# Bio-economic modeling: State-of-the-art and key priorities

Guillermo Flichman (a)

Thomas Allen (b)

(a) Centre International de Hautes Etudes Agronomiques Méditerranéennes - Institut Agronomique Méditerranéen de Montpellier – flichman@iamm.fr

(b) Bioversity International, Nutrition and Marketing Diversity Programme – t.allen@cgiar.org

The authors would like to acknowledge the participation of Hatem Belhouchette, Scientist at Institut Agronomique Méditerranéen de Montpellier (IAMM), who contributed with a review of cropping system models presented in the annex, and Imen Souissi, a PhD candidate at the IAMM, who preselected some of the models presented in this review.

# Contents

# 1 - Introduction

In recent years there has been a significant development of bio-economic models, especially those integrating biophysical models and economic mathematical programming models. This development was enhanced by the conjunction of several factors such as the multiplicity of objectives in new agricultural policies, the increase of demand for multi-disciplinary approaches for integrated assessment, and the call for more dialogue and cooperation between scientists from various disciplines. Even though an important number of bio-economic models have been developed and tested on different farming systems and under various agro-ecological conditions (Flichman and Jacquet, 2002; Janssen and van Ittersum, 2007), there is a lack of literature regarding the implicit or explicit assumptions of these models and economic theory, their main advantages compared to conventional economic approaches, and their specific contributions in strengthening collaboration and improving integration between different disciplines.

For analyzing if bio-economic models are appropriate for studying the relations between agricultural intensification and sustainability, let us first of all make a preliminary and simple definition of agricultural intensification as an increase of  yields.

Even if intensification can be defined on other production factors, as land is essentially the fixed factor for agricultural production, we assume that this is the most appropriate definition. This increase can be obtained through an augmentation of the amount of production factors other than land, on land - assuming a constant situation in terms of available technology - or as an impact of technological progress. Quite frequently yield increases yield are a consequence of both an increase in the use of other production factors and technological progress. The Green Revolution was a clear example of this. This definition implies a measurement of the relations between production factors and production in physical terms, if sustainability means the possibility of keeping a long term production capacity by preserving the quality of natural resources.

Land, water and energy are taken into account as inputs of agricultural production. On the other side, food is an output, as well as different types of pollution, changes in biodiversity, changes in landscape, depletion of natural resources (soil erosion, loss of underground water).

For analyzing the relations between intensification with land, energy, water and the environment (considering under this term both externalities and impacts on natural resources) using quantitative tools the basic condition is that these tools - bio-economic models - should apply a methodology consistent with this objective. In other words, these models should represent technology in an explicit manner, using what is usually called engineering production functions. This means that it is necessary to describe explicitly the relationships between factors of production and products in physical quantities. Models based on cost functions are therefore not able to properly analyze relationships between intensification and the environment. All the models we include in this study are based, at least partially, on engineering production functions.

In order to describe relationships between production factors and products, it is necessary to use - as basic unit of information - the production processes, and not the products. In other words, to have an approach based on production activities, in the sense of Koopmans (1951). We use here the term "products", not only to name agricultural products, but also to name all the other outputs appearing as a consequence of a specific production process (soil erosion, chemical pollution, loss of organic matter, change in bio-diversity, etc.)

We will use these definitions when looking at the different models included in this survey. In some cases, we considered models that, even if in the available publications deal only with one environmental issue, have potentially the capacity for working with more than one agricultural dimension and with one or more environmental issue.

Most of what can be found in a literature review is an application of a model in a certain context. Only a few numbers of these models seem to be "currently in use" and so potentially available for application in a different context than those considered in the publications.

Another factor that will be considered is the use of biophysical models as source of information for the bio-economic models. We can observe that this is the case for most of the bio-economic models included in this study.

We also have to clarify what type of bio-economic models we are dealing with. Following the terms used in an interesting survey of bio-economic models (Brown, 2000), one kind of model is concerned with "primarily biological process models to which an economic analysis component has been added". The other kind includes "the economic optimization models which include various bio-physical components as activities among the various choices for optimization". In between, he considers a third category that integrates in an interactive manner the biophysical and the economic models. This last category would genuinely deserve to be called "bio-economic" and be the focus of this review.

The first category includes models where agro-ecological or biological processes can be quite sophisticated. However, most of these models only account for net returns or gross margins from possible activities or combinations of activities. Lacking the capacity to simulate production decisions, even in a normative approach, these systems fell short of analyzing other than very context-specific environmental impacts[1]. Consequently, we emphasize the second and third categories in this review.

There is also a difference that has to be mentioned, depending on how the information coming from biophysical models is used. In some models, a meta-modeling approach is applied, meaning that out of simulation results of biophysical models, simplified models relying on some important variables are used as inputs of the bio-economic models. This approach is used principally in dynamic models.

There is another possible classification that can be suggested, if we take into consideration the purpose of the modeling exercise. In principle, all optimization models are normative, but in practice, when the objective of the exercise is to make an *ex-ante* assessment of different types of impacts (from new policies, technological progress or climate change…), these models can be applied in a positive manner. It usually implies representing first how a specific system works, and then, if this representation is close enough to the observed situation (we say then that the model is calibrated), by changing a set of parameters (i.e. prices, taxes, subsidies or climate change variables) it is possible to use them for making forecasts. It all depends on the assumptions underlying the goals selected in the optimization program. Are they assumed to represent a behavior? Or do they set the optimal target to attain? We do not use this classification for this review, because almost all the models considered in this study can be used in a normative as well as in a positive manner. Our choice is just to mention if the intention of the author(s) corresponds to one or the other orientation.

## 1.1 - Activities and products: some preliminary concepts

There are two ways of representing the scope of potential techniques in an economic model.

- Represent the production process, taking into account the physical quantities of inputs needed to produce one unit of output (or used per unit of a fixed resource as land, in the case of agriculture.
- Represent the production process through the production costs, using in this case a monetary measurement of inputs.

The first case implies the use of an engineering production function approach, making technology representation explicit (kg of fertilizer/ha, m3 of water for irrigation, etc). This approach allows for

---

[1] A good example of such a model is the Century ecosystem model (Antle et al, 1999). Linked to an economic simulation model, it allows quantifying the economic efficiency of alternative policies that might be used to sequester Carbon (C) in agricultural soils (in the Northern Plains region). The economic simulation model represents changes in land use and management decisions on a site-specific basis in response to economic incentives. The Century ecosystem model is used to simulate the equilibrium levels of soil C associated with the principal dryland grain production systems in the region. Model outputs are combined to assess the costs of inducing changes in equilibrium levels of soil C through different types of policies.

switching between production processes defined in a transparent way (Flichman and Jacquet, 2002; Janssen and van Ittersum, 2007).

These engineering production functions constitute the essential link between biophysical and bio-economic models. The reasons justifying a primal representation of technology are very clear: with these models we have to deal simultaneously with biophysical and economic systems and we need to quantify physical variables, as well in the inputs of the model as in the outputs, such as the level of nitrate pollution, soil erosion, etc.

The use of engineering production functions creates a strong information demand. It is necessary to have data about these engineering processes in terms if physical input-output matrices.

The basic element of this approach is the production process, or the production activity, not the final good (or product) resulting out of this process. In other words, and using an example from agricultural production, a unit of wheat grain is not the basic element, but the production process that allows obtaining a unit of wheat grain is the basic cell. A production activity describes a specific production process.

Each product can be produced by several activities, and each activity can produce several products.

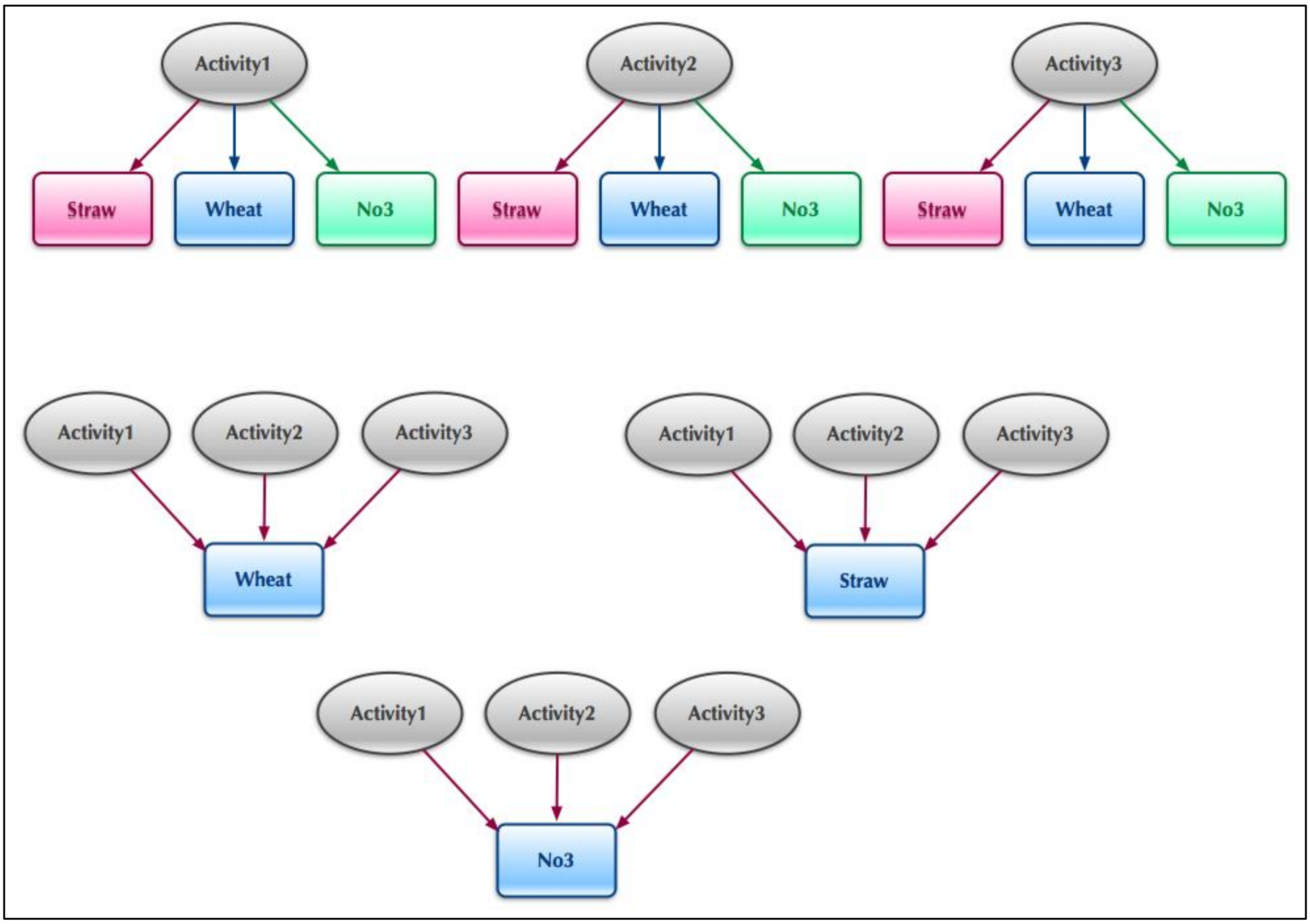
One activity is defined by the technical coefficients that represent the use of inputs needed to produce different outputs. In agricultural models, frequently these technical coefficients relate to one unit of the fixed factor (land) rather than to one unit of product. Koopmans already developed this approach many years ago:

"This method, which precludes the separate measurement of alternative processes to produce the same commodity, or the recognition of joint production, can be and is being supplemented by the study of engineering information" (Koopmans, 1951).

We will develop later the issue of joint production, what we want to clarify at this point is the relationships between activities and products.

### Diagram 1 - ACTIVITIES AND PRODUCTS

Source: Modelling the Relationship Between Agriculture and the Environment Using Bio-Economic Models: Some Conceptual Issues. G. Flichman, K. Louhichi and J.M. Boisson in G. Flichman (editor), Bio-Economic Models applied to Agricultural Systems. Springer Science Business Media 20



The scheme presented above shows the causal relationships implied in this type of model. “Products” (wheat, straw, NO3) are the outputs of production processes that are described by the activities.

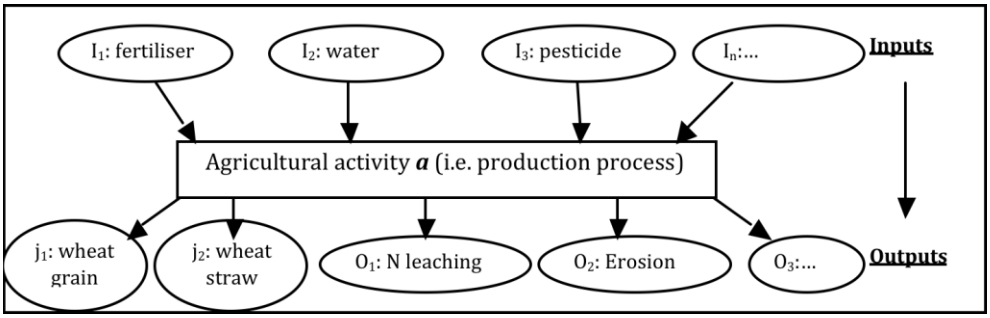
What is also important to realize is that this type of representation has two “faces”:

- One activity (or production process) has several outputs – joint production
- One product can be produced by several activities (or production processes)

In the upper part of the diagram, we can observe joint production, as several products emerge from a single production activity. In the lower part is shown the fact that one product is obtained through several production activities, allowing the existence of non-linear relationships concerning cost and production functions of the product, not of the activity.

