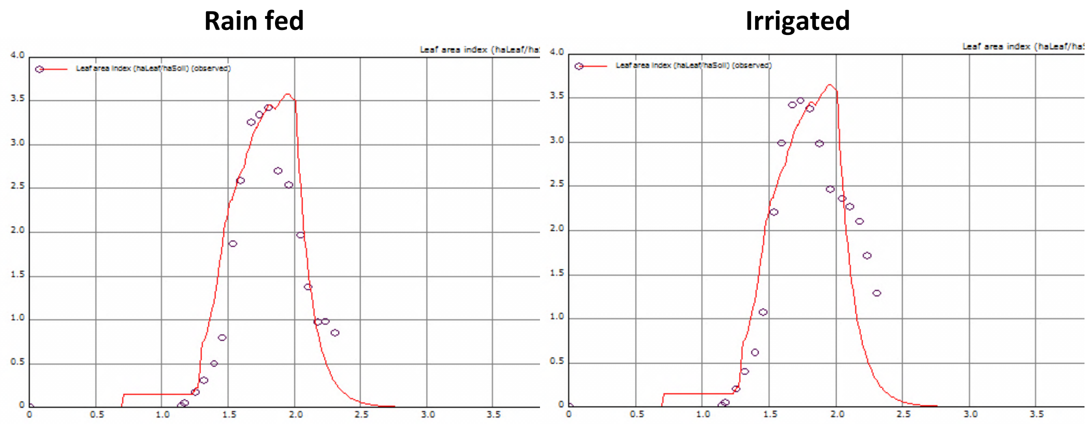

Figure 4.16 Leaf area index (*LAI*). Solid line represent simulated result, dots represents measured results.

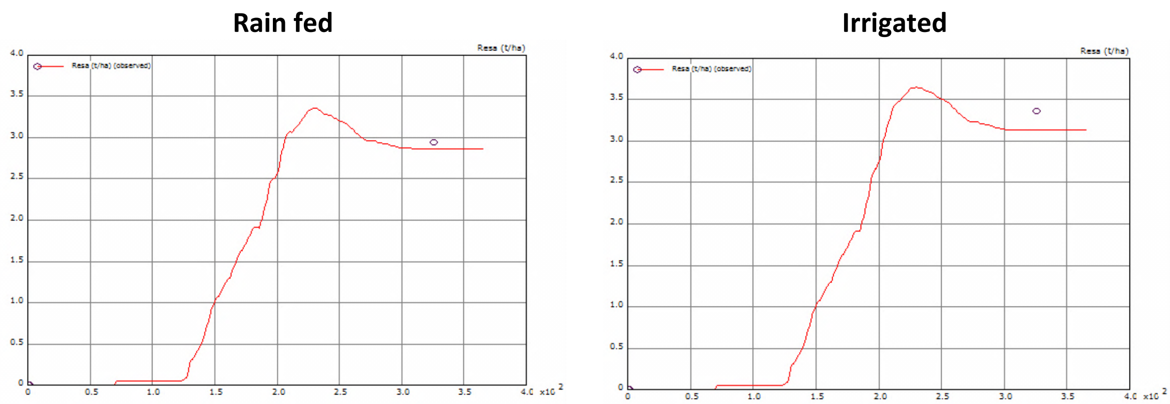

Figure 4.17 Yield (t/ha). Solid line represent simulated result, dots represents measured results.

The main aim of the work was to create and test a robust (even if simple) crop model to simulate yield response to water and nitrogen stress, for strategic and management decisions in agricultural systems. MiniCSS requires a small number of parameters and input variables to run simulations.

Table 4.12 Crop parameters for sunflower, after calibration on leaf area index

Parameter	Description	Value after calibration	unit
GDDem	GDD at start of vegetative phase	150	° C·d
GDDsc	GDD at complete soil covering	200	° C·d
GDDfl	GDD at the end of vegetative phase	381	° C·d
GDDac	GDD at start accumulation	980	° C·d
GDDpm	GDD at physiological ripening	1200	° C·d
GDDhm	GDD at harvest maturity	1500	° C·d
IniW	Initial crop biomass	0.02	t/ha
HI	Harvest index	0.35	-
Ef	Max conversion efficiency	2.5	gdm/MJ
LAR	Leaf area ratio	1.44	haLeaf/tLeaves
IFleaf	Initial fraction of leaves	0.7	-
Kext	Light extinction coefficient in the canopy	0.9	-
Ksen	Coefficient leaf senescence	0.08	-
Kc1	Kc at GDDem - water use crop coefficient	0.3	-
Kc2	Kc at GDDsc - water use crop coefficient	0.8	-
Kc3	Kc at GDDfl - water use crop coefficient	1.2	-
Kc4	Kc at GDDac - water use crop coefficient	1.1	-
Kc5	Kc at GDDpm - water use crop coefficient	0.9	-
C1	Parameter crop evap. from Table 22 in FAO Paper 56	0.6917	-
C2	Parameter crop evap. from Table 22 in FAO Paper 56	6.657	-
C3	Parameter crop evap. from Table 22 in FAO Paper 56	0.5422	-
T1	Growth minimum temperature	8.3	°C
T2	Growth minimum optimum temperature	15	°C
T3	Growth maximum optimum temperature	25	°C
T4	Growth maximum temperature	36.08	°C
Rmax	Maximum root deepening	2.2	mmS/°C/d
Kuptak	Crop NO_3 absorption	0.05	-
IniNcrop	Initial amount of nitrogen in the crop	0.1	-
Cnfix	N-fixation code (1=yes/0=no)	0	-
ConcNopt	Optimal concentration of nitrogen in crop	25	kgN/t

Some of the model parameters have a clear meaning and are easy modifiable by the user; therefore, the model seems to be suitable for a broad range of users and management decisions.

Table 4.13 Statistics of fitting for soil moisture and leaf area index, in rain fed and irrigated conditions.

Comparison variable	Rain fed Soil moisture (*Us*)	Rain fed Leaf area index (*LAI*)	Irrigated Soil moisture (*Us*)	Irrigated Leaf area index (*LAI*)
Number of observations	17	18	15	18
- Bias				
Average error (mean bias error) (AE)	-0.008	0.247	-0.012	-0.036
Coefficient of residual mass (CRM)	0.044	-0.161	0.058	0.020
- Dispersion				
Mean absolute error (MAE)	0.020	0.396	0.017	0.500
Root mean squared error (RMSE)	0.022	0.512	0.021	0.626
Modelling Efficiency (EF)	0.510	0.805	-0.188	0.717
- Outliers				
Max absolute error (MaxAE)	0.038	1.047	0.038	1.190
- Distribution				
Variance ratio (sim/obs)	0.959	1.234	1.716	1.214
Kolmogorov-Smirnov test ~Ysim=~Yobs D=	0.294	0.167	0.267	0.111
Kolmogorov-Smirnov prob ~Ysim=~Yobs	0.387	0.945	0.589	1.000
- Regression: Ysim=B0+B1*Yobs				
Costant (B0)	0.041	0.235	0.009	0.088
Slope (B1)	0.742	1.008	0.900	0.932
Determination coefficient (R^2)	0.611	0.872	0.505	0.758

The implementation of the weather generator Climak, allow to evaluate the effect of climatic change and uncertainty on cropping systems. In fact, MiniCSS can be a used to evaluate irrigation and nutritional scenarios, using the automatic cropping practices and a multi-annual simulation and for probability calculations (considering climatic variability) to determine the length of the irrigation season, irrigation water volume and nutritional needs of the crop. Furthermore, the program allows the optimization of the system by simulation experiments to obtain dose-response curves for annual irrigation water.

MiniCSS incorporates simple physiological, meteorological and agronomic knowledge that makes the application useful also for didactic purposes, enabling students to deal with the basic agronomic principles.

4.4 X-crop software description

X-crop (Figure 4.18 and Figure 4.19) is a software application with a typical graphical user interface; its main purpose is to simplify the preparation of inputs files for CSS model and to summarize the simulation results. Moreover, X-crop contains also parameter databases, useful for an easy customization of simulations; in fact, it is possible to select the parameters for different crops (soybean, maize, sunflower, sorghum, rapeseed, etc.) and parameters for different soil types. Although many parameter sets are already prepared, the user can create new ones based on the existing ones.

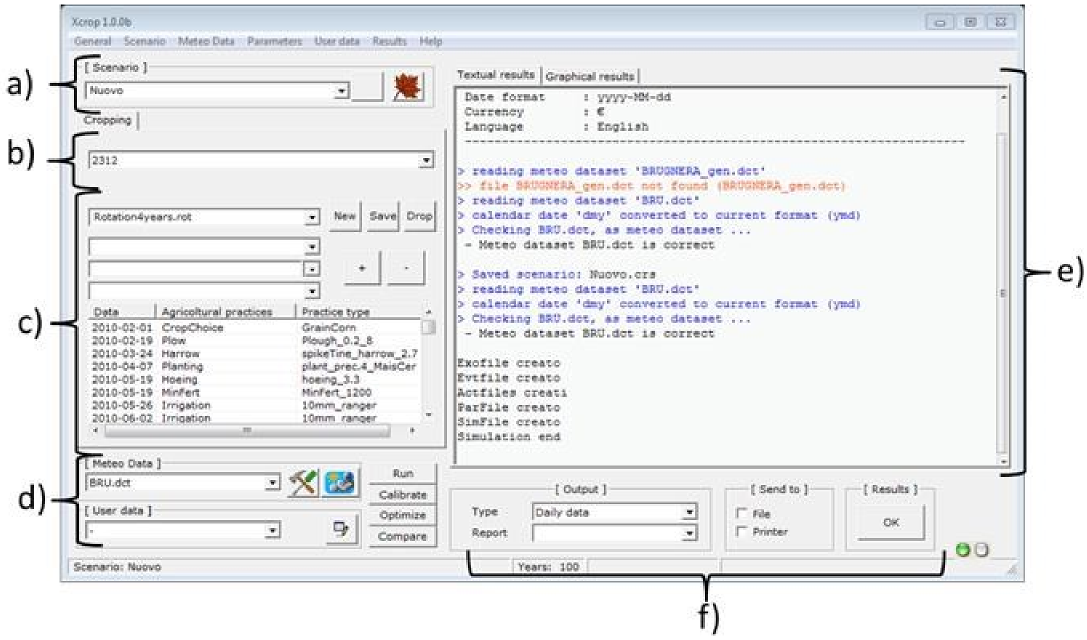

Figure 4.18 Graphic user interface of X-crop: a) sets, saves and deletes scenario files; b) selects the soil type and load soil parameters ; c) sets and loads crop rotations, that load crop parameter for each crop rotation and load management parameters ; d) sets, loads, edits, fixes and generates meteorological data file; e) result window switching between text and graphic format; f) defines how to display results (text or graphic), the result type (daily, annual, cumulated probability, response curves) and the specific report. Text or graphic results can be sent also to printer or saved.

X-crop allow to perform annual or multi-annual simulations for one year cultivation or for crop rotation; for the latter, it is possible to create different crop rotation considering not only the sowing and harvest dates but also other crop practices like ploughing, harrowing, chiselling, hoeing, chopping, mineral and organic fertilization, irrigation and pesticide..

The amount, intensity and method of tillage and agronomic techniques can be also customized or chosen from the database of agronomic practices.

By screen choices of crop rotation, crops, soil and meteorological data, users can create the "cropping scenario", which contains all the needed information for the calculation procedures.

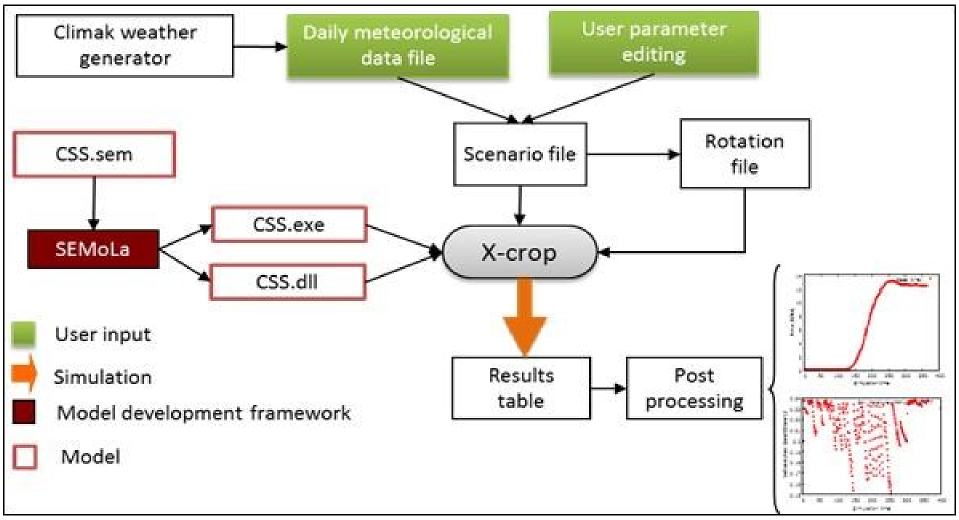

Figure 4.19 X-crop software architecture. The software uses, for setting simulations, the *scenario file* containing all the information needed to run the simulation. The *scenario file* links the chosen crop, soil and management parameters obtained from the databases; moreover it associates the rotation file prepared with the meteorological dataset to be used (note that meteorological data can be generated using the Climak weather generator). The simulation is performed by the model CSS.exe and its related DLL (dynamic-link library). This architecture allows an easy updating of the software with new versions of the model given that the software will automatically adapt itself to the new versions of the model and of databases.

4.4.1.1 The cropping scenario and the simulation process

The scenario in X-crop is a possible configuration of a given cropping system, in terms of internal factors (crop, soil, rotation, agronomic practices) and external (climate). Internal factors are definable while the external can be provided with their uncertainty. The creation of scenarios is used to evaluate possible management alternatives and to assess the risks arising from uncertainties.

In practical terms, the scenario in X-crop is a text file which contains all the needed information for the simulation: the name of the meteorological file (annual or multi-annual), the name of the crop rotation file (including crop selection) and a soil type (present in the soil database).

- The meteorological data file: the daily meteorological data required for the simulation are the same needed for CSS model (i.e. maximum and minimum mean temperature - °C, rainfall - mm/d, solar radiation - MJ/m^2, reference evapotranspiration - mm/d. A meteorological data file can have one or more years of data; the number of datasets will determines the number of simulations to be performed. The program will set up, automatically, a simple or a multi-annual simulation. The number of simulation is also function of the length of the rotation (e.g. if a 4 year rotation will be set with a 100 years meteorological file, then 25 simulation will be performed). Meteorological data can be prepared by the user in the SEMola database (dctfile) or comma separated value (csv) formats; the last can be directly created also from a spreadsheet application. Before performing simulations, X-crop checks and eventually rebuilds or fixes the data files. Moreover, synthetic meteorological data can be also created using the Climak weather generator (Rocca *et al*. 2012).
- Rotation file: The rotation file is a text file in dct format (Figure 4.20) that contains the scheduling for all the agricultural practices to be simulated, included sowing and harvesting, that indicates the beginning and the end of the crop phase. The rotation file is structured in three columns: the first is the date when the operation will be performed, the second is the agricultural practice and the third one indicates the mode or intensity of the operation. The operation mode can be selected from pre-existing database that contains all the parameter, including economy, energy and environmental parameters for the accountings.
- Parameters database: the parameters for crop, soil and agricultural practices can be selected or edited, for customizing the simulation, using the specific window (Figure 4.21). This dialog allows also to create new sets of parameters, based on the existing ones.

- The simulation process: after preparing the scenario (selected the meteorological data file, creating and chosen the rotation file and set the soil type) the simulation can be performed. During the simulation, X-crop generates in background (from the databases, meteorological data file and rotation file) the needed input files for the CSS model and runs model. After the simulation completion, results can be shown in a textual or graphical format.

```
dictionary {
    *#label     Rotation file for Xplan
    *#genby     XCrop 1.0.0b
    *#date      08-09-2012
    str10   Date        "ymd"
    str32   Operation         "Agricultural operation"
    str32   OperMode          "Operation mode"
}
2011-02-01  CropChoice  GrainCorn
2011-02-19  Plow        Plough_0.2_8
2011-03-24  Harrow      spikeTine_harrow_2.7
2011-04-07  Planting    plant_prec.4_MaisCer
2011-05-19  Hoeing      hoeing_3.3
2011-05-19  MinFert     MinFert_1200
2011-05-26  Irrigation  10mm_ranger
2011-06-02  Irrigation  10mm_ranger
2011-06-16  Irrigation  10mm_ranger
2011-06-23  MinFert     MinFert_1200
2011-06-30  Irrigation  10mm_ranger
2011-07-14  Irrigation  10mm_ranger
2011-09-22  Harvest     comb.Harvest._4.57
2012-02-01  CropChoice  GrainCorn
2012-02-19  Plow        Plough_0.2_8
2012-03-24  Harrow      spikeTine_harrow_2.7
2012-04-07  Planting    plant_prec.4_MaisCer
2012-05-19  Hoeing      hoeing_3.3
2012-05-19  MinFert     MinFert_1200
2012-05-26  Irrigation  10mm_ranger
2012-06-02  Irrigation  10mm_ranger
2012-06-16  Irrigation  10mm_ranger
2012-06-23  MinFert     MinFert_1200
2012-06-30  Irrigation  10mm_ranger
2012-07-14  Irrigation  10mm_ranger
2012-09-22  Harvest     comb.Harvest._4.57
```

Figure 4.20 X-crop rotation file in the dct format: the first 8 lines are the header (dictionary or metadata) that declares the number of variables (3) in the data section (shown in columns), their names (Date, Operation and OperMode), types and descriptions (labels). For example: the 7th April 2011 the operation planting (sowing) will be performed and waxy maize will be sowed using a precision seed-er 2.7 m with.

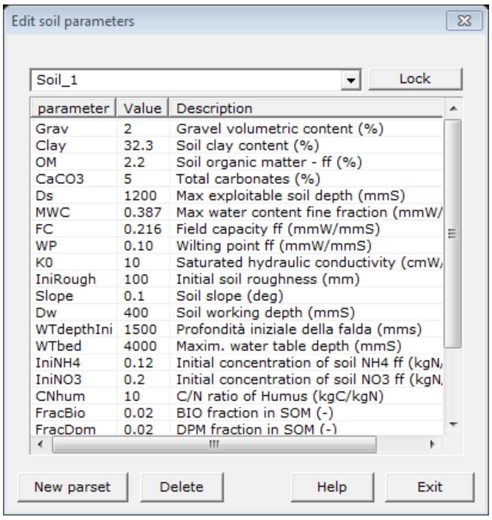

Figure 4.21 dialog for parameter database editing.

4.5 Discussions

For the simulation of crops, the model CSS (Cropping System Simulator) has been used and then integrated into the X-crop software. CSS model consider the different components of the cropping system with an high level of detail; from the case study it is suggested the possible usefulness of the CSS model (and consequently of X-crop) as a tool for the planning and risk evaluation of new energy crop and its sustainability evaluation. This derive also from the availability of a soil organic matter module, consider as crucial for the crop carbon balance and the integration of LCA analysis with biophysical models. Moreover, improvements of the water module of CSS, considering soil as multi-layer soil, can give a better representation of the system. It is important to realize also that the used version of CSS considers growth limitation due only to water and nitrogen stress. Therefore, it is suggested to improve it by implementing plant disease (pests and insects) and weeds simulation modules, in order to consider also the sources of biotic stress.

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5 Simulation of the farming system

Uncertainties about oil price, political turmoil in the oil-producing nations and the relatively low prices of farm commodities have spurred on the search for new agri-business opportunities, offered by renewable energy productions in the form of ethanol, biodiesel and biogas.

Nonetheless, bio-energy production efficiency at farm level is still questionable, depending on the commodity used, agronomic practices, climate variability and other unpredictable events. Some studies still assess the energy balance of oil and co-products as negative (Pimentel and Patzek, 2005), while others highlight the possibility of improving the energy efficiency by using energy-saving techniques (Hill *et al*., 2005).

For these reasons, farm simulation modelling is assuming increasing importance. Oriented to provide short- and long-term scenarios, it can be a useful tool to improve the planning capability of the agro-energy farm. Examples of the application of the simulation approach are the Whole-Farm Dynamic Model (GAMEDE; Vayssières *et al*., 2009), Integrated Farm System Model (Rotz and Coiner, 2006), FARMSIM (Van Wijk *et al*., 2006), SIPEAA (Donatelli *et al*., 2006) and X-farm (Danuso *et al*., 2007; Rocca *et al*. 2012). In general, from the previous works, increasing the complexity from the cropping system to the farming system involves many new fundamental representation difficulties. In particular, the concurrence of different farm activities in their requirements for farm resources (manpower, energy, machinery, time window for tillage, etc.) is not yet treated in an entirely satisfactory way.

In this chapter, we present a new version of X-farm, a software application formed by a simulation engine (a farm dynamic simulation model to manage an “agro-energy farm”, taking into specific account the crop biomass production, net energy production, environmental and economic balances) and a GUI for input preparation, model running and output presentation. An “agro-energy farm” is a farm that uses biomass to produce energy for farming activities and sells the energy exceeding the farm requirements. The fundamental module is the crop module (CSS, Cropping System Simulator; Danuso *et al*., 2003) included in X-farm to represent each field of the farm, separately.

5.1 Farming system simulation model (XF)

The X-farm model has been implemented by SEMoLa (Simple, Easy to use, Modelling Language) (Danuso, 2003). SEMoLa allows deterministic and stochastic models to be created, based on state or elements (as in Individual Based Modelling). The ontology of SEMoLa, already discussed, combines concepts of amount, flow and influence, to usefully describe the interconnected relationship in complex systems.

In the X-farm model, the farm processes are described by using the concepts of state, rate, parameter and event, while crop, livestock and energy productions, etc., are characterized by starting and ending events, temporal windows, priority in accessing resources and prerequisites.

At present, the "agro-energy farm" simulated in the X-farm model is formed by twenty-one interconnected modules (Figure 5.1) grouped into four parts: management, production, soil and accounting. The simulation time step is daily.

The farm represented by X-farm is composed of one or more fields, each of which can have different soil types, crop rotation and cropping scenarios. Other simulated activities are cattle husbandry in which each cow is considered individually throughout its productive life. The oil crops can supply seeds for the farm oil extraction chain.

The Management part simulates both crop management for each field and farm management, where crop management is intended as the management of agricultural practices and farm management considers the strategies related to oil production, cattle management, sales activities or internal use of products.
The Production part simulates the crop production of each field, oil production and milk production. The CSS-CropYield module simulates crop biomass growth and yield under different conditions, depending on climate, soil characteristics, manure and fertilizer applications, machinery use and other management choices. Potential crop growth is simulated by an implementation of the SUCROS model (van Laar *et al*., 1997), while phenology and the factors limiting production are obtained from CropSyst (Stöckle and Nelson, 1994) and CSS (Danuso *et al*., 1996). The XF-Oil module considers the entire farm oil production chain, which consists of mechanical extraction with seed crushing. In the XF-Cattle, the cattle are fed by the cake obtained after the oil extraction and other feeds from the market. X-farm considers cows in different conditions, in terms of age, weight, number of pregnancies and lactation stages. The milk production of each cow is ob-

tained from the specific lactation curve. The co-products, represented by liquid, solid wastes and manure, are used on the farm fields.

The Soil part simulates the physics, water dynamics, nitrogen balance and organic matter of the soil. The soil carbon balance is simulated by an implementation of the RothC model (Coleman and Jenkinson, 2008)

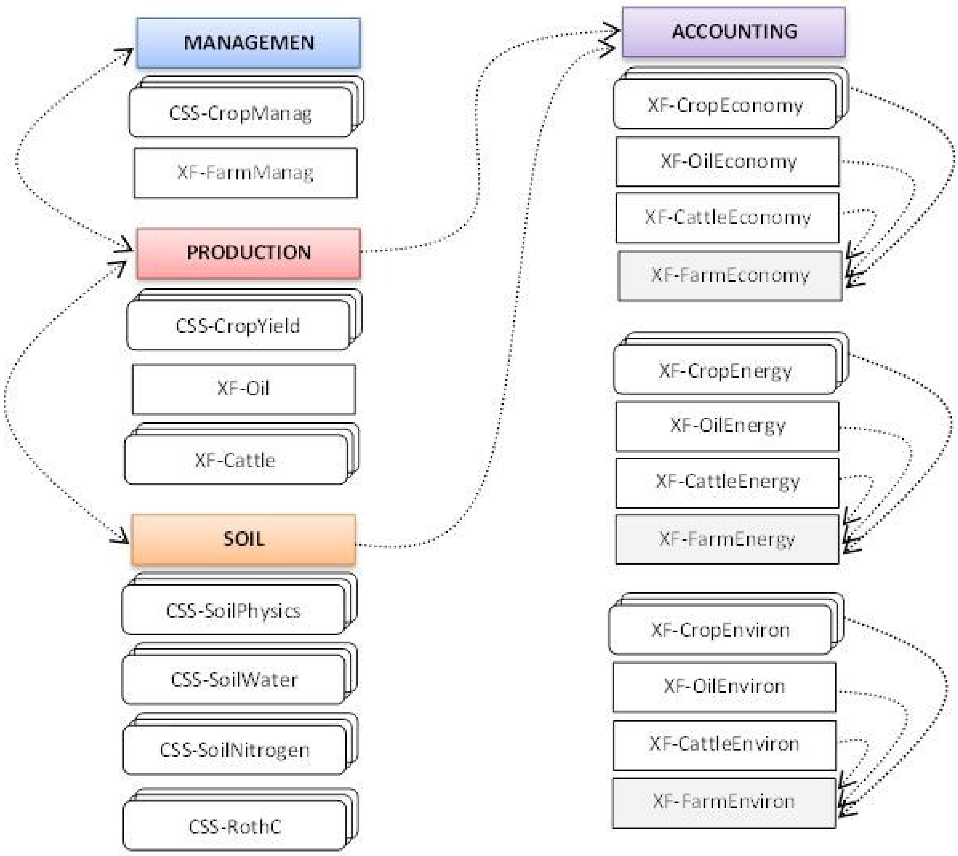

Figure 5.1 The modules of X-farm. Arrows indicate the informative relationships among modules. Note that there are two types of modules: simple modules and multiples modules. Multiples modules are represented by the concept of group. For example, in the farm we have only one oil module but for the crop and soil modules they are replicated for each field of the farm.

The Accounting part is divided into Economy, Energy and Environment and provides specific balances for crops, oil, cattle and the entire farm.

The Economy module calculates the costs of resources (including variable and fixed costs) and revenues for specific farm activities (crops, cattle and oil) and for the whole farm. The profit and economic performance indexes are calculated to provide evidence of the contribution of specific activities to the global performance. All economic information, obtained by market prices for agricultural activities (FRIMAT, 2008) is represented as input parameters to perform simulations.

The Energy modules compute both the energy inherent in the products generated on the farm and the direct and indirect energy used by crops, oil and cattle production. The Pimentel approach based on transformation coefficients has been used (Pimentel, 2003; Venturi, 2003) in the energy crop module. The parameters for the energy balance in oil processing have been obtained from trials conducted on the Experimental Farm of the University of Udine. Literature data have been used for the cattle energy balance. The information obtained by the energy modules can be used for balance purposes or to estimate the farm EROI (ratio between energy output and input).

The Environment module accounts for the direct and indirect inputs and outputs between farm and the environment.

Considering the reflexive relationship between the simulated activities and integrating their economic, environmental and energy dimension, the X-farm model can be a tool to improve the farm sustainability and advance the planning capability of the agro-energy farm.

In the next section the methodological approach used to parameterize and calibrate the crop module of X-farm is presented using a *Sorghum bicolor* L. (Moench) crop as a case study.

5.2 X-farm graphical user interface

The increasing complexity from the cropping system to the farming system, involves many new fundamental methodological issues for its representation. In particular, the competition among different farm activities for farm resources (like manpower, energy, machinery, time window for tillage, etc.) is to be considered. Moreover, the need to simultaneously manage many different plots and different crop rotations creates further difficulties not only in the development but also for users, at the input preparation stage. As described above, the farm represented by the X-farm model engine is composed by one or more fields, each of which can have different soil types and cropping scenario (rotation and cultural practices).

X-farm is run by defining “farming scenarios” that are possible farming configuration in terms of internal and external factors. Internal factors are the farm characteristics (number of fields, rotation of each field, management of each field), cropping scenario and the other farm activities (biogas, oil from seed pressing, etc.). External factors are climate, market and political issues. In the software, the internal factors are definable by parameters while the external ones can be provided with an uncertainty level. The creation of farming scenarios is used to evaluate possible management alternatives of the farm, to predict and assess the risks arising from market and climate uncertainties.

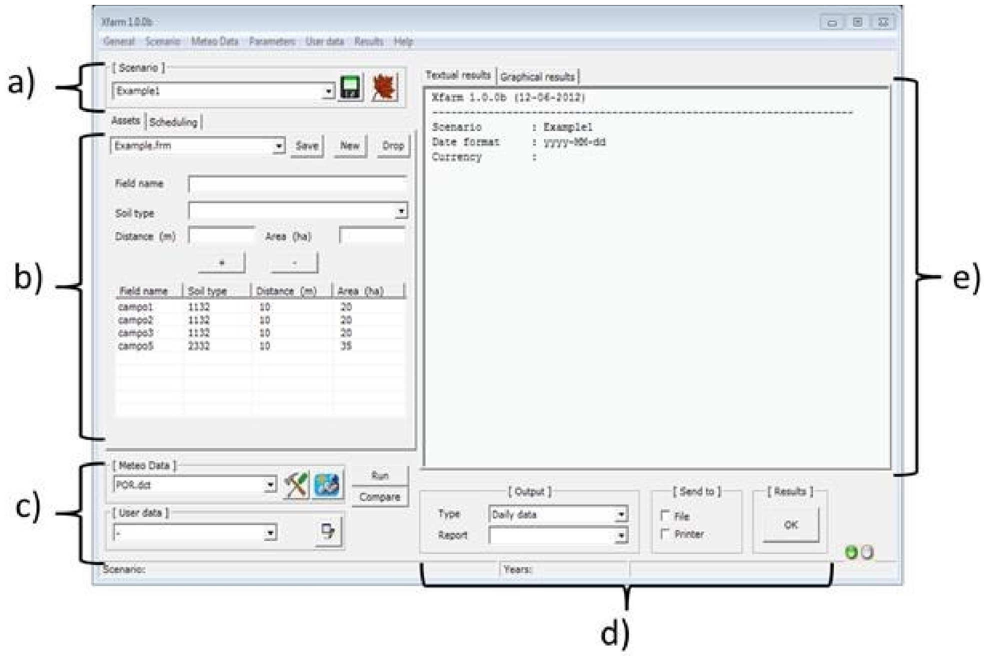

Figure 5.2 Graphic user interface of X-farm: a) sets, saves and deletes scenario files. b) Main input windows, with two pages (assets and scheduling) that allows to set and to create the farm assets and to decide the farm management (scheduling). In the first page it is possible to select an existing farm (file .frm) or create a new one. For each farm, new fields can be inserted by giving them a name, a distance from the farm centre (m), an area (m^2) and a soil type. Soil types are chosen from the soil database, assigning a specific soil type to each field. In the scheduling tab is possible to assign a crop rotation to each field. Rotations are saved to a file (rotation file, Figure 4.20). c) settings, loads, edits, fixes and generates meteorological data file. d) Defines how to display results (text or graphic), the result type (daily, annual) and the specific report. Text or graphic results can be sent also to printer or saved. e) Result window switching between text and graphic format.

A complex model as X-farm needs to be easily used, requires tools for the setting up of simulations and for the evaluation of result. The main goal of the X-farm GUI is to prepare the input information for running the X-farm model and to summarize the simulation results.

The software architecture (Figure 5.3) is similar to the already described MiniCSS and X-crop (chapter 4). For setting a simulation, the scenario file (farm scenario) is needed. This file contains, directly or indirectly, all the information required to run the XF model. The scenario file, in fact, establishes the environment for the simulation (daily meteorological data), the farm to be simulated (farm assets file) and the management of the farm fields (rotation file). Moreover, further versions of X-farm will allow achieving the simulation of biogas, oil seed pressing and cattle management, as described in the X-farm model.

