X-farm: modelling sustainable farming systems and simulation

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Abstract: *The aim of this paper is to illustrate the structure of X-farm, a model to manage farming systems under energetic, economical, ecological perspective, using the dynamic simulation approach. The farm is targeted to achieve the energetic self-sufficiency, by using a quota of the total biomass produced in farm for the production of energy as oil, biogas or heat. The structure of X-farm is composed by some integrated modules representing the main centres of farming costs and production: soil management, crop production and processing, energy production and administration. The dynamic simulation is addressed to find the best combination of crop and livestock activities in the farm plan, using a multipurpose strategic approach. The objective of energy production is afforded by using crops and reducing the energy use by optimizing energy saving techniques; the ecological objective is formulated by accounting the CO_2 emissions; the economic objective is targeted to profit maximization, constrained by the level of achievement of the energy and ecology targets. The dynamic simulation is expected to help in improving the farm management performance with the simultaneous achievement of the three objectives. Finally, combining the X-farm model with GIS techniques, the analysis will be expanded to the agro-district planning to support the regional strategy for agro-energy production.*

Keywords: *farm, model, decision support system, bio-energy, scenario, simulation, management.*

Introduction

Agricultural researchers widely recognise the importance of sustainable agricultural production systems and the need to develop appropriate methods to measure sustainability (Byerlee *et al*., 2001; Pacini *et al.*, 2003). Bio-energy production efficiency at farm level is still questionable, depending on the commodity used, agronomic practices, climate variability and other unpredictable events. Some researchers assess that the energy balance is still negative (Pimentel *et al*., 2003, 2005); other studies (Hill *et al*., 2006), suggest that the energy produced with the oil and co-products by using energy saving techniques is significantly higher of the energy spent.

Models are excellent tools to organize knowledge and help to explore alternative scenarios for the management of agricultural systems (Bechini *et al.*, 2007). Farm simulation modelling is assuming increasing importance; oriented to provide short- and long-term scenarios (Danuso, *et al.* 2007), 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 (Rots *et al.*, 2006), FARMSIM (Van Wijk *et al.*, 2006), SIPEAA (Donatelli *et al.*, 2006).

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 (manpower, energy, machinery, time window for tillage, etc.). Moreover, the need to simultaneously manage many different fields and different crop rotations, creates further difficulties.

In this paper *X-farm*, a farm dynamic simulation model developed at the University of Udine (Danuso et al., 2007) is presented. *X-farm* represents a generic "agro-energy farm", taking into specific account crop biomass production, net energy balance, environmental and economic balances. This farm is targeted to achieve the energetic self-sufficiency, by using a quota of the total biomass produced in farm for the production of energy as oil, biogas or heat.

X-farm is formed by different modules describing the farm activities; they can be grouped in different sections: management, production, soil and accountability (in terms of energy, environment and economy).

Simulations of different cropping scenarios have been performed to test the *X-farm* capabilities to simulate complex farming systems to be used as a decision-support tool.

Methods

Model implementation

X-farm has been implemented using SEMoLa (Simple, Easy to use Modelling Language). SEMoLa (figure 1) is a software application for the development of simulation models and agro-ecological knowledge integration (Danuso, 2003) that implements a declarative language. This makes the model code very easy to understand and to modify (even without computer programming skill). Therefore, SEMoLa models can be easily implemented and customized.