Thanks to this representation we can take into account the positive and negative jointness (Baumgärtner et al., 2001) associated to the production process, and to assess in an integrated manner new policies, which are mainly linked to activities and not to products.

**Diagram 2 - An agricultural activity as a production process with multi-inputs multi-outputs**



Source: idem Diagram 1

The above diagram represents an input-output linear vector concerning one single production activity.

## 1.2 - Joint products in bio-economic models

As it was already developed, each production activity has several outputs. In the simple example presented in the previous section, these products are grain, pollution and straw. All these products emerge from one production activity. They are joint products (Pasinetti, 1980; Baumgartner, 2001). The relation between a production activity, the main product (from the point of view of the firm) and the joint(s) product(s) is a fatal relation. It is impossible to produce grain without polluting or producing straw. And these relations (production activity → joint products) are thus linear ones.

Adopting this vision, we should not approach the external effect (cost or benefit for other economic agent) as a direct consequence of wheat production; we have to identify what production activity generates this cost to other agents (nitrate pollution) in physical quantities. Doing this, we consider pollution, as an output of the activity that produces both wheat and pollution as outputs. This means that for calculating the externality as a cost, we need first to have some knowledge about it as a physical product, and we need to measure it in physical terms (tons of soil erosion, kg of NO3 pollution, etc.). Fortunately, we have had access for about 20 years to dynamic biophysical models that simulate the different products related with an agricultural activity (in our case, grain, straw, pollution) within an integrated framework.

This type of representation intends to provide a mechanistic, cause-effect explanation of what is behind the external costs (or benefits). Very frequently we can find empirical approaches, trying to find statistical relations between some crop production (considered as “the” product) and some externality, like soil erosion. By construction, even if sometimes it is possible to find elegant functional forms that fit well, these relationships will always be limited to the specific case from where they have been calculated. They are purely empirical: there is a complete lack of analysis of the processes that connect, for example, grain production with soil erosion. What produces erosion is not the wheat production itself, but the way it is produced, what type of tillage is used, in what period, in connection with the weather, with the type of soil, the previous crop and many other technical issues. In other words, it is the process of production, represented by a specific activity. A certain amount of nitrate leaching is not provoked by maize production, but by a certain production activity of which maize grain is one of the outputs (i.e. a wheat-maize rotation with a specific input combination). The relation between a maize non-linear production function and the level of nitrate pollution can be extremely complicated to define and, if defined, it will not be in a chain of cause-effect relationships (because there is not a direct relation between these two variables), the empirically obtained function will be applicable only to the specific situation where it was estimated. Each agricultural technique represented by each production activity is related, in a defined environment (soil-weather) with one value of pollution or erosion, and there is no functional form that can be a priori applied to represent the relationships between two of the joint products, as they are an outcome of extremely complex processes. These can be better represented by fixed technical coefficients relating activities and products. Of course, it can be possible, out of a post-modeling exercise, to estimate non-linear relationships between different outputs of the model, using parametric procedures. But no functional form should be introduced a priori in the optimization model. The results of simulations done using a biophysical model can be synthesized in an appropriate way and introduced as linear technical coefficients in a mathematical programming model. And this procedure can be applied in a dynamic model as well as in a comparative-static one. The quality of soil, in terms of its production capacities, changes with the way it is used over time. This implies that, by essence, this issue should be analyzed using a dynamic approach. That is why the biophysical models are perfectly appropriate for doing this.

In brief, modeling the relations between agriculture, natural resources and environment needs to mobilize different types of models and knowledge. It is difficult to do so and it is also difficult to expose it.

## 2 - Survey of bio-economic models

For this purpose, a classification is carried out taking into account consideration of spatial and time scales.

- Farm models
    - Static
    - Dynamic
- Landscape models
- Regional and National Models
    - Static
    - Dynamic

Fishery and forestry models are a special case in the bio-economic literature. Some can simulate fish population dynamics or timber growth at a very detailed level. The objective is usually to determine what fishing effort or timber extraction maximizes profits – or any other welfare function – while considering renewable capacities. Most models are concerned with identifying maximum yields – referred to as sustainable yields – at which levels of stocks and profits can be maintained. Environmental sustainability usually enters these models through the impacts on the stock carrying capacity or intrinsic growth rates. The distinction between agronomic and environmental dimensions then becomes blurred. Consequently, only models explicitly mentioning environmental indicators, other than those related to the underlying population growth[2], will be presented in this review.

### 2.1 - Farm models

At the farm scale, the farm system is considered as a decision unit of agricultural system. This method allows understanding the functioning of the production unit and the interactions between production activities. The variety of bio-economic models used to assess environmental issues at the farm level, illustrates the need for diagnosis at this scale. The farm level approach is mainly used to address i) environmental policy questions; i.e. to support policy design and decision making, ii) to assess the sustainability of farm or/ and iii) to help farm producers understand and manage their production systems. Farm models could be static or dynamic.

#### *2.1.1 - Static models*

The **Tunisian Farm Model** (Mimouni et al., 2000) assesses the trade-offs between farm income and the reduction of erosion and nitrate pollution. The approach used in this paper combines a biophysical

---

[2] For example, biodiversity benefits or erosion prevention forests may provide beyond timber.

model and a mathematical programming model. The mathematical programming tool developed in this study is a statistic multi-objective programming model. The key idea is to maximize farmers' returns and minimize both soil erosion and nitrate leaching, so as to preserve the quality of soil and water resources. The biophysical model EPIC (Erosion-Productivity Impact Calculator) is used to simulate the interactions among weather, hydrology, erosion, nitrate pollution, pesticide pollution, plant growth, soil tillage and management, and plant environmental control sub-models. These data are introduced in the economic model as discrete variables through an engineering production function. The main activities considered on the farm are dairy farming, sheep breeding, and cereals and sugar beet. The monthly feed requirement for the dairy and sheep production are linked to forage cropping.

The multi-objective programming models coupled with crop simulation models appears as a useful tool to address agricultural–environmental issues.

This model allows analyzing the trade-offs between farm revenue, level of pollution (nitrates percolation) and soil erosion. The results show that, in the described conditions, it is difficult to find solutions with high revenue and low nitrate pollution and erosion. The management that allows limiting erosion in most cases increases nitrate pollution, at least with the alternative activities that are considered in the exercise.

The modeling framework presented in this study considers inputs and outputs prices as exogenous. Livestock dynamics are not taken into account.

The **Farm System Simulator Model (FSSIM)** (Louhichi et al., 2009) was developed within the SEAMLESS project (http://www.seamless-ip.org/) in response to the need for research on public policy impacts in the EU. It aims to provide policymakers with "*an integrated tool for ex-ante impact assessment of agricultural, environmental and rural development on the sustainability of agriculture and sustainable development*" (Louhichi et al., 2009). FSSIM is a static bio-economic model to assess at the farm level the impact of agricultural and environmental policies on farm performance and on sustainable development indicators. It consists of a data module for agricultural management (FSSIM-AM) and a mathematical programming model (FSSIM-MP). FSSIM-AM aims to identify current and alternative activities and to quantify their input and output coefficients (both yields and environmental effects) using the biophysical field model APES (Agricultural Production and Externalities Simulator) and other data sources. FSSIM-MP seeks to describe farmer's behavior given a set of biophysical, socio-economic and policy constraints, and to predict farmer decision-making responses under new technologies, policy market and environmental changes. FSSIM is applicable to crop-based and livestock-based farm types. The principal outputs generated from FSSIM for a specific policy are forecasts on land use, production, input use, farm income and environmental externalities (e.g. nitrogen surplus, nitrate leaching, pesticide use, etc.). Input data are fitted in the economic model as discrete variables by using engineering production function. The economic model is static, while it takes into account the dynamics of biophysical processes. The model can include farmers' risk aversion through the Risk module. For this purpose a global utility function, defined as gross margin minus risk, is maximized.

Three different livestock activities can be modeled in FSSIM, namely dairy, beef, and small ruminants (sheep and goats). Feed requirements for each different animal types and decisions as to the length of the grazing period are also taken into account for dairy activities. The feed requirements of the herd in terms of fiber, energy and protein are covered by roughage produced on farm (fresh, hay or silage), purchased roughage (hay or silage), concentrates produced on-farm or purchased concentrates. The quantities of on-farm produced and purchased feed depend mainly on prices of crop products (including feed) and inputs. The FSSIM model is linked to the Common Agricultural Policy Regionalized Impact modeling system (CAPRI) which is an EU agricultural sector model (Britz et al., 2007) used to estimate a set of initial prices for the agricultural products of all EU-27 regions.

Thanks to its modular structure, the FSSIM model can be used as a tool for facilitating future policy analysis and for understanding future farming systems. Also, FSSIM has been set-up such that it can readily simulate farm types in very different contexts (climate, soils and socio-economic conditions) and for different purposes. The reusability of the model was confirmed by the significant number of applications that have been published (Louhichi et al., 2008; Kanellopoulos et al., 2009; Kanellopoulos et al., 2010, Majewski et al., 2009; Mouratiadou et al., 2010; Traoré et al., 2009). The model is available under an Open Source license (www.seamlessassociation.org) and through its broader use it can be further tested and new modules can be added.

The **FarmDESIGN model** (Groot et al., 2012) is an extension of the static farm model FARM (Oomen and Habets, 1998). It aims at exploring the synergies and trade-offs between socio-economic and environmental objectives, such as economic performances and organic matter balance. To address the multi-functionality of agriculture, a multi-objective optimization is introduced, employing Pareto-based Differential Evolution (Storn and Price, 1997). More specifically, FarmDESIGN couples a bio-economic farm balance model to a multi-objective optimization algorithm that generates a set of alternative farm configurations that performed better than the original configuration. These alternative management options are then evaluated in terms of Pareto optimality in a normative approach.

The farm is the central management unit, consisting of interrelated components. Each component represents production activities defined by inputs and outputs. The farm balance model is a static model that calculates the "flows of organic matter, carbon, nitrogen, phosphorus and potassium to, through and from a farm, the resulting material balances, the feed balance, the amount and composition of manure, labor balance and economic results on an annual basis" (Groot et al., 2012). A steady state situation on the farm is assumed. Crop yields do not respond dynamically to fertilizer levels or other management operations. Required nutrients are calculated from the target crop yields and nutrient concentrations in products. Similarly, animal yields do not respond dynamically to management. Animal production is specified in terms of products (milk, meat, wool, eggs), which result in a set of energy and protein requirements ultimately compared with the feed balance. Various types of animals, dependent on the livestock present on the farm and the structure of the herd, can be considered provided that their requirements are expressed in the selected units for energy, protein, structure and saturation. The multi-objective optimization program then maximizes four objectives, namely the operating profit and organic matter balance, and minimizes the labor requirement and soil nitrogen losses. The model was implemented for a 96 ha mixed organic farm in the Netherlands.

This modeling study demonstrated the usefulness of multi-objective optimization in the (re)design of sustainable farming systems by means exploratory studies. It can serve as an exploratory tool to generate alternative management options that perform better with respect to a selected set of outcomes. It highlights how balancing crop-livestock interactions can help improve resource use efficiencies at farm scale. Including a water balance and incorporating erosion explicitly in the model would be valuable additions. Accounting for the added value generated by processing of crop and animal products and including resources transfer at regional level (labor and land) would also provide interesting complementary insights. Also, uncertainty on prices and policies is not addressed in this study. According to the authors, the model is generic enough to accommodate farming systems in environments that are contrasting in bio-physical conditions, farming systems configurations and data availability, since it has been used in arid regions in Mexico (Flores-Sanchez et al., 2011) and in student projects in Uruguay, Nepal and India.

FarmDESIGN is a product of the Farming Systems Ecology group (FSE) of Wageningen University. The software and related documentation are free of use and downloadable at:

https://sites.google.com/site/farmdesignmodel/download

The **Model of an Integrated Dryland Agricultural System** (**MIDAS**) (Kingwell and Pannell, 1987) is a mathematical programming model of a representative farm of the agricultural system of the eastern wheat belt of Western Australia. It is the outcome of many years of interdisciplinary work with the participation of economists, natural scientists of different disciplines, as well as farmers and computer engineers.

MIDAS was one of the first models integrating biophysical and economic components. The use of this model is essentially normative, in the sense that it explores the possibilities of integrating technological changes (different time of rotations, introduction of new varieties, changes in the tillage systems) and their effects as well on economic as on environmental variables.

This model has been used in Western Australia for a very long period. In the last years, the relatively rough biophysical components have been substituted using outputs of more advanced biophysical models, such as APSIM (Kingwell, 2003)

MIDAS is representative of and adequate for the specific agricultural systems of Western Australia, whose farming system is very homogeneous. However, it can only be questionably applied to other contexts.

The **Dairy Cow Model** (Berentsen, 2003; Berentsen and Giesen, 1994; Berentsen et al., 1998) is a linear programming model for dairy farm. It has been designed to examine the economic and environmental effects of improved productivity of Dutch dairy farming. The objective function of the model maximizes labor income. The central element in the model is a dairy cow with a fixed milk production. A fixed ratio is considered between the number of young stock and the number of dairy cows to guarantee replacement of dairy cows. Surplus calves are sold. The area of grassland and division between grazing and mowing is dependent on the interactions among animal requirements, season of the year, price of concentrates and price and availability of other forages. These interactions are all considered in the optimization process.