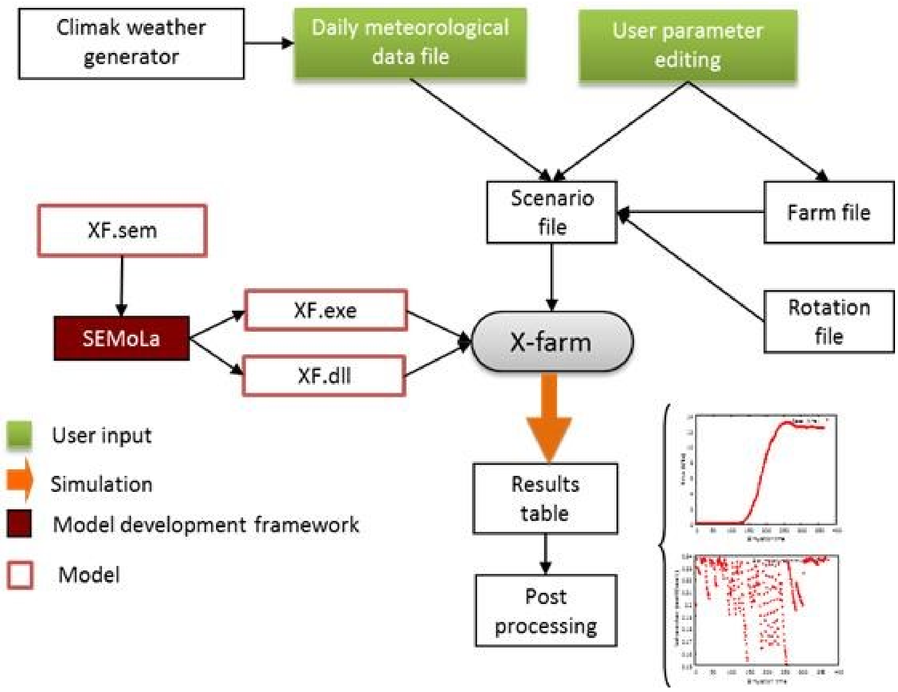

Figure 5.3 X-farm software architecture. The software uses, for setting the simulation, the *scenario file*, containing all the needed information. The *scenario file* links the chosen crop and the management parameters obtained from the databases; moreover, it associates the rotation file and the meteorological data to be use (note that meteorological data can be historical or generated using the Climak weather generator). The scenario file indicates also the farm assets to be considered (e.g. number of fields and their characteristics, soil type). The simulation is possible thanks to the model X-farm.exe and its related DLL (dynamic-link library). This architec-

ture allows an easy update because the software will adapt automatically to the new versions of the model and of databases.

- The meteorological data file: the daily meteorological data required are: maximum and minimum air temperature, °C; rainfall, mm/d; solar radiation, MJ/m^2; reference evapotranspiration, mm/d. A meteorological data file can have one or more years of data; the number of dataset will determinates the number of simulations to be performed, the program will set up automatically, a simple or a multi-annual simulation. Meteorological file can be in SEMola database dctfile (dct) or comma separated value (csv) format. The last can be directly created also from a spread sheet application. Before performing simulation, X-farm checks, and eventually rebuilds or fixes, the meteorological data. Moreover, synthetic meteorological date can be created with Climak weather generator (Rocca *et al*., 2012).

- The farm asset file: the farm asset file is a text file that includes the description of the farm to be simulated, indicating the number of fields and the name and the soil type for each field. The soil type considers the texture, soil depth, soil organic matter content, initial nitrogen content and other soil parameters. The farm asset file has also other information of the field like area (m^2), distance from the farm centre (m) and degree of plot shape regularity. Moreover other information of the farm can be introduced in this file, e.g. presence and typology of the cattle, existence of a biogas digestion plant or oil extracting facilities.

- Rotation file: The rotation file is the same file used in X-crop, so it is a text file in the dct format (Figure 4.20), containing the schedule for all the agricultural practices to be simulated, included sowing and harvesting that indicate the beginning and the end of the crop cycle.

- Parameters database: crop, soil and agricultural practices parameters can be selected or edited (for customize the simulation) using the specific window (like in X-crop - figure 4.5). This dialog allows also creating new set of parameters based on the existing ones. Unlike of X-crop, X-farm parameters database can include also other farm parameters like cattle parameter, biogas plant characteristics, oil seed pressing plan parameters, etc.

- The simulation process: after preparing the scenario (selected the meteorological data file, selecting a farm assets file and creating and chosen the rotation file and set the soil type for each farm field) the simulation can be performed. During the simulation x-farm software generates the input file required by the model for the simulation process. After simulation, the result can be shown in textual or graphical format.

5.3 X-farm parameterization and calibration for sorghum

A preliminary calibration of the crop module of X-farm has been performed using experimental data from Sorghum bicolor L. (Moench) trials. X-farm has been implemented and calibrated using the SEMoLa application which implements a modelling language into a simulation framework. Simulations of different cropping scenarios have been performed to test the X-farm capabilities to simulate complex farming systems, in order to be used as a decision-support tool.

The crop module has already been calibrated for soybean, maize, sunflower and Jerusalem artichoke (Baldini *et al*. 2012) crops. In this work, the parameterization and calibration for fiber sorghum (*Sorghum bicolor* L. Moench) parameters has also been performed. With this aim, model input files (parameter files, exogenous variables file, actions files) and the simulation scenarios files have been prepared using the SEMoLa framework. Sensitivity analysis for crop parameters against crop biomass has also been performed, calculating the mono-dimensional local sensitivity index $(\partial Y/Y)/(\partial P/P)$, where Y is the response (output) variable of the model and P is a parameter. ∂P is a small variation of the parameter and ∂Y is the related change of the simulated variable. The sensitivity variables are computed, for all the parameters of the module, with respect to the total biomass yield (t/ha), for each time step. Sensitivity analysis allows to identify best candidate parameters for calibration.

Calibration has been performed through the proper SEMoLa dialog. The calibration routine (Danuso, 1991) uses an iterative procedure (Gauss-Newton linearization method; Beck and Arnold, 1977; Draper and Smith, 1981) which minimise the residual sum of square between observed and simulated values.

The sensitivity analysis and calibration have been performed relating the simulation results to the growth analysis data obtained from a Miur Prin 2005 Project. In these trials the *Sorghum bicolor* L. (Moench) hybrid H133 was grown at the Experimental Farm of the University of Udine (North-East Italy) in 2006 and 2007, with a randomized blocks experiment and four replications. The experimental procedure involved two treatments with different levels of energy input ("Low input" and "High input"), diverse by nitrogen fertilization and irrigation frequency and amount. The model treats this information as parameters and external events. Monthly data from growth analysis were used to calibrate crop and soil parameters of X-farm, taking into account the specific cultivation techniques of each trial.

Calibration of soil parameters has been made separately for each year, combining the results from the two treatments.

Table 5.1 Main cropping practices for low and high input treatments of 2006-2007 experimental trials on sorghum.

		2006	
Doy(1)	Event(2)	low-input(3)	high-input(3)
107	Ploughing	30 cm	30 cm
131	Fertilization	120 kg P_2O_5	120 kg P_2O_5
131	Harrowing	5 cm	5 cm
158	Fertilization	14 kg N-Urea	41 kg N-Urea
176	Irrigation	-	35 mm
181	Irrigation	25 mm	24 mm
184	Fertilization	14 kg N-Urea	41 kg N-Urea
200	Irrigation	-	40 mm
256	Irrigation	-	35 mm
		2007	
Doy	Event	low-input(3)	high-input(3)
64	Ploughing	30 cm	30 cm
114	Fertilization	100 kg P_2O_5	100 kg P_2O_5
114	Harrowing	5 cm	5 cm
117	Irrigation	20 mm	20 mm
122	Irrigation	20 mm	20 mm
144	Fertilization	23 kg N-Urea	46 kg N-Urea
163	Fertilization	26 kg N-Urea	46 kg N-Urea
176	Irrigation	-	30 mm
198	Irrigation	-	40 mm
201	Irrigation	-	25 mm
205	Irrigation	-	40 mm
213	Irrigation	-	40 mm

(1) Day of the year.
(2) In the model, crop practices are represented as events.
(3) The fertilizer and irrigation amount are referred to one hectare.

After model parameterization and calibration on 2006-2007 trials data, various simulations have been performed in order to test the X-farm capability in comparing different farm cropping scenarios. As reported in Table 5.1, which summarizes the scenarios considered in our application, the X-farm model has been run on a hypothetical farm with 100 ha of arable land. The cropping scenarios considered involve three crops (maize, soybean and sunflower) for four year rotations on four fields, differing by land area and soil characteristics. Since the machinery and labour management are not yet implemented, the tillage and other cropping practices are considered as provided by contractors. Meteorological data used for the simulations are those obtained in Udine for the period 2000-2003. Table 5.2 and Table 5.3 reports detailed information about the cropping practices considered in the X-farm application example. These practices are based on the techniques usually applied in the north-east of Italy. Irrigation timings and amounts are also reported.

Table 5.2 Cropping scenarios for the simulation experiment. A farm with four fields with different soil characteristics and a four year crop rotations is hypotized and simulated.

Field soil characteristics		Field 1	Field 2	Field 3	Field 4
area	ha	40	25	15	20
sand	%	28	40	28	28
clay	%	21	19	21	21
organic matter	%	3	2.5	3	4
gravel	%	5	20	2	18
$CaCO_3$	%	0	0	0	0
soil depth	mm	1500	500	1200	1000
MWC(1)	mm/mm	0.40	0.25	0.40	0.40
FC(2)	mm/mm	0.26	0.10	0.26	0.26
WP(3)	mm/mm	0.10	0.04	0.10	0.10
YEAR	1° 2000	Maize	Maize	Maize	Soybean
	2° 2001	Soybean	Sunflower	Maize	Maize
	3° 2002	Maize	Maize	Maize	Sunflower
	4° 2003	Soybean	Sunflower	Maize	Maize

(1) Field maximum water capacity
(2) Field water capacity
(3) Field wilting point

As reported in Figure 5.4 and Figure 5.5 the simulation results obtained for the *Sorghum bicolor* biomass (solid lines) after calibration, are consistent with the data collected during the experimental trials in 2006-2007 (dots). However, the generally good agreement of simulated and obtained values is better for 2007 than 2006. The model also seems to present a realistic sensitivity to water and nutrient stresses. The calibration of soil and crop parameters allows a good agreement between simulated and experimental yield data, with determination coefficients of 0.943 and 0.974, respectively for 2006 and 2007 (Figure 5.6).

Table 5.3 Cropping practices applied to each crop in rotations of simulation experiment-

Crop	Harrowing		Mineral fertilization		Weed control (2)		Planting	Irrigation		Harvest	Ploughing	
	doy(1)	depth m	doy	amount kg/ha	doy	amount kg/ha	doy	doy	amount mm	doy	doy	depth m
Maize	131	0.15	131 158 184	120 P_2O_5 90 N-NH_4 90 N-NH_4	135	2.5	132	176 181 191 200 256	35 25 35 40 35	311	102	0.4
Soybean	131	0.15		-	140	2	150	181 191 200	25 25 25	300	102	0.4
Sunflower	150	0.15	200 200	30 P_2O_5 80 N-NH_4	150	2.5	160	181 191 200	25 25 25	280	102	0.4

(1) Day of the year
(2) Chemical weed control with herbicides

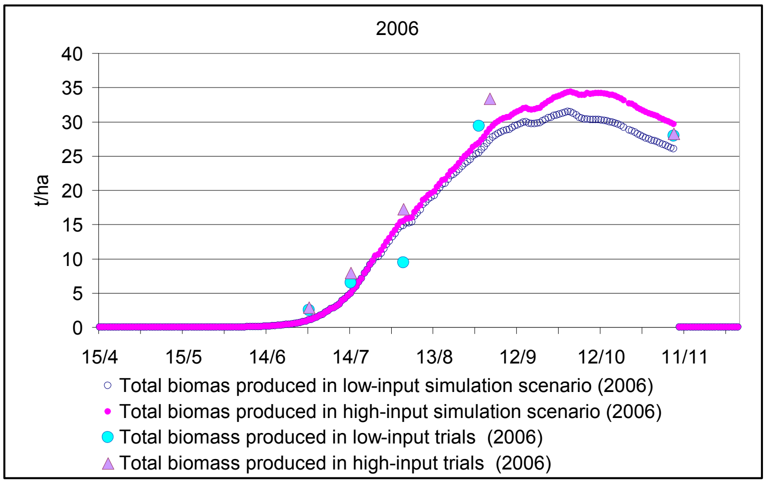

Figure 5.4 Comparison between the biomass accumulation obtained by the X-farm simulation and the experimental data for year 2006.

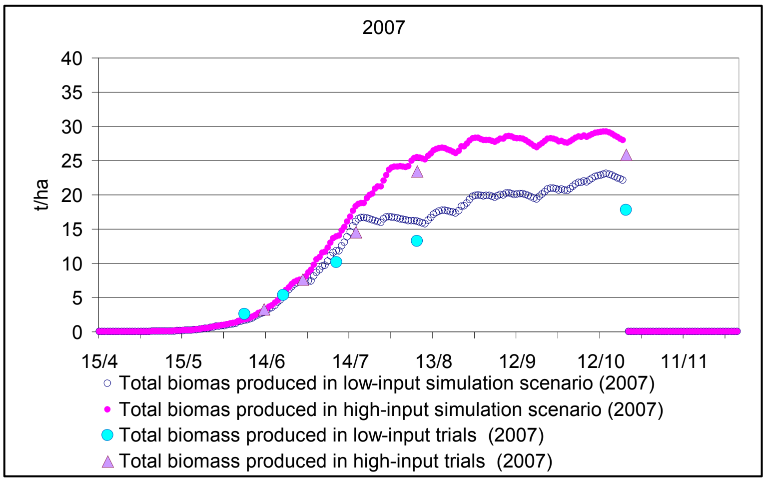

Figure 5.5 Comparison between the biomass accumulation obtained by the X-farm simulation and the experimental data for year 2007.

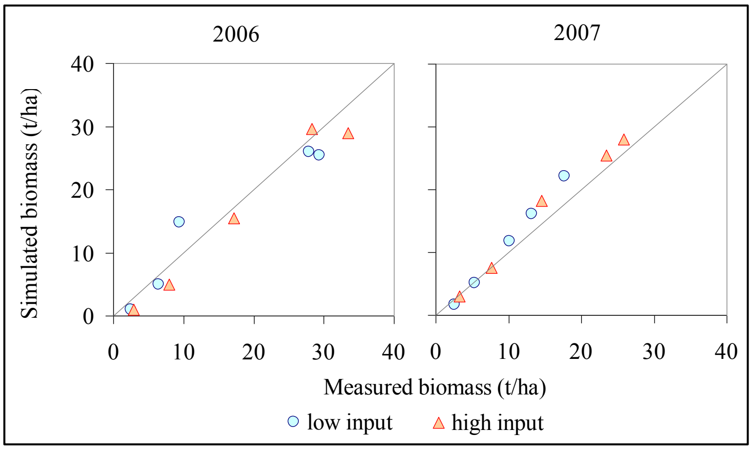

Figure 5.6 Relationships between simulated and measured sorghum biomass yields. The straight line indicates a perfect correspondence between simulated and measured data. The regressions of simulated values (S) against the measured ones (M) are the following:

2006 low input S=0.8745·M+1.1997
2006 high input S=1.0045·M-2.0106
2007 low input S=1.3582·M+1.9645
2007 high input S=1.1125·M+0.1665

Figure 5.7 reports the simulations of biomass accumulation for field rotations over a period of four years. These results, obtained comparing different cropping combinations on a hypothetical farm of 100 ha, provide important information for planning management decisions and evaluating short- and long-term scenarios. Again, we can affirm that the model is able to represent the crop production variability that is commonly experienced in real cropping systems. For example, it is possible to observe the strong effect of the drought on the maize yield in 2003 (a year with little rainfall and very high temperatures during the crop cycle). In simulations, we can also detect the effect of the soil type, given that the maize yield differs in fields 1, 2 and 3, in the same year (2000) and with the same cropping practices.

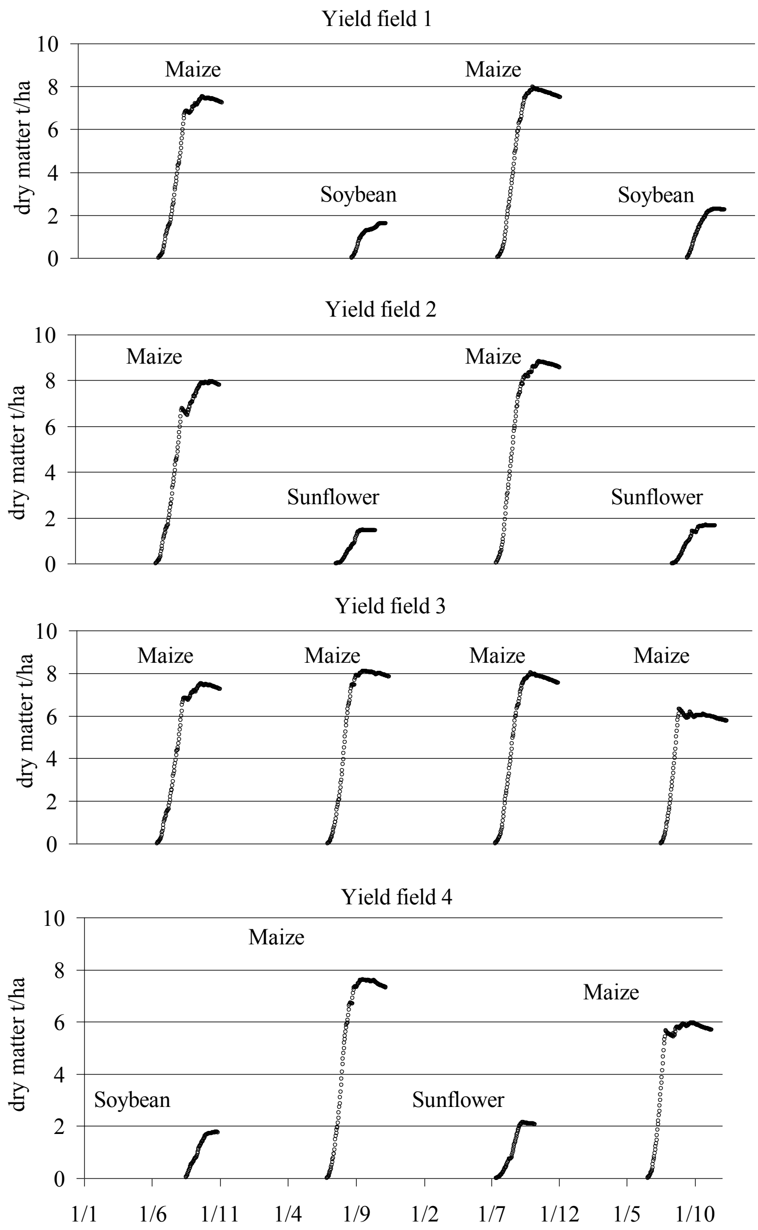

Figure 5.7 Simulated yields for the four fields of the farm and for the four years

Table 5.4 reports the simulation results in terms of economic and energy accounting. It provides information about the monetary and energy inputs to the farm and about the monetary and energy output obtained from farm activities. This information can be combined to elaborate a budget and to compare different crops and agronomic techniques, in specific soil, meteorological and market conditions. The simulation reveals that, in general terms, the economic balance of fields and farm results as being slightly positive.

These results, of course, have to be interpreted on the basis of the price levels, cropping scenarios and environmental conditions considered in the simulation experiment. The X-farm model can therefore be used to explore the effect of different farm management strategies under market and climatic uncertainties.

This poor economic result at farm level justifies the introduction of the benefits provided by European Agricultural Policies, which have not been considered in these simulations. This situation reflects the real situations where farmers' profits are almost equal to the CAP monetary subsidies.

The energy efficiency, calculated as the ratio between the crop energy output (contained in the total biomass produced) and the direct and indirect energy input, varies from 5 to 14, with an average value of 6. Among crops, the highest average efficiency has been obtained by soybean. Again, the effect of the bad weather in 2003 generated the worst energy efficiency among years (5.5).

5.4 Discussions

The main goal of this chapter was to present the X-farm model and software and test its capabilities by simulating different crop rotations and scenarios on a farm with different fields. As highlighted in the simulation outcomes, X-farm results as being a useful tool to manage sustainable farming systems and improve the planning capability of farmers. Its use is quite simple and scenario evaluations (like the one reported) can be obtained very quickly by creating an event file with the crops and agricultural practices to test and run the model or using the x-farm software.

Another type of application of the model, not shown in this work, is the possibility to set the automatic calculation of irrigation water requirements, in order to maintain the maximum yields, so raising the yields but also the crop costs in economic and energy terms.

Table 5.4 Economic and energetic accounting of the cropping scenario, for each field and for the whole farm, as simulated by X-farm.

Field-crop	Year	Economic accounting			Energy accounting			
		costs €/ha	revenues €/ha	budget €/ha	input GJ/ha	output GJ/ha	budget GJ/ha	energy efficiency
1 – maize	2000	1074	1189	115	33	197	164	5.9
1 – soybean	2001	*529	695	166	8	78	70	10.3
1- maize	2002	1110	1121	11	33	195	162	5.9
1 - soybean	2003	743	598	-145	6	91	85	14.5
Field 1	mean	864	901	37	20	140	120	9.1
2 - maize	2000	1155	1189	34	33	215	181	6.4
2 – sunflower	2001	377	723	346	14	90	75	6.2
2 – maize	2002	1270	1121	-149	33	229	196	6.9
2 – sunflower	2003	434	723	289	14	92	78	6.4
Field 2	mean	809	939	130	24	156	132	6.5
3 - maize	2000	1074	1189	115	33	197	164	5.9
3 – maize	2001	1160	1121	-39	33	207	174	6.2
3 – maize	2002	1117	1121	4	33	197	164	5.9
3 – maize	2003	853	1121	268	33	154	120	4.6
Field 3	Mean	1051	1138	87	33	189	155	5.7
4 - soybean	2000	581	763	182	8	62	54	7.7
4 – maize	2001	1084	1121	38	33	194	161	5.8
4 – sunflower	2002	542	723	182	14	118	103	8.2
4 – maize	2003	842	1121	279	33	150	117	4.5
Field 4	mean	762	932	170	22	131	109	6.5
	year	costs €	revenues €	budget €	input GJ	output GJ	budget GJ/ha	energy efficiency
Farm total	2000	3884	4331	447	110	672	562	6.1
Farm total	2001	3149	3661	511	90	569	479	6.3
Farm total	2002	4039	4086	48	116	739	622	6.4
Farm total	2003	2872	3564	692	89	487	398	5.5
Farm	mean	3486	3910	424	101	617	515	6.1

* Soybean in field 1, on 2001, received one less irrigation with respect to the other soybean crops.
- Prices of cropping inputs and of crop yields are considered the same in the four simulation years (at the average level in the last years).

In order to achieve a better description of the farming system, new developments of X-farm are currently in progress: 1) manpower and machinery modules; 2) implementation of genetic algorithms to obtain robust calibrations and optimizations; 6) a DSS version, with the automatic generation of optimized cropping practices decisions (besides irrigation, automatic generation of mineral fertilization, ploughing and harrowing events, etc. – Rocca *et al* 2011.

Despite the need for further improvements, the current version of X-farm could already be a useful tool to help in planning decisions for agro-energy productions, both at farm and territorial scale.

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6 Conclusions

The research activity was aimed to conceive, implement and test software tools for to the assessment of the cropping and farming sustainability, considering the variability and uncertainty intrinsic to the agricultural systems (climatic, economic and political). After analysing the different proposed tools for sustainability assessment available in the literature, it was decided to develop new methods based on dynamic simulation. In fact, simulation allows representing reality starting from the description of the causes of variation and it is able to make predictions about the evolution in time of the system, through the numerical solution of the describing equations. In this way, simulation models permits the assessment of the sustainability of agricultural systems, considering most of the complexity in deriving from the interaction between environmental factors and strategic decisions, allowing scenario analysis for short and long term periods, sensitivity analysis and optimization of operational parameters.

For the development of these simulation tools, large amounts of information from different sources were integrated (crop models, experimental date, climatic representation, economic dynamics, etc).

For this purpose, a modelling language and framework has been used and further developed. This framework is able to treat dynamic biophysical models with high level of complexity, supplying also easy methods for sensitivity analysis, multiple simulation and automatic calibration. The framework used was SEMoLa (Simple, Easy to use, Modelling Language) that has allowed creating new models and adapting the existing ones in a relatively easy way. In conclusion, the SEMoLa framework has been stressed in creating a large model like X-farm, demonstrating its capability for treating complexity and for the integration of agro-environmental information. Moreover, during the XF model development, new fundamental concepts in the SEMoLa language were implemented because needed for describing the overall system. Hence, new tools and modelling methodologies have been developed.

In fact, in order to achieve a better description of the cropping and farming system sustainability, some new improvements should be implemented in SEMoLa: 1) scalar and group modules integration; 2) implementation of genetic algorithms to obtain robust calibrations and optimizations; 3) different time step for each module; 4) improved methods for parameter files management. Moreover, a major improvement of SEMoLa will be obtained with the implementation of the concept of “activity” (task), theoretically already developed but not yet completely implemented. This concept, largely used in the fields of operational research, is also going to be adopted in the modelling of farm organization. The concept of task will allow subjects to be dealt with like: 1) management and use of limited resources; 2) agricultural techniques requiring a certain amount of time to be performed; 3) production of by-products, co-products or emissions during the transformation process, operated by the tasks. In SEMoLa, a task (activity) is a dynamic process leading to the transformation of the state of a material, requiring the consumption of one or more resource and producing emissions. The beginning and ending of a task is caused by events. Each task can have one or more by-product. These are considered “emissions” when not useful (negative externalities). By-products are related to the use of resources and can be calculated from the amount of resources depleted during the transformation process. For example, ploughing, at present treated as an event and so instantaneously applied, could be considered a task, that is a process transforming the field area from the untilled to the tilled state. This transformation requires resources like fuel, machinery hours, manpower hours, etc. The emissions generated are CO_2 and other pollutants to the atmosphere, heat, etc. If the resources are not available, the task is suspended or even omitted. The starting event can be linked to the crop status, weather conditions, soil moisture and availability of resources. The ending event is generated when the whole field area has been ploughed. Despite the need for further improvements, the current version of X-farm could already be a useful tool to help in planning decisions for agro-energy productions at farm level.

During the research it was fundamental to treat in detail climatic variability, in fact, climate is one of the main factors which affect farm activities and all the ecological processes of the cropping system. Therefore, the Climak weather generator was re-implemented in the SEMola language and improved. The goodness of a weather models basically depends on the model structure itself, on methods and algorithms applied for parameter estimation and on algorithms for data generation. Validation results obtained (not shown in this thesis) demonstrated that Climak can be considered an accurate tool for the generation of meteorological data. Moreover, it is suggested to focus, in further works, on the improvement of the estimation and generation procedures of evapotranspiration and on a better representation of the daily maximum and minimum air temperature variability. Furthermore, the developed version of Climak was considered sufficient for the aims of the research and has been integrated in the three software developed (MiniCSS, X-crop and X-farm). The implementation of the weather generator Climak, allow evaluating the effect of climatic change and uncertainty on cropping systems. In this way the developed applications can be a used to evaluate scenarios strategies by multi-annual simulation allowing to considering climatic variability in the assessment of the cropping and farming system sustainability.

For the simulation of crops, the model CSS (Cropping System Simulator) has been used and then integrated into the X-crop software. CSS model consider the different components of the cropping system with an high level of detail; from the case study it is suggested the possible usefulness of the CSS model (and consequently of X-crop) as a tool for the planning and risk evaluation of new energy crop and its sustainability evaluation. This derive also from the availability of a soil organic matter module, consider as crucial for the crop carbon balance and the integration of LCA analysis with biophysical models. Moreover, improvements of the water module of CSS, considering soil as multi-layer soil, can give a better representation of the system. It is important to realize also that the used version of CSS considers growth limitation due only to water and nitrogen stress. Therefore, it is suggested to improve it by implementing plant disease (pests and insects) and weeds simulation modules, in order to consider also the sources of biotic stress.

To be able to analyses the sustainability of the farm, it was considered necessary the implementation of a whole farm simulation model including, not only crops production, but also other aspects of the farm, oriented to provide short- and long-term scenarios. X-farm has been result as a useful tool to manage sustainable farming systems and to improve the planning capability of farmers. Its use is quite simple and scenario evaluations can be obtained very quickly. The strengths of X-farm with respect at the crop models is the possibility to simulate different crops at the same time, on one or more fields, each of which can have different soil types, crop rotation and cropping practices. Moreover, the farming system model consider also simulation modules for the other farm assets: cattle husbandry, in which each cow is considered individually throughout its productive life; pure oil and biodeasel production from seeds; and the biogas plant.

Although X-farm is already usable for the farming system planning and for assessing the farm sustainability, some improvements can be proposed: 1) increasing the databases for new crops and agronomic practices; 2) considering other types of externalities in the environmental analysis (acidification, pesticide, etc.), 3) improving the economic module, considering financial risk of the farm and 4) implementing an automatic decision module (virtual farming) for selling, buying and reusing farm products, taking into account the market dynamics by using econometric models and fuzzy models for the decision process.

The use of such complex models (CSSmini, CSS and XF); requires that need to be complicated procedures for selecting and calibrating parameters parameterize, calibrated and to prepare set for each specific scenario file. This; makes them not directly useful for farmers and agricultural technicians, despite they are strongly encouraged to optimize the crop/energy production at field or farm level. In fact, the research was inserted into an applicative research project for the assessment of the economic, energetic and environmental sustainability at farm level, funded for to create a decision support system tools for the planning and the optimization of the crop/energy production process, overcoming the usual approach based on standard data and tables.

To avoid the difficulties in using these models, easy to use software was developed (MiniCSS, X-crop and X-farm). These software are aimed to in simplify the preparation of inputs file for CSSmini, CSS and XF-farm models and to summarize the simulation results. Moreover their also makes available are a reserve of parameters databases, useful for customize simulations. The implemented software allows performing annual or multi-annual simulations of one year cultivation or crop rotation with just some easy commands.

In particular, MiniCSS has demonstrated that can be used as an operative tool for simulating yield response to water and nitrogen stress, for strategic and management decisions in agricultural systems. X-crop and X-farm, instead, are part of the more complete framework for bioenergy production sustainability assessment (X-plan). This application include also X-land a software that uses an integrated and interdisciplinary approach to planning biofuel supply chain at the regional level considering soil productivity, climate, location with respect to collecting centres, processing plants and road network.

The development of applicative software with the needs of the farmers in mind, allowed valorising the research and making result directly exploitable not only by the research community but also by technicians and farmers.

