Simulation of the Agro-Energy Farm with the X-Farm Model: Calibration of the Crop Module for Sorghum Yield

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Abstract

This paper presents the X-farm model, a dynamic farm simulation model created to manage sustainable farming systems and to improve the planning capability of farms. X-farm considers an "agro-energy farm" where energy self-sufficiency results from the production, transformation and use of biomass obtained from the farm crops.
The X-farm model is formed by different modules, integrated to describe the components of the agro-energy farm and grouped into management, production, soil and accountability sections (in terms of energy, environment and economy). The main farm productions are the field crop yields. The model simulates a farm in which cereal and forage yield, oil seeds, milk and meat can be sold or reused.
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 language and 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.

Key-words: farm, energy, model, crop, DSS.

1. Introduction

Uncertainties over 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 (Rots and Coiner, 2006), FARMSIM (Van Wijk et al., 2006), SIPEAA (Donatelli et al., 2006) and X-farm (Danuso et al., 2007). 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.

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In this paper, we present a new version of X-farm, 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. An "agro-energy farm" is a farm that uses biomass to produce energy for farming activities and sells the excess to 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 on the farm separately.

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 X-farm model is available in two versions:

1. X-farm user (XF): the user version, with a low 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 or for land-use evaluation.
2. X-farm development (XFD): this is the version for use by the modelers, in which all parameters are modifiable and all calculated variables can be outputted. XFD allows model calibration for specific management situations and can be used as the basis for further model development.

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.

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.

2. Methodology

2.1 Model description

The X-farm model has been implemented by SEMoLa (Simple, Easy to use, Modeling Language) (version 5.8; Danuso, 2003). SEMoLa is a simulation and 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 to manage different types of agro-environmental information. SEMoLa allows deterministic and stochastic models to be created, based on state or elements (as in Individual Based Modelling). The ontology of SEMoLa rely on the System Dynamics proposed by Forrester (1961). It combines concepts of amount, flow and influence, to describe the interconnected relationship in complex systems like those from agronomy, ecology, economy and society.

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 (Fig. 1) grouped into four parts: management, production, soil and accountability. 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 (both as milk and meat production) 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. Crop management is intended as the management of agricultural practices and farm management considers the strategies related to

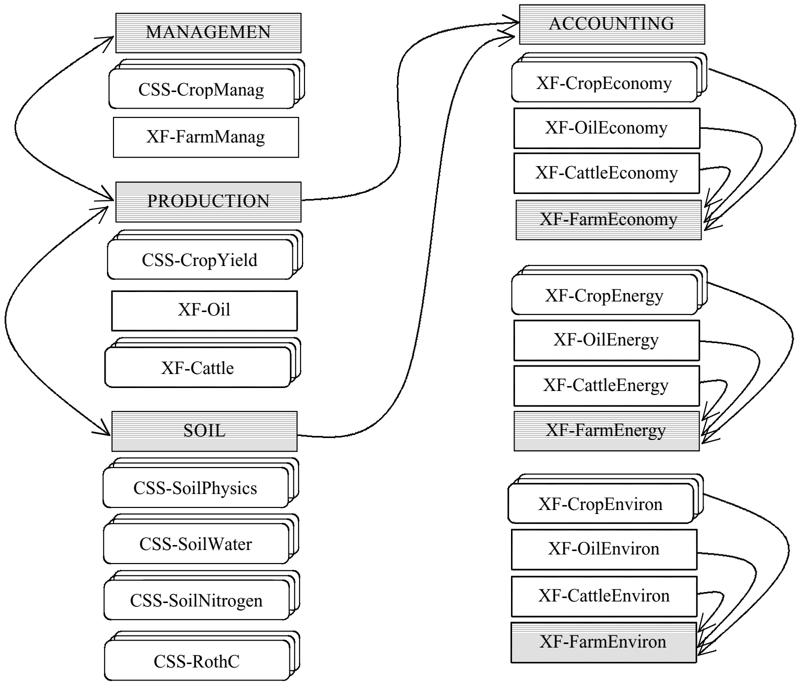

Figure 1. The modules of X-farm. Arrows indicate the informative relationships among modules. Note that there are two types of modules: simple modules and multiples modules. Multiples modules are represented by the concept of group. For example, in the farm we have only one oil module but for the crop and soil modules they are replicated for each field of the farm. Moreover, the dotted outline boxes indicates X-farm modules which development is in progress.