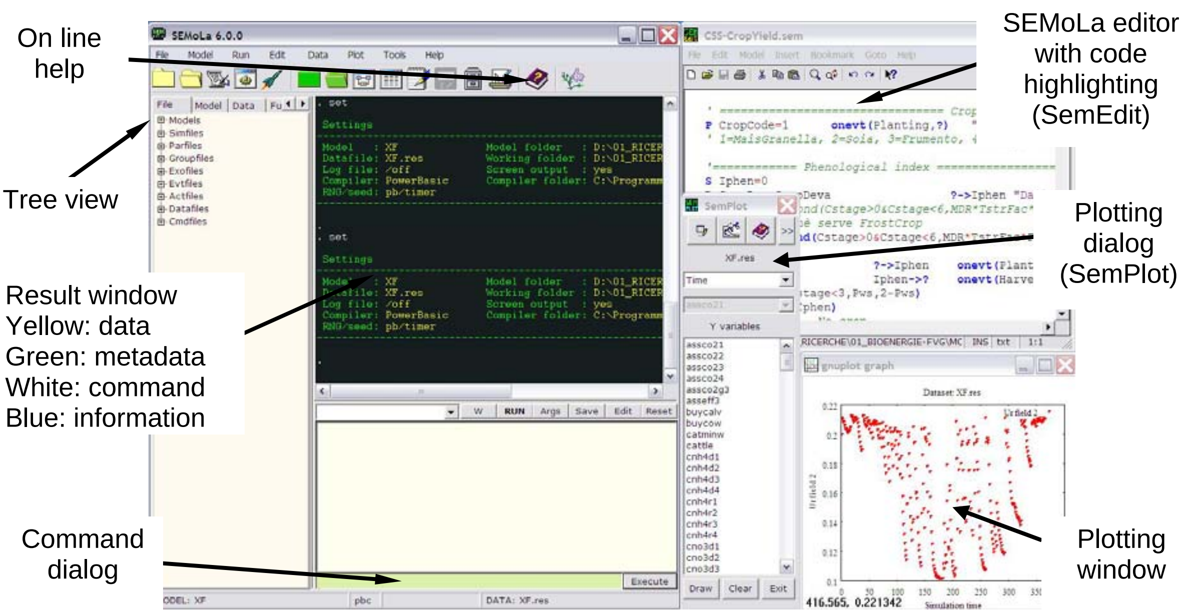


Figure 1. Main dialogs of SEMoLA 6.0 software.

SEMoLa has been developed and is maintained at the Department of Agricultural and Environmental Sciences of the University of Udine (Italy). 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 is based on the System Dynamics concepts proposed by Forrester (1961) and widely used in describing continuous systems (Muetzelfeldt, 2003).

With SEMola language, all farm processes are represented by nine types of concepts (table 1):

(i) Material: a quantity that follows the conservation law (conservative quantity). It is opposite to “information” which is not conservative. A farm system can have more than one material (e.g., water, biomass, nitrogen, money, energy) and each material can be in one or more states.

(ii) Group: an “entity” composed by elements sharing a number of common properties (i.e., state, parameter, etc.). Each element of the group can have its own inputs and outputs. The number of element can vary during simulation by events (e.g., the group of fields, the group of tractors, etc.).

(iii) State: amount of material having specific properties; it evolves in time thanks to continuous flow (rates) or by sudden modifications caused by events (impulses).

(iv) Rate: variable that regulates the flow of materials from a state to another or the exchanges of materials from the system and its environment. It depends on system information.

(v) Parameter: information of the system, constant during the simulation time. It is a static memory of the system.

(vi) Auxiliary variable: information obtained from states, parameters and exogenous variables and used in the calculation of rates, impulses and events.

(vii) Exogenous variable: informative variable generated outside the system and not under the control of the system, able to affect the system itself.

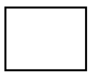
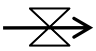
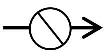
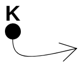
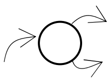
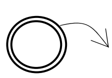
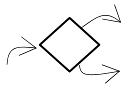
(viii) Event: something happening that determines sudden modifications of states (by impulses) or parameters.

(ix) Impulse: variable that determines an instantaneous shift of materials from a state to another, as a consequence of events.

SEMoLa language combines concepts of amount, flow and influence, to usefully describe the interconnected relations in complex systems that increase in complexity when agronomy, ecology, economy and environment are simultaneously considered.

In the *X-farm* model, the farm activities are described with the concepts of state, rate, parameter and event. Crop, livestock and energy productions are also characterized by starting and ending events, temporal windows, priority in accessing resources and prerequisites.

Table 1. Graphic representation of the SEMoLa ontology.

STATE	RATE	IMPULSE	PARAMETER	AUXILIARY VARIABLE	EXOGENOUS VARIABLE	EVENT
						

Model description

At present, the "agro-energy farm" simulated by the *X-farm* model is formed by twenty-three interconnected modules (figure 2) logically grouped into four sections: management, production, soil and accounting. The simulation time step is daily.

The farm represented is composed by one or more fields, each one with different soil types, crop rotation and cropping practices. Other simulated activities are cattle husbandry (milk and meat production) in which cows are considered individually, during its productive life. The oil crops can supply seeds for the farm oil extraction chain or for selling to the market.