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Appendix

I. CSS model SEMoLa code

```
' Model: CSS.sem
' CSS (Cropping System Simulator)
$ vers(1.0)
$ dt(1)
$ tunit(d)
'DATE
A doy=mod(time-1,365)+1          "Day of the year (1-365)"          (d)
A dweek=mod(time-1,7)+1          "Day of the week (1-7)"            (-)
A month=monthyear(year,doy)      "Month"                            (-)
A day=daymonth(year,doy)         "Day of the month"                 (-)
P year=2009
' Exogenous variables
' - meteorological
E Tmin        range(-30,50)    "Daily min air temperature"          (C)
E Tmax        range(-20,60)    "Daily max air temperature"          (C)
E Rain        range(0,400)     "Rainfall"                          (mmW)
E ETr         range(0,15)      "Reference evapotranspiration"    (mmW/d)
E Rg          range(0,40)      "Global radiation"               (MJ/m^2/d)
'Latitude
P Lat=46                       "Latitude - degs and decimals"       (deg)
A Tmed=(Tmin+Tmax)/2                         "Daily mean temperature"    (C)
A Tday=0.5*(Tmax+Tmin)+(Tmax-Tmin)/(3*PI)   "Average temperature"       (C)
A DL=daylen(Lat,time)                        "Daylenght"               (h/d)
C TonToKg=1000   "Conv. factor from tB/ha to kgB/ha"               (kgB/tB)
C mmtomc=10      "Conversion from  mm/ha to mc"                  (mc*ha/mmW)
' soil
@ CSS-SoilPhysics     "Soil physical properties dynamics"
@ CSS-SoilWater       "Soil water dynamics"
@ CSS-SoilNitrogen    "Soil nitrogen dynamics"
@ CSS-SoilRothC       "Soil organic matter by ROTHC"
' crop
@ CSS-CropYield       "Crop development and production"
@ CSS-CropManag       "Scheduled crop decisions"
' Account
@ CSS-CropEconomy     "Crop economic budget"
@ CSS-CropEnergy      "Crop energy accounting"
@ CSS-CropEnviron     "Environmental accounting"
```

```
'CSS_phenology & CSS_Crop
' Crop phenology
P CropCode=1                "Crop code"                                 (-)
S Iphen=0                   "Phenological index"                        (-)
R CropDev=CropDeva     ?->Iphen      "Daily increment of development"   (-)
A CropDeva=cond(Cstage>0&Cstage<6,MDR*TstrFac*Fphoto*Fwat*Fver,0)
I Istart ?->Iphen   onevt(Planting,1)      "Phenological index initial." (-)
I Ireset Iphen->?   onevt(Harvest,Iphen)  "Phenological index reset"    (-)
A Fwat=cond(Cstage<3,Pws,2-Pws)           "Water stress develop. corr." (-)
A Cstage=INT(IphenA Cstage=INT(Iphen)
'  Cstage=0  No crop
'  Cstage=1  from planting to emergency
'  Cstage=2  from emergency to soil covering phase
'  Cstage=3  from soil covering to storage structure setting
'  Cstage=4  from storage structure setting to accumulation
'  Cstage=5  from accumulation to maturity
'  Cstage=6  from maturity to harvest (i.e. drying)
'Influence of water stress (Pws) on photo-period
A Pws=tab(Ur\Kwstress,WPGrav\1,Uz)          "Water stress factor"      (-)
```

```
P Kwstress=0.5  range(0,0.7)  onevt(CropChoice,?)  _
        "Effect of water stress"                                   (-)
'Phenological parameters
P MDRem=0.2   onevt(CropChoice,?) "Max develop. rate for emergence"   (-)
P MDRSc=0.03  onevt(CropChoice,?) "Max develop. rate for s.c. phase"  (-)
P MDRset=0.05 onevt(CropChoice,?) "Max develop. rate for set. phase"  (-)
p MDRacc=0.08 onevt(CropChoice,?) "Max development rate for accu."    (-)
p MDRmat=0.02 onevt(CropChoice,?)  "Max development rate for maturity"(-)
A MDR=choose(Cstage\MDRem,MDRSc,MDRset,MDRacc,MDRmat)
P Tcrit1=10  range(-10,20) onevt(CropChoice,?) _
                         "Min. temp. for phen. deve."          (C)
P Tcrit2=16   range(0,30)    onevt(CropChoice,?) _
                         "Temp. for 25% opt. deve."            (C)
P Tcrit3=25   range(5,35)    onevt(CropChoice,?) _
                         "Min. opt. temp. for dev. "           (C)
P Tcrit4=35   range(5,35)    onevt(CropChoice,?) _
                         "Max. opt. temp. for dev."            (C)
P Tcrit5=45   range(10,50)   onevt(CropChoice,?) _
                         "Max. temp. for dev."                  (C)
'Temperature stress factor from WOFOST 6.0, 1994 (Supit et al.)
A TStrFac=tab(Tmed\0,Tcrit1\0.25,Tcrit2\1,Tcrit3\1,Tcrit4\0,Tcrit5)
'Photoperiod
A Fphot=cond(Cstage>1&Cstage<4,abs(Photo=1)*PHIs+ _
        abs(Photo=2)*PHIl+abs(Photo=0)*1,1)  "Photoperiod factor"    (-)
A Fphoto=cond(Fphot>0,Fphot,0)
                                  "Photoperiod factor"         (-)
p Photo=2     range(0,2)    onevt(CropChoice,?)    _
                         "Sensitivity to photo-period"         (-)
'        1: Short-day crop
'        2: Long-day crop
'        0: Crop insensitive to photo-period
'Daylength parameters
p DLif=12  range(0,24)  onevt(CropChoice,?) _
                  "Maximum daylength for short-day crops _
                   minimum for long-day crop"                 (h/d)
p DLins=14 range(0,24)  onevt(CropChoice,?)
                  "Minimum daylength for short-day crops -
                  maximum for long-day crop"                  (h/d)
A PHIl1=cond((DL>DLif)&(DLins-DLif)>0,(DL-DLif)/(DLins-DLif),1) _
                           "Factor for long-day crops"        (-)
A PHIl=cond(PHIl1>0&PHIl1<1,PHIl1,1)  "Factor for long-day crops"  (-)
A PHIs1=cond((DL<DLif)&(DLif-DLins)>0,  _
        (DLif-DL)/(DLif-DLins),1)*abs((DLif-DL)/(DLif-DLins)>0)  _
                             "Factor for short-day crops"     (-)
A PHIs=cond(PHIs1>0&PHIs1<1,PHIs1,1)  _
                            "Factor for short-day crops"      (-)
'Vernalization Cropsyst modified; CERES modified
'Hodges T. and J.T.Ritchie, The Ceres-wheat phenology model, in...
P Vsens=0       onevt(CropChoice,?) _
        "Vernalization sensitivity 1=sensitive, 0=not sensitive"    (-)
P Tl=3        onevt(CropChoice,?) "Low end temperature threshold"    (C)
P Th=10       onevt(CropChoice,?) "High end temperature threshold"   (C)
P VDstart=10  onevt(CropChoice,?) "Vernalization start"             (dV)
P VDend=50    onevt(CropChoice,?) "Vernalization end"               (dV)
S VDsum=0                 "Cumulated vernalization days"            (dV)
A Fver1=cond(Vsens=1,abs(VDsum>VDstart)*Vsens*(VDsum-VDstart)/(VDend-
VDstart),1)
                 "Vernalization factor"                              (-)
A Fver=cond(Fver1>=1,1,0)          "Vernalization factor"           (-)
A Tlm7=Tl-A Tlm7=Tl-7
A Thp7=Th+A Thp7=Th+7
```

```
'Daily increasing of vernalization factor
A Via=tab(Tmed\0.01,Tlm7\1,Tl\1,Th\0,Thp7) _
                          "Daily incre. vernali. days"                (dV/d)
R Vi=cond(Cstage>0,Via,0)   ?->VDsum    "Daily incre. vernal. days"(dV/d)
'Reversed vernalization under warm conditions
R Vr=cond(VDsum<10&Tmed>30,VrFact*(Tmed-30),0)  VDsum->? _
                                   "Reversed vernalization"          (dV/d)
P VrFact=0.5 onevt(CropChoice,?)   "Factor for reversed verna."    (dV/d/C)
C ActSpec=0.5                      "Photosint. activ spectrum"         (-)
P Albedo=0.1   onevt(CropChoice,?)         "Albedo"                   (-)
P CoefEst=0.9  range(0.1,0.9) onevt(CropChoice,?)
                          "Light extinction Coefficient"             (-)
A CoefAss=(1-Albedo)*(1-exp(-CoefEst*LAI)) _
                                   "Light absorbance coefficient"       (-)
A PARinc=Rg*ActSpec                    "PAR incidence"           (MJ/m^2/d)
A PARabs=PARinc*CoefAss                "PAR absorbed"            (MJ/m^2/d)
C ConvCO2=0.01          "Conv. fact. g/m^2 to t/ha"      (tCO2*m^2/gCO2/ha)
P AEffCoef=9   range(3,12)      onevt(CropChoice,?) _
         "Potential ass. eff. coef."                                (gCO2/MJ)
 A AssEffTe=tab(Tmed\0,Tcrit1\70,Tcrit2\88,Tcrit3\88,Tcrit5\45,Tcrit5) _
               "Assimilation eff. function temp"                  (gCO2/MJ)
A AssEff=AssEffTe/88*AEffCoef"Assimilation efficiency function" (gCO2/MJ)
A AssCO2G=ConvCO2*PARabs*AssEff "Gross CO2 assimilation"        (tCO2/ha/d)
A AssCO2=AssCO2G*TStrFac*ETStrFac _
                           "CO2 assimilation with stresses"    (tCO2/ha/d)
'Transpiration stress factor Using Belmans et al. 1983
A ETStrFac=cond(Tp>0,Ta/Tp,1) "Evapotranspiration stress factor"       (-)
A Tp=ETm*(1-exp(-0.60*LAI))            "Potential transpiration"     (mmW/d)
A Ta=tab(Ur\Kwstress,WPGrav\Tp,Uz) "Actual transpiration rate"     (mmW/d)
'Crop parameters - eg. parameters for evaporation group (maize)
P Qsow=0.02  onevt(CropChoice,?)    "Seed sowing amount"              (tB/ha)
P Dsow=50    onevt(CropChoice,?)    "Sowing depth"                     (mmS)
P C1=0.6058  onevt(CropChoice,?)    "Par. crop evap"                     (-)
P Kc1=0.4     onevt(CropChoice,?)   "Kc at em water use crop coeff"      (-)
P Kc2=0.8     onevt(CropChoice,?)   "Kc at sc"                           (-)
P Kc3=1.15    onevt(CropChoice,?)   "Kc at set"                          (-)
P Kc4=1.1     onevt(CropChoice,?)   "Kc at ac"                           (-)
P Kc5=0.7     onevt(CropChoice,?)   "Kc at mat"                          (-)
P HFleav=0 range(0,1) onevt(CropChoice,?) "Harvest flag for leaves"     (-)
P HFstem=0 range(0,1) onevt(CropChoice,?) "Harvest flag for stems"      (-)
P HFstor=1 range(0,1) onevt(CropChoice,?) _
                                   Harvest flag for storage organs"     (-)
P AlloWS=0.3   range(0,1) onevt(CropChoice,?)_
                                    "Accepted water stress level"       (-)
'Water use crop coeff
A Kc=tab(cstage\Kc1,1\Kc2,2\Kc3,3\Kc4,4\Kc5,5) "Water use crop coef." (-)
S Wleav=0         range(0,100)      "Leaves dry matter weight"       (tB/ha)
S Wstem=0         range(0,100)      "Stem dry matter weight"         (tB/ha)
S Wstor=0         range(0,100)      "Storage organs dry matter"      (tB/ha)
S Wroot=0         range(0,100)      "Root dry matter weight"         (tB/ha)
S WleavD=0        range(0,100)      "Death leaves biomass"           (tB/ha)
S WstemD=0        range(0,100)       "Death stem biomass"            (tB/ha)
S WrootD=0        range(0,100)       "Death root biomass"            (tB/ha)
I WRooIni ?->WRoot onevt(Planting,Qsow*FSowRoot)_
                                    "Root biomass plant.           (tB/ha/d)
I WLeaIni ?->Wleav onevt(Planting,Qsow*FSowLeav)
                                        "Leaves biomass"          (tB/ha/d)
I WSteIni ?->Wstem onevt(Planting,Qsow*FSowStem) "Stem biomass" (tB/ha/d)
C FSowLeav=0.33             "Fraction of sow biomass for leav"         (-)
C FSowStem=0.33             "Fraction of sow biomass for stem"         (-)
C FSowRoot=0.33             "Fraction of sow biomass for stem"         (-)
A WleavTot=Wleav+WleavD  "Total leav biomass d.m. weight"        (tB/ha/d)
A WstemTot=Wstem+WstemD  "Total stem biomass d.m. weight"        (tB/ha/d)
A WrootTot=Wroot+WrootD  "Total root biomass d.m. weight"        (tB/ha/d)
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A Wshoot=WleavTot+WstemTot+Wstor "Total shoot biomass d.m. weight"(tB/ha)
A Wstraw=WleavTot+WstemTot        "Total straw biomass d.m. weight"(tB/ha)
A Wcrop=Wshoot+WrootTot           "Total crop biomass d.m. weight" (tB/ha)
'Partitioning
A RootFrac=tab(cstage\RFem,1\RFSc,2\RFSet,3\RFac,4\RFm,5) _
                                   "Fraction of total growth to root"  (-)
p RFem=0.4    onevt(CropChoice,?) "CGR fraction to root - emergence" (-)
p RFSc=0.3   onevt(CropChoice,?) "CGR fraction to root - Soil cover" (-)
p RFSet=0.1   onevt(CropChoice,?) "CGR fraction to root - Setting"   (-)
p RFac=0.1   onevt(CropChoice,?) "CGR fraction to root - accumul."   (-)
p RFm=0.1    onevt(CropChoice,?) "CGR fraction to root - maturation" (-)
A LeavFrac=tab(cstage\LFem,1\LFSc,2\LFSet,3\LFac,4\LFm,5) _
                              "Fraction of shoot growth to leaves"  (-)
p LFem=0.7  onevt(CropChoice,?) "Growth fract. leaves/shoot - emergence"
p LFSc=0.6  onevt(CropChoice,?) "Growth fract. leaves/shoot - Soil cover"
p LFSet=0.4 onevt(CropChoice,?) "Growth fract. leaves/shoot - Settings"
p LFac=0.2  onevt(CropChoice,?) "Growth fract. leaves/shoot - accumul."
p LFm=0.2   onevt(CropChoice,?) "Growth fract. leaves/shoot - maturation"
A StemFrac=tab(cstage\SFem,1\SFSc,2\SFSet,3\SFac,4\SFm,5) _
                                   "Fraction of shoot growth to stem"
p SFem=0.3  onevt(CropChoice,?)
                 "Fract. shoot growth to stem - emergence"
p SFSc=0.4  onevt(CropChoice,?)  "Fract. shoot growth to stem - cover. "
p SFSet=0.6  onevt(CropChoice,?) "Fract. shoot growth to stem - Setting"
p SFac=0.1  onevt(CropChoice,?)  "Fract. shoot growth to stem - accumul"
p SFm=0.1  onevt(CropChoice,?)   _
                        "Fract. shoot growth to stem - maturation"    (-)
A StorFrac=1-LeavFrac-StemFrac   "Fraction of shoot growth to storage"
A PartLeav=(1-RootFrac)*LeavFrac  "Fraction total synthates to leaves"
A PartStem=(1-RootFrac)*StemFrac  "Fraction total synthates to stem"
A PartStor=(1-RootFrac)*StorFrac  "Fraction total synthates to storage"
A PartRoot=RootFrac               "Fraction total synthates to root"
C CO2toCH2O=0.68182               "From CO2 to CH2O (30/44)" (tCH2O/tCO2)
' parametri conversione (from SUCROS)
P ConvLeCo=0.7 onevt(CropChoice,?) "Conv.CH2O to leaves"        (tB/tCH2O)
P ConvSmCo=0.7 onevt(CropChoice,?) "Conv.CH2O to stem"          (tB/tCH2O)
P ConvSrCo=0.7 onevt(CropChoice,?) "Conv.CH2O to storage"       (tB/tCH2O)
P ConvRoCo=0.5 onevt(CropChoice,?) "Conv. CH2O to roots"        (tB/tCH2O)
'Growth rates
R GRleav=GRleava  ?->Wleav     "D.m. growth rate of leaves"     (tB/ha/d)
R GRstem=GRstema  ?->Wstem     "D.m. growth rate of stem"       (tB/ha/d)
R GRstor=GRstora  ?->Wstor   "D.m. growth rate storage organs"  (tB/ha/d)
R GRroot=GRroota  ?->Wroot     "D.m. growth rate of roots"      (tB/ha/d)
A GRleava=cond(Cstage>0&Cstage<=6,ConvLeCo*_
        (AssCO2*CO2toCH2O*PartLeav*Fcn),0) _
                          "D.m. growth rate of leaves"          (tB/ha/d)
A GRstema=cond(Cstage>0&Cstage<=6,ConvSmCo*_
        (AssCO2*CO2toCH2O*PartStem*Fcn),0) _
                          "D.m. growth rate of stem"            (tB/ha/d)
A GRstora=cond(Cstage>0&Cstage<=6,ConvSrCo*_
        (AssCO2*CO2toCH2O*PartStor*Fcn),0) _
                          "D.m. growth rate of storage organs"  (tB/ha/d)
A GRroota=cond(Cstage>0&Cstage<=6,_
        ConvRoCo*(AssCO2*CO2toCH2O*PartRoot*Fcn),0) _
                          "D.m. growth rate of roots"           (tB/ha/d)
A CGR=GRroota+GRleava+GRstema+GRstora  "Total crop growth rate" (tB/ha/d)
A RGR=cond(Wcrop>0,CGR/Wcrop,0)   "Relative crop growth rate"     (1/d)
'Respiration
R ResLeav=cond(Cstage>0&Wleav>0,ConvLeCo*MainLeav*Wleav,0)   Wleav->? _
                                   "Leaves respiration"         (tB/ha/d)
R ResStem=cond(Cstage>0&Wstem>0,ConvSmCo*MainStem*Wstem,0)   Wstem->? _
                                   "Stem respiration"          (tB/ha/d)
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R ResStor=cond(Cstage>0&Wstor>0,ConvSrCo*MainStor*Wstor,0)   Wstor->? _
                         "Storage organs respiration"             (tB/ha/d)
R ResRoot=cond(Cstage>0&Wroot>0,ConvRoCo*MainRoot*Wroot,0)   Wroot->? _
                         "Root respiration"                       (tB/ha/d)
'Death rates from WOFOST Spitters et al. 1989, in Rabbinge et al., Pudoc
Wageningen
R StemDea=cond(Wstem>0,SmRDR*Wstem,0)  Wstem->WstemD  _
                  "Stem death rate"                             (tB/ha/d)
R RootDea=cond(Wroot>0,RoRDR*Wroot,0)  Wroot->WrootD   _
                 "Root death rate"                               (tB/ha/d)
R LeavDR=cond(CStage>2&Wleav>0,LeavDea,0)Wleav->WleavD_
                 "Leaves death rate"                             (tB/ha/d)
A SmRDR=tab(Cstage\0,3\0.032,5)    "Relative stem death rate"        (1/d)
A RoRDR=tab(Cstage\0,4\0.013,5)    "Relative root death rate"        (1/d)
A LDWstr=cond(Tp>0,Wleav*(1-Ta/Tp)*MDRWat,0) _
                 "Potential leaves death rate for water stress" (tB/ha/d)
P MDRWat=0.03  onevt(CropChoice,?) _
                 "Max leaves death rate for water stress"            (1/d)
A LDHiLAI=Wleav*LAISInd
         "Potential leaves death rate for high LAI stress"       (tB/ha/d)
A LAISInd1=cond((0.03*(LAI-LAIc)/LAIc)<0,0,0.03*(LAI-LAIc)/LAIc) _
                         "High LAI stress index 1"                    (1/d)
A LAISInd=cond(LAISInd1<0.03,LAISInd1,0.03)  "High LAI stress index"(1/d)
A LeavDea=max(LDWstr,LDHiLAI)          "Leaves death rate"        (tB/ha/d)
P LAIc=4       onevt(CropChoice,?) "Lai for stress"            (haLeaf/ha)
'Maintenance respiration (SUCROS)
P MainLeCo=0.03  onevt(CropChoice,?) _
                         "Mainte. resp. leaves coeff."      (tCH2O/tB/d)
P MainSmCo=0.015 onevt(CropChoice,?) _
                 "Mainte. resp. stem coeff."                (tCH2O/tB/d)
P MainSrCo=0.010 onevt(CropChoice,?) _
                 "Mainte. resp. storage coeff."             (tCH2O/tB/d)
P MainRoCo=0.015 onevt(CropChoice,?) _
                 "Mainte. resp. roots coeff."               (tCH2O/tB/d)
A TMaintFa=Q10^((Tmed-Topt)/10) "Mainten. resp. temperature factor"  (-)
C Q10=2.4        "Relative increase of respiration with temp."        (-)
A Topt=(Tcrit3+Tcrit4)/2         "Mean optimal growth temperature"     (C)
A MainLeav=MainLeCo*TMaintFa_
                         "Leaves maintenance resp. coeff." (tCH2O/tB/d)
A MainStem=MainSmCo*TMaintFa_
                         "Stem maintenance resp. coeff."   (tCH2O/tB/d)
A MainStor=MainSrCo*TMaintFa_
                         "Storage maintenance resp. coeff"  (tCH2O/tB/d)
A MainRoot=MainRoCo*TMaintFa _
                         "Root maintenance respiration"     (tCH2O/tB/d)
'Leaf area index
A LAI=Wleav*Sls               "Leaf area index"                (haLeaf/ha)
p Sls=1.8   onevt(CropChoice,?)     "Specific leaf surface"     (haLeaf/tB)

' Root deepening
S Rdepth=0                          "Root depth"                     (mmS)
P Rmax=20   onevt(CropChoice,?) "Maximimum root deepening rate"     (mmS/d)
A Incroot=Rmax*TstrFac*(1/(1+(Iphen/5)^20))    "Root deepening"     (mmS/d)
a aDrate=cond((Rdepth+Incroot<Ds-100)&Cstage>0,Incroot,0) _
                                    "Root deepening (aux)"        (mmS/d)
R Drate=aDrate        ?->Rdepth       Root deepening rate"          (mmS/d)
I DRini     onevt(Planting,Dsow)    ?->Rdepth  _
                                   "Initial rooting depth"        (mmS/d)
I DRend     onevt(Harvest,(Rdepth-DrMin)) Rdepth->? _
                          "Drop root depth at crop end"             (mmS)
S HarvLeav=0       range(0,1000)   "Harvested Leaves biomass"      (tB/ha)
S HarvStem=0       range(0,1000)   "Harvested Stem biomass"        (tB/ha)
S HarvStor=0       range(0,1000)   "Harvested Storage biomass"     (tB/ha)
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I WLeaHar  Wleav->HarvLeav onevt(Harvest,WLeaHau) _
                              "Leaves d.m. harvest"          (tB/ha)
I WSteHar  Wstem->HarvStem onevt(Harvest,WSteHau) _
                              "Stem d.m. harvest"            (tB/ha)
I WStoHar  Wstor->HarvStor onevt(Harvest,WStoHau) _
                              "Stor d.m. harvest"            (tB/ha)
I WLeaDHar WleavD->HarvLeav onevt(Harvest,WLeaHauD) _
                              "Dead leaves"                  (tB/ha)
I WSteDHar WstemD->HarvStem onevt(Harvest,WSteHauD) _
                              "Dead stem"                     (tB/ha)
I SellHarvLeav     onevt(CropSelling,HarvLeav)   HarvLeav->? _
         "Reset harvested Leaves biomass for selling"         (tB/ha)
I SellHarvStem     onevt(CropSelling,HarvStem)   HarvStem->? _
          "Reset harvested stem biomass for selling"          (tB/ha)
I SellHarvStor     onevt(CropSelling,HarvStor)   HarvStor->? _
         "Reset harvested stor biomass for selling"          (tB/ha)
A WLeaHau=Wleav*HFleav      "Leaves d.m. harvest"            (tB/ha/d)
A WSteHau=Wstem*HFstem      "Stem d.m. harvest"              (tB/ha/d)
A WStoHau=Wstor*HFstor      "Storage org. d.m. harvest"      (tB/ha/d)
A WLeaHauD=WleavD*HFleav    "Dead leaves d.m. harvest"       (tB/ha/d)
A WSteHauD=WstemD*HFstem    "Dead stem d.m. harvest"         (tB/ha/d)
P FracResDPM=0.6 onevt(CropChoice,?) _
                         "Fraction of DPM in crop residues"      (%)
A HarvTot=HarvLeav+HarvStem+HarvStor  "Total d.m. harvested"    (tB/ha)
' Global nitrogen mass balances
S Nout=0                    "Total N out"                    (KgN/ha)
S Ncrop=0                     "Total crop N"                 (kgN/ha)
S Nres=0                    "Total N in residues"            (kgN/ha)
I NIniCrop ?->Ncrop    onevt(Planting,Qsow*TonToKg*Ync)_
                                    "Initial crop N"      (kgN/ha)
I NLeharv   Ncrop->Nout onevt(Harvest,WLeaHau*CNcrop)_
                                     "N leaves harvest"   (kgN/ha)
I NSmharv   Ncrop->Nout onevt(Harvest,WSteHau*CNcrop)_
                                     "N stem harvest"     (kgN/ha)
I NSrharv   Ncrop->Nout onevt(Harvest,WStoHau*CNcrop)  _
                                   "N stor. harv."        (kgN/ha)
I NTrRes    Ncrop->NRes _
         on-
evt(Harvest,Ncrop(WLeaHau*CNcrop+WSteHau*CNcrop+WStoHau*CNcrop))_
                                       "N to residues"     (kgN/ha)
' N plant demand
' (Adapted from Reuter,1986; Fageria et al.,1991; Bonciarelli,1987)
A CNcrop=cond(Cstage>=1,Ncrop/Wcrop,TonToKg*Ync)_
                                   "N content in crop"  (kgN/tB)
A Nopt=tab(cstage\Nopt1,1\Nopt2,2\Nopt3,3\Nopt4,4\Nopt5,5) _
                              "Optimum N content"            (kgN/tB)
A Fcn=tab(CNcrop\0,CNCrit*Nopt\1,Nopt)      "N growth factor"       (-)
A Ndem=cond(Cstage>=1,abs(Nopt>CNcrop)*_
                 (CGR*Nopt+Wcrop*(Nopt-CNcrop)/dt),0) _
                                       "N demand"        (kgN/ha/d)
' N plant uptake
A Nupsoila=cond((1.05*Ndem)<=(NO3r/dt),1.05*Ndem,NO3r/dt) _
                                   "Crop N uptake Aux"  (kgN/ha/d)
R Nupsoil=Nupsoila     NO3r->Ncrop      "Crop N uptake"      (kgN/ha/d)
' Crop-nitrogen parameters
p Ync=0.017  onevt(CropChoice,?) "N content in yield"         (kgN/kgB)
p CRnc=0.005 onevt(CropChoice,?) "N content in crop residue"  (kgN/kgB)
p Nopt1=30   onevt(CropChoice,?) "Optimal N concentration at em" (kgN/tB)
p Nopt2=30   onevt(CropChoice,?) "Optimal N concentration at Sc" (kgN/tB)
p Nopt3=24   onevt(CropChoice,?) "Optimal N concentration at set"(kgN/tB)
p Nopt4=17   onevt(CropChoice,?) "Optimal N concentration at ac" (kgN/tB)
p Nopt5=10   onevt(CropChoice,?) "Optimal N concentration at m"  (kgN/tB)
P CNcrit=0.35  onevt(CropChoice,?) "Critical N concen. in plant"      (-)
P CNFix=0      onevt(CropChoice,?)   "N-fixation code 1=yes/0=no"     (-)
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' N fixation
R Nupfix=cond(Nupsoila>Ndem,Cnfix*(Ndem-Nupsoila)*Fmfix,0)  ?->Ncrop _
                        "Nitrogen fixation"               (kgN/ha/d)
A Fmfix=tab(Ur\0,WPGrav\1,Uz\1,FCGrav\0,MWCGrav) _
                        "Moisture factor for N-fix"              (-)
'assimilates traslocation
P Tras=0  onevt(CropChoice,?) _
                         "code assimilates traslocation 1=yes/0=no"  (-)

R TrasStem=cond(cstage=>4&Tras=1,Wstem*KtrasStem,0)  Wstem->Wstor _
         "traslocation from stems to storage organs"          (tB/ha/d)
R TrasLeav=cond(cstage=>4&Tras=1,Wleav*KtrasLeav,0)  Wleav->Wstor _
        "traslocation from leavs to storage organs"          (tB/ha/d)
R TrasRoot=cond(cstage=>4&Tras=1,Wroot*KtrasRoot,0)  Wroot->Wstor _
        "traslocation from roots to storage organs"         (tB/ha/d)
p KtrasStem=0.022  onevt(CropChoice,?) "Coef traslocazione stem-stor"
p KtrasLeav=0.007  onevt(CropChoice,?) "Coef traslocazione leav-stor"
p KtrasRoot=0.002  onevt(CropChoice,?) "Coef traslocazione root-stor"
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' XF_soil.sem - soil characteristics and temperature
' Soil characteristics
' (Driessen 1986)
P Grav=2                "Gravel volumetric content"                  (%)
P Clay=32.3             "Soil clay content"                          (%)
P SoilTc=2                      "Soil texture class code (USDA)"     (-)
P OM=2.2                        "Soil organic matter"                (%)
P OMgrav=OM*(1-Grav/100)        "Corrected soil organic matter"      (%)
P CaCO3=5                       "Total carbonates"                   (%)
P Ds=1200                       "Max exploitable soil depth"       (mmS)
P MWC=0.387             "Max water content fine fraction"      (mmW/mmS)
P FC=0.216              "Field capacity ff"                    (mmW/mmS)
P WP=0.10               "Wilting point ff"                     (mmW/mmS)
P Bd=MWC/((100-OMgrav)/100/DensMin+OMgrav/100/DensOM) _
                        "Bulk density"                          (gS/ccS)
C DensMin=2.65          "Density of minerals"                   (gS/ccS)
C DensOM=1.43           "Density organic matter"                (gS/ccS)
' Soil water parameter
C Gamma=0.018       "Pore characteristics constant"             (1/mm^2)
P S0=11.73              "Standard sorptivity"                (cmW/d^0.5)
P Ctz=3.97  "Transmission zone hydr. conductivity"               (cmW/d)
P MWCGrav=MWC*(1-Grav/100) _
                "Max water content corrected for gravel"       (mmW/mmS)
P FCGrav=FC*(1-Grav/100)   "Corrected FC"                      (mmW/mmS)
P WPGrav=WP*(1-Grav/100)   "Corrected WP"                      (mmW/mmS)
P A1=0.0231               "Param. of K=f Psir/P                 (1/cmW)
P A2=14.4           "Param. of K=f Psir/P>=Pmax"             (cmW^2.4/d)
P Pmax=300          "Suction limit"                              (cmW)
P K0=10            "Saturated hydraulic conductivity"            (cmW/d)
' Soil mass
A SmasW=Dw*ConvMass*Bd*(1-Grav/100)   "Soil mass till to Dw depth"(tS/ha)
A SmasS=Ds*ConvMass*Bd*(1-Grav/100)   "Soil mass till to Ds depth"(tS/ha)
A SmasR=Dr*ConvMass*Bd*(1-Grav/100)   "Soil mass of Dr depth"     (tS/ha)
A SmasD=(Ds-Dr)*ConvMass*Bd*(1-Grav/100) "Soil mass of Dd depth"  (tS/ha)
C ConvMass=10   "Conv. factor from mmS*g/cc to t/ha" (tS/ha/(mmS*gS/ccS))
' Soil roughness
' Furrows depth (SoilRough) decreases by the weathering in time till to a
minimum value RoughMin
S SoilRough=IniRough     "Soil roughness"                           (mm)
P IniRough=100          "Initial soil roughness"                    (mm)
P RoughMin=20            "Minimum roughness"                        (mm)
R AggDisgr=cond(SoilRough>RoughMin,Fdisg*SoilRough,0)  SoilRough->?  _
                           "Aggregates disgregation"                (mm)
A Fdisg=KdisgMin*FdisgT*FdisgR   "Aggregates disgregation factor"   (mm)
C KdisgMin=0.01                  "Minimum disgregation rate"       (1/d)
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A FdisgT=cond(Tmed<0,2,1)          "Low temp. disgregation factor"       (-)
A FdisgR=tab(Rain\1,10\3,60)       "Rain disgregation factor"            (-)
I RoughVar  onevt(Plow,Krough-SoilRough)     ?->SoilRough _
                        "Roughness variation by tillage"              (mm)

I RoughDecr onevt(Harrow,SoilRough-RoughMin)  SoilRough->? _
                                 "Roughness decrease for tillage"    (mm)
' Maximum surface water
A SSmax=SoilRough*ConvFurr*(sin(Alf)*(cos(Alf)+sin(Alf)*tan(Bet)))/   _
        (4*cos(Sigm*Pi/180)*cos(Slope*Pi/180)) _
                        "Max water storage in soil surface"          (mmW)
P Sigm=35                          "Furrows angle"                   (deg)
P Slope=0.1                       "Soil slope"                       (deg)
p Bet=Pi/2-(Sigm+Slope)*Pi/180      "Internal parameter - Beta"         (-)
p Alf=(Sigm-Slope)*Pi/180           "Internal parameter - Alfa"         (-)
C ConvFurr=0.99                    "Conv. factor water storage"    (mmW/mmS)
' Soil temperature
S Tsoil=IniTsoil                          "Soil temperature"            (C)
p IniTsoil=5                                "Initial soil temperature" (C)
R Tempvar=Kdel*(Tmed-Tsoil)   ?->Tsoil  "Soil temperature variation" (C/d)
p Kdel=0.3                       "Delay coefficient for soil temp."       (1/d)
' Soil working depth
P Dw=400                          "Soil working depth"                  (mmS)
' Soil layers depth
P DrMin=100                       "Minimum size of root layer"          (mmS)
A Dr=cond(Rdepth>DrMin,Rdepth,DrMin) "Depth of root layer"              (mmS)
A Dd=Ds-Dr                              "Depth of deep layer"           (mmS)
```

```
' XF_Water
C ConvLen=10      "Conv. factor from cm to mm"                       (mmW/cmW)
S Rs=IniRs         range(0,1000)  "Soil surface water reserve"         (mmW)
S Rr=IniMoi*DrMin  range(0,1000) "Soil root layer water reserve"       (mmW)
S Rd=IniMoi*(Ds-DrMin)    range(0,1000)_
                          "Soil deep layer water reserve"              (mmW)
S Wtab=WtabIni            range(0,1000000) "Water table reserve"       (mmW)
P IniRs=0.1         "Initial soil surface water reserve"            (mmW/mmS)
P IniMoi=0.2        "Initial soil moisture"                         (mmW/mmS)
P WtabIni=(WTbed-WTdepthIni)*MWCGrav _
                               "Water table initial reserve"           (mmW)
'Layer conditions and moisture surface reserve
A DefRs=cond(Rs<SSmax,SSmax-Rs,0)  _
                    "Water deficit for full surface reserve"           (mmW)
'Root layer  conditions NB: Dr and Dd always >0
A Ur=Rr/Dr          "Moisture of root layer"                        (mmW/mmS)
A DefFCr=cond(Dr*FCGrav-Rr>0,Dr*FCGrav-Rr,0) _
                     "Water deficit to FC root layer"                  (mmW)
A Psir=exp(sqrt((log(MWCGrav)-log(Ur))/Gamma)) _
                    "Matric suction root layer"                        (cmW)
A Kr=cond(Psir<Pmax,ConvLen*K0*exp(-A1*Psir),ConvLen*A2*Psir^(-1.4)) _
                    "Hydr. conduct. root layer"                      (mmW/d)
'Deep layer  conditions
A Ud=Rd/Dd                "Moisture of deep layer"                  (mmW/mmS)
A DefFCd=cond(Dd*FCGrav-Rd>0,Dd*FCGrav-Rd,0) _
                          "Water deficit to FC deep layer"             (mmW)
A Psid=exp(sqrt((log(MWCGrav)-log(Ud))/Gamma)) _
                          "Matric suction deep layer"                  (cmW)
A Kd=cond(Psid<Pmax,ConvLen*K0*exp(-A1*Psid),ConvLen*A2*Psid^(-1.4)) _
                          "Hydr. conduct. deep layer"                (mmW/d)
' Working layer  conditions
A Uw=cond(Cstage>0,Ur,Drmin)  "Water in Dw - simplified"         (mmW/mmS)
' Infiltration rate  (P.M. Deiessen)
A Sa=S0*(1-Ur/MWCGrav)        "Actual sorptivity"              (cmW/d^0.5)
A Imax=ConvLen*(Sa*(dt^(-0.5))+Ctz)   "Maximum infiltration rate"  (mmW/d)
```