This model has a strictly normative approach. This means that it does not try to reproduce a given situation and to simulate impact of policy changes, as most of the other models do, but to provide guidelines to farmers in order to ameliorate their practices.

The macro dairy farm model is developed at farm level and based on a static approach. It does not consider the interaction between farm and the system environment nor the possibility of resource transfer between farmers. The farmer is assumed risk neutral.

This modeling framework was built to serve the purposes of a wider project. The main objective of this project concerns an analysis of possible effects of changing circumstances on Dutch dairy farms. The model developed can be used to examine different questions in the field of institutional and technical change on dairy farms. Moreover, it offers the possibility to examine questions for dairy farms that differ in intensity and in size.

The Dairy farm model was used by van Calker et al. (2004) to determine how farm management adjustments and environmental policy affect different sustainability attributes. Compared to the previous version of the model, it includes economic and ecological indicators. The net farm income is included for measuring economic sustainability, while eutrophication potential, nitrate concentration in groundwater, water use, acidification potential, global warming potential and ecotoxicity are included as ecological indicators. The ecological indicators are determined from the Life Cycle Assessment (LCA) method.

The **Multi-Objective Decision support tool for Agri-ecosystem Management model (MODAM)** (Meyer-Aurich et al., 1998; Zander and Kächele, 1999; Kächele and Dabbert 2002; Meyer-Aurich, 2005; Uthes et al., 2008) is a multi-objective linear programming model used to address economic and environmental analysis of sustainable farming practices. It consists of a set of relational databases and analytical functions which allows computing the economic and environmental impacts of farming decisions related to land use alternatives (e.g. nitrogen balance, energy input, soil erosion and global warming potential of the production process). This framework is composed of six hierarchically linked modules: i) a plant production module (PLANT) which stores the sequential plant production activities; ii) a farm module (FARM) which integrates the farm capacities and animal production system; iii) an economic module (ECON) which allows the calculation of gross margin; iv) a Linear Programming module (LP) which optimizes land use in terms of economic returns and soil erosion targets; v) an ecological module (ECOL) which allows the ecological evaluation of cropping practices; vi) and a last module (INDEX) which considers the site specific soil and calculate erosion for each plant production activity. These modules describe production activities in a way that allows an economic and ecological analysis of the production process. As such, the model can be considered as complying with a positive approach; however, as the level of tolerated soil loss has to be predefined in the optimization, it could also be interpreted as a goal-orientated normative model.

MODAM is a farm simulation tool that enables the modeling of farm decisions, and their economic and environmental effects. It allows simulating scenarios for different land use options and goal attainment levels, as well as policy scenarios, such as the influence of prices and policy regulations on farmers' decisions and the effect of the resulting agricultural practices on the indicators of sustainability. Prices and policy regulations are the driving forces of the model. The model is static and refers to a partial equilibrium situation, ie it takes into account neither the variability of climatic conditions nor the influence of market on farmers' behavior and the interaction between farmers. This model presents other limitations since livestock is fixed and the interactions between animal and crop practices are not explicitly described.

Multi-criteria optimization tools like MODAM can help to illustrate the interdependencies in agro-ecosystems and estimate trade-offs. MODAM has already been applied in various studies in north-east Germany (Schuler and Kächele, 2003; Zander, 2003). Because of its modular and hierarchical structure, MODAM can be applied to various agro-ecological problems. However, for specific applications, adjustments have to be made. According to Zander and Kächele (1999), this modeling framework is well suited for single farm analysis as well as for regional models, for static as well as dynamic approaches. However, until now it has only been applied in a static way at farm level.

MODAM is hosted by the Institute of Socio-Economics at the Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany. Related documentation and overview of the model are downloadable at: http://www.modam.eu/

The **Bio-economic Macro model** (Tanure, 2013) announces “a novel conceptual macro-model with a system approach of the agricultural and livestock production environment”. This static modeling approach adapted several sub-models of pre-existing studies: (i) meteorological; (ii) pasture; (iii) animal; (iv) crop–livestock integration; (v) crop; (vi) soil; (vii) pasture-animal; (viii) and pasture-soil to produce necessary biophysical inputs data for the economic model. The recent publication includes a conceptual model only, so for the moment it is not operational.

### *2.1.2 - Dynamic models*

The **Cebalat Model (**Belhouchette et al., 2012) developed a dynamic-recursive-stochastic bio-economic model to evaluate the sustainability of farm irrigation systems in the Cebalat district in northern Tunisia. This modeling approach addressed the challenging topic of sustainable agriculture through a model linking a biophysical model to a bio-economic model. The difference in terms of methodology, compared with the previous models is the stochastic dimension of this model. Concretely, the bio-economic farm model has a moving time horizon of 10 years, assuming that long-term decisions are taken according to rainfall probability.

A crop growth simulation model (CropSyst) was used to build a database to determine the relationships between agricultural practices, crop yields and environmental effects (salt accumulation in soil and leaching of nitrates) in a context of high climatic variability. A reduced “meta model” was estimated based on the results of CropSyst simulations, to calculate the yield reduction for the following period of simulation according the crop pattern chosen by the model in the previous period.

As in the Lima model, a re-initialization of the multi-periodic model is computed introducing the results of the first period and running the model again for a 10-year horizon. But at the end of each period, several branches of different trajectories are open. Modern computers can cope with the "curse of dimensionality". Anyway, it was necessary to use an ad-hoc method to define typical trajectories for analyzing the results.

For simulating animal production the number of animal units has been kept fixed for the whole simulation timeframe.

When dealing with environmental problems in agriculture, time scale is very important because environmental issues are often characterized by long-term processes. (Janssen and Van Ittersum, 2007), but using recursive models involves the construction of large matrices that makes the result assessment difficult. This model does not consider the dynamics of the herd stock (animal is considered as fixed unit). Prices of products and inputs are considered exogenous.

This approach proved that it is possible to represent the evolution of farm decisions within a given year and over a period of years by taking into account a wide range of biophysical conditions (soil, rainfall), crop practices, land use or agro-management systems and types of production (fodder, grain). This methodology could also be re-used to simulate different scenarios combining biophysical, crop diversity and socio-economic conditions (e.g. price liberalization, water quotas, etc.) as well as new techniques that may be released by industry and extension services (e.g. new varieties resistant to major diseases and soil salt accumulation, new cropping techniques such as conservation agriculture or organic farming promoted in a region etc.). This study is an application of the approach, first developed by Blanco and Flichman (Blanco and Flichman, 2002) and applied in a doctoral thesis (Belhouchette, 2004).

## 2.2 - Landscape level

The **Integrated Land use Model (ILM)**3 (Schönhart et al., 2011) addresses the biodiversity effects, at farm and landscape levels, of land use intensity and landscape development. ILM is a static mixed-integer linear programming farm model with spatial field contexts. It combines the crop rotation model CropRota (Schönhart et al., 2009), the bio-physical process model EPIC (Williams, 1995) and a farm optimization model FAMOS[space] (Schönhart et al., 2011). CropRota provides typical crop rotations on the farm level, which are integrated in EPIC together with geo-referenced field and climate data to simulate crop yields and other bio-physical outcomes such as soil sediment losses and changes in soil organic carbon stocks. Field and farm specific crop yields, crop rotations, and environmental outcomes are input to the spatially explicit farm optimization model FAMOS[space], which maximizes total farm gross margin subject to resource endowments and several balance equations. It builds on the FAMOS (Forest and Agricultural Optimization Model) model (Schmid, 2004) by integrating spatial field contexts, thus allowing for environmental and landscape structure analysis.

The model covers all relevant crop and livestock production activities, management variants, and policy options as well as field attributes of the region. The livestock production component includes the type and amount of animals raised and the farming system (organic versus conventional production) taking into account coupled livestock subsidies for suckler cows, bulls, and calves. FAMOS[space] includes interaction between livestock and crop production components through the Feed balances which guarantee animal specific nutrient demands that are supplied from internally produced or purchased forage and concentrates.

Land use intensity is considered by crop rotation choices, nutrient application rates (nitrogen, phosphate and potassium) as well as mowing frequencies. Four intensity levels can be tested in the model: high intensity, medium intensity, low intensity, and organic farming. The cost-effectiveness of different agri-environmental measure to achieve biodiversity targets is assessed by scenario analysis. Fields are the spatial decision units in FAMOS[space]. This structure allows introducing landscape

---

[3] The model can be referred to as the FAMOS[space] model.

metrics to quantify the spatial biodiversity impacts of landscape development scenarios. The Shannon's diversity index (SDI, Weaver and Shannon, 1949) is used as indicator of landscape biodiversity.

This modeling approach addresses several methodological challenges related to integrated land use optimization models at landscape levels such as "model evaluation, data availability, the trade-offs between model complexity, size and dynamics, and the linkages to disciplinary knowledge" (Schönhart et al., 2011). This approach contributes to closing a methodological gap in the scientific literature by allowing for spatial modeling of landscape elements. However, it requires high resolution landscape data, which could be restrictive in some contexts.

This framework couples integrated and static approaches as the CropRota, EPIC, and FAMOS[space] modules are structured in a sequential order, where the former two provide input data to the latter without feedbacks. Decisions in FAMOS[space] reflect actual producers' choices assuming efficient farm resource utilization. As such, it would be classified as a positive approach model. This typical procedure for integrated land use models (Zander and Kächele, 1999; van Ittersum et al., 2008; Wei et al., 2009) reduces model complexity and solving time, as well as data demand on exogenous market conditions, but neglects issues such as land use transition processes or strategic decision making for investments (Weersink et al., 2002; Janssen and van Ittersum, 2007). Furthermore, although operating at a larger scale than the farm level, interactions among farms are not considered. Interactions are determined only by exogenously given prices for inputs and outputs. Finally, the modeling approach didn't take into account the long-term structural developments of farms via land markets.

This work has been prepared within the Sustainable Development School (dokNE) at BOKU University of Natural Resources and Applied Life Sciences, Vienna, Austria and was also supported by the FP7 project "Climate Change – Terrestrial Adaptation & Mitigation in Europe" (ccTAME) funded by the European Commission. FAMOS[space] is developed in GAMS (General Algebraic Modeling System).

The **Ginchi Bio-Economic Model** (Okumu et al, 2000) uses a watershed-level dynamic non-linear mathematical programming model to optimize a weighted utility function wherein three goals are incorporated (cash income, leisure and basic food production). It is used to identify the economic-environmental trade-offs among various possible technologies and policies. The model takes into account crop and livestock constraints, rising household food requirements, and forestry activities, as well as the biophysical aspects of soil erosion and soil nutrient balances arising from these activities. Data for input and output coefficients was collected by structured questionnaire. The dynamic model addresses the issue of the long-term effects (12-year time horizon) of soil erosion on income and food self-sufficiency. It incorporates a dynamic relationship among soil loss, productivity and community welfare. It also considers soil nutrient balances for N, P and K. Cumulative soil losses are computed for each year and these determine crop yields in the following year after accounting for the effects of chemical fertilizer and dung manure applications.

This approach considers a single decision-maker and thus doesn't consider the heterogeneity of farmers' decision making. Furthermore, the model does not include a component for risk analysis. However, it does endogenize the effects of land degradation. Assessment of environmental concerns at a watershed level better addresses the natural delineation of the landscape, and hence the biophysical scale of environmental issues. The model considers resource multi-functionality and the multi-dimensional trade-offs that emerge from this. It also integrates the feedback to productivity through use of modified Universal Soil Loss Equation (USLE) to change yield potential and takes into account the seasonality of land and labor use as well as labor type (male, female and children).

## 2.3 - National and Regional models

Applied at regional scale, bio-economic models aim to optimize the total production of a specified region in relation to its technical options and economic and social aspirations (Stoorvogel, 1995; Bouman et al., 1999). Regional scale analysis provides the possibility of integrating the interactions and competitions between farms in the region when considering the possibilities of resources transfer between farms (e.g. labor and land). This type of model is generally complex because it takes into account the diversity of production systems in the region. At the regional scale, the application of bio-economic approaches usually involves a classification of farms in order to define a typology able to represent the diversity of farming systems and extrapolate the results of a sub-set of farms to the whole region studied. The use of representative farms is still an approximation of reality and depends on the available data, which leads to an aggregation bias that must be minimized. But any modeling exercise implies some level of simplification of the real system, as in all cases, what is important is to choose this simplification according to the objectives of the study and to understand what kind of bias this simplification may produce.

### *2.3.1 - Static models*

The **Sustainable Options for Land USe model (SOLUS)** (Bouman et al., 1998; Bouman et al., 1999) explores sustainable land use options at the regional level by quantifying trade-offs between socio-economic and biophysical sustainability objectives.