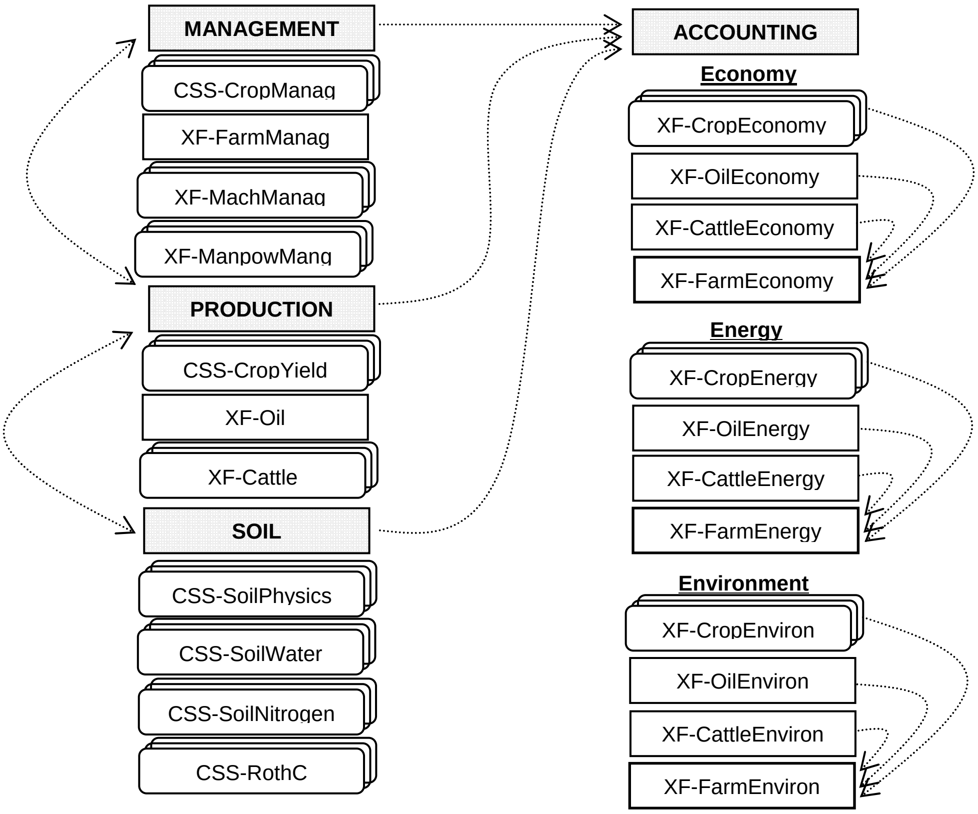


Figure 2. The modules of *X-farm*. Arrows indicate the informative relationships among modules. Note that there are two types of modules: simple modules and multiples modules. Multiples modules are represented by the concept of group (individual base model). For example, in the farm there is only one oil module but the crop and soil module are replicated in order to represent each field of the farm.

The *Production* section simulates the crop yield of each field, oil extraction from seeds and milk production from cattle. In particular, for the simulation of crops, *X-farm* uses the module *CSS-CropYield* obtained from the CSS model (Cropping System Simulator; Danuso *et al.*, 1999) and simulates crop biomass growth and yield under different conditions, depending on climate, soil characteristics, manure and fertilizer applications, tillage and other management choices like irrigation. 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 implemented as in CropSyst (Stöckle and Nelson, 1994). The *XF-Oil* module deal with the oil production process, consisting of mechanical extraction by seed pressing and use of vegetable oil. This oil can be used as fuel in farm machinery, in cogeneration of electric and thermal energy, or for the production of biodiesel by transesterification. In this way the energy self-sufficiency of the farm is achieved and the exceeding oil or energy can be sold to the market (Rosa, 2008; Rosa, 2009). In the *XF-Cattle*, the cattle are fed by the cake, being the co-product of the oil extraction and by 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 obtained from the specific lactation curve. The co-products, represented by wastes or manure are spread as organic fertilizer to the fields.

The *Soil* section considers soil as divided into one or two layers, depending on the dynamics of the involved material (water, organic matter, nitrogen). The depth of the upper layer changes according to the crop root growth, from the soil surface to the maximum depth explored by roots during the crop life. The soil type is classified as function of the amount of sand and clay. The other soil characteristics (water field capacity, wilting point, maximum water capacity, organic matter content, etc.) are parameters that can be suggested by the model or inserted by the user. All soil parameters are corrected for the amount of gravel.