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' Water inputs
A DurW=(Rain/Rih)                        "Duration of wet period"    (h)
A DurI=(Irri/Iih)                        "Duration of wet period"    (h)
'Water input (Rain+Irri) reach soil to Rs with hourly intensity "Rhi"
P Rih=5                    "Rainfall hourly intensity"             (mmW/h)
P Iih=10                   "Irrigation hourly intensity"           (mmW/h)
A PotIncSupRain=cond(Rih>Imax,(Rih-Imax)*DurW,Rih*DurW) _
        "Potential increment surface water due to rain"             (mmW)

A PotIncSupIrri=cond(Iih>Imax,(Iih-Imax)*DurI,Iih*DurI) _
 "Potential increment surface water due to irrigation"                (mmW)
A PotIncSupWat=PotIncSupRain+PotIncSupIrri _
        "Potential increment surface water (Rs+RunOff)"              (mmW)
A aIncRs=cond(PotIncSupWat>DefRs,DefRs,PotIncSupWat-aRunOff) _
        "Actual increment of surface reserve"                       (mmW/d)
A aRunOff=cond(PotIncSupWat>UseWat,PotIncSupWat-UseWat,0) _
         "Water run-off"                                            (mmW/d)
A UseWat=DefRs+aIncrRr+aIncrRd+aIncrWt      "Water use"               (mmW)
A aPotInfRr=Rs+PotIncSupWat  _
        "Total potential infiltrable water in Rr"                    (mmW)
A aIncrRr-
Vi=cond((aPotInfRr>Imax*DurW+Imax*DurI),Imax*DurW+Imax*DurI,aPotInfRr) _
        "Incremento Rr limitato da Vi"                               (mmW/d)
A aIncrRrDef=cond(aPotInfRr>DefFCr,DefFCr,aPotInfRr) _
         "Incremento Rr limitato da Def Rr"                         (mmW/d)
A aIncrRr=min(aIncrRrVi,aIncrRrDef) _
                 "Acqua che va in Rr"                               (mmW/d)
A aPotInfRd=cond(aPotInfRr>aIncrRr,aPotInfRr-aIncrRr,0) _
                "Percolazione potenziale in Rd"                     (mmW/d)
A aIncrRdKr=cond((aPotInfRd>Kr),Kr,aPotInfRd) _
                 "Incremento Rd limitato da Kr"                      (mmW/d)
A aIncrRdDef=cond(aPotInfRd>DefFCd,DefFCr,aPotInfRd) _
                 "Incremento Rd limitato da Def Rd"                 (mmW/d)
A aIncrRd=min(aIncrRdKr,aIncrRdDef) _
                 "Acqua che va in Rd"                               (mmW/d)
A aPotInfWt=cond(aPotInfRd>aIncrRd,aPotInfRd-aIncrRd,0) _
        "Percolazione potenziale in Wt (acqua non trattenuta)"      (mmW/d)
A aIncrWtKd=cond(aPotInfWt>Kd,Kd,aPotInfWt) _
         "Incremento Wt limitato da Kd (vel infilt strato deep)"    (mmW/d)
A aIncrWtDef=cond(Ddw>100,aPotInfWt,0) _
         "Incremento Rd limitato da distanza da falda"             (mmW/d)
A aIncrWt=min(aIncrWtKd,aIncrWtDef) _
         "Acqua che va in Wt"                                      (mmW/d)
A ETm=ETr*Kc                   "Maximum evapotransp."              (mmW/d)
A Uz=WPGrav+(FCGrav-WPGrav)*(C1+0.04*(5-ETm)) _
                 "Critical moist. for stress"                      (mmW/mmS)
A aETa=tab(Ur\0,WPGrav\ETm,Uz)  _
                      "Actual crop evapotranspiration rate"         (mmW/d)
P DDrate=1          range(0,50)     "Deep drainage rate"            (mmW/d)
A WTdepth=WTbed-Wtab/MWCGrav        "Water table depth"               (mmS)
P WTdepthIni=1500               "Initial water table depth"           (mms)
P WTbed=4000                    "Maxim. water table depth"            (mmS)
A Drw=cond(WTdepth-Dr>0,(WTdepth-Dr)/ConvLen,5) _
                          "Distance water table-1/2 layer r"          (cmS)
A Ddw=cond((WTdepth-Ds+Dd/2)>0,(WTdepth-Ds+Dd)/ConvLen,5) _
                          "Dist. water table-deep layer"              (cmS)
' Capillary rise
A CR1=CapRise(SoilTc,Psir,Drw,Wtab,K0) _
                "Potential capillary rise to r layer"               (mmW/d)
A aIncrRrWtKd=cond((CR1>Kd),Kd,CR1)                                (mmW/d)
A aIncrRrWtDef=cond(CR1>DefFCr,DefFCr,CR1)                         (mmW/d)
A aIncrWtRr=min(aIncrRrWtKd,aIncrRrWtDef                            (mmW/d)
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A CR2=CapRise(SoilTc,Psid,Ddw,Wtab,K0) _
                "Potential capillary rise to d layer"          (mmW/d)
A aIncrRdWtDef=cond(CR2>DefFCd,DefFCd,CR2)                      (mmW/d)
A aIncrRdWtDist=cond(Ddw<5000,CR2,0)                            (mmW/d)
A aIncrRdWt=min(aIncrRdWtDef,aIncrRdWtDist)                     (mmW/d)
R IncRs=aIncRs     ?->Rs  "Increment of surface reserve"        (mmW/d)
R IncrRr=aIncrRr   ?->R   "Incremento Rr"                       (mmW/d)
R IncrRd=aIncrRd   ?->Rd  "Incremento Rd"                       (mmW/d)
R RunOff=aRunOff   ?->TotRoff     "Water run-off"               (mmW/d)
R IncrWt=aIncrWt   ?->Wtab        "Incremento Wta               (mmW/d)
R ETa=aETa    Rr->WairET "Actual crop evapotranspiration rate"  (mmW/d)
R EvapoRs=cond(Rs>ETr,Etr,Rs)   Rs->WairET                      (mmW/d)
I IcrDsow    onevt(planting,cond(Dsow>DrMin,Ud*(Dsow-Drmin),0)   Rd->Rr  _
         "Water from Dd on planting if Dsow>DrMin"              (mmW/d)
R Icr=cond(Rdepth>DrMin,Ud*aDrate,0) Rd->Rr          _
         "Water from Dd by root deepening"                      (mmW/d)
I RedistW     onevt(Harvest,Rr-(Ur*DrMin)) Rr->Rd    _
              "Water redistribution at harvest"                 (mmW)
R CRr=aIncrWtRr  Wtab->Rr   "Actual capillary rise to r"        (mmW/d)
R CRd=aIncrRdWt  Wtab->Rd   "Actual capillary rise to d"        (mmW/d)
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```
' Model: XF_RothC.sem
S BIO=IniSOM*FracBio  range(0,10)  "Biomass in BIO"             (tB/ha)
S DPM=IniSOM*FracDpm  range(0,40) _
                      "Biomass in Decompo. plant material"      (tB/ha)
S RPM=IniSOM*FracRpm  range(0,20)  "Biomass in RPM"             (tB/ha)
S HUM=IniSOM*FracHum  range(0,80)  "Biomass in HUM"             (tB/ha)
S IOM=IniSOM*FracIom  range(0,2)   "Inert organic matter"       (tB/ha)
P IniSOM=(OMgrav/100)*Dw*BD*10     "Initial soil organic matter" (tB/ha)
P FracBio=0.02  range(0,0.08)     "BIO fraction in SOM"           (-)
P FracDpm=0.02  range(0,0.08)     "DPM fraction in SOM"           (-)
P FracRpm=0.14  range(0,0.4)      "RPM fraction in SOM"           (-)
P FracHum=0.72  range(0,0.9)      "Hum fraction in SOM"           (-)
P FracIom=0.10  range(0,0.2)      "IOM fraction in SOM"           (-)
A SOM=DPM+RPM+BIO+HUM+IOM    "Total soil organic matter"        (tB/ha)
A SOC=Chum*SOM                    "Total SOC"                   (tC/ha)
' Decomposition rate constants
P drDPM=0.025                     "Time Coef for DPM"             (1/d)
P drRPM=0.0008                    "Time Coef for RPM"             (1/d)
P drBIO=0.002                     "Time Coef for BIO"             (1/d)
P drHUM=0.00005                   "Time Coef for HUM"             (1/d)
P scDec=0.0045          "Scaling Factor of ResDecr ratio"         (-)
P ResDecr=(scDec*(1.85+1.6*exp(-0.0786*clay)))  _
                  "CO2/(BIO+HUM) ratio function of clay"          (-)
P BH=0.46               "BIO/HUM ratio for (BIO+HUM) q.ty"        (-)
I OrgHUMUS ?->HUM onevt(OrgFert,QDMorg*HUMcont/100)_
                                  "Org. fert. to HUMUS"   (tOM/ha)
I OrgRPM   ?->RPM onevt(OrgFert,QDMorg*RPMcont/100)_
                                   "Org. fert. to RPM"    (tOM/ha)
I OrgDPM   ?->DPM onevt(OrgFert,QDMorg*DPMcont/100)_
                                   "Org. fert. to DPM"    (tOM/ha)
I OrgBIO   ?->BIO onevt(OrgFert,QDMorg*BIOcont/100) _
                                   "Org. fert. to DPM"    (tOM/ha)
I OrgNH4   ?->NH4r  onevt(OrgFert,QorgFert*(DMcont/100)*_
       (DMinorg/100)*(NH4cont/100)*1000)_
                      "NH4 from org fert"     (kgN/ha)
A drT=47.9/(1+exp(106/(Tsoil+18.256)))  "Temp modif factor"
A drM=tab(DefFCr\1,0\1,20\0.2,45)           "Soil Moist modif factor"
A drCov=cond(cstage>1&cstage<7,0.6,1)   "Soil cover  modif factor"
S DrTill=1           "Decomposition rate tillage factor"
I DrTillSet  ?->drtill  onevt(Plow,KdrTill-DrTill) _
                                    "Reset tillage factor"
P Kdrtill=1      onevt(plow,1.5\Harrow,1.2\Extirp,1.3\Chisel,1.5)
R DrTillDecay=KdrDecay*DrTill*(DrTill-1)/DrTill DrTill->? "_
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                                                Declay tillage"            (-)
P KdrDecay=0.05      "Coeff.iciente declay factor tillage"
A DrFact=drT*drM*drCov*DrTill       "Overall decomposition rate factor"
S Residues=0        range(0,1000)     "Crop residues on soil"          (tB/ha)
I WLeaRes  Wleav->Residues onevt(Harvest,Wleav-WLeaHau) _
                           "Leaves d.m. to residues"               (tB/ha/d)
I WSteRes  Wstem->Residues onevt(Harvest,Wstem-WSteHau) _
                           "Stem d.m. to residues"                 (tB/ha/d)
I WStoRes  Wstor->Residues onevt(Harvest,Wstor-WStoHau) _
                           "Stor. org. d.m. to residues"            (tB/ha/d)
I WRooDPM    Wroot->DPM  onevt(Harvest,Wroot*FracResDPM) _
                           "Root d.m. to residues"                 (tB/ha/d)
I WRooRPM    Wroot->RPM  onevt(Harvest,Wroot*(1-FracResDPM) _
                           "Root d.m. to residues"                 (tB/ha/d)

I WLeaResD    WleavD->Residues  onevt(Harvest,(WleavD-WLeaHauD)) _
                           "Dead leaves d.m. to residues"          (tB/ha/d)
I WSteResD    WstemD->Residues  onevt(Harvest,(WstemD-WSteHauD)) _
                           "Dead stem d.m. to residues"             (tB/ha/d)
I WRooDPMd    WrootD->DPM   onevt(Harvest,WrootD*FracResDPM)    _
                           "Root d.m. to residues"                  (tB/ha/d)
I WRooRPMd    WrootD->RPM   onevt(Harvest,WrootD*(1-FracResDPM)) _
                           "Root d.m. to residues"                  (tB/ha/d)
V ResOM=when(Plow|Harrow|Chisel|Chopper)     "Residue tansfer to DPM/RPM"
I ResDPM     Residues->DPM   onevt(ResOM,Residues*FracResDPM*Ksubsoil) _
          "Residues to DPM at plowing"                              (tB/ha/d)
I ResRPM     Residues->RPM onevt(ResOM,Residues*(1-FracResDPM)*Ksubsoil) _
                           "Residues to RPM at plowing"             (tB/ha/d)
P Ksubsoil=0.9    "Subsoiling coefficient - fract DM subsoiled"          (-)
R ResDecSur=0.6*KresDec*Residues  Residues->?
                     "Soil surface residues decay to CO2 atm"          (tB/d)
R ResDecDPM=0.3*KresDec*Residues  Residues->DPM
                     "Soil surface residues decay to soil DPM"         (tB/d)
R ResDecRPM=0.1*KresDec*Residues  Residues->RPM
                     "Soil surface residues decay to soil RPM"         (tB/d)
P KresDec=0.0001    "Residue decay coefficient"                         (1/d)
A DRPM=RPM+DPA DRPM=RPM+DPM
R DecnDPM=cond(DPM>0.01,DPM*drfact*drDPM,0) DPM->? _
                                 "Decompos DPM as biomass"      (tB/ha/d)
R DecnRPM=cond(RPM>0.01,RPM*drfact*drRPM,0) RPM->? _
                                 "Decompos RPM as biomass"      (tB/ha/d)
R DecnBIO=cond(BIO>0.01,BIO*drfact*drBIO,0) _
                         BIO->?         "Decompos BIO"          (tB/ha/d)
R DecnHUM=cond(HUM>0.01,HUM*drfact*drHUM,0)  _
                         HUM->?         "Decompos HUM"          (tB/ha/d)
R InnBIO=BH*1/(1+ResDecr)*totdecn    ?->BIO  _
                     "Bio fraction of new decay"                (tB/ha/d)
R InnHUM=(1-BH)*1/(1+ResDecr)*totdecn    ?->HUM _
                     "Hum fraction of new decay"                (tB/ha/d)
A Totdecn=DrFact*(DPM*drDPM+RPM*drRPM+BIO*drBIO+HUM*drHUM) _
                     "Sum of new decay"                         (tB/ha/d)
A HBsynt=totdecn*1/(1+ResDecr)*Fnitro  _
             "Humus and microbial biomass synthesis"            (tB/ha/d)
A Fnitro=1/(Khalf+NH4dw)  _
                     "H and B factor in function of nitrogen amount"     (-)
P Khalf=20          "NH4 in Dw to obtain 50% of max Fnitro"          (kgN/ha)
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' XF_SoilN
S NH4r=DrMin*IniNH4*(1-Grav/100)    "Ammonia in soil root layer"  (kgN/ha)
S NO3r=DrMin*IniNO3*(1-Grav/100)   "Nitrate in soil root layer"   (kgN/ha)

S NH4d=(Ds-DrMin)*IniNH4*(1-Grav/100) _
                           "Ammonia in soil deep layer"          (kgN/ha)
S NO3d=(Ds-DrMin)*IniNO3*(1-Grav/100) _
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                        "Nitrate in soil deep layer"           (kgN/ha)
I NH4fert  onevt(MinFert,QMinFert*ContNH4) ?->NH4r  _
                        "Ammonium ferti."                      (kgN/ha)
I NO3fert  onevt(MinFert,QMinFert*ContNO3) ?->NO3r  _
                        "Nitrate ferti."                       (kgN/ha)
R Amincr=TonToKg*(DecnDPM+DecnRPM)*CRnc*Fripa        ?->NH4r _
                        "NH4 in miner. DPM/RPM-root layer"   (kgN/ha/d)
R Amincd=TonToKg*(DecnDPM+DecnRPM)*CRnc*(1-Fripa)        ?->NH4d _
                        "NH4 in miner. DPM/RPM-deep layer"   (kgN/ha/d)

R Aminhr=TonToKg*(DecnHUM+DecnBIO)*Chum/CNhum*Fripa       ?->NH4r   _
                        "NH4 in miner. HUM/BIO-root layer"   (kgN/ha/d)
R Aminhd=TonToKg*(DecnHUM+DecnBIO)*Chum/CNhum*(1-Fripa) ?->NH4d   _
                        "NH4 in miner. HUM/BIO-deep layer"   (kgN/ha/d)
R Aimmr=TonToKg*HBsynt*Chum/CNhum*Fripa                  NH4r->?   _
                        "NH4 immobilization - root layer"    (kgN/ha/d)
R Aimmd=TonToKg*HBsynt*Chum/CNhum*(1-Fripa)             NH4d->?    _
                        "NH4 immobilization - deep layer"    (kgN/ha/d)
R Nitrr=cond(NH4r>0,Nmax*Fcorn*NH4sr/(Kn+NH4sr),0)      NH4r->NO3r   _
                        "Nitrification rate - root layer"    (kgN/ha/d)
R Nitrd=cond(((NH4d-aAcr*dt)>0),Nmax*Fcorn*NH4sd/(Kn+NH4sd),0)_
        NH4d->NO3d      "Nitrification rate - deep layer"    (kgN/ha/d)
A Nitrraux=cond(NH4r>0,Nmax*Fcorn*NH4sr/(Kn+NH4sr),0)
A Nitrdaux=cond(((NH4d-aAcr*dt)>0),Nmax*Fcorn*NH4sd/(Kn+NH4sd),0)
R Acr=aAcr          NH4d->NH4r    "NH4 from root deepening"      (kgN/ha/d)
R Ncr=aNcr          NO3d->NO3r    "NO3 from root deepening"      (kgN/ha/d)
I RedistNH4 onevt(Harvest,NH4r*Fripa) NH4r->NH4d _
                             "NH4 redistri. at harvest"     (kgN/ha)
I RedistNO3 onevt(Harvest,NO3r*Fripa) NO3r->NO3d _
                             "NO3 redistri. at harvest"     (kgN/ha)
R NO3roff=(DrRoff/Dr)*NO3r*FrunOff       _
                        NO3r->NO3swater "NO3 run-off"         (kgN/ha/d)
R NH4roff=(DrRoff/Dr)*NH4sr*FrunOff      _
                        NH4r->NH4swater "NH4 run-off"         (kgN/ha/d)
A FrunOff=tab(aRunoff\0,0\1,80)                                      (-)
C DrRoff=5                                                          (mm)
P IniNH4=0.12    "Initial concentration of soil NH4 ff"         (kgN/mmS)
P IniNO3=0.2     "Initial concentration of soil NO3 ff"         (kgN/mmS)
A CNH4r=NH4r*1000/SmasR      "Concentration of NH4 in root layer"   (ug/g)
A CNH4d=NH4d*1000/SmasD      "Concentration of Nh4 in deep layer"   (ug/g)
A CNH4sr=NH4sr*1000/SmasR    "Concentration of NH4sr in root layer" (ug/g)
A CNH4ar=NH4ar*1000/SmasR    "Concentration of NH4ar in root layer" (ug/g)
A CNH4sd=NH4sd*1000/SmasD    "Concentration of NH4sd in root layer" (ug/g)
A CNH4ad=NH4ad*1000/SmasD    "Concentration of NH4ad in root layer" (ug/g)
A CNO3r=NO3r*1000/SmasR      "Concentration of NO3 in root layer"   (ug/g)
A CNO3d=NO3r*1000/SmasD      "Concentration of NO3 in deep layer"   (ug/g)
A aAcr=cond(Dd>0,(NH4d/Dd)*aDrate,0)   "NH4 from root deepening"(kgN/ha/d)
A aNcr=cond(Dd>0,(NO3d/Dd)*aDrate,0)   "NO3 from root deepening"(kgN/ha/d)
A Ft1=1.071^(Tsoil-35)        "Temp fact miner/nitr Cabon,1991"      (-)
A Ft3=10/(1+exp(106/(Tsoil+18.3)))   "Temp fact miner Jenkinson,1987"   (-)
A Ftd=tab(Tsoil\0,0\0.25,10\0.5,20\1,30)_
               "Temp fact miner/nitr/denitr Hansen,1991"            (-)
A pFr=log(Psir)/log(10)        "Log10 of Psi as cm (r)"             (-)
A Fmmr=tab(pFr\0.6,0\1,1.5\1,2.5\0,6.5)  _
                    "Moisture fact. miner. Hansen et al,1991 (r)"      (-)
A Fmnr=tab(pFr\0,0\1,1.5\1,2.5\0,5)   _
                   "Moisture fact. nitr. Hansen et al,1991 (r)"        (-)
A WSDr=Ur/MWCGrav     "Soil water satur. degree (r)"                  (-)
A Fmdr=tab(WSDr\0,0.8\0.2,0.9\1,1)
                  "Moisture fact. denitr. - Hansen,1991 (r)"          (-)
A pFd=log(Psid)/log(10) "Log10 of Psi as cm (d)"                      (-)