At the heart of SOLUS model is the agricultural sector model REALM (Regional Economic and Agricultural Land-use Model). This linear programming model identifies the optimal combination of production systems by maximizing the economic surplus at sector level. Coupled with technical coefficient generators for cropping and livestock activities, and integrated with geographic information system (GIS), SOLUS explores the long-term policy impacts on economic and environmental sustainability objectives. Sustainability is addressed in terms of economic surplus; labor employment; and in terms of environmental indicators N, P and K balance (nitrogen, phosphate and potassium); N losses through (de)nitrification, volatilisation and leaching, use of pesticide active ingredients; biocide index. Two technical coefficient generators were used: one for livestock activities, PASTOR, and one for crop activities, LUCTOR (See box below).

**Technical coefficient generators**

The **PASTOR** (Pasture and Animal System Technical coefficient generatOR) and **LUCTOR** (Land Use Crop Technical coefficient generator) quantify land use systems in terms of inputs and outputs based on the integration of systems-analytical knowledge, standard agronomic and animal husbandry data and expert knowledge. PASTOR quantifies livestock systems while LUCTOR is geared towards cropping systems. Main inputs include costs, labor requirements, fertilizer use and application of crop protection agents. Outputs are production and a number of associated environmental indicators (Hengsdijk et al., 1999).

This modeling approach is a regional optimization based on land use choices within sub-regions and land units. The SOLUS model incorporates endogenous output prices and wages at the regional level. At the same time, it takes into account the heterogeneity in land use options and land unit characteristics at the local level; i.e. it incorporates heterogeneity of technologies, resource endowments and constraints in terms of land use options and land unit characteristics. This model allows also farmer decision making to import labor from outside the region. The link to external market (supply and demand) is made through elasticity of product and labor supply and demand (Brown, 2000).

This framework allows exploring, at the aggregate level of the region or sector, the possibilities and impact of policy measures, such as environmental taxes/subsidies, on economic surplus and environmental indicators. However, it does not account directly for the farm level where actual land use decisions are made. In a normative approach, the model optimizes societal economic welfare rather than models individual decisions based on their individual priorities and constraints. Also, biological processes are fixed for a particular period.

The SOLUS methodology was part of REPOSA (Research Program on Sustainable. Agriculture), a cooperation project between Wageningen University, the Center for Research and Education in Tropical Agriculture (CATIE) and the Costa Rican Ministry of Agriculture and Livestock. No recent applications or publications have been identified. SOLUS is developed in GAMS (General Algebraic Modeling System).

The **Mali Bio-Economic Farm Household model** (Kuyvenhoven et al., 1995; Kruseman and Bade, 1998; Ruben et al., 2000) assesses farmers' responses to agrarian policies, and their effectiveness to improve farm income and soil fertility. It consists in a linear farm household optimization model, integrating different resource endowments as well as bio-physical processes.

The model is an extension of traditional farm household models (Barnum and Squire, 1979; Singh et al., 1986), assuming non-separability between production and consumption decisions (Sadoulet and De Janvry, 1995). In some countries, production and consumption decisions are more likely to be linked because the deciding entity is both a producer and a consumer. As long as markets are perfect for all goods, including labor, households are indifferent between consuming own-produced and market-purchased goods and allocate indifferently production between consumption and market sales. In other words, consumption decisions do not affect production decisions and production is independent of household preferences and income. However, if there are market failures, non-separability regarding production and consumption decisions has to be assumed and a household approach might be necessary (depending on whether the good for which market fails is important in production).

Sadoulet and De Janvry (1995) provide a comprehensive review of household models. Formally, the production, consumption and labor decisions can be integrated into a single household problem, which maximizes a consumer utility function defined over a vector of commodities. While following this household approach, in practice, authors (Kruseman and Bade, 1998) consider multiple objectives to account for consumer preferences (consumption utility) and producer decisions. Farm household decisions on allocation of land, labor and capital resources for crop and production technique choice are simulated in a linear programming framework with consumption levels and farm income, adjusted for the monetized loss of soil fertility, as the objective variables optimized subject to budget and resource constraints and to a production function. Available resources, specific production activities for arable cropping, livestock and pasture management are taken into account. The production activity module describes the agro-ecological processes that determine production options for cropping, pasture, livestock and forestry activities. Different technical coefficients are defined for currently applied farming practices (generally based on soil mining), as well as for alternative practices that guarantee more sustainable resource use (i.e. non-negative nutrient and organic matter balances). The biophysical data are integrated as discrete variables in the economic model.

The farm households are then aggregated to the regional level to assess the supply response and the potential price effects as they interact with demand. This partial equilibrium analysis allows capturing the interactions between different types of households and between farm households and local markets. Regional aggregation allows prices to be determined endogenously on regional markets. The relations with the non-agricultural sector and with other regions are considered through the opportunity costs of labor (migration).

These procedures are applied to evaluate the impact at farm household and regional level of technology improvement and a variety of policy instruments: improvement of infrastructure, price support, land, policy and credit schemes. The major advantage of the modeling approach lies in the simultaneous estimation of welfare and sustainability effects of crop and technology choice at farm household and regional level. As such, the modeling approach lies somewhere between a positive describing approach and a normative prescribing approach. The model offers important information about the required incentives to bridge the gap between actual practices and more sustainable land use (Brown, 2000).

This methodology was developed in the program on Sustainable Land Use and Food Security supported by the Netherlands' Ministry of Agriculture, Nature Conservation and Fisheries and Ministry of Foreign Affairs. The final version of the farm household model was written in GAMS (General Algebraic Modeling System). See Kruseman's doctoral work (2000) for detailed information on the model.

**FSSIM-DEV** model is a further development of FSSIM model. It was developed by the JRC (Joint Research Centre) of the European Commission and the CIHEAM-IAMM. It introduced several important changes and improvements with respect to FSSIM.

This model was developed targeting at agricultural systems of developing countries. It considers farm household consumption, production and labor allocation decisions as non-separable. The reason for doing so is the existence of severe market imperfections. On the other side, FSSIM-DEV is not an econometric model, as it is the case of most household models, it is a non-linear optimization model, in which the basic unit of information on the production side is the production activity.

As described in the Final Report of the project, (Louhichi et al, 2013) … "FSSIM-Dev is designed to capture five key features of developing countries' agriculture: non-separability of production and consumption decisions; interaction among farm households for market factors; heterogeneity of farm households with respect to their both consumption baskets and resource endowments; inter-linkage between transaction costs and market participation decisions; and the seasonality of farming activities and resource use…."

This model is built on a modular base, and uses a specific Database, has an Electronic Survey designed to enter the data in the DB and a Graphical user interface, for performing runs of the model without touching the code.

The **Dairy farming model** (van de Ven, 1996; Ten Berge et al., 2000; van de Ven et van Keulen, 2006) explores dairy farming systems that meet the environmental policy objectives and analyses the perspectives for development. This model is a static approach where multiple goals linear programming is used as optimization technique (Hengsdijk and van Ittersum, 2003). The model reconciles economic objectives (maximizing income per ha) with ecological objectives (minimizing nutrient leakages and maximizing landscape values).

The model describes options of different intensities for producing feed in the field, for processing or buying feed and for converting feed into milk. The combinations of different intensities result in different types of income levels, different nutrient emissions into the ecosystem and different abilities to manage the landscape. Inputs and outputs of "all possible" combinations are quantified systematically by technical coefficient generators for grass, maize, fodder beet and milk, based on experiments, the literature and expert judgment. The interactions between forage (maize and fodder beet) and animal activities are considered through a feed balance.

The dairy farming model can easily be used to explore the scope of new technologies or alternative policies within a normative perspective. However, this approach represents a regional model in which farmer's behavior has not been taken into account. According to the authors, the model could be applied at farm scale if we assume the homogeneity of farm characteristics; which is unrealistic.

Furthermore, there is no interaction between farmers and market. Farmers' degree of risk aversion is also not addressed in this modeling exercise.

This model was initially developed by van de Ven (1996) in the context of his PhD thesis.

**A regional agricultural model using a plant growth simulation program as activities generator** (Deybe and Flichman, 1991) is a static regional model, using linear programming. It represents the agricultural system of the northern part of Argentine Pampa region. This model is one of the first using information from a biophysical model (EPIC) in order to simulate the vectors of activities considering simultaneously yields, costs and erosion levels. A market for land, machinery and labor inside the region is taken into account, allowing exchanges of these production factors between the different farm types that are represented. Simulations are performed for analyzing the impacts of changes in prices on production levels, farmers' income and erosion levels.

The methodology used in this model concerning the simulation of the factors of production markets at a regional level is close to the one developed later on in FSSIM-DEV.

### *2.3.2 - Dynamic models*

The **Multilevel Analysis Tool for Agricultural Policy model (MATA)** (Deybe and Gerard, 1994; Gerard et al., 1994; Deybe, 1998) is a dynamic-recursive model using non-linear mathematical programming. It allows ex ante simulation of the impacts of agricultural policies - as well as external shocks - on economic welfare and agricultural sector performances at aggregate levels.

It consists of a set of modules, namely: (i) a macro-economic module, (ii) a production or farming system module, and (iii) a commodity chain module. The macroeconomic module describes the general context, both in macro-economic terms and institutionally. MATA is essentially a sectorial model, macroeconomic variables enter the model as exogenous variables (i.e. input prices, import prices, etc.) and can also be set to allow simulation scenarios. The production module represents farming activities for several types of representative farms. Production opportunities and constraints faced by farmer are determined by agro-climatic and socio-economic conditions for each farm type. Regional agricultural production results from the aggregation of individual productions. The model assumes that farmer's decisions are taken on the basis of expectations of gross margins and potential. The commodity chain module represents processing industry and consumer behavior. It evaluates consumer welfare and nutrient intakes, indicates employment and level of activity in agro-processing industries, and calculates endogenous prices for the products.

The MATA model was originally developed by researchers at CIRAD (France). It is a flexible tool, combining a micro-macro modeling approach with a dynamic and recursive structure. Risk measures of agricultural activities are also taken into account. Even if it has not been applied for analyzing environmental and natural resources issues, the structure of the model could allow this type of analysis that is the reason that justifies including it in this survey.

The **Tunisian dynamic regional model** (Louhichi et al., 1999; Louhichi et al., 2010) analyses the impact of soil and water conservation policies in a Tunisian region. A multi-objective modeling approach is used. In addition to the maximization of revenue, objectives in terms of impact on the environment are added. The bio-economic model is a primal-based approach that combines the biophysical model EPIC to an economic mathematical programming model. The EPIC model was mobilized to estimate discrete production and externality functions. The economic model seeks to assess the economic and ecological impacts of erosion control policies at farm and regional levels.

The bio-economic model consists on a non-linear multi-period recursive programming farm model.

The multi-period dimension means that each year, the income of three years is optimized. On the basis of the initial situation, production plans for the coming years are determined, taking into account all available information about the future, namely the expectations on prices and yields. The recursive dimension enters the optimization program by considering explicitly dynamic interactions across periods. More specifically, results of period t affect the baseline in period t +1, i.e. for each period the starting values are the end values of the last period. The application of such models can take into account various types of "recursive equations", other than those used for the transfer from one horizon to another, namely the investment equation. Based on the results of the previous horizon, the model provides insight into investment decisions.

This modeling approach considers the interaction between crop practices and animal production activity. For livestock, two different animal activities for meat and milk production are modeled, namely bovine and ovine. The dynamic-recursive approach is also used for modeling herd demography. It reflects the demographic growth and the production process over time. Each animal category is analyzed separately but linked to other animal categories by explicit relations. Culling and fertility rates, which depend on farmers' strategies in terms of renewal and performance, are taken as exogenous parameters, whereas traded animals (sold and purchased animals) are determined endogenously. Animal feed requirements as well as quality characteristics of the available feed are quantified using the Tunisian feed evaluation and rationing system for protein and energy. The feed requirements of the herd in terms of fiber, energy and protein are covered by forage produced on farm (hay or silage), purchased forage or purchased concentrates.

The experience gained in this study allowed to demonstrate the importance of bio-economic approach to assess the effectiveness of specific policy measures designed for supporting the conservation of water and soil in a semi-arid region of Tunisia. The model was applied at a regional level in a semi-arid region, based on the definition of a set of representative farm types. Prices were set exogenously.

The **Lima bio-economic micro watershed model** (Barbier and Bergeron, 1999) is a further development of the **Burkina bio-economic village model** (Barbier, 1996, 1998). A first version of this methodology was applied in a Master Dissertation (non published) in 1993 (Barbier, 1993) [4]. The method is close to the one applied by Louhichi (Louhichi et al., 1999; Louhichi et al., 2010)

Using a primal-based approach, it assesses the impact of policy interventions on land management in Honduras. The objective function maximizes an aggregate community welfare function subject to constraints on level, quality and distribution of key production factors (land area, soil fertility, labor and cash availability), as well as food consumption and market demand for foods. The method combines a recursive and dynamic linear programming model with a biophysical model of soil condition and plant growth that predicts yields and land degradation for different type of land, land use and cropping patterns. The model is both dynamic (with a 5-year planning horizon) and recursive (over the 20-year period, 1975-1995). The first year results are used recursively as the initial resources of a new multi-period model for the following planning period and so on. The recursive nature of the model allows adjustments from year-to-year using real historical prices, which are introduced into the model between simulations. The resources carried over from year-to-year in the simulation are population, livestock, tree volume, soil depth, and soil conservation structures. The model was designed to account for the whole of the micro-watershed level but it allows the two social groups (ranchers and small farmers) to interact at the level of the local labor market. The integration of biophysical information in the economic model was done using input-output vectors obtained from the results of EPIC biophysical model. The natural resource management component of the model includes soil erosion equations, and interactions among livestock, crops and forest. This modeling approach allows for migration (in and out), selection of crop, animal and perennial (pine groves, coffee) production methods, allocation of output (consumption, storage and/or sale).