The *SoilWater* module simulates the soil water content taking into account actual evapo-transpiration, runoff and infiltration. Drainage to water table and capillary rise are simulated, according to Rijtema (1969) and Driessen (1986).

Nitrogen content (as nitrate and ammonium) is calculated in the *Soil Nitrogen* module, separately for root layer and deep layer. Moreover, the model simulates the nitrogen content in crop yields, crop residues and soil organic matter. Crop residues decay is considered in the soil organic matter balance, by an implementation of the *RothC* model (Coleman *et al*., 2008). This model divides organic matter into easily decomposable residues, resistant to decomposition residues, humus and microbial biomass, with different mineralization coefficients.

The *Management* section simulates agricultural cropping activities for each field and farm strategies, related to oil processing, livestock holdings, sales and internal use of products (*XF-cropManag* and *XF-FarmManag*). All processes, requiring the use of resources in terms of manpower and machinery for the farm organization, are simulated in the modules *XF-ManpowManag* and *XF-MachManag*.

The *Accounting* section is divided in the *Economy*, *Energy* and *Environment*, providing specific balances for crops, oil, cattle and for the whole farming system.

The *Economy* modules calculate the full costs of resources (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 every activity to the global performance. Economic information, obtained from market prices for agricultural activities (FRIMAT, 2008) is used as input parameters to the model. The economic information output is presented as data files to support decisions of investments and the analyses of the performance evaluation of the results obtained in each activity (Rosa, 2009)

The *Energy* modules compute both the energy of the farm products and the direct and indirect energy used by crops, oil and cattle production. The Pimentel approach based on transformation coefficients has been used (Pimentel *et al.*, 2003; Venturi *et al.*, 2003) in the energy crop module. The parameters for the energy balance in oil processing have been obtained from trials performed at 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* modules account for the direct and indirect inputs and outputs between farm and environment. To compare the environmental performance of the different farm activities, an equivalent function for each of them is defined and normalized for LCA (life cycle assessment) approach analysis (Kim *et al.*, 2005). Information to perform it is obtained from literature and simulated data.

The *X-farm* model is available in two versions:

1) *X-farm* user (XF): the user version, with a reduced number of input parameters and output variables. In this version, most of the model parameters are automatically inserted by selecting a crop, organic fertilizer type, etc. However, the following exogenous input variables are also required: daily minimum and maximum air temperature (°C), rainfall (mm/d), reference evapotranspiration (mm/d), global radiation at the earth's surface ($MJ/m^2/d$). This version can be used for farm strategic decision-support and scenario analysis. XF inputs and outputs are reported in figure 3.

2) *X-farm* development (XFD): is the version for modellers, in which all parameters are modifiable and all calculated variables are make available. XFD allows model calibration for specific management situations and can be used as the basis for further model developments.

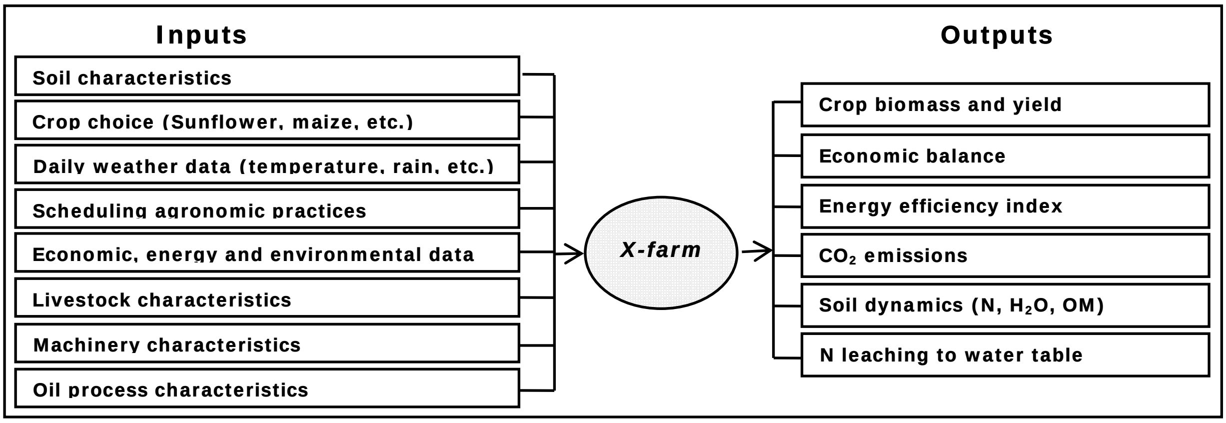


Figure 3. Inputs and outputs for the X-farm user model

In the *X-farm* user version, many crop, economic and environmental parameters are built-in to the executable model. In the XFD they are inserted in files updatable by the user.