A Fmmd=tab(pFd\0.6,0\1,1.5\1,2.5\0,6.5)  _
                  "Moisture fact. miner. - Hansen et al,1991 (d)"     (-)
A Fmnd=tab(pFd\0,0\1,1.5\1,2.5\0,5)   _
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                  "Moisture fact. nitr. - Hansen et al,1991 (d)"       (-)
A WSDd=Ud/MWCGrav        "Soil water satur. degree (d)"                (-)
A Fmdd=tab(WSDr\0,0.8\0.2,0.9\1,1)           _
                  "Moisture fact. denitr. Hansen,1991 (d)"             (-)
adsorbed & solution NH4 is considered as instantaneous based on soil ex-
change capacity for ammonium (CS)
A Argumr=CS^2*(1+Ke)^2+2*CS*Ke*NH4r*(1-Ke)+Ke^2*NH4r^2    _
                  "Argument in NH4ar equation"                 (kgN^2/ha^2)
A Argumd=CS^2*(1+Ke)^2+2*CS*Ke*NH4d*(1-Ke)+Ke^2*NH4d^2    _
          "Argument in NH4ad equation"                         (kgN^2/ha^2)
A NH4ar=(CS+NH4r+(CS-sqrt(Argumr))/Ke)/2 _
                  "N-NH4 excangeable - root layer"                 (kgN/ha)
A NH4ad=(CS+NH4d+(CS-sqrt(Argumd))/Ke)/2 _
                  "N-NH4 excangeable - deep layer"                 (kgN/ha)
P Ke=10                 "Eq. const. Max ads. rate/Krel"                (-)
P CS=800                "Max. exc. capac. N-NH4"                   (kgN/ha)
A NH4sr=NH4r-NH4ar      "N-NH4 in soil solution - root layer"      (kgN/ha)
A NH4sd=NH4d-NH4ad      "N-NH4 in soil solution - deep layer"      (kgN/ha)
A CWNO3r=cond(Rr>0,NO3r/Rr,0) _
                         "NO3 concen. in root layer water"    (kgN/ha/mmW)
A CWNO3d=cond(Rd>0,NO3d/Rd,0)_
                          "NO3 concen. in deep layer water"   (kgN/ha/mmW)
A CWNH4r=cond(Rr>0,NH4sr/Rr,0)_
                          "NH4 concen. in root layer water"   (kgN/ha/mmW)
A CWNH4d=cond(Rd>0,NH4sd/Rd,0)_
                          "NH4 concen. in deep layer water"   (kgN/ha/mmW)
A NH4dw=NH4sd*Fripa+NH4sr*(1-Fripa)_
                          "NH4 available in Dw layer"              (kgN/ha)
A Fripa=cond(Dr>=Dw,1,Dr/Dw)    "Root layer fraction"                  (-)
C Chum=0.5                      "Carbon content in humus"        (kgC/kgOM)
P CNhum=10                      "C/N ratio of Humus"              (kgC/kgN)
' Nitrification (NH4s ->NO3) (Ft->Cabon,1991
A Fcorn=Ft1*Fmnr*(0.33*7.9-1.36)_
                           "Nitrific. factor for temp./moisture"       (-)
P Kn=15            "NH4sol at 1/2 max rate"                        (kgN/ha)
P Nmax=10          "Max nitrification rate"                      (kgN/ha/d)
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' CSS-CropManag
V Harrow=?  msg(Harrow_mm:)  disp(SoilRough)   "Soil harrowing"
V Hoeing=?  msg(Hoeing_mm:)  disp(SoilRough)   "Soil hoeing"
V Extirp=?  msg(Extirp_mm:)  disp(SoilRough)   "Extirpation"
V Chisel=?  msg(Chisel_mm:)  disp(SoilRough)   "Chiselling"
V Plow=?    msg(Plowing_mm:) disp(SoilRough)   "Ploughing"
V Chopper=? msg(chopper)                       "Chopping"
V MinFert=? msg(N_P_K_fertilization_kg/ha:) disp(QMinFert) _
                                                   "Mineral fert."
V OrgFert=? msg(Organic_fertilization_t/ha:) disp(QorgFert)_
                                                   "Organic fert."
V Irrigation=?   msg(Irrigation_mmW)    disp(Vad)   _
                                              "Scheduled irrigation"
V CropChoice=?  msg(Crop_Choice)              "Crop choice"
V Planting=?    msg(Planting)                 "Crop planting"
V Pesticide=?      msg(Pesticide_g/ha:)  disp(Qpest)  _
                                                 "Pesticide treatment"
V Harvest=?     msg(Harvest)                     "Crop harvest"
P Krough=200   onevt(Plow,?\Harrow,?\Extirp,?\Hoeing,?\Chisel,?)    _
                          "Roughness created by tillage"             (mm)
P QMinFert=100 onevt(minfert,?) "Amount of mineral fertiliz."   (kgMF/ha)
P ContNH4=0.46 onevt(minfert,?) "Fraction of NH4 in fertile."        (-)
P ContNO3=0.0    onevt(minfert,?) "Fraction of NO3 in fertiliser"    (-)
P ContN=ContNH4+ContNO3             "Total N content in fert."       (-)
P ContP=0.15          onevt(minfert,?)  "Fraction of P in fertiliser"  (-)
P ContK=0                           "Fraction of K in fertiliser"    (-)
```

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P QorgFert=50 onevt(orgfert,?)    "Organic fertilizer as it is"     (tB/ha)
P DMcont=20   onevt(orgfert,?) "Dry matter content of organic fert."  (%)
P DMorg=97    onevt(orgfert,?) "Organic content of d.m. DMcont"       (%)
P HUMcont=45  onevt(orgfert,?)       "Humus content in DMorg"         (%)
P DPMcont=25  onevt(orgfert,?)       "DPM content in DMorg"           (%)
P RPMcont=25  onevt(orgfert,?)       "RPM content in DMorg"           (%)
P BIOcont=5   onevt(orgfert,?)       "BIO content in DMorg"           (%)
P NH4cont=20  onevt(orgfert,?)       "N content in DMinorg"           (%)
P DMinorg=100-DMorg         "Inorganic content of d.m. DMcont"        (%)
P QDMorg=QorgFert*(DMcont/100)*(DMorg/100) "Dry organic matter"    (tB/ha)
P Qpest=10  onevt(Pesticide,?)       "Pesticide amount"            (kg/ha)
P Vad=0     onevt(irrigation,?)      "Irrigation volume"             (mmW)
P Iauto=0      range(0,1)            "Automatic irrigation with Ur    (-)
P Isou=0         "Irrig. water source: 1=groundwater;0=other"         (-)
P IrrEff=0.9  range(0,1)     "Irrigation efficiency"                  (-)
I IncrIWW ?->IrriWatWt _
        onevt(Irrigation,Vad*abs(Isou=1)\AutoIrri,DefFCr*abs(Isou=1)) _
                         "Irrigation rate from wt"                  (mmW)
I IncrIWO   ?->IrriWatOt  _
        onevt(Irrigation,Vad*abs(Isou=0)\AutoIrri,DefFCr*abs(Isou=0)) _
                         "Irrigation rate from other"              (mmW)
A Irri=cond(Irrigation,Vad*IrrEff,0)+cond(AutoIrri,DefFCr*IrrEff,0)  _
                         "daily irrigation water"
V AutoIrri=when(Cstage>0&Cstage<6&Ur<(1-AlloWS)*Uz&Iauto=1) _
         "Automatic irrigation"  msg(autoirri: mmW) disp(DefFCr)
I WsupWt          Wtab->?
                         onevt(Irrigation,Vad*IrrEff*abs(Isou=1)\_
                         AutoIrri,DefFCr*IrrEff*abs(Isou=1))  _
                         "Water supply from water table"         (mmW/d)
I WairWt                 ?->WairIrr _
        onevt(Irrigation,Vad*(1-IrrEff)*abs(Isou=1)_
                 \AutoIrri,DefFCr*(1IrrEff)*abs(Isou=1)) _
                         "Water loss in ambient air"             (mmW/d)
I WairOt          ?->WairIrr
onevt(Irrigation,Vad*(1-IrrEff)*abs(Isou=0)\_
                 AutoIrri,DefFCr*(1-IrrEff)*abs(Isou=0))  _
                         "Water loss in ambient air"              (mmW/d)
A WlossAtm=WairIrr+WairET"Total cumulated water in atmosphere"      (mmW)
V Tillage=when(Harrow|Extirp|Chisel|Plow)  msg(Tillage) "Soil tillage"(-)
V ErrTillage=when(Cstage>0&Tillage)  _
        end(Error:_Tillage_with_standing_crop)     "Tillage error"
V DryWT=when(WTAB<=0) end(Error:_Exausted_water_table)_
                          "Error for exhausted water table"
' Model: CSS_Economy.sem
' ECONOMIC BUDGET AT CROP LEVEL
S CropDebt=0                    "Crop costs "                     (Eu/ha)
S CropCredit=0                 "Crop revenues"                    (Eu/ha)
I CropSell onevt(CropSelling,PLV)  ?->CropCredit  "Crop revenue"  (Eu/ha)
A PLV=(HarvStor*PxStor*(1+HumidStor))+(HarvLeav*PxLeav*(1+HumidLeav))+ _
       (HarvStem*PxStem*(1+HumidStem))    "Revenues"             (EU/ha)
P FlagStore=0 onevt(Harvest,1\CropSelling,0) _
                          "Flag product ready for sell"           (-)
V CropSelling=when(FlagStore=1)                "Selling"
(-)
A CropBudget=CropCredit-CropDebt           "Crop economy balance"
(Eu/ha)
P HumidStor=0.14  onevt(CropChoice,?) "Storage organs sell moisture"  (-)
P HumidLeav=0.3   onevt(CropChoice,?) "Leave sell moisture"           (-)
P HumidStem=0.3   onevt(CropChoice,?) "Stem organs sell moisture"     (-)
I PayHarrow ?->CropDebt  onevt(Harrow,PxHarrow)     "Harrowing cost"
(Eu/ha)
I PayPlow   ?->CropDebt onevt(Plow,PxPlow)          "Ploughing cost"
(Eu/ha)
I PayChisel ?->CropDebt onevt(Chisel,PxChisel)      "Chisel cost"
(Eu/ha)
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I PayHoeing ?->CropDebt onevt(Hoeing,PxHoeing)      "Hoeing cost"  (Eu/ha)
I PayExtirp ?->CropDebt onevt(Extirp,PxExtirp)      "Extirp cost"  (Eu/ha)
I PayMinFert ?->CropDebt onevt(MinFert,PxMFOp+(PxFertMin*QMinFert)) _
                                         "Min fert cost"           (Eu/ha)
I PayOrgFert  ?->CropDebt _
        onevt(OrgFert,PxOrgFertOp+(PxFertOrg*QorgFert)) _
                                         "Org fert cost"           (Eu/ha)
I PayPlanting  ?->CropDebt onevt(Planting,PxPlantOp+(PxPlant*Qsow)) _
                                         "Planting cost"           (Eu/ha)
I PayIrri     ?->CropDebt _ onevt(Irrigation,PxIrri+(PxWater*Vad)_
                          \AutoIrri,PxIrri+(PxWater*DefFCr))   _
                                         "Irrigation cost"         (Eu/ha)
I PayPest  ?->CropDebt   onevt(Pesticide,PxPestOp+(PxPest*Qpest)) _
                                         "Pesticide cost"          (Eu/ha)
I PayHarvest  ?->CropDebt onevt(Harvest,PxHarvest) "Harvest cost"  (Eu/ha)
I PayChopping ?->CropDebt  onevt(Chopper,PxChopping) _
                                  "Chopping cost"                  (Eu/ha)
P PxStor=130      onevt(CropChoice,?)  "Price of storage biomass"  (Eu/t)
P PxLeav=0        onevt(CropChoice,?)  "Price of leave biomass"    (Eu/t)
P PxStem=0        onevt(CropChoice,?)  "Price of steam biomass"    (Eu/t)
P PxPlow=75       onevt(Plow,?)        "Price of ploughing"        (Eu/ha)
P PxHarrow=27     onevt(Harrow,?)      "Price of harrowing"        (Eu/ha)
P PxPlantOp=56    onevt(Planting,?)    "Price of planting "        (Eu/ha)
P PxPlant=8       onevt(Planting,?)    "Price of seeds "           (Eu/kg)
P PxPestOp=45     onevt(Pesticide,?)   "Price of pesticide "       (Eu/ha)
P PxPest=40       onevt(Pesticide,?)   "Price of pesticide"        (Eu/kg)
P PxMFOp=4        onevt(MinFert,?)     "Price of mineral fert."    (Eu/ha)
P PxFertMin=0.3   onevt(MinFert,?)     "Price of fertilizer"       (Eu/kg)
P PxIrri=47       onevt(Irrigation,?)  "Price of irrigation "      (Eu/ha)
P PxWater=3       onevt(Irrigation,?)  "Price of water 10mc=1mm"  (Eu/mmW)
P PxHarvest=191   onevt(Harvest,?)     "Price of harvest "         (Eu/ha)
P PxOrgFertOp=45   onevt(OrgFert,?)    "Price of organic fert. "   (Eu/ha)
P PxFertOrg=50   onevt(OrgFert,?)     "Price of manure"            (Eu/t)
P PxExtirp=70    onevt(Extirp,?)      "Price of extirping"         (Eu/ha)
P PxHoeing=45    onevt(Hoeing,?)      "Price of hoeing"            (Eu/ha)
P PxChisel=60    onevt(Chisel,?)      "Price of chiselling"        (Eu/ha)
P PxChopping=30 onevt(Chopper,?)      "Price of chopping"          (Eu/ha)
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' Model: CSS_Energy.sem
C GJtoMJ=1000   "Conversion factor from GJ to MJ"                 (MJ/GJ)
'Indicators
A Ebalance=CropEnerOut-TotEnInput _
                          "Energy balance for total crops"       (GJ/ha)
A Eeff=cond(TotEnInput>0,CropEnerOut/TotEnInput,0) _
                           "Energy effi. total crop"                (-)
A EHarvbalance=CropEnerHarv-TotEnInput _
                          "Energy balance for harvest"           (GJ/ha)
A EeffH=cond(TotEnInput>0,CropEnerHarv/TotEnInput,0) _
                                 "Energy eff. for harvest"          (-)
S CropEnerOut=0            "Total energy in the crop"            (GJ/ha)
I EnergOut onevt(harvest,TotCropEner) ?->CropEnerOut _
                               "Energy in crop"                     (GJ)
A Eleav=(Wleav+WleavD)*ECleav    "Energy in leaves biomass"      (MJ/ha)
A Estem=(Wstem+WstemD)*ECstem    "Energy in stems biomass"       (MJ/ha)
A Estor=Wstor*ECstor             "Energy in storage biomass"     (MJ/ha)
A Eroot=(Wroot+WrootD)*ECroot    "Energy in root biomass"        (MJ/ha)
A TotCropEner=(Eleav+Estem+Estor+Eroot)/GJtoMJ _
                               "Total energy in crop"            (GJ/ha)
S CropEnerHarv=0         "Total energy in the harvest"           (GJ/ha)
I EnergHarv onevt(harvest,HarvCropEnergy) ?->CropEnerHarv _
                          "Energy harvest"                          (GJ)
A HarvCropEnergy=(HEleav+HEstem+HEstor)/GJtoMJ _
                          "Harve. crop energy"                   (GJ/ha)
A HEleav=HarvLeav*ECleav  "Energy in harve. leaves"              (MJ/ha)
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A HEstem=HarvStem*ECstem       Energy in harve. stems"                    (MJ/ha)
A HEstor=HarvStor*ECstor      "Energy in harve. storage"                  (MJ/ha)
S DirEnInput=0               "Direct energy input for the crop"           (MJ/ha)
S InDirEnInput=0             "Indirect energy input for the crop"         (MJ/ha)
A TotEnInput=(DirEnInput+pippo)/GJtoMJ    "Total energy input"            (GJ/ha)
' Crop energy inputs - Energy parameters
P EnergFuel=55      "Energy for fuel"                                     (MJ/kgF)
P EnrLubr=80        "Energy for oil"                                      (MJ/kgL)
P EnTrac=132        "Energy for kg of tractor"                            (MJ/kgT)
P EnMacc=74         "Energy for kg of agricultural machine"               (MJ/kgM)
P TracWeight=3000  _
        onevt(Harrow,?\Plow,?\Chisel,?\Hoeing,?\_
        Extirp,?\MinFert,?\OrgFert,? _
        \Planting,?\Pesticide,?\Harvest,?\Irrigation,?\chopper,?)_
         "tractor weight"                                                 (kg)
P TracLife=7000   _
        onevt(Harrow,?\Plow,?\Chisel,?\Hoeing,?\_
        Extirp,?\MinFert,?\OrgFert,? _
        \Planting,?\Pesticide,?\Harvest,?\Irrigation,?\chopper,?)
                         "Useful life"                                    (h)

I InDiMinFert       ?->DirEnInput     onevt(MinFert,DirEnMinFert) _
                         "Direct energy input"                            (MJ)
I InInMinFert       ?-> InDirEnInput onevt(MinFert,IndEnMinFert)  _
                         "Indirect energy input"                          (MJ)
A DirEnMinFert=EnergFuel*ConFuelMinFert+EnrLubr*ConLubMinFert         _
                         "Direct energy input"                            (MJ/ha)
A IndEnMinFert=IndEnMinFert1+IndEnMinFert2    _
                          "Indirect energy input"                         (MJ/ha)
A IndEnMinFert1=(ContN*EnMinFertN+ContP*EnMinFertP+ContK*EnMinFertK)_
                   *QminFert                                              (MJ/ha)
A IndEnMinFert2=(EnTrac*TracWeight)*MinFertTime/TracLife+_
(EnMacc*MinFertWeight)*MinFertTime/MinFertLife                 (MJ/ha)
P EnMinFertN=103      "Energy content for kg of N"                        (MJ/KgN)
P EnMinFertP=22.3     "Energy content for kg of P"                        (MJ/KgP)
P EnMinFertK=0        "Energy content for kg of K"                        (MJ/KgK)
I InDiOrgFert       ?->DirEnInput            onevt(OrgFert,DirEnOrgFert)  _
                  "Direct energy input"                                   (MJ)
I InInOrgFert       ?->InDirEnInput          onevt(OrgFert,IndEnOrgFert)  _
                   "Indirect energy input"                                (MJ)
A DirEnOrgFert=EnergFuel*ConFuelOrgFert+EnrLubr*ConLubOrgFert           _
                     "Direct energy input"                                (MJ/ha)
A IndEnOrgFert=(EnTrac*TracWeight)*OrgFertTime/TracLife+_
                         (EnMacc*OrgFertWeight)*OrgFertTime/_
                         OrgFertLife+EnOrgFert*QorgFert*tontokg         _
                         "Indirect energy input"                          (MJ/ha)
P EnOrgFert=0.572      "Energy for the production of orgfert"             (MJ/kg)
I InDiPlant       ?->DirEnInput     onevt(Planting,DirEnPlant)  _
                       "Direct energy input"                              (MJ)
I InInPlant       ?->InDirEnInput           onevt(Planting,IndEnPlant)  _
                            "Indirect energy input"                       (MJ)
A DirEnPlant=EnergFuel*ConFuelPlant+EnrLubr*ConLubPlant                 _
                            "Direct energy input"                         MJ/ha)
A IndEnPlant=(EnTrac*TracWeight)*PlantTime/TracLife+_
                   (EnMacc*PlantWeight)   _
                   *PlantTime/PlantLife+EnSeed*Qsow                _
                          "Indirect energy input"                         (MJ/ha)
P EnSeed=10                "Energy for production of seed"                (MJ/kg)
I InDiPest        ?->DirEnInput     onevt(Pesticide,DirEnPest)  _
                                         "Direct energy input"            (MJ)
I InInPest        ?->InDirEnInput   onevt(Pesticide,IndEnPest)  _
                                         "Indirect energy input"          (MJ)
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A DirEnPest=EnergFuel*ConFuelPest+EnrLubr*ConLubPest _
                                         "Direct energy input"   (MJ/ha)
A IndEnPest=(EnTrac*TracWeight)*PestTime/TracLife+(EnMacc*PestWeight) _
                                 *PestTime/PestLife+EnPest*Qpest _
                                         "Indirect energy input" (MJ/ha)
P EnPest=220        "Energy to produce pesticide"               (MJ/kg)
I InDiHarrow      ?->DirEnInput  onevt(Harrow,DirEnHarrow)   _
                        "Direct energy input"                      (MJ)
I InInHarrow      ?->InDirEnInput  onevt(Harrow,IndEnHarrow)       _
                        " Indirect energy input "                  (MJ)
A DirEnHarrow=EnergFuel*ConFuelHarrow+EnrLubr*ConLubHarrow   _
                        "Direct energy input "                     (MJ)
A IndEnHarrow=(EnTrac*TracWeight)*HarrTime/TracLife+(EnMacc*HarrWeight) _
           *HarrTime/HarrLife    " Indirect energy input "     (MJ/ha)
I InDiPlow        ?->DirEnInput      onevt(Plow,DirEnPlow)     _
                        "Direct energy input"                      (MJ)
I InInPlow        ?->InDirEnInput    onevt(Plow,IndEnPlow)     _
                       "Indirect energy input"                    (MJ)
A DirEnPlow=EnergFuel*ConFuelPlow+EnrLubr*ConLubPlow               _
                                "Direct energy input"          (MJ/ha)
A IndEnPlow=(EnTrac*TracWeight)*PlowTime/TracLife+(EnMacc*PlowWeight) _
                 *PlowTime/PlowLife
                        Indirect energy input"  _              (MJ/ha)
I InDiChisel      ?->DirEnInput  onevt(Chisel,DirEnChisel)      _
                                "Direct energy input"              (MJ)
I InInChisel      ?->InDirEnInput  onevt(Chisel,IndEnChisel)    _
                                 "Indirect energy input"           (MJ)
A DirEnChisel=EnergFuel*ConFuelChisel+EnrLubr*ConLubChisel        _
                                 "Direct energy input"         (MJ/ha)
A IndEnChisel=(EnTrac*TracWeight)*ChiselTime_
                /TracLife+(EnMacc*ChiselWeight)  _
                *ChiselTime/ChiselLife_
               "Indirect energy input"                         (MJ/ha)
I InDiHoeing      ?->DirEnInput    onevt(Hoeing,DirEnHoeing)  _
                               "Direct energy input"              (MJ)
I InInHoeing      ?->InDirEnInput          onevt(Hoeing,IndEnHoeing)  _
                        "Indirect energy input"                   (MJ)
A DirEnHoeing=EnergFuel*ConFuelHoeing+EnrLubr*ConLubHoeing            _
                        "Direct energy input"                  (MJ/ha)
A IndEnHoeing=(EnTrac*TracWeight)*HoeingTime/TracLife_
                +(EnMacc*HoeingWeight) _
                *HoeingTime/HoeingLife _
                    "Indirect energy input"                    (MJ/ha)
I InDiExtirp      ?->DirEnInput    onevt(Extirp,DirEnExtirp)  _
                        "Direct energy input"                     (MJ)
I InInExtirp      ?->InDirEnInput          onevt(Extirp,IndEnExtirp)  _
                        "Indirect energy input"                   (MJ)
A DirEnExtirp=EnergFuel*ConFuelExtirp+EnrLubr*ConLubExtirp        _
                        "Direct energy input"                  (MJ/ha)
A IndEnExtirp=(EnTrac*TracWeight)*ExtirpTime/_
                TracLife+(EnMacc*ExtirpWeight)_
                *ExtirpTime/ExtirpLife  _
                    "Indirect energy input"                    (MJ/ha)
I InDiChopper      ?->DirEnInput          onevt(Harrow,DirEnChopper)  _
                        "Direct energy input"                     (MJ)
I InInChopper      ?->InDirEnInput        onevt(Chopper,IndEnChopper)  _
                        "Indirect energy input"                   (MJ)
A DirEnChopper=EnergFuel*ConFuelChopp+EnrLubr*ConLubChopp             _
                                "Direct energy input"          (MJ/ha)
A IndEnChopper=(EnTrac*TracWeight)*HarrTime/TracLife+(EnMacc*HarrWeight)_
                        *HarrTime/HarrLife       _
                                "Indirect energy input"        (MJ/ha)


I InDiHarv        ?->DirEnInput    onevt(Harvest,DirEnHarv)            _
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                                   "Direct energy input"                   (MJ)
I InInHarv      ?->InDirEnInput       onevt(Harvest,IndEnHarv)       _
                                   "Indirect energy input"                 (MJ)
A DirEnHarv=EnergFuel*ConFuelHarv+EnrLubr*ConLubHarv                       _
                                   "Direct energy input"                (MJ/ha)
A IndEnHarv=cond(MaccsemiMov=1,IndEnHarv1,IndEnHarv_
                                   "Indirect energy input"              (MJ/ha)
A IndEnHarv1=cond(TracLife=0,0,(EnTrac*TracWeight)*HarvTime/TracLife) _
                                   "Indirect energy input"             (MJ/ha)
A IndEnHarv2=cond(TracLife=0|HarvLife=0,0,(EnTrac*TracWeight)_
        *HarvTime/TracLife+(EnMacc*HarvWeight)*HarvTime/HarvLife)_
                                   "Indirect energy input "             (MJ/ha)
I InDiIrri      ?->DirEnInput    onevt(Irrigation,DirEnIrri) _
                                 "Direct energy input"                 (MJ/ha)
I InInIrri      ?->InDirEnInput onevt(Irrigation,IndEnIrri) _
                                 "Indirect energy input"               (MJ/ha)

A Wirri=cond(Autoirri=1,DefFCr,Vad)                      _
                                      "Irrigation water volume"          (mmW)
A DirEnIrri=Wirri*choose(ModIrri\0,8.28,8.28,8.28,9.72)  _
                                      "Indirect energy input"         (MJ/mmW)
P ModIrri=1          onevt(Irrigation,?)_
                                      "Irrigation method"                  (-)
A IndEnIrri=2.5*mmtomc+cond(ModIrri>0,(EnTrac*TracWeight)_

      *IrriTime/TracLife+(EnMacc*IrriWeight)*IrriTime/IrriLife,0) _
                                       "Indirect energy input"        (MJ/mmW)
P IrriTime=6.5      onevt(Irrigation,?)  "Duration of irrigation"          (h)
P IrriLife=1200     onevt(Irrigation,?) _
                                 "Useful life of the irri. machine"        (h)
P IrriWeight=800    onevt(Irrigation,?)  "Weight of machinery"            (kg)
P ConFuelHarrow=9    onevt(Harrow,?)    "Fuel consumption"             (kg/ha)
P ConLubHarrow=0.42  onevt(Harrow,?)    "Oil consumption"              (kg/ha)
P HarrWeight=1200    onevt(Harrow,?)    "Weight"                          (kg)
P HarrTime=0.5    onevt(Harrow,?)   "Time required for harrowing"      (h/ha)
P HarrLife=2000   onevt(Harrow,?)   "Useful life of the harrow machine"  (h)
P ConFuelPlow=43 onevt(Plow,?) "Fuel consumption"                      (kg/ha)
P ConLubPlow=2    onevt(Plow,?) "Oil consumption"                      (kg/ha)
P PlowWeight=1500 onevt(Plow,?)  "Weight"                                 (kg)
P PlowTime=1.9     onevt(Plow,?)  "Time required for ploughing"        (h/ha)
P PlowLife=2000    onevt(Plow,?)  "Useful life of the plough"             (h)
P ConFuelChisel=43   onevt(Chisel,?)    "Fuel consumption"             (kg/ha)
P ConLubChisel=2     onevt(Chisel,?)    "Oil consumption"              (kg/ha)
P ChiselWeight=720   onevt(Chisel,?)    "Weight"                          (kg)
P ChiselTime=0.8   onevt(Chisel,?) "Time required for chiselling"  (h/ha)
P ChiselLife=1200  onevt(Chisel,?) "Useful life of the chisel machine"  (h)
P ConFuelHoeing=5  onevt(Hoeing,?) "Fuel consumption"                  (kg/ha)
P ConLubHoeing=0.2 onevt(Hoeing,?)"Oil consumption"                    (kg/ha)
P HoeingWeight=980   onevt(Hoeing,?)    "Weight"                          (kg)
P HoeingTime=0.4   onevt(Hoeing,?) "Time required for hoeing"          (h/ha)
P HoeingLife=2000  onevt(Hoeing,?) "Useful life of the hoeing machine"(h)
P ConFuelExtirp=10   onevt(Extirp,?)    "Fuel consumption"             (kg/ha)
P ConLubExtirp=0.4   onevt(Extirp,?)    "Oil consumption"              (kg/ha)
P ExtirpWeight=1400  onevt(Extirp,?)    "Weight"                          (kg)
P ExtirpTime=0.8     onevt(Extirp,?)    "Time required for Extirp"     (h/ha)
P ExtirpLife=2000    onevt(Extirp,?)  _
                                 "Useful life of the Extirp machine"        (h)
P ConFuelMinFert=5   onevt(MinFert,?)   "Fuel consumption"             (Kg/ha)
P ConLubMinFert=0.2  onevt(MinFert,?)   "Oil consumption"              (Kg/ha)
P MinFertWeight=1200 onevt(MinFert,?)   "Weight"                          (kg)
P MinFertTime=0.1    onevt(MinFert,?)   "Time required for minfert"  (h/ha)
P MinFertLife=1200   onevt(MinFert,?)   _
                                     "Useful life of the minfert machine"   (h)
P ConFuelOrgFert=5   onevt(OrgFert,?)   "Fuel consumption"            (kg/ha)
P ConLubOrgFert=0.2  onevt(OrgFert,?)   "Oil consumption"              (kg/ha)
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```
P OrgFertWeight=2000 onevt(OrgFert,?)  "Weight"                      (kg)
P OrgFertTime=0.5    onevt(OrgFert,?)  "Time required for orgfert"  (h/ha)
P OrgFertLife=2000   onevt(OrgFert,?)  _
                         "Useful life of the OrgFert machine"         (h)
P ConFuelPlant=4     onevt(Planting,?) "Fuel consumption"          (kg/ha)
P ConLubPlant=0.2    onevt(Planting,?) "Oil consumption"           (kg/ha)
P PlantWeight=700    onevt(Planting,?) "Weight"                       (kg)
P PlantTime=1.1   onevt(Planting,?) "Time required for planting"  (h/ha)
P PlantLife=1000  onevt(Planting,?) _
                         "Useful life of the planting machine"        (h)
P ConFuelPest=1   onevt(Pesticide,?) "Fuel consumption"            (kg/ha)
P ConLubPest=0.1    onevt(Pesticide,?) "Oil consumption"           (kg/ha)
P PestWeight=260    onevt(Pesticide,?) "Weight"                       (kg)
P PestTime=0.2     onevt(Pesticide,?) "Time required for spraying"  (h/ha)
P PestLife=1200    onevt(Pesticide,?) "Useful life of the machine"     (h)
P ConFuelHarv=11    onevt(Harvest,?)   "Fuel consumption"           (kg/ha)
P ConLubHarv=0.5    onevt(Harvest,?)   "Oil consumption"            (kg/ha)
P MaccsemiMov=1     onevt(Harvest,?)   "Machinery type"                (-)
P HarvWeight=500    onevt(Harvest,?)   "Weight"                        (kg)
P HarvTime=0.3      onevt(Harvest,?)   "Time required for harvest"  (h/ha)
P HarvLife=5000     onevt(Harvest,?)   _
                         "Useful life of the harvest machine"          (h)
P ConFuelChopp=9    onevt(Chopper,?)   "Fuel consumption"           (kg/ha)
P ConLubChopp=0.42  onevt(Chopper,?)   "Oil consumption"            (kg/ha)
P ChoppWeight=1200  onevt(Chopper,?)   "Weight"                        (kg)
P ChoppTime=0.5     onevt(Chopper,?)  "Time required for Chopping"  (h/ha)
P ChoppLife=2000    onevt(Chopper,?)  _
                              "Useful life of the Chopper machine"     (h)
P ECleav=19000 onevt(CropChoice,?)  "Energy content of leaves"      (MJ/t)
P ECstem=19000 onevt(CropChoice,?) "Energy content of stems"        (MJ/t)
P ECstor=18520 onevt(CropChoice,?) _
                         "Energy content of storage organs"         (MJ/t)
P ECroot=14000 onevt(CropChoice,?) "Energy content of roots"        (MJ/t)
```

```
' Model: CSS-CropEnviron.sem
' Crop environmental accounting
A TotCO2atm=CO2atmR-CO2sink+CO2atmS+CO2atmDt+CO2atmIt+N2OCO2eqT+CO2Urea _
                          "CO2eq emission balance"               (tCO2eq/ha)
A CO2Fix=CO2sink          "CO2eq fix"                            (tCO2eq/ha)
A CO2Emm=CO2Urea+N2OCO2eqT+CO2atmIt+CO2atmDt+CO2atmS+CO2atmR _
                                   "CO2eq emission"               (tCO2eq/ha)
P N2ONtoN2O=44/28                     "N2ON to N2O - da IPCC"            (-)
P N2OtoCO2eq=298                      "Equivalent indicator"             (-)
' 298 for 100 years - IPCC
' 289 for 20  years - IPCC
' 153 for 500 years - IPCC
A N2O=N2ONdirect*N2ONtoN2O _
          "direct N2O-N emissions produced from managed soils"      (kgNO2)
A N2OCO2eq=N2O*N2OtoCO2eq "CO2eq due to N2O emissions in kg" (kgCO2eq/ha)
A N2OCO2eqT=N2OCO2eq/tontokg _
                     "CO2eq due to N2O emissions in ton"         (tCO2eq/ha)
S N2ONdirect=0   _
  "direct N2O-N emissions from N inputs to managed soils"          (kgN/ha)
I FsnNO3r    onevt(MinFert,Qminfert*ContNO3*EF1)     NO3r->N2ONdirect _
    "emissions of fertiliser N-NO3 applied to root layer"          (kgN/ha)
I FsnNH4r    onevt(MinFert,Qminfert*ContNH4*EF1)      NH4r->N2ONdirect _
     "emissions of fertiliser N-NH4 applied to root layer"         (kgN/ha)
I Fon   onevt(OrgFert,QorgFert*DMcont/100*_
                DMinorg/100*NH4cont/100*tontokg*EF1)_
                NH4r->N2ONdirect  _
                "emissions organic N applied to soils"             (kgN/ha)

I Fcr        onevt(Harvest,Residues*tontokg*CRnc*EF1)  ?->N2ONdirect  _
              "emissions of N in crop residues"                     (kgN/ha)
R FsomDPM=(DecnDPM*Chum*1/CNhum)*tontokg*EF1             NH4r->N2ONdirect _
```

```
              "emissions of N in from DPM  mineralisation"      (kgN/ha/d)
R FsomRPM=(DecnRPM*Chum*1/CNhum)*tontokg*EF1          NH4r->N2ONdirect  _
              "emissions of N in from RPM mineralisation"       (kgN/ha/d)
R FsomBIO=(DecnBIO*Chum*1/CNhum)*tontokg*EF1          NH4r->N2ONdirect  _
              "emissions of N in from BIO mineralisation"       (kgN/ha/d)
R FsomHUM=(DecnHUM*Chum*1/CNhum)*tontokg*EF1         NH4r->N2ONdirect  _
              "emissions of N in from HUM mineralisation"       (kgN/ha/d)
P EF1=0.01   "emission factor for N2O emissions from N inputs"        (-)
S CO2Urea=0                 "CO2 emission by using urea"        (tCO2eq/ha)
I EmCO2Urea  onevt(MinFert,QminFert/tontokg*EFu*CtoCO2*ureaMinFert) _
              ?->CO2Urea   "CO2 emission by urea"              (tCO2eq/ha)
A ureaMinFert=cond(ContNH4=0.46,1,0)    "urea 1=yes 0=no"              (-)
P EFu=0.20                     "emission factor for urea from IPCC"    (-)
S NO3gwater=0              "NO3 drained to water table"           (kgN/ha)
S NH4gwater=0              "NH4 drained to water table"           (kgN/ha)
S NO3swater=0              "NO3 to run-off water"                 (kgN/ha)
S NH4swater=0              "NH4 to run-off water"                 (kgN/ha)
' leaching
R NO3leachR=aIncrWt*CWNO3r NO3r->NO3gwater  _
                           "NO3 leaching root to wtable"        (kgN/ha/d)
R NO3leachD=aIncrWt*CWNO3d NO3d->NO3gwater  _
                           "NO3 leaching deep to wtable"        (kgN/ha/d)
R NH4leachR=aIncrWt*CWNH4r NH4r->NH4gwater  _
                           "NH4 leaching root to deep"          (kgN/ha/d)
R NH4leachD=aIncrWt*CWNH4d NH4d->NH4gwater _
                           "NH4 leaching deep to wtable"        (kgN/ha/d)
S TotRoff=0       "Total water runoff"                              (mmW)
S WairET=0       "ET water emitted to the atmosphere"               (mmW)
S WairIrr=0      "Irrigation water emitted to the atmosphere"        (mmW)
S IrriWatWt=0    "Total irrigation water use from water table"       (mmW)
S IrriWatOt=0    "Total irrigation water use from other sources"     (mmW)
S CO2atmR=0      "CO2 emission balance for crop"                (tCO2eq/ha)
S CO2sink=0          "CO2 fixed"                               (tCO2eq/ha)
R EmCO2Leav=cond(Cstage>0&Cstage<7,MainLeav*Wleav/CO2toCH2O,0)_
                               ?->CO2atmR  _
          "CO2 emission due to Leaves respiration"          (tCO2eq/ha/d)
R EmCO2Stem=cond(Cstage>0&Cstage<7,MainStem*Wstem/CO2toCH2O,0)_
                     ?->CO2atmR  _
          "CO2 emission due to Stem respiration"            (tCO2eq/ha/d)
R EmCO2Stor=cond(Cstage>0&Cstage<7,MainStor*Wstor/CO2toCH2O,0)    _
                  ?->CO2atmR  _
          "CO2 emission due to Storage organs respiration"   (tCO2eq/ha/d)
R EmCO2Root=cond(Cstage>0&Cstage<7,MainRoot*Wroot/CO2toCH2O,0)    _
                  ?->CO2atmR  _
                  "CO2 emission due to Root respiration"     (tCO2eq/ha/d)
R CO2leav=GRleava/CO2toCH2O   ?->CO2sink  "CO2 fixed"      (tCO2eq/ha/d)
R CO2stem=GRstema/CO2toCH2O   ?->CO2sink  "CO2 fixed"      (tCO2eq/ha/d)
R CO2stor=GRstora/CO2toCH2O   ?->CO2sink  "CO2 fixed"      (tCO2eq/ha/d)
R CO2root=GRroota/CO2toCH2O   ?->CO2sink  "CO2 fixed"        (tCO2eq/ha/d)
S CO2atmS=0          "CO2 emission balance for soil activity"  (tCO2eq/ha)
R ResDecAtm=0.6*KresDec*Residues/CO2toCH2O      ?->CO2AtmS     _
                  "Soil surface residues decay to CO2 atm"    (tCO2eq/ha/d)
R ResnDPM=ResDecr/(1+ResDecr)*decnDPM*CtoCo2   ?->CO2atmS     _
                  "Soil respiration of DPM"                 (tCO2eq/ha/d)
R ResnRPM=ResDecr/(1+ResDecr)*decnRPM*CtoCo2   ?->CO2atmS     _
                  "Soil respiration of RPM"                 (tCO2eq/ha/d)
R ResnBIO=ResDecr/(1+ResDecr)*decnBIO*CtoCo2   ?->CO2atmS    _
                  "Soil respiration of BIO"                 (tCO2eq/ha/d)


R ResnHUM=ResDecr/(1+ResDecr)*decnHUM*CtoCo2   ?->CO2atmS    _
                  "Soil respiration of HUM"                   (tCO2eq/ha/d)
P CtoCO2=44/12    "From carbon to carbon dioxide"                 (CO2/C)
```