This model is similar to the Burkina model (Barbier, 1996, 1998) with the added advantage of overcoming the limitation it had of assuming all households were the same. In fact, this model allows for household heterogeneity within the watershed by specifying two different types of farmers. Moreover, compared to the previous version of the model, this model included an environmental component, which is erosion. However, it does not incorporate risk aversion into decision-making and links the years only through price changes. This model is used to address of medium and long-term viability of agrarian systems at the micro-watershed level as well as the differential impact on different social groups of farmers. This application illustrates the ability of such approach to compare the actual events with what might have occurred under different policy scenarios.

Modeling at the village level is one way to deal with the fact that land degradation issues are only addressed to a limited extent by farm level (or household level) analysis especially when land is not privately held (as is the case in much of Africa) (Brown, 2000).

This model is property of IFPRI.

---

[4] Barbier B. (1993). *Durabilité des systèmes agraires : modélisation technico-économique d'un village de la zone cotonnière du Burkina-Faso*. Mémoire (Master of Science) : CIHEAM-IAMM, Montpellier (France). 213 p.

**A Dynamic Model of California's Hardwood Rangelands** (Standiford and Howitt, 1991)

« The objective of this study is to assess the likely impacts of different biological and economic conditions on oak stands by developing a multiple resource management model for hardwood rangelands ». For achieving this purpose, engineering production functions are estimated allowing representing the relationships between different activities and resources.

This approach assumes that ranchers decide the level of oak tree retention and stock of cattle on the basis of cattle and firewood markets, taking into account the links between oak tree cover and forage production, the rate of growth of these resources, and the potential for alternative economic enterprises such as commercial hunting.

The methodology applied, based on optimal control theory, is based on dynamic mathematical programming, optimizing actual revenue for a defined time horizon. Decisions are done year by year, based both on biological and economic factors. Price uncertainty is represented using a chance constraint method.

An interesting difference of this model respect most bio-economic models dealing with forestry is the use of a mathematical programming model instead of a dynamic programming approach. From a mathematical point of view, the problem is the same, but from a practical perspective, the chosen method allows to deal with more complex issues (Blanco et al., 2002, 2011) as it is the case for this model.

This model uses a normative approach, in the sense that the purpose is to « assess optimal oak tree canopy and livestock stocking under different biological and economic conditions », taking also into account the hunting activity.

The **COst Benefit Analysis for Sustainability model (COBAS)** simulates the effects of different management options on the stocks, fishers and regional economy (Ulrich et al., 2002). It is dynamic bio-economic model of fisheries that also encompasses the regional economy to assess industry and community led stock recovery plans. Accounting for the interactions between fish stocks, the size and effort of the fishing fleet and regional output, different management decisions are evaluated in terms of costs and benefits analysis. COBAS was developed as part of the Invest in Fish South West (IiFSW) project, with a focus on the English Channel and Celtic Sea.

Key components of the model include commercial fishing sector (further sub-divided in two different biological and economic components), recreational sector and regional economy. Model's components are interlinked with each other; output of one component enters the other components as input. Each endogenous variable is updated year by year.

The biological component aims to estimate the stocks dynamic. The levels of catches produced by the commercial and recreational fisheries have a direct impact on the stock surviving the year. Management options are simulated directly in the economic component of the commercial sector via effort, estimated in terms of days at sea, fleet (number of vessels) and commercial catch. The outputs of the economic component are directed to the biological component, and vice versa. Impacts of the fishing activities on the environment are also estimated through the economic component, by an ad hoc Environmental Impact Index (EII). Results produce management advice in terms of both economic and biological indicators. Given the revenue and employment generated by commercial and recreational fishing, model's output on total production and employment, deriving also from fish processing, wholesale, retail, boat repair, etc., can be simulated by a multiplier process.

The model is to be used to assess a range of management options, such as days at sea limits (including tie-ups); decommissioning schemes; limits/bans of particular gear types; restrictions on engine power, boat size, etc; changes in total allowable catches; levies (management cost recovery, industry funded buyback); price intervention. Policy options can also be modeled, such as Mesh size restrictions and other technical measures; seasonal/area closures; permanent area closures, and post-harvest options (traceability, ecolabelling). As reported above, the model has been used to simulate technical measures. However, results highlighted that the limited information on the effects of this types of management options do not allow the model to produce realistic outcomes. The complex structure of the model is very data demanding.

COBAS model was developed by the Centre for the Economics and Management of Aquatic Resources (CEMARE) and the Centre for Environment, Fisheries & Aquaculture Science (CEFAS). COBAS is developed in GAMS (General Algebraic Modeling System). COBAS code is not available.

**A generic framework for fishery systems**

Developed within the EFIMAS project, the **FLR model** (Fisheries Library in R) can be considered an operational and generic fisheries management evaluation framework. It is a multi-stock and multi-fleet simulation toolbox simulating and evaluating the biological, social and economic consequences of a range of fishery management options. Simulations are performed using an integrated suite of software facilities with implementation of a common language (in R) and interface.

A broad range of software packages (descriptive fisheries/fleets/stock assessment models as well as other evaluation and analysis tools) and existing databases have been used in FLR to produce advice to management bodies. These models have been implemented for different purposes, however essentially applied to EU fisheries.

In principle these models are purely biological (assessment and biological management evaluation), but the implementation using FLR allows the possibility of performing economic and environmental analysis using the existing classes and packages. It can provide advice on effort regulations, total allowable catches, harvest control rules, selectivity changes, fishery closures, enforcement effort and environmental variables.

A key element is the inclusion of uncertainty into the biological and economic modules. This tool provides a common framework to perform analysis and a common structure to incorporate data. In principle, the data requirements of the DCR (Data Collection Regulation) are sufficient, but it depends on the fishery to be analyzed. Users require expertise in R programming (Prellezo et al., 2009).

# 3 - Challenges

## 3.1 - Calibration issues in activity based models

There is an important literature concerning calibration of mathematical programming models. As bio-economic models have some specific characteristics defined in the first part of this paper, we try here to develop the problems and the possible solutions for calibrating this type of models.

As it was already defined above:

1 - The basic information of bio-economic models is related to a production activity (or production process)

2 - This basic information is consistent with “engineering data” originated by a biophysical model, or obtained from statistics and/or expert knowledge, combined with economic information concerning costs and prices.

3 - If these activities are the basic “cells” of the model, it is possible to make some strong but realistic assumptions concerning the costs. Each activity can be represented by a linear vector where can be defined, per unit of land, all the technical coefficients of the activity.

4 - From point 3, it is clear that this corresponds to the type of specification used by Koopmans (1951) (and many other economists).

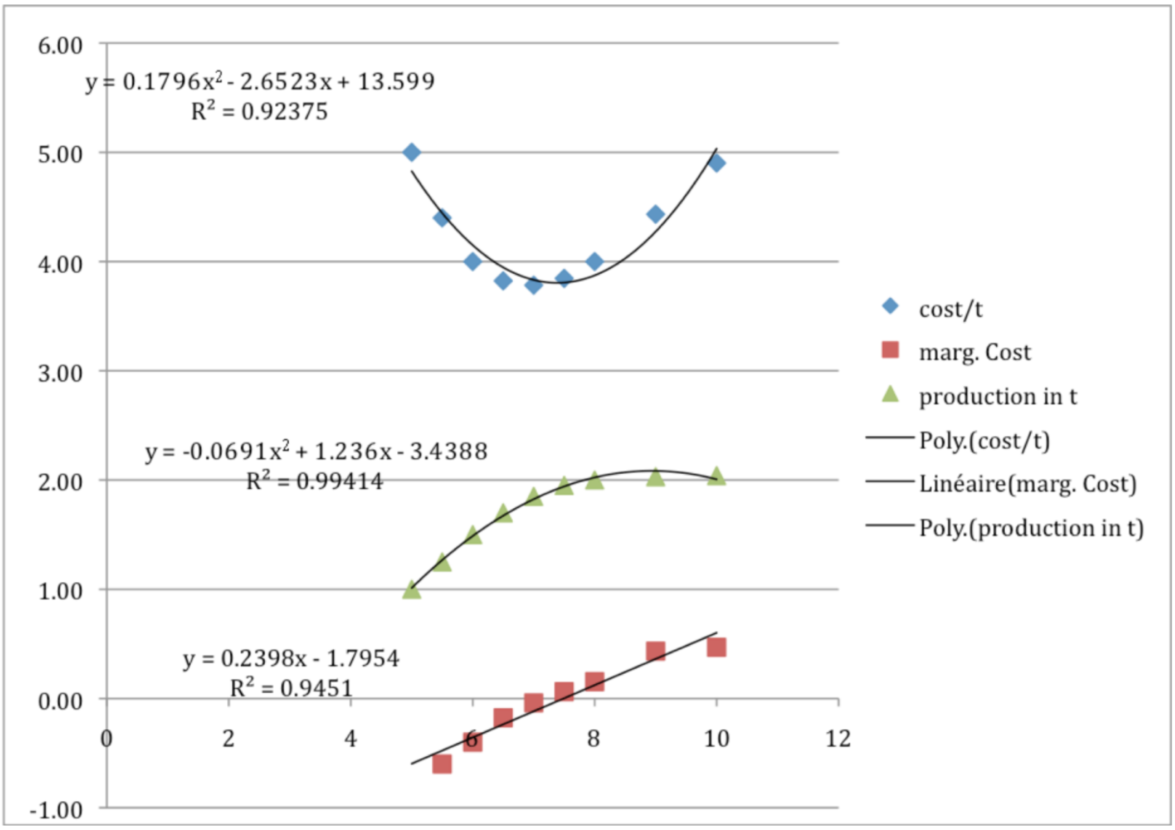
This does not question the traditional specification of costs, usually nonlinear as production increases, at the product level. Non-linearities at product level can be recovered by a linear specification of costs with quantity produced at activity level.  Let us make a small example to clarify this issue.

**Table 1 - costs and production of 9 activities producing wheat**

| | cost/ha | cost/t | marg. Cost | production in t |
|---|---|---|---|---|
| activ1 | 5 | 5.00 | | 1 |
| activ2 | 5.5 | 4.40 | -0.6 | 1.25 |
| activ3 | 6 | 4.00 | -0.4 | 1.5 |
| activ4 | 6.5 | 3.82 | -0.2 | 1.7 |
| activ5 | 7 | 3.78 | 0.0 | 1.85 |
| activ6 | 7.5 | 3.85 | 0.1 | 1.95 |
| activ7 | 8 | 4.00 | 0.2 | 2 |
| activ8 | 9 | 4.43 | 0.4 | 2.03 |
| activ9 | 10 | 4.90 | 0.5 | 2.04 |

It is easy to realize that in this example we have nine activities that may produce wheat on a specific soil-weather condition. If we consider the nine activities together, we will obtain the classical representation of cost functions. A quadratic cost function and a linear marginal cost function can be easily produced from these figures. But these functions belong to a product, not to an activity.

**Average Costs, Yields and Marginal Costs**



In this section we will deal with one important problem, that is model calibration and with a family of methods widely used to solve this problem. We mean Positive Mathematical Programming (PMP) and all the further developments that followed the first formulation of this approach (Howitt, 1995).

LP models may produce overspecialized solutions, due to lack of active constraints. For solving this problem, LP modelers used to introduce artificial constraints. The basic PMP idea is to find how to "reveal" the "real" costs farmers are facing, using available information. The standard version of PMP consists in revealing these costs by imposing in a first step a set of constraints to the LP model in order to reproduce the observed situation in terms, i.e. of cropping pattern. The dual values of these constraints will provide a revealed additional cost associated with the activity. Adding these costs to the ones we had in the original LP model provides a degenerate solution. But, as following standard economic theory, we should assume that costs are not linear, what is proposed is to introduce an increasing marginal cost to the original value, in order to attain the intercept with the observed quantity. The assumption is that average costs are different from marginal costs (in LP models average costs are equal to marginal ones). Part of the PMP literature consists in how to define the slope of the linear marginal cost (for simplification, we assume a quadratic cost function). Models will be exactly calibrated with ANY slope, but of course, forecasting exercises results will be different with different slopes …, which one is the good one?

Following an empiricist view, the literature on this field moved increasingly towards an econometric approach, including existing information from time series or from cross-section analysis in order to define these slopes, and also to define the crossed relationships between the activities (price cross elasticities of supply). Another option later developed is to introduce directly cost functions in the model, obtained by econometric estimations. We are more and more far from an engineering production function approach.

These methods may be perfectly adequate if we are dealing with highly aggregate models (big regional models, national agricultural sector models) in which the activities and the products are the same thing or almost the same thing, in an informational context where the quality of production factors represented is heterogeneous and this heterogeneity is not explicitly specified (i.e. differences in soil and climate), because the information is not easily available. But they are inadequate if we are working with models at the scale of a farm, or a small region, and with the purpose of integrating in the model refined biophysical information necessary to provide an adequate assessment concerning environmental and natural resources issues.