Farm simulation experiments

A simulation of the crop production, for different cropping scenarios, performed to show the *X-farm* model capabilities in comparing different farming strategies is presented. As reported in table 2, which summarizes the scenarios considered in this application, the *X-farm* model has been run on a hypothetical farm of 100 ha of arable land, using actual meteorological data observed in Udine (North-East Italy, 46°03´N 13°14´E) obtained from the Meteorological Service of the Friuli Venezia Giulia region, for the period 2000-2003. The cropping scenarios considered involve three crops (maize, soybean and sunflower), four year rotations and four fields, differing by land area and soil characteristics. The tillage and other cropping practices are assumed as provided by contractors. Table 3 reports detailed information about the events and cropping practices considered in this *X-farm* application example. These practices are based on the techniques usually applied in the North-East of Italy. Irrigation timings and amounts are reported in table 3.

Simulations are set up by preparing a simulation file (*simfile*) that allows to perform simple or multiple simulations. The *simfile* make a reference to parameters, meteorological data (exogenous variables) and cropping practices (events). Parameters are contained in *parfile*, *gpafiles* and *actfiles*; meteorological data are in *exofile* and cropping practices are in *evtfile*. They can contain more than one dataset that can be selected by customizing *simfile*. In this way it is possible to create different complex simulations combining soil parameters, meteorological data and cropping scenarios.

Parfile contains values for the scalar parameters; *gpafiles* are used to modify values of the group parameters, while *actfiles* modify values only when events occur. Parameter values in *parfile* and *gpafiles* are set before the beginning of the simulation. Instead, those in *actfiles* are assigned to parameters at the time of occurrence of specific events (cropping practices).

This structure of input files allows the simulation of different cropping scenarios and crop rotations. Figure 4 reports the SEMoLa simulation framework dialogs for editing input files.

Another type of application of the model is the possibility to set up the automatic calculation of irrigation water requirements, in order to maintain the maximum yields but also raising the costs and energy input.