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S CO2atmD=0       "direct CO2 emission from cropping in kg"    (kgCO2eq/ha)
A CO2atmDt=CO2atmD/tontokg _
                   "direct CO2 emission from cropping in ton"   (tCO2eq/ha)
S CO2atmI=0        "indi. CO2 emission from cropping in kg"    (kgCO2eq/ha)
A CO2atmIt=CO2atmI/tontokg _
                   "indi. CO2 emission from cropping in ton"    (tCO2eq/ha)
P CO2IndFuel=0.53  "CO2-eq emitted for  1 kg of fuel"         (kgco2eq/kgF)
P CO2DirFuel=3.1   "CO2 during combustion"                   (kgco2eq/kgF)
P CO2IndLub=1.04   "CO2-eq emitted for 1 kg of oil"          (kgco2eq/kgF)
P CO2Trac=6.05     "CO2-eq emitted to produce 1kg tractor"   (kgco2eq/kgT)
P CO2Macc=4.42     "CO2-eq emitted to produce 1kg machinery"(kgco2eq/kgM)
I InCO2DMinFer      ?->CO2atmD  onevt(MinFert,CO2DMinFer) _
   "direct CO2 emission from mineral fertilization"             (kgco2eq)
I InCO2IMinFer      ?->CO2atmI  onevt(MinFert,CO2IMinFer) _
   "indi. CO2 emission from mineral fertilization"              (kgco2eq)
A CO2DMinFer=(CO2IndFuel+CO2DirFuel)*_
        ConFuelMinFert+CO2IndLub*ConLubMinFert _
        "direct CO2 emission from mineral fertilization"     (kgco2eq/ha)
A CO2IMinFer=CO2IMinFer1+CO2IMinFer2    _
        "indi. CO2 emission from mineral fertilization"      (kgco2eq/ha)
a CO2IMinFer1=(CO2Trac*TracWeight)*MinFertTime/TracLife+          _
              (CO2Macc*MinFertWeight)*MinFertTime/MinFertLife  _
         "direct CO2 emission from mineral fertilization"    (kgco2eq/ha)
a CO2IMinFer2=(ContN*CO2IMinFerN+ContP*CO2IMinFertP+ContK*CO2IMinFertK)_
  *QminFert  "indi. CO2 emission from mineral fertilization" (kgco2eq/ha)
P CO2IMinFerN=3.29   "CO2-eq for producing 1 kg di N"         (kgco2eq/KgN)
P CO2IMinFertP=0     "CO2-eq for producing 1 kg di P"         (kgco2eq/KgP)
P CO2IMinFertK=0     "CO2-eq for producing 1 kg di K"         (kgco2eq/KgK)
I InCO2DOrgFer    ?->CO2atmD        onevt(OrgFert,CO2DOrgFert)   _
  "direct CO2 emission from organic fertilization"              (kgco2eq)
I InCO2IOrgFert   ?->CO2atmI        onevt(OrgFert,CO2IOrgFert) _
          "indi. CO2 emission from organic fertilization"       (kgco2eq)
A CO2DOrgFert=(CO2IndFuel+CO2DirFuel)_
        *ConFuelOrgFert+CO2IndLub*ConLubOrgFert  _
        "direct CO2 emission from organic fertilization"     (kgco2eq/ha)
A CO2IOrgFert=(CO2Trac*TracWeight)*_
        OrgFertTime/TracLife+(CO2Macc*OrgFertWeight)_
        *OrgFertTime/OrgFertLife+CO2IndOrgFer*QorgFert*tontokg          _
        "indi. CO2 emission from organic fertilization"      (kgco2eq/ha)
P CO2IndOrgFer=0.311  _
  "CO2-eq for producing 1 kg organic fertilizer"               (kgco2eq/kg)
I InCO2DPlant    ?->CO2atmD    onevt(Planting,CO2DPlant)  _
        "direct CO2 emission from planting"                       (kgco2eq)
I InCO2IPlant    ?->CO2atmI        onevt(Planting,CO2IPlant) _
        "indi. CO2 emission from planting"                        (kgco2eq)
A CO2DPlant=(CO2IndFuel+CO2DirFuel)*_
                ConFuelPlant+CO2IndLub*ConLubPlant         _
                "direct CO2 emission from planting"          (kgco2eq/ha)
A
CO2IPlant=(CO2Trac*TracWeight)*PlantTime/TracLife+(CO2Macc*PlantWeight)_
        *PlantTime/PlantLife+CO2ISeed*Qsow     _
        "indi. CO2 emission from planting"                   (kgco2eq/ha)
P CO2ISeed=1.8    "CO2-eq for producing 1 kg of seeds"         (kgco2eq/kg)

I InCO2DPest        ?->CO2atmD          onevt(Pesticide,CO2DPest)  _
        "direct CO2 emission from planting from pesticide"      (kgco2eq)
I InCO2IPest        ?->CO2atmI          onevt(Pesticide,CO2IPest)  _
        "indi. CO2 emission from pesticide"                       (kgco2eq)
A CO2DPest=(CO2IndFuel+CO2DirFuel)*ConFuelPest+CO2IndLub*ConLubPest   _
   "direct CO2 emission from planting from pesticide "        (kgco2eq/ha)
A CO2IPest=(CO2Trac*TracWeight)*PestTime/TracLife+(CO2Macc*PestWeight)  _
        *PestTime/PestLife+CO2IndPest*Qpest        _
        "indi. CO2 emission from pesticide"                    (kgco2eq/ha)
P CO2IndPest=7.7 "CO2-eq for producing 1 kg of pesticide"      (kgco2eq/kg)
I InCO2DHarrow      ?->CO2atmD      onevt(Harrow,CO2DHarrow)  _
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                 "direct CO2 emission from harrowing"              (kgco2eq)
I InCO2IHarrow      ?->CO2atmI      onevt(Harrow,CO2IHarrow)          _
       "indi. CO2 emission from harrowing"                         (kgco2eq)


A CO2DHarrow=(CO2IndFuel+CO2DirFuel)*_
        ConFuelHarrow+CO2IndLub*ConLubHarrow     _
      "direct CO2 emission from planting from harrowing"          (kgco2eq)
A CO2IHarrow=(CO2Trac*TracWeight)*HarrTime/TracLife+_
    (CO2Macc*HarrWeight) _
   *HarrTime/HarrLife   "indi. CO2 emission from harrowing"  (kgco2eq/ha)
I InCO2DPlow        ?->CO2atmD    onevt(Plow,CO2DPlow)          _
                 "direct CO2 emission from ploughing"             (kgco2eq)
I InCO2IPlow        ?->CO2atmI    onevt(Plow,CO2IPlow)          _
                 "indi. CO2 emission from ploughing"               (kgco2eq)
A CO2DPlow=(CO2IndFuel+CO2DirFuel)*ConFuelPlow+CO2IndLub*ConLubPlow_
               "direct CO2 emission from ploughing"            (kgco2eq/ha)
A CO2IPlow=(CO2Trac*TracWeight)*PlowTime/TracLife+(CO2Macc*HarrWeight) _
    *PlowTime/PlowLife   "indi. CO2 emission from ploughing" (kgco2eq/ha)
I InCO2DChisel      ?->CO2atmD      onevt(Chisel,CO2DChisel)
            "direct CO2 emission from chiselling"                 _
I InCO2IChisel      ?->CO2atmI      onevt(Chisel,CO2IChisel)       (kgco2eq)
            "indi. CO2 emission from chiselling"                  _
A CO2DChisel=(CO2IndFuel+CO2DirFuel)_                              (kgco2eq)
        *ConFuelChisel+CO2IndLub*ConLubChisel      _
        "direct CO2 emission from chiselling"                   (kgco2eq/ha)
A CO2IChisel=(CO2Trac*TracWeight)*ChiselTime_
   /TracLife+(CO2Macc*ChiselWeight)  _
   *ChiselTime/ChiselLife "indi. CO2 emissioni from quisling"(kgco2eq/ha)
I InCO2DHoeing      ?->CO2atmD    onevt(Hoeing,CO2DHoeing)         _
           "direct CO2 emission from hoeing"                       (kgco2eq)
I InCO2IHoeing      ?->CO2atmI    onevt(Hoeing,CO2IHoeing)        _
        "indi. CO2 emission from hoeing "                          (kgco2eq)
A CO2DHoeing=(CO2IndFuel+CO2DirFuel)*_
        ConFuelHoeing+CO2IndLub*ConLubHoeing     _
        "direct CO2 emission from hoeing "                     (kgco2eq/ha)
A CO2IHoeing=(CO2Trac*TracWeight)*HoeingTime/_
  TracLife+(CO2Macc*HoeingWeight) _
  *HoeingTime/HoeingLife "indi. CO2 emission from hoeing"    (kgco2eq/ha)
I InCO2DExtirp      ?->CO2atmD    onevt(Extirp,CO2DExtirp)          _
                "direct CO2 emission from extirp"
(kgco2eq)
I InCO2IExtirp      ?->CO2atmI    onevt(Extirp,CO2IExtirp)        _
                "indi. CO2 emission from extirp"                   (kgco2eq)
A CO2DExtirp=(CO2IndFuel+CO2DirFuel)*_
        ConFuelExtirp+CO2IndLub*ConLubExtirp  _
        "direct CO2 emission from extirp"                      (kgco2eq/ha)
A CO2IExtirp=(CO2Trac*TracWeight)*ExtirpTime_
  /TracLife+(CO2Macc*ExtirpWeight)* _
  ExtirpTime/ExtirpLife   "indi. CO2 emission from extirp"   (kgco2eq/ha)
I InCO2DChopper      ?->CO2atmD          onevt(Harrow,CO2DChopper) _
                 "direct CO2 emission from chopper"              (kgco2eq)
I InCO2IChopper      ?->CO2atmI          onevt(Chopper,CO2IChopper)  _
                "indi. CO2 emission from chopper "                 (kgco2eq)
A CO2DChopper=(CO2IndFuel+CO2DirFuel)*_
        ConFuelChopp+CO2IndLub*ConLubChopp _
        "direct CO2 emission from chopper "                   (kgco2eq/ha)
A CO2IChopper=(CO2Trac*TracWeight)*_
        HarrTime/TracLife+(CO2Macc*HarrWeight) _
        *HarrTime/HarrLife "indi. CO2 emission from chopper"(kgco2eq/ha)
I InCO2DHarv         ?->CO2atmD       onevt(Harvest,CO2DHarv)         _
        "direct CO2 emission from harvest"                         (kgco2eq)
I InCO2IHarv         ?->CO2atmI       onevt(Harvest,CO2IHarv)         _
        "indi. CO2 emission from harvest "                         (kgco2eq)
A CO2DHarv=(CO2IndFuel+CO2DirFuel)*_
```

```
                           ConFuelHarv+CO2IndLub*ConLubHarv      (kgco2eq/ha)
A CO2IHarv=cond(MaccsemiMov=1,CO2IHarv1,CO2IHarv2)               (kgco2eq/ha)


A CO2IHarv1=cond(TracLife=0,0,_
        (CO2Trac*TracWeight)*HarvTime/TracLife)  (kgco2eq/ha)
A CO2IHarv2=cond(TracLife=0|HarvLife=0,0,(CO2Trac*TracWeight) _
        *HarvTime/TracLife+(CO2Macc*HarvWeight)*HarvTime/HarvLife) _
        "indi. CO2 emission from harvest"                        (kgco2eq/ha)
```

II. CSSmin model SEMoLa code

```
' MiniCSS
$ vers(1.1$ vers(1.1)
$ dt(1$ dt(1)
$ tspan(1,365$ tspan(1,365)
$ tunit(d)$ tunit(d)
' output vars
$ outvar(Rain,Etr,Tmax,Tmin,Rg$ outvar(Rain,Etr,Tmax,Tmin,Rg)
$ outvar(GDD,Cstage,Kc,Fws,FN,Ft,WStem,Wleaf,Wcrop,Yield,LAI,SellYield
$ outvar(IrriCost,FertCost,AltriCos,CostTot,Plv,CropBudg$
$ outvar(IrriEng,FertEng,ENGuse,ENGTotIn,ENGTotOut,Ebalance,EROI$
$ outvar(NumIrri,Wirri,NumFert,Nfert$ outvar(NumIrri,Wirri,NumFert,Nfert)
$ outvar(NH4,NO3,NH4GW,NO3GW,NO3roff,NH4roff,Denit,Ncrop$
$ outvar(Dsoil$ outvar(Dsoil)
$ outvar(SOM,SOC,IOM,BIO,HUM,RPM,DPM$ outvar(SOM,SOC,IOM,BIO,HUM,RPM,DPM)
$ out-
var(WatSup,IrriWat,Arunoff,Runoff,Drainage,RU,Gwater,Us,Uz,ETa,RFU,DEfici
t$
' Exogenous variables
E Rain range(0,1000)      "Rainfall"
(mmW/d)
E ETr range(0,30)         "Reference evapotranspiration"
(mmW/d)
E Tmax range(-40,60)      "Daily maximum air temperature"      (C)
E Tmin range(-60,40)      "Daily maximum air temperature"      (C)
E Rg range(0,50)          "Daily solar global radiation"
(MJ/mq/d)
A Temp=(Tmax+Tmin)/2      "Daily mean air temperature"
            (C)
' sections
@ CSSMini_crop            "Crop growth and phenology"
@ CSSMini_soil            "Soil"
@ CSSMini_water           "Soil water"
@ CSSMini_nitrogen        "Nitrogen in the system"
@ CSSMini_som             "Soil organic matter"
@ CSSMini_Manag           "Crop agronomic practices"
@ CSSMini_economy         "Crop economy balance"
@ CSSMini_energy          "Crop energy balance"
```

```
' MiniCSS_crop
'Phenology
S GDD=0 range(0,5000)             "Sum of temperatures (GDD)"        (C*d)
R STday=STdayA ?->GDD             "Daily increasing of GDD"           (C)
a STdayA=cond(Temp>T1,Temp-T1,0)  "Daily increasing of GDD (aux)"     (C)
' Kc Crop coefficients for water use
A Kc=tab(GDD\Kc1,GDDem\Kc2,GDDsc\Kc3,GDDfl\Kc4,GDDac\Kc5,GDDpm) _
                                   "Water use crop coeff."             (-)
A Uz=WPgrav+(FCgrav-WPgrav)*(1-Z) "Critical moist. for stress"  (mmW/mmS)
A z=1-(C1/(1+C2*exp(-C3*ETm)))    "Critical moist. for stress"  (mmW/mmS)
A Fws=tab(Us\0,WPGrav\1,Uz)       "Water stress factor"               (-)
A Ft=tab(Temp\0,T1\1,T2\1,T3\0,T4)  "Temperature growth factor"       (-)
A FN=tab(ConcNcrop\0,0\1,ConcNopt)  "Effect of N nutrition on growth" (-)
P Cstage=0  _
       onevt(Semina,1\SeminaAuto,1\Emerge,2\CoperTerr,3\ _
             Fioritu,4\IniAccum,5\MatuFisio,6\MatuRacco,7) _
                                  "Crop phenological stage"           (-)
V Emerge=when(GDD>GDDem&Cstage=1)  msg(Emergenza)  "Emergence"        (-)
V CoperTerr=when(GDD>GDDsc&Cstage=2)_
                 msg(CoperturaTerreno)          "Complete S.C"        (-)
V Fioritu=when(GDD>GDDfl&Cstage=3)_
                 msg(Fioritura)                 "Flowering"          (-)
```

```
V IniAccum=when(GDD>GDDac&Cstage=4)_
                 msg(InizioAccumulo)  "Beg. acc."                    (-)
V MatuFisio=when(GDD>GDDpm&Cstage=5)_
                 msg(MaturazioneFisiologica) "Phys. matu"            (-)
V MatuRacco=when(GDD>GDDhm&Cstage=6)_
                 msg(MaturazioneRaccolta)    "Har. maturi"           (-)
' Cstage=0 No crop
' Cstage=1 Emergency phase (Planting-GDDem)
' Cstage=2 Soil covering (GDDem-GDDsc)
' Cstage=3 Vegetative phase (GDDsc-GDDfl)
' Cstage=4 Flowering phase (GDDfl-GDDac)
' Cstage=5 Accumulation phase (GDDac-GDDpm)
' Cstage=6 Drying phase (GDDpm-GDDhm)
' Cstage=7 Waiting for harvest phase (GDDhm-Harvest)
P GDDem=90      range(20,150)    "Start vegetative phase (emergence)(C*d)
P GDDsc=450     range(50,400)    "Complete soil covering"          (C*d)
P GDDfl=800     range(100,600)   "End vegetative phase"            (C*d)
P GDDac=1100    range(100,1000)  "Start accumulation"              (C*d)
P GDDpm=1400    range(500,1600)  "Physiological ripening"          (C*d)
P GDDhm=1600    range(800,2000)  "Harvest maturity"                (C*d)
' Biomass
S Wstem=0       "Crop biomass - no active leaves"                  (t/ha)
S Wleaf=0       "Active leave biomass "                            (t/ha)
A Wcrop=Wstem+Wleaf      "Total crop biomass"                      (t/ha)
I RiniWs ?->Wstem _
        onevt(Semina,IniW*(1-IFleaf)\SeminaAuto,IniW*(1-IFleaf))_
                 "Initial biomass with seed the rest"              (t/ha)
I RiniWl ?->Wleaf _
        onevt(Semina,IniW*IFleaf\SeminaAuto,IniW*IFleaf) _
                 "Initial of biomass with seed to leaf"            (t/ha)
a GR1=(Ef*IRAD)/100*Ft*FN*Fwa GR1=(Ef*IRAD)/100*Ft*FN*Fws
' /100 converts g/mq to t/ha
R GR=cond(cstage>1,GR1*(1-Krip),0)?->Wstem "Crop growth rate"    (t/ha/d)
R GRleaf=cond(cstage>1,GR1*Krip,0) ?->Wleaf  "Leaf growth rate"  (t/ha/d)
A Yield=HI*Wcrop                  "Yield"                          (t/ha)
A LAI=Wleaf*LAR          "Leaf area index"                (haLeaf/haSoil)
A Krip=tab(GDD\IFleaf,0\0,GDDac)  "Biomass fraction to leaves"
A IRAD=Rg*(1-exp(-Kext*LAI))      "Intercepted radiation"     (MJ/mq/day)
R ResStem=Kresp*Wstem     Wstem->?  "Stem respiration"
R ResLeaf=Kresp*Wleaf     Wleaf->? "L eaves respiration"
A Kresp=TAB(temp\0,10\0.001,15\0.005,25\0.01,35) _
                          "Respiration coefficient"                 (1/d)
R SenLeaf=Fsen*Wleaf      Wleaf->Wstem     "Leaf senescence"
A Fsen=cond(GDD>GDDac,Ksen,0)              "Senescence factor"
P IniW=0.01     range(0.01,1)     "Crop initial biomass "          (t/ha)
P HI=0.5        range(0.1,1)      "Harvest index"                   (-)
P Ef=4          range(1,7)        "Max conversion efficiency"     (gdm/MJ)
P LAR=1.2       range(0.5,2.5)    "Leaf area ratio"        (haLeaf/tLeaves)
P IFleaf=0.8    range(1,0.2)      "Initial fraction of leaves"      (-)
P Kext=0.7      range(0,1)        "Light extinction coeff. in the canopy"
P Ksen=0.08     range(0,0.3)      "Leaves senescence coefficient "
P Rmax=1.2   range(0.5,2)      "Maximum root deepening"           (mmS/C/d)
P Kc1=0.4    range(0,1.5) "Kc at GDDem - water use crop coefficient"  (-)
P Kc2=0.8    range(0,1.5) "Kc at GDDsc - water use crop coefficient"  (-)
P Kc3=1.15   range(0,1.5) "Kc at GDDfl - water use crop coefficient"  (-)
P Kc4=1.1    range(0,1.5) "Kc at GDDac - water use crop coefficient"  (-)
P Kc5=0.4    range(0,1.5) "Kc at GDDpm - water use crop coefficient"  (-)
P C1=0.6058 "Parameter crop evap. from Table 22 in FAO Paper 56"      (-)
P C2=11.86   "Parameter crop evap. from Table 22 in FAO Paper 56"     (-)
P C3=0.6017 "Parameter crop evap. from Table 22 in FAO Paper 56"      (-)
P T1=10         range(0,15)       "Minimum growth temperature"        (C)
P T2=26         range(5,30)       "Minimum optimum growth temperature (C)
P T3=34         range(10,35)      "Maximum optimum growth temperature (C)
P T4=48         range(25,45)      "Maximum growth temperature"        (C)
P Kuptak=0.05   "Crop NO3 uptake coefficient"                         (-)
```

```
P IniNcrop=0.1     "Crop initial nitrogen amount"                  (kg/ha)
P Cnfix=0          "N-fixation code (1=yes/0=no)"                    (-)
P ConcNopt=25      "Crop optimum nitrogen concentration"           (kgN/t)
P CRnc=0.005       "N content in crop residue"                   (kgN/kgB)
```

```
' MiniCSS_soil
' Soil temperature
S Tsoil=-S Tsoil=-1
R Scambio=Ktras*(Temp-Tsoil) ?->TsoiR
C Ktras=0.08                         "Heat transfer coefficient in soil"
' Soil Characteristics
P Grav=5       range(0,40)           "Grave"                              (%)
P Clay=32.3    range(5,90)  "Soil clay content"                           (%)
P Ks=350       range(5,1000)         "Saturated conductivity"         (mmW/d)
P WP=0.15      range(0.01,0.22)      "Wilting point"                (mmW/mmS)
P FC=0.25      range(0.05,0.4)       "Water field capacity"         (mmW/mmS)
P MWC=0.38     range(0.3,0.6)        "Maximum water capacity"       (mmW/mmS)
P WPGrav=WP*(1-Grav/100)  "Wilting point"                           (mmW/mmS)
P FCGrav=FC*(1-Grav/100)  "Water field capacity"                    (mmW/mmS)
P MWCGrav=MWC*(1-Grav/100)           " Maximum water capacity"      (mmW/mmS)
P Dw=400                             "Soil working depth"               (mmS)
P DsMax=800                          "Max exploitable depth"            (mmS)
P BB=(log(0.2)-log(15))/(log(FCgrav/MWCgrav)-log(WPgrav/MWCgrav))_
                                     "Campbell Psi=Psie*(Us/MWC)^BB"
P Psie=exp(log(15)+BB*log(FCgrav/MWCgrav))_
                                     "Campbell Psi=Psie*(Us/MWC)^BB"
'Root deepening
S Dsoil=Dsmin range(0,4000)          "Root depth (useful soil layer)"   (mmS)
C Dsmin=100                          "Minimum soil depth"               (mmS)
A Incroot=cond(Cstage>0&Cstage<6,(Rmax*STdayA/(1+(GDD/GDDac)^20)),0) _
                                     "Root deepening day"             (mmS/d)
A Dratex=cond(Dsoil+Incroot<DsMax,Incroot,0) _
                          "Root deepening (aux)"                      (mmS/d)
R Drate=Dratex ?->Dsoil                        "Root deepening rate"  (mmS/d)
A Tmass=Dsoil*ConvMass*Bd            "Soil mass till to Dsoil depth"  (tS/ha)
C ConvMass=10      "Conv. factor from mmS*g/cc to t/ha"(tS/ha/(mmS*gS/ccS))
A Bd=MWCgrav/((100-Som)/100/DensMin+Som/100/DensOM) _
                          "Soil bulk density"                       (gS/ccS)
C DensMin=2.65                       "Density of minerals"          (gS/ccS)
C DensOM=1.43                        "Density organic matter"       (gS/ccS)
P IniSOM=2.2       range(0,10)       "Soil organic matter - ff"           (%)
c FracDpm=0.02                       "DPM fraction in SOM"                (-)
c FracRpm=0.14                       "RPM fraction in SOM"                (-)
P FracHum=1-(FracDpm+FracRpm+FracBio+FracIom)"Hum fraction in SOM"       (-)
C FracBio=0.02                                 "BIO fraction in SOM"      (-)
C FracIom=0.10                                 "IOM fraction in SOM"      (-)
C Kumus=0.0001            "Coeff. mineralizzazione humus"                 (-)
C Krpm=0.01               "Coeff. mineralizzazione RPM"                   (-)
C Kdpm=0.02               "Coeff. mineralizzazione DPM"                   (-)
C KrpmUm=0.01             "Coeff. umificazione RPM"                       (-)
C Chum=0.5                "Carbon content in humus"                 (kgC/kgOM)
C CNhum=10                "C/N ratio of Humus"                       (kgC/kgN)
C BH=0.46                 "BIO/HUM ratio for (BIO+HUM) q.ty"              (-)
' 0.5 = Carbon content in humus; 10 = rate C/N in humus.
' azoto
P IniNH4=30               "Initial N-NH4 in soil"                    (kgN/ha)
P IniNO3=20               "Initial N-NO3 in soil"                    (kgN/ha)
C Ke=10            "Eq. const. Max ads. rate/Krel"                        (-)
C CS=800                  "Max. exc. capac. N-NH4"                   (kgN/ha)
C Knitri=0.7              "Coefficiente di nitrificazione"                (-)
C Dmax=0.01               "Coeff. denitr. - max a MWC/10 C"             (1/d)
```

```
' MiniCSS_Water
A WatSup=Rain+IrriWat            "Daily water supply"                (mmW)
A IrriWat=IrriWatAuto+IrriWatTurno+IrriWatSche_
              "Irrigation water supply"                              (mmW)
A IrriWatAuto=cond(IrriAuto=1,vad,0)_
             "Automatic irri. water supply"                          (mmW)
A IrriWatTurno=cond(IrriTurno=1,vad,0)_
             "Turn irri. water supply"                               (mmW)
A IrriWatSche=cond(IrriSched=1,RVadSched,0)_
             "Schedul. irri. water supply"                           (mmW)
'infiltrazione
A Infilt=cond(Rain<Ks,WatSup,Ks)_
            "Infiltrabile water in soil in 1 day"                    (mmW)
R InfSoil=cond(Infilt<Deficit,Infilt,Deficit) ?->RU _
            "Infiltrabile water that which remains in the soil"   (mmW/d)
A VAd=cond(deficit>Ks,Ks,deficit*(2-EffIrri))
S Arunoff=0                           "Total run-off water"         (mmW)
R RunOff=cond(Rain>Ks,WatSup-Infilt,0)_
         ?->Arunoff              "Run-off water"                    (mmW/d)
R Drainage=cond(Infilt<Deficit,0,(Infilt-Deficit)*0.3) ?->Gwater _
                                 "Drainage"                         (mmW/d)
' Water from deep to root depth
R Icr=cond(Dsoil>DsMin,FCgrav*Dratex,0) ?->RU_
                          "Water from deep to root"                (mmW/d)
' Water balance
S RU=Usini*Dsoil          "Water reserve in useful soil layer"      (mmW)
P Usini=0.10              "Initial soil moisture"               (mmW/mmS)
S Gwater=0                "Water in phreatic layer"                 (mmW)
A Us=RU/Dsoil             "Soil moisture"                       (mmW/mmS)
A ETm=ETr*Kc              "Maxim. evapotranspiration"             (mmW/d)
R ETa=tab(Us\0,WPgrav\ETm,Uz)RU->?_
                          "Actual evapotranspiration"             (mmW/d)
A Deficit=Dsoil*(FCgrav-Us) "Deficit a field capacity"              (mmW)
A SWsat=Us/MWCgrav          "Degree of soil water saturation"
A RFU=(Us-Uz)*Dsoil         "Easily usable water reserve"           (mmW)
```

```
' MiniCSS_nitrogen
' mineralization
C TonToKg=1000                        "Conversion ton to kg"      (-)
R Amincr=TonToKg*(DecnDPM+DecnRPM)*CRnc      ?->NH4 _
                                "NH4 in miner. DPM/RPM"       (kgN/ha/d)
R Aminhr=TonToKg*(DecnHUM+DecnBIO)*Chum/CNhum ?->NH4 _
                                "NH4 in miner. HUM/BIO"       (kgN/ha/d)
R RlisNH4=cond(ConcNH4>0,ConcNH4*Drainage,0) NH4->NH4GW_
                                 "leaching NH4"                  (kgN/d)
I NH4fert onevt(FertNH4Auto,AutoQfertN\FertNH4,SchedQfertN) ?->NH4 _
                                     "N fertilization"          (kgN/ha)
R NH4cr=Dratex*iniNH4/(Dsmax-Dsoil) ?->NH4 _
                                "NH4 from root deepening"     (kgN/ha/d)
R NO3cr=Dratex*iniNO3/(Dsmax-Dsoil) ?->NO3_
                                 "NO3 from root deepening"    (kgN/ha/d)
A Ftd=tab(Tsoil\0,0\0.25,10\0.5,20\1,30) _
                 "Temp. fact min/nitr/denitr (Hansen ,1991)"
A Psi=Psie*((Us/MWCgrav)^(-BB))*10 "Water potential "               (cm)
A pF=log(Psi)/log(10)            "Log10 of Psi (as cm)"
A Fmm=tab(pF\0.6,0\1,1.5\1,2.5\0,6.5) _
                          "Moist. fact miner. (Hansen et al,1991)"
A Fmn=tab(pF\0,0\1,1.5\1,2.5\0,5) _
                          "Moist fact nitr (Hansen et al,1991)"
A Fmd=tab(SWsat\0,0.8\0.2,0.9\1,1)     "Moist. fact denitr (Hansen,1991)"