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 XF-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 obtained 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).

Accounting modules are 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 for 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 and 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).

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 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. Using the SEMoLa environment, simulations of different cropping scenarios have also been performed to show the X-farm model capabilities.

2.2 Crop model parameterization and calibration

The crop module has already been calibrated for soybean, maize, sunflower and Jerusalem artichoke crops. In this work, the parameterization and calibration for fiber sorghum 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. 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 a 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 us to identify best candidate parameters for calibration.

Calibration has been performed through the proper routine (Danuso, 1991) that 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 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 treatment with different levels of energy input ("Low input" and "High input"), diverse by nitrogen fertilization and irrigation frequency and amount.

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.

2.3 Simulation scenarios

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 2, which summarizes the scenarios considered in the application, the 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 labor 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 3 reports detailed information about the cropping practices considered in this example. These practices are based on the techniques usually applied in the north-east of Italy. Irrigation timings and amounts are also reported.

In X-farm, simulations are set up by preparing a simulation file (*simfile*) containing one or more simulations (multiple simulation) that are launched in the same run. *Simfile* refers to parameters, meteorological data and cropping practices (events). Scalar parameters are contained in a parameter file (*parfile*), group parameters in *gpafiles* and in *actfiles* (that files contains parameters changed by external events); meteorological data are in *exofile* and cropping practices are in the event file (*evtfiles*). Each of them can contain more than one dataset that can be selected when customizing *simfiles*. In this way it is possible to create different com-

Table 1. Main cropping practices for low and high input treatments of 2006-2007 experimental trials on sorghum.

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

Table 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 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) Field maximum water capacity.
(2) Field water capacity.
(3) Field wilting point.

Table 3. Cropping practices applied to each crop in rotations of simulation experiment.

Crop	Harrowing		Mineral fertilization		Weed control[2]		Planting	Irrigation		Harvest	Plowing	
	doy[1]	depth m	doy	amount kg/ha	doy	amount kg/ha	doy	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.
(2) Chemical weed control with herbicides.