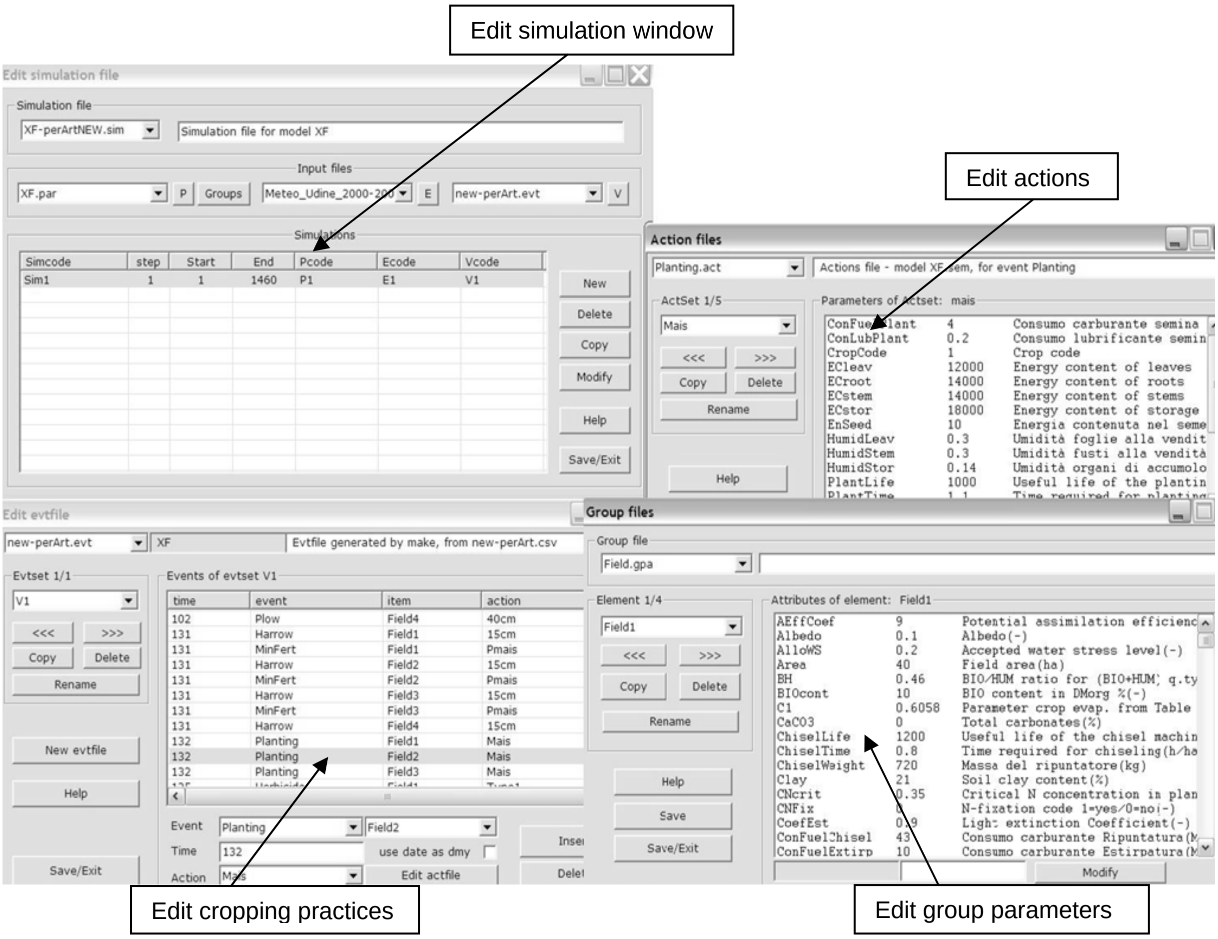


Figure 4. The SEMoLa simulation framework dialogs for editing input files.

Table 2. Cropping scenarios for the simulations: soil characteristics and four-year crop rotation for an hypothetic farm with four fields.

		Field 1	Field 2	Field 3	Field 4
Acreage	ha	40	25	15	20
sand	%	28	40	28	28
clay	%	21	19	21	21
organic mater	%	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) Soil maximum water capacity
(2) Soil water capacity
(3) Soil wilting point

Table 3. Cropping practices applied to each crop in rotations.

Crop	Harrowing		Mineral fertilization		Chemical weed control		Planting	Irrigation		Harvest	Plowing	
	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 $N\text{-}NH_4$ 90 $N\text{-}NH_4$	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 $N\text{-}NH_4$	150	2.5	160	181 191 200	25 25 25	280	102	0.4

(1) Day of the year

Results

Figure 5 reports the simulations of biomass accumulation for each field rotation, over a period of four years. These results, obtained comparing different cropping combinations on a hypothetical farm of 100 ha, provide important information for management decisions in short- and long-term scenarios. The model represent the actual crop production variability that is commonly experienced in the North-East Italy environment. For example, it is possible to observe the stronger effect of the drought on 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.