A ConcNH4=cond(RU>0,NH4s/RU,0)_
```

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         "Concentration of NH4 in soil solution"                    (kgN/mc)
A ConcNO3=cond(RU>0,NO3/RU,0)_
          "Concentration of NO3 in soil solution"                   (kgN/mc)
' Balance between ammonium immobilized and in solution
S NH4=IniNH4 range(0,1000) "Ammonium amount in soil"                (kgN/ha)
A Argum=CS^2*(1+Ke)^2+2*CS*Ke*NH4*(1-Ke)+Ke^2*NH4^2 _
                         "Argument in NH4a equation"            (kgN^2/ha^2)
A NH4a=(CS+NH4+(CS-sqrt(Argum))/Ke)/2_
                         "NH4 adsorbed in soil colloids"           (kgN/ha)
A NH4s=NH4-NH4a                    "NH4 in soil solution"
R NH4roff=cond(ConcNH4>0,RunOff*ConcNH4,0) NH4->? _
                         "Losses of NH4 by run-off                  (kgN/d)
A NH4dw=NH4*Dsoil/Dw      "NH4 available in Dw layer"              (kgN/ha)
S NO3=IniNO3 range(0,1000)"Nitrate amount in soil"                 (kgN/ha)
R Rnitri=Knitri*NH4s*Fmn*Ftd NH4->NO3 "Nitrification rate"          (kgN/d)
R RlisNO3=cond(ConcNO3>0&Drainage>0,ConcNO3*Drainage,0) NO3->NO3GW _
                         "leaching rate - NO3"                      (kgN/d)
R NO3roff=cond(ConcNO3>0,RunOff*ConcNO3,0) NO3->? _
                         "Losses of NO3 by run-off"                 (kgN/d)
S Ndenit=0 range(0,200)   "Nitrogen denitrificated"                   (kgN)
R Denit=cond(Us<(0.8*MWCgrav),0,Dmax*Fmd*NO3*Ftd) NO3->Ndenit   _
                         "Denitrification"   (kgN/ha/d)
S NH4GW=0 range(0,500)    "Ammonium amount in groundwater"            (kgN)
S NO3GW=0 range(0,500)    "Nitrate amount in groundwater"             (kgN)
S Ncrop=IniNcrop          "Nitrogen in crop biomass"               (kgN/ha)
A ConcNcrop=cond(Wcrop>0,Ncrop/Wcrop,0)_
                 "Nitrogen concentration in crop biomass"
A Ndem=GR1*ConcNopt+Wcrop*(ConcNcrop-ConcNcrop)_
                 "Crop N demand"                                  (kg/ha/d)
R Nuptake=cond(1.05*Ndem<=NO3disp,1.05*Ndem,NO3disp) NO3->Ncrop_
                                 "Crop N uptake"                 (kg/ha/d)
A NO3disp=cond(NO3>5,NO3,0)         "NO3 available"
R Nfix=Cnfix*Fmfix*(Ndem-NO3disp)/dt ?->Ncrop_
                              "Nitrogen fixation"                 (kg/ha/d)
A Fmfix=tab(Us\0,WPgrav\1,Uz\1,FCgrav\0,MWCgrav)_
                              "Moisture factor N-fix"                (0-1)
```

```
' Model: mini_RothC.sem
' decomposable plant material (DPM)
' resistant plant material (RPM)
' soil biomass (BIO)
' Humus (HUM)
S BIO=SOMCal*FracBio "Biomass or microorganism"                     (tB/ha)
S DPM=SOMCal*FracDpm "Biomass of Decom.Plant Material (DPM)"        (tB/ha)
S RPM=SOMCal*FracRpm "Biomass of Resistant plant Material (RPM)"    (tB/ha)
S HUM=SOMCal*FracHum "Humus"                                        (tB/ha)
S IOM=SOMCal*FracIom "Inert organic matter"                         (tB/ha)
S CO2atmS=0    "Cumulated CO2 to atmosphere soil activity"        (tCO2/ha)
P SOMCal=(IniSomgrav/100)*Dw*(1-Grav/100)*1.5*10 _
                 "Initial soil org. matter"                         (tB/ha)
P IniSOMgrav=IniSOM*(1-Grav/100) "Corrected soil organic matter - ff" (%)
A SOM=DPM+RPM+BIO+HUM+IOM          "Total soil organic matter"      (tB/ha)
A SOC=Chum*SOM                     "Total SOC"                      (tC/ha)
C drDPM=0.025             "Time Coef. for DPM"                        (1/d)
C drRPM=0.0008            "Time Coef. for RPM"                        (1/d)
C drBIO=0.002             "Time Coef. for BIO"                        (1/d)
C drHUM=0.00005  "Time Coef. for HUM"                                 (1/d)
C scDec=0.0045            "Scaling Factor of ResDecr ratio"            (-)
P ResDecr=(scDec*(1.85+1.6*exp(-0.0786*clay))) _
                 "CO2/(BIO+HUM) ratio function of clay"               (-)
A drT=47.9/(1+exp(106/(Tsoil+18.256)))      "Temp modif factor"       (-)
A drM=tab(Deficit\1,0\1,20\0.2,45)          "Soil Moist modif factor" (-)
P drCov=1                                   "Soil cover modif factor" (-)
A DrFact=drT*drM*drCov             "Overall decomposition rate factor" (-)
```

```
R DecnDPM=DPM*drfact*drDPM DPM->? "Decompos DPM as biomass"      (tB/ha/d)
R DecnRPM=RPM*drfact*drRPM RPM->? "Decompos RPM as biomass"      (tB/ha/d)
R DecnBIO=BIO*drfact*drBIO BIO->?         "Decompos BIO"          (tC/ha/d)
R DecnHUM=HUM*drfact*drHUM HUM->?         "Decompos HUM"          (tC/ha/d)
R InnBIO=BH*1/(1+ResDecr)*totdecn  ?->BIO_
                          "Bio fraction of new decay"             (tB/ha/d)
R InnHUM=(1-BH)*1/(1+ResDecr)*totdecn ?->HUM _
                         "Hum fract of new decay"                 (tB/ha/d)
A Totdecn=DrFact*(DPM*drDPM+RPM*drRPM+BIO*drBIO+HUM*drHUM) _
                         "Sum of new decay"                       (tB/ha/d)
A HBsynt=totdecn*1/(1+ResDecr)*Fnitro      _
                 "Humus and microbial biomass synthesis"          (tB/ha/d)
A Fnitro=1/(Khalf+NH4dw)"H and B factor nitrogen availability"       (-)
P Khalf=20       "NH4 in Dw to obtain 50% of max Fnitro"           (kgN/ha)
R ResnDPM=ResDecr/(1+ResDecr)*decnDPM ?->CO2atmS _
                         "Soil respiration of DPM"                (tC/ha/d)
R ResnRPM=ResDecr/(1+ResDecr)*decnRPM ?->CO2atmS _
                         "Soil respiration of RPM"                (tC/ha/d)
R ResnBIO=ResDecr/(1+ResDecr)*decnBIO ?->CO2atmS _
                         "Soil respirat. BIO"                     (tC/ha/d)
R ResnHUM=ResDecr/(1+ResDecr)*decnHUM ?->CO2atmS _
                         "Soil respirat. HUM"                     (tC/ha/d)
```

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' CSSMini_Manag - Crop agronomic practices
V FertNH4Auto=when((1-FN)>Kdn&Cstage>0&Cstage<3&AutoFertN=1&_
                         Rain<0.5&Ndem>NO3disp)_
                         msg(Concimazione_kg_concime:) disp(AutoQfertN)_
                         "NH4 Fertilisation"
S FertOk=1
R CarFertOk=cond(NO3disp<Ndem&FertOk>0,1,-FertOk+1) ?->FertOR
V IrriAuto=when((Us<Uirri)&(Cstage>0)&_
       (Cstage<7)&(IrriCrit=2)&(Rain=0))   _
       msg(Auto_Irrigation_mm:) disp(Vad) _
       "Automatic irrigation"
V IrriSched=when(?) msg(Sched_Irrigation_mm:) disp(VadSched) "Irrigation"
V IrriRuota=after(TurnoV IrriRuota=after(Turno)
V IrriTurno=when(IrriRuota&Time>IrriStart&Time<IrriEnd&IrriCrit=3)_
                  msg(Turn_Irrigation_mm:) disp(Vad)        "Irrigation"
V Semina=when(?) msg(Sowing_Scheduled)     "Sowing"
R TempOK=cond(Temp>=T1&SeminaOK>0&Cstage<1,1,-(SeminaOK-1)) ?->SeminaOK _
                 "Temperature OK for sowing"
S SeminaOK=1
V SeminaAuto=when(time>SowStart&Cstage=0&SeminaOK>4&AutoSow&Rain<5) _
                  msg(sowing_Auto)                 "Sowing"
V FertNH4=when(?) msg(Concimazione_NH4_kgN:)_
                  disp(SchedQfertN) "NH4 fertilization"
' 3 types of irrigation: Automatic agronomic, Automatic fixed dates,
Scheduled
P VadSched=5 onevt(IrriSched,?) "Irrigation volume (scheduled)"      (mm)
P RVadSched=VadSched*EffIrri "Real irrigation volume"                (mm)
P SchedQfertN=75 onevt(FertNH4,?) "N ferti.amount (scheduled)"      (kgN)
P IrriCrit=2     "Irrigation type: 1=scheduled 2=automatic 3=fixed"
P AutoFertN=0    "Automatic irrigation 1=on 0=off"
P AutoSow=1      "Automatic sowing 1=on 0=off"
P SowStart=100   "Starting day for sowing"                           (-)
P EffIrri=0.9    "Irrigation efficiency"                             (-)
P Turno=7        "Turn (days)"                                       (-)
P IrriStart=150  "Beginning of irrigation station (doy)"             (-)
P IrriEnd=280    "End of irrigation station (doy)"                   (-)
P AutoQFertN=50  "Amount of fertilizer for fertilization"           (kgN)
P Kdn=0.4                "Nitrogen stress tolerated"                 (-)
P Kdw=0.4                "Water stress tolerated"                    (-)
A Uirri=WPgrav+(uz-WPgrav)*(1-Kdw) _
                         "Critical soil moisture for irri."        (mmW)
```

```
S Numirri=0                "Number of irrigation events per year"
I IncNirri onevt(IrriAuto,1\IrriSched,1\IrriTurno,1) ?->NumIrri _
S Numfert=0                "Number of fertilization events per year"    (-)
I InNfert onevt(FertNH4Auto,1\FertNH4,1) ?->NumFert _
                           "Increase of number of fertilizations"
S Wirri=0 range(0,2000)    "Total crop irrigation volume"               (mm)
I AcWirri ?->Wirri onevt(IrriAuto,Vad\IrriSched,Vad\IrriTurno,Vad) _
                           "Increase of irrigation volume"              (mm)
S Nfert=0 range(0,600)     "Total N fertilizer distributed"            (kgN)
I AcNfert ?->Nfert onevt(FertNH4Auto,AutoQfertN\FertNH4,SchedQfertN) _
         "Increase of number of nitrogen distributed"                 (kgN)
```

```
' crop costs and revenues
V NewEcYear=when(SeminaAuto|Semina) _
                   "New year event-for loading fixed costs"            (-)
V EndEcYear=when(cstage=7&Endflag=0) _
                   "New year event - for loading revenues"             (-)
P Endflag=0 onevt(EndEcYear,1)
C mmtom3=10                          "mm to m3"                        (-)
' Costs
S IrriCost=0               "Total irrigation cost"                    (Eu)
I ICost onevt(IrriAuto,CoIrri\_
                   IrriSched,CoIrri\_
                   IrriTurno,CoIrri\_
                   NewEcYear,IrFixCostYear) _
         ?->IrriCost       "Cost Increment for each irrigation"  (Eu)
A CoIrri=(IrriWcost+IrriFCost+IrriLCost)*Vad*mmtom3+IrFixCostYear _
                           "Cost per irrigation"                      (Eu)
P IrriWcost=0.15           "Water cost"                            (Eu/mc)
P IrriLCost=0.1            "Labor cost"                            (Eu/mc)
P IrriFCost=0.08           "Fuel cost "                            (Eu/mc)
P IrFixCostAd=0            "Fixed cost for each irrigation"           (Eu)
P IrFixCostYear=102        "Annual fixed cost for irrigation "        (Eu)
S FertCost=0               "N fertilization costs"                    (Eu)
I FCost onevt(FertNH4Auto,CoFert\FertNH4,CoFert) ?->FertCost _
                   "Cost Increment for each fertilization "           (Eu)
A CoFert=NfertCost*QfertN+NdistCost  "Cost per fertilization"         (Eu)
A QfertN=cond(AutoFertN,AutoQfertN,SchedQfertN) _
         "Fertilizer amount for each fertilization type"              (Eu)
P NfertCost=0.28                   "Nitrogen fertilizer cost"      (Eu/kg)
P NdistCost=35             "Fertilizer distribution cost"             (Eu)
S AltriCos=0                                "Other crop costs"        (Eu)
I OthCost onevt(NewEcYear,OtherCosts) ?->AltriCos_
                           "Other cost Increment"                     (Eu)
P OtherCosts=650           "Other crop costs"                      (Eu/ha)
A CostTot=IrriCost+FertCost+AltriCos        "Total crop costs"        (Eu)
' Revenues
S PLV=0                            "Crop income"                      (Eu)
I InPlv onevt(EndEcYear,Plva) ?->PLV "Increment income"               (Eu)
A Plva=cond(SubType=1,Plva1+Subsid,Plva1+(Subsid*SellYield))_
                                  "Plv"                            (Eu/ha)
a Plva1=(PriceY*SellYield)+(PriceR*(Wcrop-(1-HI))) "Plv"           (Eu/ha)
P SubType=1                        "Falg subsidy type: 1=/ha 0=/ton"
P PriceY=130                       "Yield price"                    (Eu/t)
P PriceR=0                         "Residues price"                 (Eu/t)
P Subsid=500               "Common Agricultural Policy subsidy"       (Eu)
A SellYield=yield/(1-RefMo) "Yield with comercial mosture"             (t)
P RefMo=0.15                "Comercial mosture"                        (-)
A CropBudg=PLV-CostTot      "Crop economic budget"                    (Eu)
```

```
' CSSmini_Energy
' INPUT
S IrriEng=0       "Total irrigation energy input"                     (MJ)
I IEngIrri onevt(IrriAuto,TotEngIrri\IrriSched,TotEngIrri\ _
                   IrriTurno,TotEngIrri) ?->IrriEng              _
             "Increment of energy input of each irrigation"        (MJ)
A TotEngIrri=cond(FlagEngIrri=1,ENGirri,(DirEngIrri+IndEngIrri)) _
                  "Energy of each irrigation"                       (MJ)
A DirEngIrri=ECfuels*vad*mmtomc     "Irrigation direct energy"    (MJ/mc)
A IndEngIrri=(ECwater+EClabour)*vad*mmtomc _
                                   "Irrigation indirect energy"   (MJ/mc)
C mmtomc=10
P ECwater=2.5     "Energy to bring water to the field"            (MJ/mc)
P EClabour=0.0073 "Manpower energy use"                           (MJ/mc)
P ECfuels=8.8      "Energy in fuel"                               (MJ/mc)
P ENGirri=5000     "Irrigation energy"                          (MJ/Irri)
P FlagEngIrri=0    "Flac type energy calcolation _
                   0=/mc (analitico) 1=/irri (totale)"               (-)
S FertEng=0       "Total fertilization energy input"                (MJ)
I IEngFert onevt(FertNH4Auto,EngFert\FertNH4,EngFert) ?->FertEng _
                  "Increment of energy for each fertilization"      (MJ)
A EngFert=ECNfert*QfertN+ECNdist "Energy for each fertilization"    (MJ)
P ECNfert=66      "Energy to produce mineral fertilizer"          (MJ/kg)
P ECNdist=407             "Energy to distribute fertilizer      (MJ/dist)
' altri
P ENGuse=6800             "Other crop energy input"               (MJ/ha)
A ENGTotIn=IrriEng+FertEng+ENGuse "Total crop input energy"         (MJ)
' OUTPUT
S ENGTotOut=0             "Total crop output energy"               (MJ)
I IENGOut onevt(EndEcYear,ENGcrop) ?->ENGTotOut_
                           "Increment energy output"                (MJ)
A ENGcrop=ENGYield+ENGResid        "Total crop energy"              (MJ)
A ENGYield=Yield*ECstore                   "Energy in yield"        (MJ)
A ENGResid=(Wcrop-Yield)*ECres             "Energy in residues"     (MJ)
P ECstore=18520                            "Energy in yield"      (MJ/t)
P ECres=17300              "Energy in residues"                   (MJ/t)
'Indicators
A Ebalance=ENGTotOut-ENGTotIn  "Energy balance for crops"         (MJ/ha)
A EROI=cond(ENGTotIn>0,ENGTotOut/ENGTotIn,0) "Energy efficiency"     (-)
```

III. X-farm model SEMoLa code

```
' Model: X-Farm.sem
$ vers(1.0)
$ dt(1)
$ tspan(1,365)
$ tunit(d)
' Exogenous variables
E Tmin range(-30,50)            "Daily min air temperature"          (C)
E Tmax range(-20,60)            "Daily max air temperature"          (C)
E Rain range(0,500)             "Rainfall"                         (mmW/d)
E ETr range(0,15)               "Reference evapotranspiration"     (mmW/d)
E Rg range(0,40)        "Global radiation at Earth surface"    (MJ/m^2/d)
P Lat=46                "Latitude - degs and decimals"             (deg)
A Tmed=(Tmin+Tmax)/2            "Daily mean temperature"              (C)
A Tday=0.5*(Tmax+Tmin)+(Tmax-Tmin)/(3*PI)_
                        "Average daytime temperature"                 (C)
A DL=daylen(Lat,time)           "Daylenght"                         (h/d)
A doy=mod(time-1,365)+1         "Day of the year (1-365)"             (d)
A dweek=mod(time-1,7)+1         "Day of the week (1-7)"               (d)
C TonToKg=1000          "Conv. factor from tB/ha to kgB/ha"       (kgB/tB)
C gtokg=1000            "Conv. factor from g to kg"                 (g/kg)
C cmtom=100             "coef. cm to m"                             (cm/m)
' Farm fields
G Field=4               "Farm fields"
P Field.Area=10         "Field area"                                  (ha)
A FarmArea=gsum(Area)   "Total cultivable farm area"                  (ha)
' Farm activities decision
P Oil_Produ=1                  "Oil production 1=yes 0=no"
P Livestock_Produ=1            "Animal production 1=yes 0=no"
P Livestock_Type=1             Animal production 1=milk 0=meat"
P Biogas_Produ=1               "Biogas production 1=yes 0=no"
' crop production (CSS - appendix 1)
@ CSS-SoilPhysics       group(Field)
@ CSS-SoilWater         group(Field)
@ CSS-SoilNitrogen      group(Field)
@ CSS-SoilRothC         group(Field)
@ CSS-CropManag         group(Field)
@ CSS-CropYield         group(Field)
@ CSS-CropEconomy       group(Field)
@ CSS-CropEnergy        group(Field)
@ CSS-CropEnviron       group(Field)
' oil production
@ XF-Oil          if(Oil_Produ=1)  "Oil production"
@ XF-OilEconomy   if(Oil_Produ=1)  "Oil production economy accounting"
@ XF-OilEnergy    if(Oil_Produ=1)  "Oil production energy accounting"
' Livestock production
@ XF-Cattle       if(Livestock_Produ=1)     "Animal production"
' FARM resources
@ XF-Tractors                     "Tractors management"
@ XF-Machinery                    "Machinery management"

' Biogas production
@ XF-Biogas         if(Biogas_Produ=1) "Biogas production"
@ XF-BiogasEconomy  if(Biogas_Produ=1) "Biogas economy accounting"
@ XF-BiogasEnergy   if(Biogas_Produ=1) "Biogas energy accounting"
@ XF-BiogasEnviron  if(Biogas_Produ=1) "Biogas environmental accounting"

' Farm accounting
@ XF-FarmEconomy                  "Farm economic budget"
@ XF-FarmEnergy                   "Farm energy accounting"
@ XF-FarmEnviron                  "Farm environmental accounting"
```

```
' == X-FARM_Oil ====
' Production of pure vegetable oil and biodiesel from oilseeds
' general parameters
P CropOil=1               "1= oilseed 0=no oilseed"                    (-)
P CropToOil=1             "1= to press 0=no to press                   (-)
P BuySeed=1               "1=buy from out of the farm 0=no"            (-)
P MaVoSeed=0.77           "density of the seed"                    (tB/mc)
P SeedOilCont=0.40        "Oil content in the seed"               (tol/tB)
P PressCapHkg=39          "Processing capacity per hour"           (kgB/h)
A PressCapH=(PressCapHkg/tontokg) "Processing capacity per hour"    (tB/h)
P HpressDay=10            "Daily operation time"                     (h/d)
' processing seeds
S OilSeedSt=IniOilSeedSt          "Oil seeds in the farm store"       (tB)
S SemeLavorato=0                  "worked seed"                       (tB)
P IniOilSeedSt=3                  "Initial oil seeds"                 (tB)
I SeedLoad onevt(LoadOilSeed,HarvStor*Area) HarvStor->OilseedSt _
                                  "Storage oilseed                    (tB)
V LoadOilSeed=when(harvest&CropOil=1&CropToOil=1)
I GetOilSeed onevt(BuyOilSeed,OilSeedBuy) ?->OilseedSt _
                          "Buy oilseeds for pressing"                 (tB)
P OilseedStCrit=3         "Minimum quantity of oilseeds"              (tB)
P OilSeedBuy=50           "Amount of oilseeds bought"                 (tB)
V BuyOilSeed=when(BuySeed=1&OilseedSt<OilseedStCrit)_
                   msg(BUY SEED!! ton:) _
                   disp(OilSeedBuy)        "purchase seed"
V OilseedStVuota=when(OilseedSt=0) msg(SEED FINISH!!!)
A PressCapD=PressCapH*HpressDay   "Processing capacity seeds day"   (tB/d)
R SeedPress=cond(OilSeedSt>0&dweek>0&dweek<=6,SeedPress1,0) _
      OilSeedSt->SemeLavorato   "Speed processing seeds"            (tB/d)
A SeedPress1=cond(PressCapD<OilSeedSt,PressCapD,OilSeedSt) _
                          "Speed processing seeds"                  (tB/d)
S OilCrude=0              "Total crude oil stored"                   (tol)
S OilDec=0                "Total decanted oil stored"                (tol)
S OilFilt=0               "Total filtered oil stored"                (tol)
S OilFanghi=0             "Total sludge product"                     (tol)
A QOilSpre=OilseedSt*SeedOilCont "Oil extracted from the seeds"      (tol)
R PressOil=cond(QOilSpre>0,SeedPress*SeedOilCont*RendEstr,0) _
                          ?->OilCrude _
                  "Crude oil production capacity"                  (tol/d)
A RendEstr=0.85   "Extraction-efficiency oil volume fraction"          (-)
R DecantaOil=cond(OilCrude>0,PressOil*(1-FrazFanghi),0) _
                          OilCrude->OilDec _
                          "Decanted oil production"                (tol/d)
R DecantaFanghi=cond(OilCrude>0,PressOil*FrazFanghi,0) _
                          OilCrude->OilFanghi _
                          "Sludge production"
P FrazFanghi=0.15         "Fraction sludge decantation"                (-)
R FiltraOil=DecantaOil*RendFilt OilDec->OilFilt  _
                          "Filtered oil production"                (tol/d)
P RendFilt=0.99           "Filtration efficiency"                      (-)
S PelletSto=0             "Total pellet stored (fresh weight)"        (tP)
R PressPellet=SeedPress*(1-SeedOilCont*RendEstr) ?->PelletSto _
                                  "Pellet production"               (tP/d)
A TotProdotti=OilFilt+OilFanghi+PelletSto
```

```
' Model: XF-OilEconomy.sem XF-OilEnergy.sem
S OilDebt=0                       "Oil production costs"              (Eu)
S OilCredit=0                     "Revenues from oil production"      (Eu)
A OilBudget=OilCredit-OilDebt     "Oil production budget"             (Eu)
V OilSelling=when(OilFilt>0&Dweek=1)      "Selling weekly oil "        (-)
V PelletSell=when(PelletSto>0&Dweek=2)    "Selling weekly pellet"      (-)
' Oil Revenues
I OilSell onevt(OilSelling,PxOil*OilFilt) ?->OilCredit "Oil revenue" (Eu)
```

```
I CakeSell onevt(PelletSell,PxPan*PelletSto) ?->OilCredit_
                         "Pellet revenue"                        (Eu)
P PxOil=1300                     "Oil price"                    (Eu/t)
P PxPan=197                      "Pellet proce"                 (Eu/t)
I PayBuySeed onevt(BuySeed,PxSeed*OilSeedBuy) ?->OilDebt _
                                 "Payment seed for press"         (Eu)
P PxSeed=200                     "price seed for press"         (Eu/t)
A EnElectPress=PowPress*Electr  "Electricity consumption"        (MJ)
P PowPress=4              "power absorbed by the press motor"    (kWh)
P Electr=10.80 _
        "energy consumption by type of electrical distribution"  (MJ/kWh)
'Electricity, low voltage, at grid/IT U 10,80 MJ/kWh
'Electricity, medium voltage, production IT, at grid/IT U 9,73 MJ/kWh
'Electricity, high voltage, production IT, at grid/IT U 9,63 MJ/kWh
'Electricity, high voltage, at grid/IT U 9,66 MJ/kWh
A EnElectOil=EnElectPress*OilFilt/FiltraOil _
                 "daily energy consumption"                     (MJ/d)
```

```
' - XF-Cattle.sem
G Cattle=105 newon(Birth,Nborn\BuyCow,HowBuy\BuyCalv,HowCalv) _
dropon(SellOldCow\SellYoungMale\SellYoung)_
                          "Number of cows in the stable"           (n)
V Cattle.Birth=when(Pregnant&AgePreg>GestaTime)     "Event birth"   (-)
P Cattle.Pregnant=0 onevt(fecond,1\Birth,0)        "Flag pregnant"  (-)
V Cattle.Fecond=when(Age>IniCarr&Age<FineCarr&Pregnant=0&_
                 AgePreg>(GestaTime+IntParFec))     "fecundation"   (-)
P Nborn=1                        "Number of calves for eacbirth"    (-)
A Gravide=gcount(cattle,pregnant=1)       "Number of pregnant"      (n)
A Nascite=gcount(cattle,Birth)   "Number of births"                 (n)
C IniCarr=365                    "Age of beginning of career"       (d)
C FineCarr=1500          "Age of end of career"                     (d)
C GestaTime=300          "Duration of gestation"                    (d)
C IntParFec=100          "Birth-fecundation interval"               (d)
S Cattle.Age=AgeIni              "Ege"                              (d)
P Cattle.AgeIni=200 ifnew(Birth,0\BuyCow,600\BuyCalv,100)_
                                  "Initial age"                     (d)
R Cattle.CAgeing=dt              ?->Age   "Ageing of cows"   (d/d)
A Cattle.InProd=cond(Age>IniCarr&Age<FineCarr,1,0)_
                  "flag 1=in productio0=no"                         (-)
A Nvacche=gcount(cattle,age=>720)         "Number of cows"          (n)
A Nvitelle=gcount(cattle,age=>7&age<180)  "Number of calves"        (n)
A Nmanzette=gcount(cattle,age>180&age<IniCarr) "Number of heifers"  (n)
A Nmanze=gcount(cattle,age=>IniCarr&age<720) "Number of old heifers" (n)
A NviteNati=gcount(cattle,age>=0&age<7)        "Number new-born"    (n)
A Ngiovenche=gcount(cattle,age=>365&age<720&pregnant=1) _
                                 "Number pregnant heiers"           (n)
A Cowinprod=gcount(cattle,age>720&age<FineCarr)_
                          "Number of cows in career"               (n)
S Cattle.AgePreg=0                        "Days from fertilization" (d)
R Cattle.PAgeing=dt ?->AgePreg   "Ageing during pregnancy"        (d/d)
I Cattle.PageReset AgePreg->? onevt(Fecond,AgePreg) _
                                 "Reset of AgePreg"                 (d)
P Cattle.Sex=1 ifnew(Birth,rBern(Pfratio)\BuyCow,1\BuyCalv,1)_
                                 "Sex 0=male 1=female"
P Pfratio=0.55                   "Probability female new-borns"
A Nmale=gcount(Cattle,Sex=0)     "Male number"                      (n)
A Nfemale=gcount(Cattle,Sex=1)   "Female number"                    (n)
' quality
P Cattle.Qual=1 ifnew(Birth,FQual\BuyCow,1\BuyCalv,1) "Cow quality" (-)
P FQual=rBern(0.1)                        "Quality Probability"
A NQual=gcount(cattle,Qual=1A NQual=gcount(cattle,Qual=1)
A NBasQual=gcount(cattle,Qual=0A NBasQual=gcount(cattle,Qual=0)
'sells
V Cattle.SellOldCow=when(Age>=1825)       "Selling cows end career"
```

```
V Cattle.SellYoungMale=when(Sex=0)         "Selling young males"
V Cattle.SellYoung=when(Qual=0)   "Sale young females of low quality"
A TotOldVendute=gcount(Cattle,SellOldCow)
A TotSellYoungMale=gcount(Cattle,SellYoungMale)
A TotSellYoung=gcount(Cattle,SellYoungMale)
' buys
V BuyCow=when(Cowinprod<80&Cattle<110) "Buy young males"
V BuyCalv=when(Nvitelle<10&Cattle<110) "Buy young"
P HowBuy=1
P HowCalv=1
' weight
S Cattle.Weight=WeightIni
ifnew(Birth,WCalf\BuyCow,WCowBuy\BuyCalv,WCalvBuy)                (kg)
P Cattle.WeightIni=500    "Initial weight "                        (kg)
R Cattle.RWeight=cond(Age<730,0.643,0) ?->Weight _
                        "Daily weight in the first two years of life"
A CatMinW=gmin(WeightA CatMinW=gmin(Weight)
P WCalf=30                "Born weight"                            (kg)
P WCowBuy=500             "Weight cow"                             (kg)
P WCalvBuy=200            "Weight calve"                           (kg)
' milk production
S Cattle.DayMilk=S Cattle.DayMilk=0
R Cattle.ProdMilk=ProdMilka ?->DayMil
A Cattle.ProdMilka=cond(InProd=1,ProdDay,0)
A Cattle.ProdDay=tab(AgePreg\28,0\33,28\33,60\8,300)
A MilkProdDay=gsum(ProdMilka)
A MilkProdDayC=MilkProdDay/Cowinpro
' manure production
S Cattle.Deiez=0                                 "Total manure"    (kg)
R Cattle.ProdDeiez=DeiezCoeff*Weight ?->Deiez "Daily manure"      kg/d)
P DeiezCoeff=(86/1000)                                             (-)
A DeiezTot=gsum(Deiez)                                             (Kg)
A Cattle.StageNoProd=tab(Age\1,0\1,90\2,91\2,180\3,181\3,330\4,331\4,730)
' 1=calf0-3 months, 2=calf3-6, 3=heifer6-11, 4=heifer12-24,
A Cattle.StageProd=cond(InProd=1&Age<1825,tabprod,8)
A Cattle.tabprod=tab(mod(DayMilk,365)\5,1\5,305\6,306\6,340\7,341\7,365)
```

```
' XF-Tractors and XF-Machinery
G Tract=3                                  "Farm tractors"          (-)
S Tract.TractAge=TractAgeIni               "Tractor age"            (d)
P Tract.TractAgeIni=0                      "Initial age of tractor"    (d)
R Tract.TractAging=dt ?->TractAge          "Tractor aeging"        (d/d)
I Tract.ResetTractAge onevt(BuyTract,TractAge) TractAge->? _
                                           "Reset tractor age"      (d)
V Tract.BuyTract=when(ScrapTract)                  "Buy tractor"  (-)
V Tract.ScrapTract=when(TractAge>TractUseLife)     "Tractor scrapping" (-)
P Tract.TractUseLife=10000         "Useful life of tractor"         (d)
P Tract.TractWeight=800   "Tractor weight"                          (kg)
P Tract.Power=100                  "tractor power"                  (kW)
P Tract.Conspe=240                 "Fuel specific consumption"    (gr/kWh)
C Beta=1.2                         "Safety factor - Lazzari 2005"   (-)
' Plough
G PlowMac=PlowMacIni               "Ploughs"                        (-)
P PlowMacIni=2                     "Initial number of plough in farm"  (-)
S PlowMac.PlowAge=PlowAgeIni       "Plough age"                     (d)
P PlowMac.PlowAgeIni=0             "Initial age of plough"          (d)
R PlowMac.PlowAging=dt ?->PlowAge          "Plough ageing"         (d/d)
I PlowMac.ResetPlowAge onevt(BuyPlowMac,PlowAge) PlowAge->? _
                                           "Reset plough age"       (d)
P PlowMac.PlowUseLife=5475                 "useful life of plough"  (d)
V PlowMac.BuyPlowMac=when(ScrapPlowMac)            "Buy plough"     (-)
V PlowMac.ScrapPlowMac=when(PlowAge>PlowUseLife)   "Scrapping plough" (-)
P PlowMac.PlowDepth=0.3                    "Working depth"          (m)
P PlowMac.PlowShare=2              "Number of ploughshares"         (n)
P PlowMac.PlowWeight=590           "Plough weight"                 (kg)
```