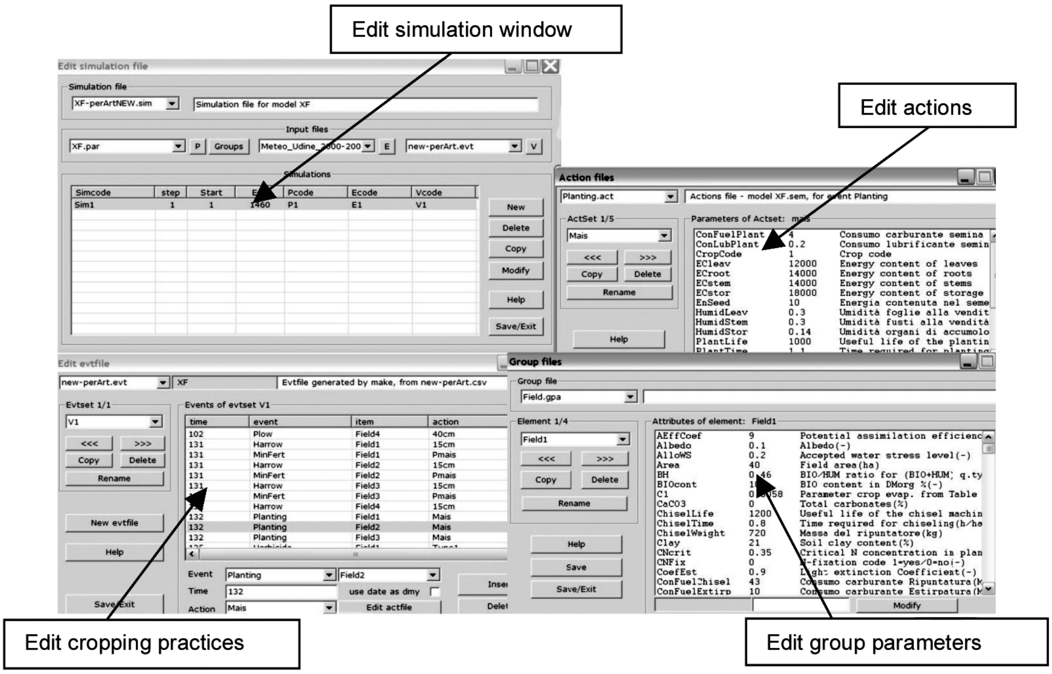

Figure 2. The SEMoLa simulation framework dialogs for editing input files.

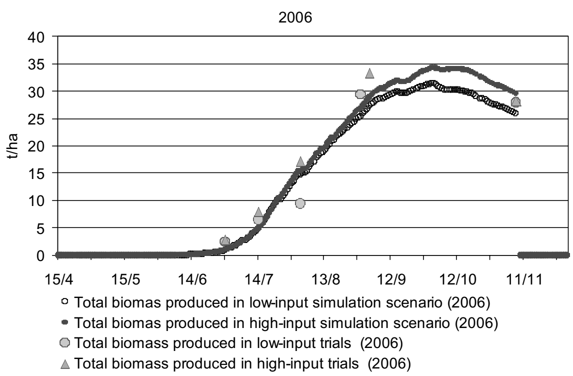

Figure 3. Comparison between the biomass accumulation obtained by the X-farm simulation and the experimental data for year 2006.

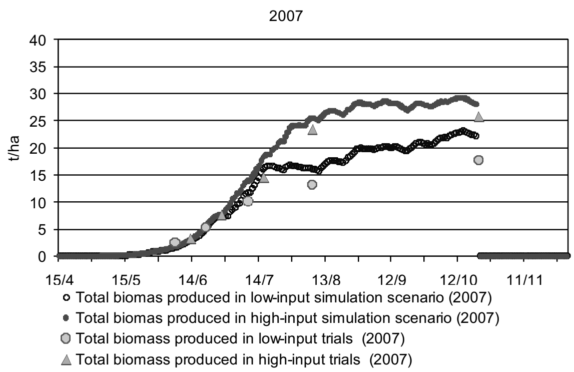

Figure 4. Comparison between the biomass accumulation obtained by the X-farm simulation and the experimental data for year 2007.

plex simulations combining soil parameters, meteorological data and cropping scenarios.

This file structure of input files allows cropping scenarios to be created and crop rotations performed. Figure 2 reports the SEMoLa simulation framework dialogs for editing input files.

3. Results

As reported in Figures 3, 4 and 5 the simulation results obtained for the sorghum 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 experimental 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 0.94 and 0.97, respectively for 2006 and 2007.