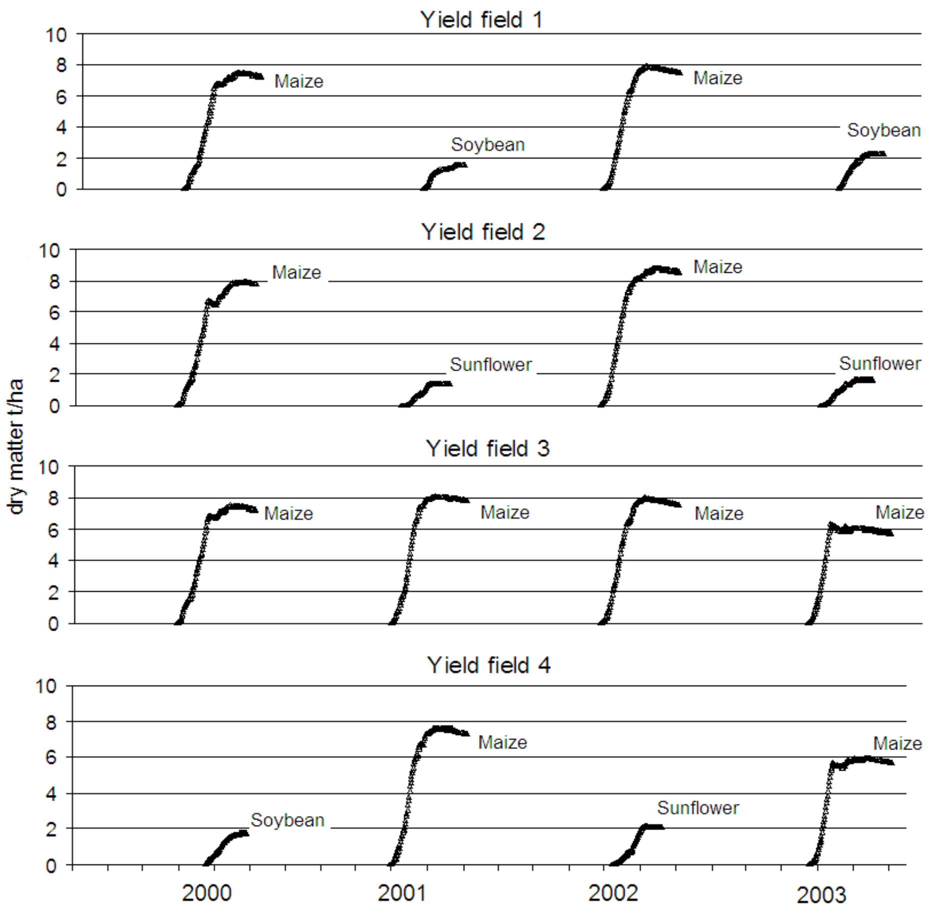


Figure 5. Simulated yields for the four fields of the farm, during the four rotation years.

Table 4 reports the simulation results 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. These figures can be combined to elaborate a budget and to compare different crops and agronomic techniques, in specific pedological, meteorological and market conditions. The simulation reveals that for almost all the cases, the economic balance of fields and farm results to be only slightly positive. These results, of course, must be interpreted on the basis of the price levels, cropping scenarios and environmental conditions considered in the simulation trials. The *X-farm* model can therefore be used to explore the effect of different farm management strategies under market and climatic risks. 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 simulation reflects the actual situations in which 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 with soybean. Again, the effect of the bad weather in 2003 generated the worst energy efficiency among years (5.5).

Table 4. Economic and energetic accounting of the cropping scenario, for each field and for the whole farm, as simulated by X-Farm.

Field - crop		**Economic accounting**			**Energy accounting**			
	year	**costs €/ha**	**revenues €/ha**	**profit €/ha**	**input GJ/ha**	**output GJ/ha**	**balance 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 €**	**profit €**	**input GJ**	**output GJ**	**balance GJ/ha**	**energy efficiency**
Total crop	2000	3884	4331	447	110	672	562	6.1
	2001	3149	3661	511	90	569	479	6.3
	2002	4039	4086	48	116	739	622	6.4
	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).

Conclusions

The *X-farm* model has been presented and different crop rotations and scenarios on a hypothetic four-fields farm have been performed. As highlighted in the simulation outcomes, *X-farm* results to be a useful tool to manage sustainable farming systems. Its use is quite simple and scenario evaluations can be obtained quickly by creating event data files with the agricultural practices and parameters file with the pedological traits.

In order to achieve a better description of the farming system, new developments of *X-farm* are currently in progress: 1) biogas production module; 2) implementation of genetic algorithms to obtain robust calibrations and optimizations; 3) improvement of the LCA analysis for different farm energy production; 4) a decision support system (DSS) version, with the automatic generation of optimized cropping practices decisions (irrigation, automatic generation of mineral fertilization, plowing and harrowing events, etc.); 5) integration between GIS and farm model to create land indicators and to point out trends of specific phenomena (Hartkamp et al., 1999). *X-farm* will be linked to SemGrid (Danuso *et al.*, 2006) a raster GIS developed at the Department of Agricultural and Environmental Sciences of Udine University.

Moreover, a major improvement of *X-farm* will be obtained through the implementation (in progress) of the concept of task (activity) in the SEMoLa language. This concept, largely used in operational research, is also going to be adopted in the modelling of farm organization (Mazzetto *et al.*, 2003). The concept of task will allow to deal with: 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 is a dynamic process leading to the transformation of the state of a material, which requires the consumption of one or more resource and produces emissions. The beginning and ending of a task is caused by events. For example, plowing is now treated as an event, instantaneously applied. Considering plowing as a task, there is a process that transforms 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.

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.

Both versions are freely available from the authors as an executable file (binary) and also as SEMoLa source code. The SEMoLa code is easy to understand and to modify, without requiring specific programming skills. An *X-farm* help file is also included in the installation package.

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