```
A PlowMac.PlowWidthWork=RLaPf*PlowDepth*PlowShare "Working width"    (m)
A PlowMac.RLaPf=tab(PlowDepth\2,0\1.7,0.1\1.54,0.2\_
              1.33,0.3\1.25,0.4\1.1,0.5\1.0,0.6)
                                                  "rate with/depth" (-)
P PlowMac.PlowUnitPow=0.8  "Power absorbed by the machine"      (kW/m/cm)
A PlowMac.PlowTeorPow=PlowUnitPow*PlowWidthWork*PlowDepth _
                           "Theory power absorbed"              (kW)
A PlowMac.PlowPowReq=PlowTeorPow*PlowRappBeta "Real power absorbed"  (kW)
A PlowMac.PlowRappBeta=Beta/PlowRenGanc " Power efficiency ratio"     (-)
P PlowMac.PlowRenGanc=0.6          "Performance to the hook"          (-)
P PlowMac.PlowWorkRest=580 "Coefficient of resistance to working"(N/m*cm)
A PlowMac.PlowFt=PlowWorkRest*PlowWidthWork_
              *PlowDepth*cmtom          "Traction force"              (N)
A PlowMac.plowGa=PlowFt/PlowCoffAderenz    "Adherent weight"          (N)
A PlowCoffAderenz=0.45                  "Coefficient of adhesion"     (-)
A PlowMac.PlowTracPowReq=PlowGa/PlowDenonm "Tractor power needed"    (kW)
P PlowMac.PlowDenonm=570
P PlowMac.PlowTracPow=50                "Tractor real power"         (kW)
A PlowMac.PlowG=PlowTracPowReq/PlowTracPow       "Engine load"        (-)
A PlowMac.PlowCCh=Cs/gtokg*PlowG*PlowTracPow"Fuel consumption"      (g/h)
P PlowMac.PlowVel=6                              "Working speed" (km/h)
A PlowMac.PlowWorkCap=PlowVel*PlowWidthWork/10*PlowInEffCamp _
                                                 "Work capacity" (ha/h)
P PlowMac.plowInEffCamp=0.8        "Field index efficiency"           (-)
A PlowMac.PlowCC=PlowCCh/PlowWorkCap    "Fuel consumption"        (kg/ha)
A PlowMac.PlowCL=PlowCC*CCartoCLub/100  "Oil consumption"         (kg/ha)
' Harrow
G HarrMac=HarrMacIni               "Harrows"                          (-)
P HarrMacIni=1                     "Initial number of harrows in farm (-)
S HarrMac.HarrAge=HarrAgeIni       "Harrow age"                       (d)
P HarrMac.HarrAgeIni=0             "Initial harrow age"               (d)
R HarrMac.HarrAging=dt ?->HarrAge "Harrow ageing"                   (d/d)
I PlowMac.ResetHarrAge onevt(BuyHarrMac,HarrAge) HarrAge->? _
                                   "Reset harrow age"                 (d)
P HarrMac.HarrUseLife=3650         "Useful life of harrow"            (d)
V HarrMac.BuyHarrMac=when(ScrapHarrMac)        "Buy harrow"           (-)
V HarrMac.ScrapHarrMac=when(HarrAge>HarrUseLife) "Scrapping harrow"   (-)
P HarrMac.HarrDepth=0.1            "Working depth"                    (m)
P HarrMac.HarrWeight=800           "Harrow weight"                   (kg)
P HarrMac.HarrWidthWork=3.5                "Working width"            (m)
P HarrMac.HarrUnitPow=tab(clay\2,20\5,80)_
                          "Power absorbed by the machine"         (kW/m)
A HarrMac.HarrTeorPow=HarrUnitPow*HarrWidthWork_
                          "Theory power absorbed"                    (kW)
A HarrMac.HarrPowReq=HarrTeorPow*HarrRappBeta _
                           "Real power absorbed"                     (kW)
A HarrMac.HarrRappBeta=Beta/HarrRenGanc "Power efficiency ratio"      (-)
P HarrMac.HarrRenGanc=0.           "Performance to the hook"          (-)
P HarrMac.HarrWorkRest=220_
                         "Coefficient of resistance to working"  (N/m*cm)
A HarrMac.HarrFt=HarrWorkRest*HarrWidthWork*HarrDepth_
                          "Traction force"                            (N)
A HarrMac.HarrGa=HarrFt/HarrCoffAderenz          "Adherent weight"    (N)
A HarrCoffAderenz=0.25             "Coefficient of adhesion"          (-)
A HarrMac.HarrTracPowReq=HarrGa/HarrDenonm  "Tractor power needed"   (kW)
P HarrMac.HarrDenonm=700
P HarrMac.HarrTracPow=60                  "Tractor real power"       (kW)
A HarrMac.HarrG=HarrTracPowReq/HarrTracPow         "Engine load"      (-)
A HarrMac.HarrCCh=Cs/gtokg*HarrG*HarrTracPow    "Fuel consumption" (kg/h)
P HarrMac.HarrVel=8                     "Working speed"            (km/h)
A HarrMac.HarrWorkCap=HarrVel*HarrWidthWork/10*HarrInEffCamp _
                                        "Work capacity"          (ha/h)
P HarrMac.HarrInEffCamp=0.8             "Field index efficiency"
A HarrMac.HarrCC=HarrCCh/HarrWorkCap      "Fuel consumption"      (kg/ha)
A HarrMac.HarrCL=HarrCC*CCartoCLub/100  "Oil consumption"         (kg/ha)
```

```
' Universal seeder
G SowRMac=SowRMacIni                "Uni. seeders"
P SowRMacIni=1          "Initial number of seeders in farm "          (-)
S SowRMac.SowRAge=SowRAgeIni        "Seeder age"                      (d)
P SowRMac.SowRAgeIni=0              "Initial age of seeder"           (d)
R SowRMac.SowRAging=dt ?->SowRAge "Seeder ageing"                   (d/d)
I PlowMac.ResetSowRAge onevt(BuySowRMac,SowRAge) SowRAge->? _
                                        "Reset seeder age"            (d)
P SowRMac.SowRUseLife=4380              "Useful life of seeder"       (d)
V SowRMac.BuySowRMac=when(ScrapSowRMac)         "Buy seeder"          (-)
V SowRMac.ScrapSowRMac=when(SowRAge>SowRUseLife)  "Scrapping seeder"  (-)
P SowRMac.SowRWeight=710                "Seeder weight"              (kg)
P SowRMac.SowRWidthWork=3                       "Working width"       (m)
P SowRMac.SowRUnitPow=tab(grav\3,5\5,20) _
                                "Power absorbed by the machine     (kW/m)
A SowRMac.SowRPowReq=SowRUnitPow*SowRWidthWork_
                                 "Tractor power needed"              (kW)
P SowRMac.SowRFtUni=850                 "Traction power"             (Nm)
A SowRMac.SowRFt=SowRFtUni*SowRWidthWork   "Traction force"           (N)
A SowRMac.SowRGa=SowRFt/SowRCoffAderenz    "Adherent weight"          (N)
A SowRCoffAderenz=0.15                  "Coefficient of adhesion"     (-)
A SowRMac.SowRTracPowReq=SowRGa/SowRDenonm "Tractor real power"      (kW)
P SowRMac.SowRDenonm=700
P SowRMac.SowRTracPow=30                "Tractor real power"         (kW)
A SowRMac.SowRG=SowRTracPowReq/SowRTracPow       "Engine load"        (-)
A SowRMac.SowRCCh=Cs/gtokg*SowRG*SowRTracPow   "Fuel consumption"  (kg/h)
P SowRMac.SowRVel=6                     "Working speed"            (km/h)
A SowRMac.SowRWorkCap=SowRVel*SowRWidthWork/10*SowRInEffCamp _
                                         "Work capacity"           (ha/h)
P SowRMac.SowRInEffCamp=0.8             "Field index efficiency"      (-)
A SowRMac.SowRCC=SowRCCh/SowRWorkCap    "Fuel consumption"        (kg/ha)
A SowRMac.SowRCL=SowRCC*CCartoCLub/100  "Oil consumption"         (kg/ha)
 'Precision seeder
G SowPMac=SowPMacIni                "Precision seeder"
P SowPMacIni=1     "Initial number of prec. Seeder in farm"           (-)
S SowPMac.SowPAge=SowPAgeIni        "Prec. Seeder age"                (d)
P SowPMac.SowPAgeIni=0              "Initial age"                     (d)
R SowPMac.SowPAging=dt ?->SowPAge "Prec. Seeder ageing"             (d/d)
I PlowMac.ResetSowPAge onevt(BuySowPMac,SowPAge) SowPAge->? _
                                    "Reset age"                       (d)
P SowPMac.SowPUseLife=4380          "Useful life of prec. seeder"     (d)
V SowPMac.BuySowPMac=when(ScrapSowPMac) "Buy pre. seeder"             (-)
V SowPMac.ScrapSowPMac=when(SowPAge>SowPUseLife)_
                                 "Scrapping prec. seeder"             (-)
P SowPMac.SowPWeight=1140 "Pre. Seeder weight"                       (kg)
P SowPMac.NRow=6          "Number of lines"                           (n)
P SowPMac.SowPUnitPow=3.5 "Power absorbed by the machine"          (kW/m)
A SowPMac.SowPPowReq=SowPUnitPow*NRow "Theory power absorbed"        (kW)
P SowPMac.SowPFtUni=500             "Traction force"             (Nfila)
A SowPMac.SowPFt=SowPFtUni*NRow     "Traction force"                  (N)
A SowPMac.SowPGa=SowPFt/SowPCoffAderenz "peso aderente"               (N)
A SowPCoffAderenz=0.15                "Coefficient of adhesion"       (-)
A SowPMac.SowPTracPowReq=SowPGa/SowPDenonm "Tractor power needed"    (kW)
P SowPMac.SowPDenonm=700
P SowPMac.SowPTracPow=40                "Tractor real power"         (kW)
A SowPMac.SowPG=SowPTracPowReq/SowPTracPow       "Engine load"        (-)
A SowPMac.SowPCCh=Cs/gtokg*SowPG*SowPTracPow   "Fuel consumption"  (kg/h)
P SowPMac.SowPVel=6                             "Working speed" (km/h)
A SowPMac.SowWorkCap=SowPVel*NRow*SowPInEffCamp "Work capacity"    (ha/h)
P SowPMac.SowPInEffCamp=0.8         "Field index efficiency"          (-)
A SowPMac.SowPCC=SowPCCh/SowWorkCap     "Fuel consumption"        (kg/ha)
A SowPMac.SowPCL=SowPCC*CCartoCLub/100  "Oil consumption"         (kg/ha)
'herbicide (descriptions like above)
G WeedMac=WeedMacIni
P WeedMacIni=1                                                        (-)
```

```
S WeedMac.WeedAge=WeedAgeIni                                    (d)
P WeedMac.WeedAgeIni=0                                          (d)
R WeedMac.WeedAging=dt ?->WeedAge                             (d/d)
I PlowMac.ResetWeedAge onevt(BuyWeedMac,WeedAge) WeedAge->?     (d)
P WeedMac.WeedUseLife=3650                                      (d)
V WeedMac.BuyWeedMac=when(ScrapWeedMac)                         (-)
V WeedMac.ScrapWeedMac=when(WeedAge>WeedUseLife)                (-)
P WeedMac.WeedWeight=660                                       (kg)
P WeedMac.WeedWidthWork=12                                      (m)
P WeedMac.WeedUnitPow=1.5                                    (kW/m)
P WeedMac.WeedCapc=1.05                                        (mc)
A WeedMac.WeedPowReq=WeedUnitPow*WeedWidthWork                 (kW)
P WeedMac.WeedFtUni=500                                      (N/mc)
A WeedMac.WeedFt=WeedFtUni*WeedCapc                             (N)
A WeedMac.WeedGa=WeedFt/WeedCoffAderenz                         (N)
A WeedCoffAderenz=0.2                                           (-)
A WeedMac.WeedTracPowReq=WeedGa/WeedDenonm                     (kW)
P WeedMac.WeedDenonm=700                                        (-)
P WeedMac.WeedTracPow=30                                       (kW)
A WeedMac.WeedG=WeedTracPowReq/WeedTracPow                      (-)
A WeedMac.WeedCCh=Cs/gtokg*WeedG*WeedTracPow                 (kg/h)
P WeedMac.WeedVel=7                                          (km/h)
A WeedMac.WeedWorkCap=WeedVel*WeedWidthWork/10*WeedInEffCamp (ha/h)
P WeedMac.WeedInEffCamp=0.8                                     (-)
A WeedMac.WeedCC=WeedCCh/WeedWorkCap                        (kg/ha)
A WeedMac.WeedCL=WeedCC*CCartoCLub/100                      (kg/ha)

' hoeing (descriptions like above)
G HoeiMac=HoeiMacIni
P HoeiMacIni=1                                                  (-)
S HoeiMac.HoeiAge=HoeiAgeIni                                    (d)
P HoeiMac.HoeiAgeIni=0                                          (d)
R HoeiMac.HoeiAging=dt ?->HoeiAge                             (d/d)
I HoeiMac.ResetHoeiAge onevt(BuyHoeiMac,HoeiAge) HoeiAge->?     (d)
P HoeiMac.HoeiUseLife=3650                                      (d)
V HoeiMac.BuyHoeiMac=when(ScrapHoeiMac)                         (-)
V HoeiMac.ScrapHoeiMac=when(HoeiAge>HoeiUseLife)                (-)
P HoeiMac.HoeiDepth=0.1                                         (m)
P HoeiMac.HoeiWeight=800                                       (kg)
P HoeiMac.HoeiWidthWork=3.5                                     (m)
P HoeiMac.HoeiUnitPow=tab(clay\2,20\5,80)                    (kW/m)
A HoeiMac.HoeiTeorPow=HoeiUnitPow*HoeiWidthWork                (kW)
A HoeiMac.HoeiPowReq=HoeiTeorPow*HoeiRappBeta                  (kW)
A HoeiMac.HoeiRappBeta=Beta/HoeiRenGanc                         (-)
P HoeiMac.HoeiRenGanc=0.6                                       (-)
P HoeiMac.HoeiWorkRest=220                                (N/m*cm)
A HoeiMac.HoeiFt=HoeiWorkRest*HoeiWidthWork*HoeiDepth           (N)
A HoeiMac.HoeiGa=HoeiFt/HoeiCoffAderenz                         (N)
A HoeiCoffAderenz=0.25                                          (-)
A HoeiMac.HoeiTracPowReq=HoeiGa/HoeiDenonm                     (kW)
P HoeiMac.HoeiDenonm=700                                        (-)
P HoeiMac.HoeiTracPow=60                                       (kW)
A HoeiMac.HoeiG=HoeiTracPowReq/HoeiTracPow                      (-)
P HoeiCs=0.28                                              (kg/kWh)
A HoeiMac.HoeiCCh=HoeiCs/gtokg*HoeiG*HoeiTracPow             (kg/h)
P HoeiMac.HoeiVel=8                                          (km/h)
A HoeiMac.HoeiWorkCap=HoeiVel*HoeiWidthWork/10*HoeiInEffCamp (ha/h)
P HoeiMac.HoeiInEffCamp=0.8
A HoeiMac.HoeiCC=HoeiCCh/HoeiWorkCap                        (kg/ha)
A HoeiMac.HoeiCL=HoeiCC*CCartoCLub/100                      (kg/ha)
' Spandiconcime (descriptions like above)
G SpreMac=1                                                     (-)
S SpreMac.SpreAge=SpreAgeIni                                    (d)
P SpreMac.SpreAgeIni=0                                          (d)
R SpreMac.SpreAging=dt ?->SpreAge                             (d/d)
```

```
I PlowMac.ResetSpreAge onevt(BuySpreMac,SpreAge) SpreAge->?         (d)
P SpreMac.SpreUseLife=3650                                           (d)
V SpreMac.BuySpreMac=when(ScrapSpreMac)                              (-)
V SpreMac.ScrapSpreMac=when(SpreAge>SpreUseLife)                     (-)
P SpreMac.SpreWeight=660                                            (kg)
P SpreMac.SpreWidthWork=12                                           (m)
P SpreMac.SpreUnitPow=1.5                                         (kW/m)
P SpreMac.SpreCapc=1.05                                             (mc)
A SpreMac.SprePowReq=SpreUnitPow*SpreWidthWork                      (kW)
P SpreMac.SpreFtUni=500                                           (N/mc)
A SpreMac.SpreFt=SpreFtUni*SpreCapc                                  (N)
A SpreMac.SpreGa=SpreFt/SpreCoffAderenz                              (N)
A SpreCoffAderenz=0.2                                                (-)
A SpreMac.SpreTracPowReq=SpreGa/SpreDenonm                          (kW)
P SpreMac.SpreDenonm=700                                             (-)
P SpreMac.SpreTracPow=30                                            (kW)
A SpreMac.SpreG=WeedTracPowReq/WeedTracPow                           (-)
A SpreMac.SpreCCh=Cs/gtokg*WeedG*WeedTracPow                      (kg/h)
P SpreMac.SpreVel=7                                               (km/h)
A SpreMac.SpreWorkCap=WeedVel*WeedWidthWork/10*WeedInEffCamp      (ha/h)
P SpreMac.SpreInEffCamp=0.8                                         (-)
A SpreMac.SpreCC=WeedCCh/WeedWorkCap                             (kg/ha)
A SpreMac.SpreCL=WeedCC*CCartoCLub/100                           (kg/ha)
' Ripuntatore (descriptions like above)
G ChisMac=ChisMacIni
P ChisMacIni=1                                                     (-)
S ChisMac.ChisAge=ChisAgeIni                                       (d)
P ChisMac.ChisAgeIni=0                                             (d)
R ChisMac.ChisAging=dt ?->ChisAge                                  (d/d)
I ChisMac.ResetChisAge onevt(BuyChisMac,HoeiAge) ChisAge->?        (d)
P ChisMac.ChisUseLife=3650                                         (d)
V ChisMac.BuyChisMac=when(ScrapChisMac)                            (-)
V ChisMac.ScrapChisMac=when(ChisAge>ChisUseLife)                   (-)
P ChisMac.ChisDepth=0.5                                            (m)
P ChisMac.ChisWeight=510                                           (kg)
P ChisMac.ChisWidthWork=2.1                                        (m)
P ChisMac.ChisUnitPow=tab(clay\2,20\5,80)
         (kW/m)
A ChisMac.ChisTeorPow=HoeiUnitPow*ChisWidthWork                    (kW)
A ChisMac.ChisPowReq=ChisTeorPow*ChisRappBeta
(kW)
A ChisMac.ChisRappBeta=Beta/ChisRenGanc                            (-)
P ChisMac.ChisRenGanc=0.4                                          (-)
P ChisMac.ChisWorkRest=200                                      (N/m*cm)
A ChisMac.ChisFt=ChisWorkRest*ChisWidthWork*ChisDepth              (N)
A ChisMac.ChisGa=ChisFt/ChisCoffAderenz                            (N)
P ChisCoffAderenz=0.25                                             (-)
A ChisMac.ChisTracPowReq=ChisGa/ChisDenonm                          (kW)
P ChisMac.HoeiDenonm=700                                           (-)
P ChisMac.ChisTracPow=60                                            (kW)
A ChisMac.ChisG=ChisTracPowReq/ChisTracPow                         (-)
P HoeiCs=0.28                                                  (kg/kWh)
A ChisMac.ChisCCh=ChisCs/gtokg*ChisG*ChisTracPow                 (kg/h)
P ChisMac.ChisVel=6                                              (km/h)
A ChisMac.ChisWorkCap=ChisVel*ChisWidthWork/10*ChisInEffCamp    (ha/h)
P ChisMac.ChisInEffCamp=0.8
A ChisMac.ChisCC=ChisCCh/ChisWorkCap                            (kg/ha)
A ChisMac.ChisCL=ChisCC*CCartoCLub/100                          (kg/ha)
' Spandiliquami (descriptions like above)
G LiqManSpMac=LiqManSpIni
P LiqManSpIni=1                                                    (-)
S LiqManSpMac.LiqManSpAge=LiqManSpAgeIni                           (d)
P LiqManSpMac.LiqManSpAgeIni=0                                     (d)
R LiqManSpMac.LiqManSpAging=dt ?->LiqManSpAge                      (d/d)
I LiqManSpMac.ResetLiqManSpAge onevt(BuyLiqManSp,LiqManSpAge _
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                 LiqManSpAge->?                                      (d)
P LiqManSpMac.LiqManSpUseLife=3650                                   (d)
V LiqManSpMac.BuyLiqManSp=when(ScrapLiqManSp)                        (-)
V LiqManSpMac.ScrapLiqManSp=when(LiqManSpAge>LiqManSpUseLife)        (-)
P LiqManSpMac.LiqManSpWeight=1500                                    (kg)
P LiqManSpMac.LiqManSpWidthWork=4                                    (m)
P LiqManSpMac.LiqManSpUnitPow=3.5                                    (kW/t)
P LiqManSpMac.LiqManSpCapc=5                                         (t)
A LiqManSpMac.LiqManSpFt=LiqManSpUnitPow*LiqManSpCapc_
                        +LiqManSpUnitPow*LiqManSpWeight              (kW)
P LiqManSpMac.LiqManSpFtUni=9.8                                      (N/mc)
A LiqManSpMac.LiqManSpGa=LiqManSpFt/LiqManSpCoffAderenz              (N)
A LiqManSpCoffAderenz=0.4                                            (-)
A LiqManSpMac.LiqManSpTracPowReq=LiqManSpGa/LiqManSpDenonm           (kW)
P LiqManSpMac.LiqManSpDenonm=700                                     (-)
P LiqManSpMac.LiqManSpTracPow=30                                     (kW)
A LiqManSpMac.LiqManSpG=LiqManSpTracPowReq/LiqManSpTracPow           (-)
A LiqManSpMac.LiqManSpCCh=Cs/gtokg*LiqManSpG*LiqManSpTracPow         (kg/h)
P LiqManSpMac.LiqManSpVel=7                                          (km/h)
A LiqManSpMac.WeedWorkCap=WeedVel*WeedWidthWork/10*_
                                WeedInEffCamp                        (ha/h)
P LiqManSpMac.WeedInEffCamp=0.8
A WeedMac.WeedCC=WeedCCh/WeedWorkCap                                 (kg/ha)
A WeedMac.WeedCL=WeedCC*CCartoCLub/100                               (kg/ha)
```

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' XF-Biogas

C R=0.082057458          "Gas constant"                ((atm*mc)/(kmol*K))
C TempNorm=273.15        "Normal temperature"                        (K)
C PresNorm=1             "Normal presure"                            (atm)
C mmCH4=16.042           "Molar mass of methane"             (kgST/kmolCH4)
C mmCO2=44.01            "Molar mass of carbon dioxide"      (kgST/kmolCH4)
C HourInDay=24           "Number of hours in a day"                  (h/d)
C PCICH4=8.79            "lower heating value of methane"          (kWh/m³)
P moltom3=((R*TempNorm)/PresNorm) _
                 "conversion from moles to cubic meters"         (m³/kmol)
C CSH2O=0.000001163      "Specific heat of water"                (MJ/kg/°C)
C H2Odensity=1000        "Water density"                           (kg/mc)
C kWhToMJ=3.6            "from kWh a MJ"                           (kg/mc)
V startDigest=when(?)   msg(power on digester)
P WhenStart=0            onevt(startDigest,Time)
P DigesOpen=0            onevt(startDigest,1)
A Trench.DigesYes=cond(StorageTrench>LoadingRate,DigesOpen,0)
S digestingST=0  "Mass of material in the digester"                (kgST)
S digestate=0            "Digested in the digester"                 (kgST)
S BgCH4=0                "Methane"                                  (kgST)
S BgCO2=0                "Carbon dioxide"                           (kgST)
R Trench.storToDiging=DigesYes*LoadingRate StorageTrench->digestingST _
                         "Digester filling rate"                  (kgST/d)
P CH4inB=0.53    "Fraction of methane content in the biogas"         (-)
P FermConst=0.15  "Constant speed of production of biogas"         (1/d)
P TDig=40                "Process temperature"                       (°C)
P TempFactor=mbell(Tdig,40,40,10,3) _
                 "Correction factor dependent on temperature"        (-)
A FermRate=fermConst*TempFactor "Rate of fermentation"              (1/d)



A DigToCH4=BioMetPot/moltom3*mmCH4 _
             "Fraction of methane produced by anaerobic digestion"   (-)
A DigToCO2=BioMetPot*(1/CH4inB-1)/moltom3*mmCO2 _
             "Fraction of carbon dioxide produced by anaerobic digestion"  (-)
A DigToDigestate=1-(DigToCH4+DigToCO2)_
                 "Fraction of digestate from anaerobic digestion"    (-)
R FermToCH4=FermRate*DigestingST*DigToCH4 digestingST->BgCH4 _
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  "Rate of production of methane from anaerobic digestion"        (kgST/d)
R FermToCO2=FermRate*DigestingST*DigToCO2 digestingST->BgCO2 _
  "Rate of production of carbon dioxide from anaerobic digestion"(kgST/d)
R FermToDigestate=FermRate*DigestingST*DigToDigestate_
                digestingST->digestate_
  "Rate of production of digestate from anaerobic digestion"     (kgST/d)
A FermToDigesAux=FermRate*DigestingST*DigToDigestate _
"Rate of production of digestate from anaerobic digestion"       (kgST/d)
P PowToVol=tab(elecEnginePower\39.5,100\15.1,100\15.1,250\_
               8.4,250\8.4,500\7.6,500\7.6,1000\6.7,1000) _
"Factor between relative volume of the digester and engine power"     (-)
A Trench.VolDayOut=LoadingRate/TrenchDensity _
"Volume of incoming material from each trench"                       (mc)
A TotVolDayOut=gsum(VolDayOut) "Total volume of incoming material"   (mc)
A VolDig=elecEnginePower*PowToVol_
         "Estimate the total volume of digester"                     (mc)
A RitTime=cond(TotVolDayOut<10,20,VolDig/TotVolDayOut)_
                "Retention time"                                      (d)
R digestingOut=digestingST/RitTime digestingST->digestateStor _
               "Rate of emptying of the digester"                 (kgST/d)
S elecEnergy=0                  "Electric energy"                   (kWh)
S termEnergy=0                  "Thermal energy"                    (kWh)
R CO2fromCH4=BgCH4*(mmCO2/mmCH4) ?->BgCO2
               "Production rate of CO2 from combustion"           (kgST/d)
R CH4toCO2=BgCH4 BgCH4->?       "Rate of methane combustion"      (kgST/d)
P elecEnginePower=250        "Electric power cogeneration"           (kW)
P termEnergyFlag=0 _
"1 if the heat used, 0 only electricity"                              (-)
A resaElec=cond(termEnergyFlag,tab(elecEnginePower\0.358,64\0.387,64\ _
0.387,105\0.364,105\0.364,125\0.385,125\0.385,190\0.381,190\0.381,250\ _
0.388,250\0.388,330\0.382,330\0.382,361\0.404,361\0.404,526\0.400,526\ _
0.400,635\0.405,635\0.405,703\0.399,703\0.399,834\0.420,834\0.420,888\ _
0.415,888\0.415,999\0.408,999\0.408,1063\0.422,1063\0.422,1190\_
0.421,1190\0.421,1484),0.450)   "Yield in electrical energy"      (kWt/kW)
A resaTerm=cond(termEnergyFlag,tab(elecEnginePower\0.474,64\0.444,64\ _
0.444,105\0.474,105\0.474,125\0.429,125\0.429,190\0.408,190\0.408,250\ _
0.450,250\0.450,330\0.422,330\0.422,361\0.408,361\0.408,526\0.408,526\ _
0.408,635\0.409,635\0.409,703\0.422,703\0.422,834\0.397,834\0.397,888\ _
0.403,888\0.403,999\0.401,999\0.401,1063\0.396,1063\0.396,1190\_
0.396,1190\0.396,1484),0.181)    "Yield in thermal energy"        (kWt/kW)
R CH4toElecEnergy=BgCH4*1/mmCH4*moltom3*PCICH4*resaElec ?->elecEnergy _
                           "Rate of electricity production"        (kWh/d)
R CH4toTermEnergy=BgCH4*1/mmCH4*moltom3*PCICH4*resaTerm ?->termEnergy _
                           "Rate of heat production"               (kWh/d)
A RealElecEngPwr=RealEngPwr*resaElec _
                        "Electric power generated by engine"       (Kw)
A RealTermEngPwr=RealEngPwr*resaTerm _
                        "Thermic power generated by engine"        (Kw)
A RealEngPwr=BgCH4*1/mmCH4*moltom3*PCICH4/HourInDay _
                        "Total power produced by the engine"        (Kw)
S Trench.LoadingRate=0  "Daily load to the digester"             (kgST/d)
A PwrFrac=cond(RealElecEngPwr<1,0,_
               (elecEnginePower-RealElecEngPwr)/RealElecEngPwr)_
                " Correction factor respect the real power"           (-)
A Trench.LoadRateInit=elecEnginePower/0.40*_
      HourInDay/PCICH4/0.400*(StorageTrench/StorageTrenchTot)_
      "Daily load at the plant"                             (kgST/d/d)
```

```
R Trench.LoadingRateRate=cond(time=WhenStart,LoadRateInit,_
               LoadingRate*PwrFrac/RitTime) ?->LoadingRate _
           "Correction rate of daily load"                     (kgST/d/d)
A LoadingRateTot=gsum(LoadingRate)
               "Total correction of daily load"                (kgST/d/d)
S digestingBMP=0        "Potential methane"                      (mcCH4)
R Trench.BMPIn=BMPTr*SVTr*LoadingRate ?->digestingBMP _
```

```
                              "Filling rate digester"            (mcCH4/d)
R BMPOutToCH4=FermRate*DigestingST*BioMetPot digestingBMP->? _
                              "Real output of methane"           (mcCH4/d)
R BMPOutToStor=digestingBMP/RitTime digestingBMP->? _
                              "Potential output of methane"      (mcCH4/d)
A BioMetPot=cond(digestingST>0,digestingBMP/digestingST,0) _
                             "Methane Biochemical Potential" (mcCH4/kgST)
S digestateStorN=0     " Total nitrogen in the digestate stored"     (kgN)
R Trench.NtoDigestate=cond(StorageTrench=0,0,_
               StorageNTrench/StorageTrench*LoadingRate) _
                        StorageNTrench->digestateStorN _
"Transfer rate of nitrogen from the trenches of the digestate"     (kgN/d)
A digestateN=digestateStorN/digestateStor _
               "Fraction of nitrogen in the digestate"          (kgN/kgST)
```

```
' Model: XF_Energy.sem
' - Farm energy balance
A CropTotEneIN=Gsum(TotEnInput)   "Total energy input"             (GJ/ha)
A CropTotEneOUT=Gsum(CropEnerOut) "Total energy in the crop"       (GJ/ha)
A FarmEnerIn=(FarmArea*CropTotEneIN)  "Farm energy input"             (GJ)
A FarmEnerOut=(FarmArea*CropTotEneOUT)  "Farm energy output"          (GJ)
A FarmEneBalance=FarmEnerOut-FarmEnerIn _
                              "Farm energy balance (all crop)"        (GJ)
A FarmEneEff=cond(FarmEnerIn>0,FarmEnerOut/FarmEnerIn,0)_
                           "Farm energy efficiency (all crop)"        (-)
A TotHarvEnergy=Gsum(HarvCropEnergy)_
                           "Harvested crop energy (farm output)"   (GJ/ha)
A FarmHarvEnergy=FarmArea*TotHarvEnergy "Energy out of the farm"      (GJ)
A FarmEneBalOut=FarmHarvEnergy-FarmEnerIn_
                        "Farm energy balance (harvested)"             (GJ)
A FarmEneEffOut=cond(FarmEnerIn>0,FarmHarvEnergy/FarmEnerIn,0) _
                        "Farm energy efficiency(harvested)"            (-)
```

```
' Model: XF_Environ.sem 29-6-2011
' Farm environmental accounting
' Nitrogen
S NtoAtm=0              "Farm nitrogen output to atmosphere"      (kgN/ha)
S Nmarket=0             "Farm nitrogen output to market"          (kgN/ha)
S NO3gwater=0           "NO3 drained to water table"              (kgN/ha)
S NH4gwater=0           "NH4 drained to water table"              (kgN/ha)
S NO3swater=0           "NO3 to run-off water"                    (kgN/ha)
S NH4swater=0           "NH4 to run-off water"                    (kgN/ha)
A Ninput=Nfert+Nleach+Nfix "Farm system nitrogen input"            (kg/ha)
A NetNex=               "Net nitrogen farm exchange"            (kgN/ha/d)
' CO2 emission to atmosphere
S CO2atm=0                 "Cumulated CO2 to atmosphere"         (tCO2/ha)
A CtoAtmDir=CHum*OMtoAtm "Direct farm carbon output to atmos"     (kgC/ha)
S CtoAtmInd=0     "Indirect farm carbon output to atm"            (kgC/ha)
A Cinput=0        "Farm carbon input"                              (kg/ha)
A NetCex=               "Net CO2 farm exchange"               (kgCO2/ha/d)
' water
S TotRoff=0           "Total cumulated runoff"                      (mmW)
```