Detailed bio-economic models applying a primal representation of technology should not face the problem of overspecialization. The fact of having different land constraints according to soil characteristics, water availability, defining periods for tillage activities constraints, adequate rotation and labor constraints, etc. on one side, and a realistic introduction of risk on the other side can drastically reduce or eliminate the overspecialisation issue. Having several activities for each product avoids also the existence of abrupt changes in the solutions in terms of products. But this does not mean that obtaining a calibrated model for a base period situation is an easy job. Data are not perfect, there may be always some level of error in the specification of the model and calibration may be needed.

The important question is to know whether assuming a non-linear cost specification, as do PMP and GME models is an adequate solution. The answer is negative. **It is not a good solution if the model is activity based. If each product is produced by several activities, imposing to each activity a non linear cost is inadequate as it is absolutely more realistic to assume that the average cost *per activity* is equal to the marginal cost. As mentioned above, linear costs per activity may imply non linear costs per product.**

The cost of one ton of wheat produced on a specific soil and weather conditions, with an identified technology is very likely linear. If activities are well enough defined there is no reason to seem that costs increase (or decrease) with increase of production. The cost of the product increases with quantity when we move between different qualities of resources or we employ more resources, but this is already represented with the changes in the mix of activities and not within one activity. Production functions **for activities** are of Leontief type.

A possible solution can be to use an “almost linear” specification for the revealed cost that emerges from the dual values of the constrained activities in the first phase of standard PMP. Theoretically, it seems a good choice, as there is no reason to assume that marginal costs are different from average costs; we assume that they are only slightly different, in order to be able to obtain a calibrated solution to the model. The weight of the revealed part of the cost can be then interpreted as an error term.

An important advantage of this approach concerns the cost specification of the activities that are not observed in the base year and also for the marginal observed activity. As we keep an almost linear approach, we can respect the "engineering" definition of these costs, introducing a very small non-linear portion, the same we used for the observed activities, because it will not create a significant bias to the forecasting capabilities of the model. We keep a more consistent methodological approach and we avoid "black boxes" made out from functional forms – usually adopted for their mathematical qualities – and/or empirical estimations emerging from information not adapted to the situation that is going to be analyzed[5].

---

[5] If time series are used to estimate the cost functions, they do not represent the present technology. If cross-section estimations are employed they do not represent the real soil and climate conditions existing in the region.

### 3.2 - The issue of "available data"

We consider that data do not grow on wild forests; they are a deliberate construction. If we have a clear conceptualization on how the data are going to be used, we can "build" them in the appropriate manner. The necessary information needed to build the vectors that are the mathematical expression of the production activities is never directly available, that is why it seems necessary to develop a Data Base (DB) structure coherent with the models for which these data are going to be applied. This DB should be built allowing a constant development, so the structure should allow the possibility of introducing new information. As one of the objectives of BioSight is precisely the construction of data, it should be possible to adapt these data in the required format in order to be used by bio-economic models.

### 3.3 - Indicators for big regions, nations or global level

Considering that bio-economic models - as we understand them - can be elaborated at the level of a farm and/or a small region, another challenge is to find some way to create a linkage with models working at a national, continental or global level using indicators that can be calculated from the results obtained by the bio-economic models. It may be possible - even if it is very ambitious - to build a sample of representative regions (taking into account as well ecological and socio-economic characteristics) and from the results obtained on that regions, make an expansion of these results at a larger scale. For doing this, a meta-modeling approach could be used. This idea was developed for the SEAMLESS European Project [6], but not applied.

## 4 - Assessment concerning the available models and their possible use in BioSight Project

Only a small number of the models that have been reviewed are potentially available:

MODAM (*)

ILM (*)

FARM DESIGN (*)

MATA

FSSIM-MP (*)

FSSIM-DEV (*)

LIMA

CEBALAT

SOLUS

COBAS (*)

The models marked (*) are being used or have been used recently.

Most of the literature concerns applications of models that do not have a detailed available documentation about the model itself. The small number of models listed above may be available as there are owned by different institutions. One of them is IFPRI property (the LIMA Model).

---

[6]. SEAMLESS Integrated Project, EU 6th Framework Programme, Contract No. 010036-2

In principle, all the models considered in this survey are - explicitly or implicitly - in most cases implicitly, based on production activities. Almost all of them use the same computer language (GAMS, General Algebraic Modeling System)

The most “generic” ones, in the sense of potentially applicable in heterogeneous conditions, are MODAM, FSSIM-MP, FSSIM-DEV and MATA. All of them have not been necessarily applied for several agricultural dimensions combined with more than one environmental issue, but all of them are potentially capable of doing so, that is the reason why we include them. ILM might not be as generic as the above mentioned models, however its spatially explicit specification needs to be noted.

Nevertheless, there is not a model enough generic to be able to be used directly as a tool in a BioSight Project. The three more “generic” are FSSIM-DEV, FSSIM-MP and MODAM. The last two have been applied in European study cases; FSSIM-DEV was applied in a West African study.

What are then the possibilities of using existing models for BioSight Project?

There is one common denominator to the majority of the reviewed bio-economic models, and it is the use of production activities as basic cell of information. Even in the cases where non-linear production functions are estimated, this estimation is done using engineering information that consists essentially in linear vectors describing the multiple inputs and outputs of a specific activity.

Out of this evidence, it seems that the most appropriate way for developing an area of bio-economic modeling could be the following one:

- Develop a Data Base appropriate for introducing the type of information that is needed for using bio-economic models, meaning by one side the construction of an Electronic Survey for introducing the data, and the necessary modules for transforming this data in a way that they can be used by the bio-economic model (s)
- Create a library of modules, from the existing models and - if necessary - new ones, adapting them in order to be able to use the data that is collected with the DB.

In principle, no existing model can be immediately applied for the purpose of BioSight Project without some additional work. But the experience acquired in the building and use of some of those models can allow building a modular structure that combined with an appropriate database should permit the analysis of the relations between agricultural intensification and sustainability in very different contexts. Some of the models present in this survey demanded several years of work. Nevertheless, applying them in a specific context will always demand additional time. The existing “capital” in bio-economic models is important, but heterogeneous. An additional effort in terms of building modules out of some of the existing models, combined with a data-base specifically structured for this purpose, will be important, but feasible in a reasonable period of time.

MODAM and FSSIM-DEV have a DB consistent with the specification of the model.

## 4.1 - The “ideal” model

| |
|---|
| What would the “ideal” bio-economic model look like? |
| • Modular structure, allowing the choice of modules to be applied in specific applications. This idea was inspired by what is being done for biophysical models (cropping systems models) |
| • Dynamic model, essentially because the treatment of natural resources issues is always dynamic. Even if it is possible to use inputs of biophysical models - that are dynamic - in a static bio-economic model, it is frequently necessary to allow for feedbacks between the two models and that implies a dynamic structure.<br>o Recursive integration of impact of natural resources on production and of production choice on natural resources, using a meta-modeling approach. |
| • Small regional model, it does not seem realistic to develop this type of model for very big regions or whole countries. Farm level may not be appropriate in many cases, as it cannot represent exchange of production factors between farms at a regional level.<br>o Model that takes into account interactions between farms through a market of production factors |
| • Generic model, in the sense of its flexibility - through its modular structure - to be applied with “small” additional work to different conditions |
| • Allows simulating different types of risk |
| • Includes a household module, essential for many situations in developing countries |
| • Includes the possibility of using different calibration methods |
| |

From the survey of models, the “ideal” model does not exist, but the know-how for producing one exists and combining characteristics of presented models can make it possible. Let us be optimistic.

In the following table, essential characteristics of some of the reviewed model are presented. It is possible to realize that combining the methods used in ILM, FSSIM-DEV and CEBALAT, we are close to our “ideal model”.

## 4.2 Principal characteristics of selected bio-economic models

| PRINCIPAL CHARACTERISTICS OF SELECTED BIO-ECONOMIC MODELS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | LEVEL | KEY STRENGTH | KEY WEAKNESS | REGIONS OF APPLICATION | TREATMENT OF AGENTS BEAHAVIOUR | AGRICULTURAL ISSUES | ENVIRON-MENTAL ISSUES | FOOD ISSUES | TREATMENT OF TIME |
| MODAM | FARM | Modular structure | Lack of farm interactions on resources and fixed livestock | North-Central European Regions | Risk neutral. Positive approach+goal-oriented normative | Arable crops, livestock | Erosion | NO | Static (claiming a possible dynamic use, not applied) |
| ILM | FARM-LANDSCAPE | Spatial specification, treatment of several environmental issues | Lack of farm interactions | Central Europe (Austria) | Positive approach. No risk analysis | Arable crops, livestock: includes interactions | Carbon emissions, biodiversity | NO | Static (bio-physical model dynamic) |
| FARM DESIGN | FARM | Treatment of trade-offs between economic and environmental objectives - Genericity | Yields are fixed as targets, do not depend on management options | The Netherlands, Mexico, Uruguay,Nepal,India | Positive approach. No risk analysis | Arable crops, livestock: includes interactions | Organic matter, Nitrate emissions | NO | Static |
| FSSIM-MP<br>FSSIM-DEV | FARM<br>FARM-REGION | Modular structure. Genericity. Linkage with a DB | Complexity. Need of "ad hoc" linkage with bio-physical model | FSSIM-MP several European Region .<br>FSSIM-DEVS, Sierra Leone | Positive approach. Considers risk. Allows different calibration methods | Arable crops, livestock, permanent crops: includes interactions | Potentially all issues dealt with the coupled biophysical model | YES | Static (bio-physical model dynamic) |
| CEBALAT | FARM | Feed-back between biophysical and economic | Complexity<br>Fixed livestock | Tunisian region | Positive approach. Stochastic resolution | Arable crops, livestock | Salinity | NO | Dynamic-Recursive-Stochastic |

## References

Barbier B., Bergeron G. 1999. Impact of policy interventions on land management in Honduras: results of a bioeconomic model. *Agricultural Systems,* vol. 60, n. 1, p. 1-16. http://www.sciencedirect.com/science/article/pii/S0308521X99000153

Barbier, B. 1996. Impact of market and population pressure on production, incomes and natural resources in the dryland savannas of West Africa: Bio economic modeling at the village level. EPTD Discussion Paper No. 21, IFPRI.

Barbier, B. and G. Bergeron. 1999. Impact of policy interventions on land management in Honduras: results of a bioeconomic model. Agricultural Systems 60:1-16.

Barbier, B.. 1998. Induced innovation and land degradation: Results from a bioeconomic model of a village in West Africa. Agricultural Economics 19:15-25

Barnum, H. and L. Squire, 1979. An Econometric Application of the Theory of the Farm-Household. Journal of Development Economics, 6:79-102.

Belhouchette H. 2004. Evaluation de la durabilité de successions culturales à l'échelle d'un périmètre irrigué en Tunisie : utilisation conjointe d'un modèle de culture (Cropsyst), d'un SIG et d'un modèle bio-économique. Thèse (Dr. d'Université en Sciences Agronomiques): Ensa (Montpellier). France. 155 p.

Belhouchette H., Blanco M., Wery J., Flichman G. 2012. Sustainability of irrigated farming systems in a Tunisian region: a recursive stochastic programming analysis. Computers and Electronics in Agriculture, August 2012, vol. 86, p. 100-110.

Berentsen P.B.M. 2003. Effects of animal productivity on the costs of complying with environmental legislation in Dutch dairy farming. *Livestock Production Science,* vol. 84, n. 2, p. 183-194. 0301-6226. http://www.sciencedirect.com/science/article/pii/S030162260300229X

Berentsen, P.B.M., Giesen G.W.J., 1995. An environmental-economic model at farm-level to analyse institutional and technical change in dairy farming. Agricultural Systems 49, 153-175.

Berentsen, P.B.M., Giesen, G.W.J., Schneiders, M.M.F.H., 1998. Conversion from conventional to biological dairy farming: Economic and environmental consequences at farm level. Biological Agriculture and Horticulture. 16, 311–328.

Blanco Fonseca, M & Flichman, G. 2002, “Dynamic optimisation problems: different resolution methods regarding agricultural and natural resource economics”, Working paper, http://www.iamm.fr/ressources/opac_css/doc_num.php?explnum_id=2699 http://oa.upm.es/5910/1/RecursiveStochasticProgramming_BlancoFlichman_2002.pdf

Blanco-Fonseca, M., G. Flichman, G, Belhouchette, H., Dynamic optimisation problems, Different resolution methods regarding agriculture and natural resource economics in Bio-Economic Models Applied to Agricultural Systems, Springer 2011, 29-57.

Bouman B.A.M., Jansen H.G.P., Schipper R.A., Nieuwenhuyse A., Hengsdijk H., Bouma J. 1999. A framework for integrated biophysical and economic land use analysis at different scales. *Agriculture, Ecosystems & Environment,* vol. 75, n. 1:2, p. 55-73. http://www.sciencedirect.com/science/article/pii/S0167880999000596

Bouman B.A.M., Nieuwenhuyse A. 1999. Exploring options for sustainable beef cattle ranching in the humid tropics: a case study for the Atlantic Zone of Costa Rica. *Agricultural Systems,* vol. 59, n. 2, p. 145-161. 0308-521X. http://www.sciencedirect.com/science/article/pii/S0308521X98000870

Britz, W., Pérez, I., Zimmermann, A., Heckelei, T., 2007. Definition of the CAPRI Core Modelling System and Interfaces with other Components of SEAMLESS-IF.SEAMLESS Report No. 26, SEAMLESS Integrated Project, EU 6th Framework Programme, Contract No. 010036-2, p. 114. <www.seamlessassociation.org>.