Figure 6 reports the simulations of biomass

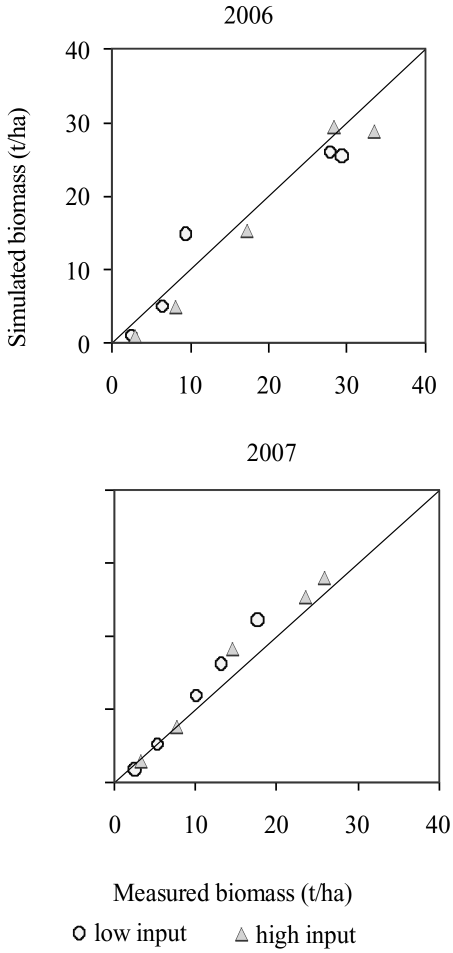

Figure 5. Relationships between simulated and measured sorghum biomass yields. The straight line indicates a perfect correspondence between simulated and measured data. The regressions of simulated values (S) against the measured ones (M) are the following:
2006 low input S = 0.8745·M+1.1997
2006 high 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.

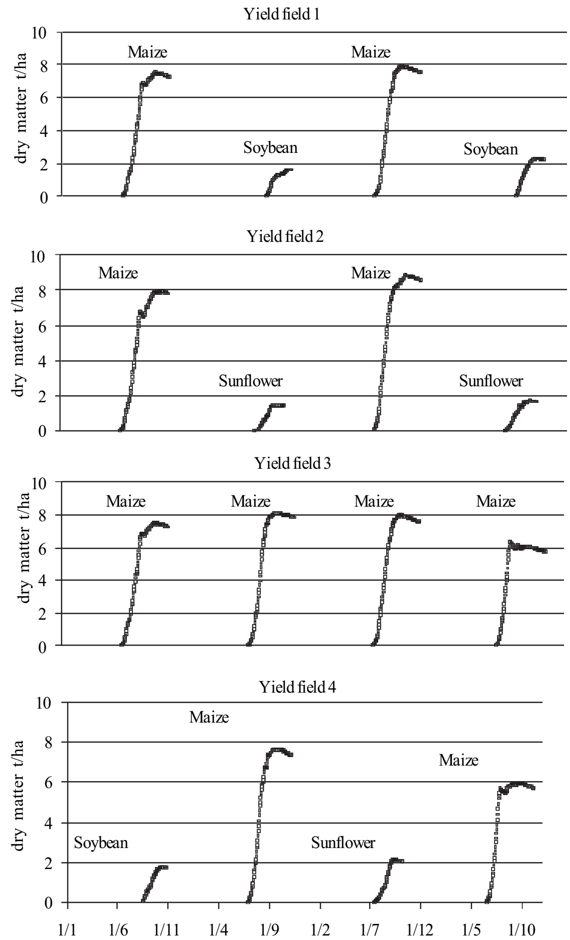

Figure 6. Simulated yields for the four fields of the farm and for the four years

accumulation for crop 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.

Table 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 pedological, 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 inter-

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	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).

preted on the basis of the price levels, cropping scenarios and environmental conditions considered in the simulation experiment. X-farm 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 Common Agricultural Policies (CAP), which have not been considered in these simulations. This 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).

4. Conclusion

The main goal of this paper was to present the X-farm model 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 can be obtained very quickly by creating file of events with the agricultural practices.

Another type of application of the model, not shown in this paper, 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.

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) livestock and biogas production module; 3) on-farm seed pressing for oil extraction; 4) implementation of genetic algorithms to obtain robust calibrations and optimizations; 5) LCA analysis for the alternative sources of energy produced on farms; 6) a DSS version, with the automatic generation of optimized cropping practices decisions (besides irrigation and mineral fertilization, also plowing, harrowing and other events).

Moreover, a major improvement of X-farm will be obtained with the implementation of the concept of "task" in the SEMoLa language. This concept, largely used in the fields of operational research, is also going to be adopted in the modeling of farm organization (Mazzetto and Bonera, 2003).

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 is a dynamic process leading to the transformation of the state of a material, requiring the consumption of one or more resources 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, plowing is now treated as an event, instantaneously applied. Considering it as a task, plowing is seen as a process that transform 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. 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 plowed.

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

X-farm is freely available from the authors upon request, as "user version" and "development version", both as SEMoLa source code or executable application.

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