Brown D.R. (2000). A review of bio-economic models. *Cornell African Food Security and Natural Resource Management (CAFSNRM) Program,* vol. 102,

Calker, K.J.v., Berentsen, P.B.M., de Boer, I.M.J., Giesen, G.W.J., Huirne, R.B.M., 2004. An LP model to analyse the economic and ecological sustainability on Dutch dairy farms: model presentation and application for experimental farm. Agricultural Systems 82, 139–160.

Donnelly, J.R., et al., 2002. Agricultural Systems 74: 115-139.

Flichman G., Louhichi K., Boisson J.M. (2011). Modelling the Relationship Between Agriculture and the Environment Using Bio-Economic Models: Some Conceptual Issues. *Bio-Economic Models applied to Agricultural Systems,* p. 3-14.

Flores-Sanchez, D., Kleine Koerkamp-Rabelista, J., Navarro-Garza, H., Lantinga, E.A., Groot, J.C.J., Kropff, M.J., Rossing, W.A.H., 2011. Diagnosis for ecological intensification of maize-based smallholder farming systems in the Costa Chica, Mexico. Nutr. Cycl. Agroecosyst. 91, 185–205. http://dx.doi.org/10.1007/s10705-011-9455-.

Groot J.C.J., Oomen G.J.M., Rossing W.A.H. 2012. Multi-objective optimization and design of farming systems. Agricultural Systems, vol. 110, p. 63-77.

Hengsdijk, H., Bouman, B., Nieuwenhuyse, a. and H. Jansen, 1999. Quantification of land use systems using technical coefficient generators: a case study for the Northern Atlantic zone of Costa Rica. Agricultural Systems, 61(2):109-121.

Hengsdijk, H., van Ittersum, M.K., 2003. Formalizing agro-ecological engineering for future-oriented land use studies. European Journal of Agronomy 19, 549–562.

Hijmans R.J. and M.K. van Ittersum, 1996. Aggregation of spatial units in linear programming models to explore land use options. Netherlands Journal of Agricultural Science 44: 145- 162.

Howitt, R., 1995. American J. of Agricultural Economics Volume 77, Issue 2Pp. 329-342.

Jansen H.G.P., Stoorvogel J.J. 1998. Quantification of aggregation bias in regional agricultural land use models: application to Guácimo county, Costa Rica. Agricultural Systems, vol. 58, n. 3, p. 417-439. http://www.sciencedirect.com/science/article/pii/S0308521X98000390

Janssen S., van Ittersum M.K. 2007. Assessing farm innovations and responses to policies: a review of bio-economic farm models. Agricultural Systems, vol. 94, n. 3, p. 622-636.

Kachele H, Dabbert S. 2002. An economic approach for a better understanding of conflicts between farmers and nature conservationists-an application of the decision support system MODAM to the Lower Odra Valley National Park. Agricultural Systems 74:241–255

Kanellopoulos, A., Berentsen, P.B.M., Heckelei, T., Van Ittersum, M.K., Oude Lansink, A.G.J.M., 2010. Assessing the forecasting performance of a generic bio-economic farm model calibrated with two different PMP variants. Journal of Agricultural Economics 61, 274–294.

Kanellopoulos, A., Hengsdijk, H., Janssen, S., Van Ittersum, M.K., 2009. Ex-ante assessment of the abolishment of the EU set aside policy: results from a bioeconomic farm analysis. In: Proceedings of the Conference on Integrated Assessment of Agriculture and Sustainable Development Setting the Agenda of Science and Policy (AgSAP 2009). Egmond aan Zee, The Netherlands, 10–12 March 2009. Wageningen University and Research Centre, Wageningen, pp.478–479.

Kruseman G., Bade J. 1998. Agrarian policies for sustainable land use: bio-economic modelling to assess the effectiveness of policy instruments. Agricultural Systems, vol. 58, n. 3, p. 465-481. http://www.sciencedirect.com/science/article/pii/S0308521X98000419

Kruseman, G. 2000. Bio-economic Household Modelling for Agricultural Intensification. PhD dissertation, Wageningen University, Wageningen.

Kuyvenhoven, A., R. Ruben and G. Kruseman. 1995. Options for sustainable agricultural systems and policy instruments to reach them. In: Bouma, J., A. Kuyvenhoven, B.A.M. Bouman, J.C. Luyten and H.G. Zandstra (Eds.), Eco-Regional Approaches for Sustainable Land Use and Food Production, pp. 187-212, Kluwer, Netherlands

Keating, B.A., Carberry, P. Hammer G.L Probert, M.E Robertson M.J, Holzworth D, Huth N.I, Hargreaves, J.N.G Meinke H, Hochman, McLean Z G, Verburg K, Snow,V Dimes, J.P, Silburne, M.,Wang, B, Brown,S, Bristow K.L, Asseng, S, Chapman,S, McCown R.L, D.M Freebairn, C.J Smith. An overview of APSIM, a model designed for farming systems simulation. European Journal of Agronomy. Volume 18, Issues 3–4, January 2003, Pages 267–288

Kingwell, R.S. & D.J. Pannell (Eds), 1987. MIDAS, a bioeconomic model of a dryland farmsystem. Pudoc, Wageningen.

Louhichi K., Flichman G., Boisson J.M. 2010. Bio-economic modelling of soil erosion externalities and policy options: a Tunisian case study. Journal of Bioeconomics, vol. 12, n. 2, p. 145-167.

Louhichi K., Flichman G., Boisson J.M.2010. Bio-economic modelling of soil erosion externalities and policy options: a Tunisian case study. Journal of Bioeconomics, vol. 12, n. 2, p. 145-167.

Louhichi K., Flichman G., Zekri S. 1999. Un modèle bio-économique pour analyser l'impact de la politique de conservation des eaux et du sol. Economie rurale, vol. 252, n. 1, p. 55-64.

Louhichi, K., Belhouchette, H., Flichman, G., Therond, O., Wery, J., 2008. Impact assessment of the 2003 CAP reform and the nitrate directive on the arable farming system in the Midi-Pyrénées region: bio-economic modelling at field, farm and regional levels. In: 109th Seminar, November 20–21, 2008, Viterbo, Italy.

Louhichi, K., Flichman, G., Zekri, S., 1999. A bio-economic model for analysing the impact of soil and water conservation policies applied to a Tunisian farm.OT: Un modele bio-economique pour analyser l'impact de la politique de conservation des eaux et du sol. Le cas d'une exploitation agricole tunisienne. Economie Rurale 252, 55–64.

Louhichi, K., Hengsdijk, H., Janssen, S., Bigot, G., Perret, E., 2009. EU dairy farming in the face of change: an exploration using a bio-economic farm model. In:Proceedings of the Conference on Integrated Assessment of Agriculture and Sustainable Development Setting the Agenda of Science and Policy (AgSAP). Egmond aan Zee, The Netherlands, 10–12 March 2009. Wageningen University and Research Centre, Wageningen, pp. 262–263.

Louhichi,K., Gomez y Paloma,S., Belhouchette, H., Allen, T., Fabre, J., Blanco Fonseca,M., Chenoune, R., Acs,S., and Flichman, G. Modelling Agri-Food Policy Impact at Farm-household Level in Developing Countries (FSSIM-Dev). Application to Sierra Leone. Joint Research Centre. JRC Scientific and Policy Reports, 2013.

Majewski, E., Was, A., Belhouchette, H., Louhichi, K., Mouratiadou, I., 2009. Impact Assessment of policy changes on the arable sector using the FSSIM model: case study of the Zachodniopomorskie NUTS region. In: Proceedings of the Conference on Integrated Assessment of Agriculture and Sustainable Development Setting the Agenda of Science and Policy (AgSAP). Egmond aan Zee, The Netherlands, 10–12 March 2009. Wageningen University and Research Centre, Wageningen, pp. 484–485.

Meyer-Aurich A. 2005. Economic and environmental analysis of sustainable farming practices : a Bavarian case study. Agricultural Systems, vol. 86, n. 2, p. 190-206. 0308-521X. http://www.sciencedirect.com/science/article/pii/S0308521X04001763

Meyer-Aurich, A., Zander, P., Werner, A., Roth, R., 1998. Developing agricultural land use strategies appropriate to nature conservation goals and environmental protection. Landscape and Urban Planning 41, 119–127.

Mimouni M., Zekri S., Flichman G. 2000. Modelling the trade-offs between farm income and the reduction of erosion and nitrate pollution. Annals of Operations Research, vol. 94, n. 1-4, p. 91-103.

Mouratiadou, I., Russell, G., Topp, C., Louhichi, K., Moran, D., 2010. Modelling common agricultural policy–water framework directive interactions and cost effectiveness of measures to reduce nitrogen pollution. Water Science & Technology 61, 2689–2697.

Okumu, B. N., M. A. Jabbar, D. Colman, N. Russell, M. Saleem, J. Pender. 2000. Technology and policy impacts on economic performance, nutrient flows and soil erosion at watershed level: The case of Ginchi in Ethiopia. In Global Development Network (World Bank) 2000 conference on 'Beyond economics—Multidisciplinary approaches to development', Tokyo, Japan (p. 11-14).

Oomen, G., Habets, A., 1998. Using the static whole farm model FARM and the dynamic model NDICEA to integrate arable and animal production. In: H. van Keulen, E.A. Lantinga & H.H. van Laar (eds): Proceedings of an International Workshop on Mixed Farming Systems in Europe, Dronten/Wageningen, The Netherlands, 25-28 May 1998. Ir. A.P. Minderhoudhoeve-series, 2, 217-223.

Prellezo, R., Accadia, P., Andersen, J. L., Andersen, B. S., Buisman, E., Little, A., Nielsend, R., Poosg, JJ., Powelle, J. and Röckmann, C. (2012). A review of EU bio-economic models for fisheries: The value of a diversity of models. Marine Policy, 36(2), 423-431.

Ruben, R., A. Kuyvenhoven and G. Kruseman. 2000. Bio-economic models for eco-regional development: Policy instruments for sustainable intensification. In: Lee, D.R. and C.B. Barrett (Eds.), Tradeoffs or Synergies? Agricultural Intensification, Economic Development and the Environment in Developing Countries, CAB International.

Sadoulet, E. and A. De Janvry, (1995). Quantitative Development Policy Analysis. Baltimore: The Johns Hopkins University Press, 438p.

Schmid, E., 2004. FAMOS – Farm Optimization System. Discussion Paper DP-09-2004. Institute for Sustainable Economic Development. University of Natural Resources and Applied Life Sciences,Vienna.

Schönhart M., Schauppenlehner T., Schmid E., Muhar A. (2011). Integration of bio-physical and economic models to analyze management intensity and landscape structure effects at farm and landscape level. Agricultural Systems, vol. 104, n. 2, p. 122-134. http://www.sciencedirect.com/science/article/pii/S0308521X10000557

Schönhart, M., Schmid, E., Schneider, U.A., 2009. CropRota – A Model to Generate Optimal Crop Rotations from Observed Land Use. Discussion Paper DP-45-2009. Institute for Sustainable Economic Development. University of Natural Resources and Applied Life Sciences, Vienna.

Singh, I., L. Squire and J. Strauss (Eds), 1986. Agricultural Household Models: Extensions, Applications and Policy. Baltimore: Johns Hopins University Press, 323p.

Standiford, R.B. and R.E. Howitt. 1991. A dynamic model of California's hardwood rangelands. In: Proceedings of the Oak Woodlands and Hardwood Rangeland Management. Research Symposium, Davis, CA. USDA Forest Service General Technical Report PSW-126, pp. 279-285.

Schuler, J., Ka¨chele, H., 2003. Modelling on-farm costs of soil conservation policies with MODAM. Environ. Sci. Policy 6, 51–55.

Stoorvogel, J. J. 1995. Integration of computer-based models and tools to evaluate alternative land use scenarios as part of an agricultural systems analysis. Agri-cultural Systems 49, 353-367.

Storn, R., Price, K., 1997. Differential evolution – a simple and efficient heuristic for global optimization over continuous spaces. J. Global Optim. 11, 341-359.

Tanure S., Nabinger C., Becker J.o.L. Bioeconomic model of decision support system for farm management. Part I: Systemic conceptual modeling. Agricultural Systems, vol. 115, n. 0, p. 104-116. http://www.sciencedirect.com/science/article/pii/S0308521X12001448

Ten Berge, H.F.M., van Ittersum, M.K., Rossing, W.A.H., van de Ven, G.W.J., Schans, J., 2000. Farming options for The Netherlands explored by multi-objective modelling.

Traoré, B., Louhichi, K., Rapidel, B., 2009. A bio-economic model to analyse the performance of the cotton sector in Mali. In: Proceedings of the Conference on Integrated Assessment of Agriculture and Sustainable Development Setting the Agenda of Science and Policy (AgSAP). Egmond aan Zee, The Netherlands, 10–12 March 2009. Wageningen University and Research Centre, Wageningen, pp. 276–277.

Ulrich, C., Le Gallic, B., Dunn, M. R., & Gascuel, D. (2002). A multi-species multi-fleet bioeconomic simulation model for the English Channel artisanal fisheries. Fisheries Research, 58(3), 379-401.

Uthes S, Sattler C, Reinhardt F-J, Piorr A, Zander P, Happe K, Damgaard M, Osuch A (2008) Ecological effects of payment decoupling in a case study region in Germany. Journal of Farm Management 13:219–230

van de Ven, G.W.J., 1996. A mathematical appraoch to comparing environmental and economic goals in dairy farming on sandy soils in the Netherlands. Ph.D. Thesis, Wageningen Agricultural University, Wageningen, p. 239. Available at [http://edepot.wur.nl/137971]

Van Ittersum, M.K., Ewert, F., Heckelei, T., Wery, J., Alkan Olsson, J., Andersen, E., Bezlepkina, I., Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A.E., van der Wal, T., Wien, J.E., Wolf, J., 2008. Integrated assessment of agricultural systems – a component-based framework for the European union (SEAMLESS).Agr. Syst. 96, 150–165.

Weaver, W., Shannon, C.E., 1949. The Mathematical Theory of Communication.University of Illinois, Urbana Izaurralde, R.C.,

Williams, J.R., McGill, W.B., Rosenberg, N.J., Jakas, M.C.Q., 2006. Simulating soil C dynamics with EPIC: model description and testing against long-term data. Ecol. Model. 192, 362–384.

Weersink, A., Jeffrey, S., Pannell, D., 2002. Farm-level modeling for bigger issues. Rev. Agric. Econ. 24, 123–140.

Wei, Y., Davidson, B., Chen, D., White, R., 2009. Balancing the economic, social and environmental dimensions of agro-ecosystems: an integrated modeling approach. Agr. Ecosyst. Environ. 131, 263–273.

Williams, J.R., 1995. The EPIC model. In: Singh, V.P. (Ed.), Computer Models of Watershed Hydrology. Water Resources Publications, Colorado, pp. 909–1000.

Zander P., Kächele H. 1999. Modelling multiple objectives of land use for sustainable development.

Agricultural Systems, vol. 59, n. 3, p. 311-325. 0308-521X.

http://www.sciencedirect.com/science/article/pii/S0308521X99000177

Zander, P., 2003. Agricultural land use and conservation options: a modelling approach. PhD thesis, Wageningen University, The Netherlands.

# Annex[7]

## Cropping system models[8]

### Introduction

The definition of cropping system models as mathematical programs to estimate plant growth as function of environmental variables started many decades ago. Since then, crop models have evolved including sub-models to estimate plant development, and several other processes relevant to the simulation of the interaction plant/soil affected by weather and agricultural management (Donatelli and Confalonieri, 2011). With this evolution, it becomes possible to: i) produce engineering production functions, hence comparing, from biophysical point of view, yield, resource use, and externalities of agricultural production systems (Belhouchette et al., 2011), and ii) explore hypothesis of resource uses and allow defining adaptation strategies to changing climate and scenarios of resource availability, as well as defining thresholds of externalities to limit the environmental impact of production systems (Donatelli and Confalonieri, 2011).

The lack of appropriate information is a severe problem for using these models to generate agricultural production activities for mathematical programming models. Frequently they lack detailed information on conditions, i.e. limited and unlimited water and nitrogen conditions, management practices (dates and rates of irrigation and fertilization) (Launay and Guérif, 2005). In most case they do not include the effects of insects, pests and diseases and they require long and arduous surveys of a large number of farms (Biarnes et al., 2004).

### Model selection and evaluation

In this approach, to allow for flexibility the cropping systems models are often no linked dynamically with the farm model but interfaced through an engineering production coefficients database. By doing that, it becomes possible in many studies to assess the impacts of very complex scenarios, such as the implantation of policies, environmental directives and measures (water framework, nitrate, pesticide…) and the variation of socio-economic context (price of products, labor…) and technological innovations (rotation, new varieties…), on the sustainability of farms.

Two options existed for using cropping systems models for producing data to be introduced in bio-economic models:

- Reuse already existing cropping systems models without introducing significant modifications. This option was progressively criticized, because most of them operated as one comprehensive entity with a specific structure and detail for simulating crop growth and soil nutrient (often nitrogen) cycling processes (e.g. EPIC, Sharpley and Williams, 1990; STICS, Brisson et al., 2003). Consequently, little flexibility is given to the model user when the degree of detail included in simulation models correspond to the specific research question addressed and should be kept as simple as the nature of their objectives to minimize data requirements (Passioura, 1996; Sinclair and Seligman, 1996),
- For each application, build a new model 'ad hoc' (Passioura, 1996), which quickly appears as a very expensive and time consuming method.

Recently, by the development of a modular framework (Donatelli et al, 2011; Adam et al., 2011), a third way of developing and using crop simulation models came into the picture. In fact, it becomes possible to construct ad-hoc crop growth modules customized to specific simulation problems. Those modules could be extracted as much as possible from existing crop models (e.g. CropSyst, APES, STICS, APSIM…) and then integrated in a framework in order to develop the modeling solution (MS) adapted to the target of the study. In practice, the modeler (i.e. potential user of the framework) must

---

[7] By Hatem Belhouchette (CIHEAM-IAMM).

[8] Most of biophysical models integrated in bio-economic models are cropping system models.

in the first place clearly define the purpose of the model application, before selecting and using a crop simulation model. The flexibility and modularity of the new generation of cropping system models (such as APES, Donatelli et al., 2011), due to its component-oriented design, enables an easy technical assembly of these different modules in the same platform. But associated methodology should be provided to facilitate the selection and evaluation of models (Ahuja and Howell, 2002). Not only should the crop modeling framework be an ‘‘implementation framework’’ (Van Evert et al., 2005) considering each module as a black box, but also a ‘‘modeling framework’’ (Van Evert et al., 2005) to formalize how to use these various modules.

A very important problem concerns the availability and quality of data concerning soil, climate, crop and crop management that should be used to correctly evaluate the cropping system models ability to simulate the key phenological, growth and morphological variables by using experimental data as input. In most of the classical methods of model evaluation, calibration and validation are often done on two different sets of independent experimental data (Odum, 1983; Shugart, 1984; Jorgensen, 1986; Power, 1993). The big advantage in this case is that real measured data is used to evaluate the model's performance (Poluektov, 1991). However, it is often difficult to find an independent set of data for model validation, i.e. data that have not been used for calibration (Stöckle et al., 2003). The main reason is that the measured data needed for model evaluation mainly consists of variables that are usually measured under limited soil, crop management and climate conditions: such experiments are very time and cost consuming.

This procedure (calibration and evaluation) becomes more complicated when the use of cropping models at regional scale to simulate yield and externalities is addressed. The difficulty is to find relevant measured input data covering the large diversity of the biophysical conditions (soil and weather), variables characterizing the initial soil conditions (soil water content, organic matter, soil nitrogen content) and crops (yield, biomass, LAI…) and externalities. In such context, the performance in a large range of cropping conditions is assessed by following usually three main methods:

- Develop an experiment protocol for representative areas (farms) in term of biophysical conditions and cropping systems (Belhouchette et al., 2010, Oreskes et al., 1994). The larger and diverse the region, the higher the cost (in term of money and time) of the survey (Belhouchette et al., 2008). This type of procedure is often used for specific regions and crops in order to advise farmers in managing their cropping systems.
- Calibrate the model with several dynamic and cumulative variables (yield, biomass, LAI, N-leaching…) but under limited cropping conditions, and then the validation is done for a wider range of cropping systems but usually only for crop yield which is the common variable measured in all crop experiments (Therond et al, 2010; Faivre et al., 2004; Van Ittersum et al., 2003; Jagtap and Jones, 2002; Bouman et al., 1996).
- Evaluate the model by using input-output data extracted through farmer surveys and existing regional databases (Clavel et al., 2011; Therond et al., 2010; Faivre et al., 2004; Middelkoop and Janssen, 1991).

This type of analysis is mainly used to assess the impacts of climate change or socio-economic and environmental policy analysis under a large range of crop, management, soil, and climate conditions. Obtaining this information is very expensive and time consuming. To overcome these problems, engaging in the process local and regional experts, who have detailed knowledge on the crop growing conditions in the region (Clavel et al., 2011) has been seen recently as a good alternative to experimental data. Local experts with a good knowledge of regional crops, soils and farms can provide not only the detailed input (climate, management) and output data, but also the intermediate variables data of shoot and root growth and water and nitrogen balances (Mahmoud, 2012).

# References

Ahuja, L.R.M.L., Howell, T.A., 2002. Whole System Integration and Modelingessential to agricultural Science and Technology in the 21st century, Agricultural system models in the field research and technology transfer. Lewis Publishers, pp. 1–7.

Belhouchette, H., Braudeau, E., Hachicha, M., Donatelli, M., Mohtar, R., Wery, J., 2008. Integrating spatial soil organization data with a regional agricultural management simulation model: a case study in northern Tunisia. American Society of Agricultural and Biological Engineers ISSN 0001-235, 51(3); 1099-1109

Belhouchette, H., Louhichi K., Therond O., Mouratiadou I., Wery J., Ittersum M.v., Flichman G., 2011. Assessing the impact of the Nitrate Directive on farming systems using a bio-economic modelling chain. Agricultural Systems, 104(2): 135-145.

Biarnès, A., Rio P., Hocheux, A., 2004. Analyzing the determinants of spatial distribution of weed control practices in a Languedoc vineyard catchment, Agronomie 24,187–196.

Bouman, B.A.M., Van Keulen, H., Van Laar, H.H., Rabbinge, R., 1996. The 'School of de Wit' crop growth simulation models: a pedigree and historical overview. Agricultural Systems 52, 171–198.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., 2003. An overview of the crop model STICS. European Journal of Agronomy 18, 309–332.Passioura, 1996

Clavel, L., Soudais, J., Baudet, D., Leenhardt, D., 2011. Integrating expert knowledge and quantitative information for mapping cropping systems. Land Use Policy 28 (1): 57-65.

Donatelli, M, and R. Confalonieri, R., Biophysical Models for Cropping System Simulation ; in Bio-Economic Models applied to Agricultural Systems (Flichman, G. editor) Springer, 2011

Faivre, R., Leenhardt, D., Voltz, M., Benoît, M., Papy, F., Dedieu, G., Wallach, D., 2004. Spatialising crop models. Agronomie 24, 205–217.

Launay, M., Guerif, M., 2005. Assimilating remote sensing data into a crop model to improve predictive performance for spatial applications. Agriculture, Ecosystems & Environment, 111, 321−339.

Middelkoop, H., Janssen, L. L. F., 1991. Implementation of temporal relationships in knowledge based classification of satellite images. Photogrammetric Engineering & Remote Sensing, 57, 937−945.

Jagtap, S.S., Jones, J.W., 2002. Adaptation and evaluation of the CROPGRO-soybean model to predict regional yield and production. Agriculture, Ecosystems and Environment 93, 73–85.

Jorgensen, S.E., 1986. Fundamentals of Ecological Modelling. Elsevier, Amsterdam, 389 pp.

Oreskes, N., Shrader-Frechette, K., Belitz. K., 1994. Verifcation, validation, and confirmation of numerical models in the earth science. Science (Washington, DC) 263: 641-646.

Odum, H.T., 1983. Systems Ecology. John Wiley & Sons, New York, NY, 644 pp.

Power, M., 1993. The predictive validation of ecological and environmental models. Ecol. Model., 68: 33-50.

Poluektov, R.A., 1991. Agroecosystem dynamics simulation. Hydrometeoizdat, Leningrad, Russia.

Sharpley A.N., Williams J.R., 1990. EPIC-Erosion Productivity Impact Calculator. Model Documentation. US Department of Agriculture Technical Bulletin 1

Sinclair, T., Seligman, N.G., 1996. Crop Modeling: From Infancy to Maturity. Agronomy Journal 88, 698–704.Adam et al., 2011

Stöckle, C.O., Donatelli, M., Nelson R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron., 18, 289-307.

Shugart, H.H., 1984. A Theory of Forest Dynamics. Springer- Verlag, New York, NY.

Therond, O., Hengsdijk, H., Casellas, E., Wallach, D., Adam, M., Belhouchette, H., Oomen, R., Russell, G., Ewert, F., Bergez, J, E., Janssen, S., Wery, J., Van Ittersum, M.K., 2010. Using a cropping system model at regional scale: Low-data approaches for crop management information and model calibration. Agric. Ecosyst. Environ. (2010).

Therond, O., Hengsdijk, H., Casellas, E., Wallach, D., Adam, M., Belhouchette, H., Oomen, R., Russell, G., Ewert, F., Bergez, J, E., Janssen, S., Wery, J., Van Ittersum, M.K., 2010. Using a cropping system model at regional scale: Low-data approaches for crop management information and model calibration. Agric. Ecosyst. Environ.

Van Evert, F.K., Holzworth, D., Muetzelfeldt, R.M., Rizzoli, A.E.; Villa, F., (Eds), 2005. Convergence in integrated modeling frameworks In: Proceedings of the MODSIM 2005 International Congress on Modelling and Simulation, Melbourne, December, 2005. – Melbourne, Australia: Modelling and Simulation Society of Australia/New Zealand, MODSIM 2005 International Congress on Modelling and Simulation.

Van Ittersum, M.K., Donatelli, M., 2003. Modelling cropping systems highlights of the symposium and preface to the special issues. European Journal of Agronomy 18, 187–394.