Modelling Agricultural Diffuse Pollution: CAP – WFD Interactions and Cost Effectiveness of Measures

Ioanna Mouratiadou[1, 2], Cairistiona Topp[2], Dominic Moran[2]

[1]University of Edinburgh; [2]Scottish Agricultural College
Contact: I.Mouratiadou@sms.ed.ac.uk

Paper prepared for presentation at the 107th EAAE Seminar *"Modelling of Agricultural and Rural Development Policies"*. Sevilla, Spain, January 29th -February 1st, 2008

Abstract

Within the context of the Water Framework Directive (WFD) and the Common Agricultural Policy (CAP), the design of effective and sustainable agricultural and water resources management policies presents multiple challenges. This paper presents a methodological framework that will be used to identify synergies and trade-offs between the CAP and the WFD in relation to their economic and water resources environmental effects, and to assess the cost-effectiveness of measures to control water pollution, in a representative case study catchment in Scotland. The approach is based on the combination of a biophysical simulation model (CropSyst) with a mathematical programming model (FSSIM-MP), so as to provide a better understanding and representation of the economic and agronomic/environmental processes that take place within the agricultural system.

Keywords: **Bio-economic Modelling, Water Framework Directive, Common Agricultural Policy**

1. Introduction

Agriculture is seen as the sector that creates the biggest challenge for the sustainable management of water resources. This challenge relates to the reduction of diffuse pollution from agricultural sources and to the regulation of agricultural water consumption. In the EU, the Water Framework Directive (WFD) reflects the increasing prominence given to tackling these problems. One of the most important milestones is the establishment of River Basin Management Plans by 2009. These will be providing detailed information on how the environmental objectives will be reached by 2015 according to the Programme of Measures (POM). In accordance with the approach emphasised by the WFD, the POM should provide the most cost-effective measures to reach the environmental requirements. The agricultural sector, one of the sectors that give rise to significant pressures in most water bodies, is expected to be clearly affected by the POM. Implementation of the WFD is taking place against a background of reform in the agricultural sector (Common Agricultural Policy (CAP)) and strong linkages can be identified between the two policies. These relate to the effects of the decoupling of payments, the imposition of cross compliance measures, and the potential new agri-environmental measures.

Within this context, the design of effective and sustainable agricultural and water resources management policies presents multiple challenges. Against the background of the WFD and the CAP, there are two conflicting goals in relation to agriculture: minimise the impacts of the sector on the water environment while maximising its economic return. Therefore, an approach that considers both the socio-economic and environmental outcomes of agricultural production is needed. Nevertheless, the agricultural system is dominated by complex and interacting agronomic, environmental and production processes. Analysing and modelling such a system requires understanding of both natural and social sciences. This paper presents a methodological framework that uses a bio-economic modelling approach in order to provide a better understanding of the complexity of the agricultural system. CropSyst (Stöckle *et al*., 2003) is used for the estimation of crop yields, nitrate leaching and soil erosion, based on climate, soil type, crop characteristics, inputs of production, and management practices. FSSIM-MP (van Ittersum *et al*., 2007), a bio-economic mathematical programming model developed under the EU FP6 Integrated Project SEAMLESS, is used for modelling farmers' decision making under different water and agricultural policy scenarios.

In the next section previous studies on the WFD will be briefly reviewed and the need for a more inclusive approach incorporating the effects of the CAP and information on biophysical processes will be identified. In the third section, the main methodological properties of the bio-economic modelling methodology are outlined. This is followed by a discussion of different approaches concerning spatial and temporal scale and a description of how these are treated in our study. The fifth section provides background information on the case study area of the Lunan Water Catchment and the main data sources used for this research, and summarises the policy scenarios and measures that will be assessed. The final section concludes with some remarks on the appropriateness of the methodology for WFD purposes.

2. Previous Research on the WFD

A variety of studies assess the socio-economic and environmental implications of alternate water policy options by means of mathematical programming modelling. However, few of these studies analyse explicitly the interactions of the WFD with CAP. Additionally, there is a clear focus on water quantity rather than water quality problems. CAP influences the pressures exercised by agriculture on water quality in multiple ways. First, the decoupling of subsidies and production levels and the introduction of the Single Farm Payment, is expected to direct farmers from a subsidy-oriented to a market-oriented approach, thus changing the composition and levels of agricultural output. Secondly, the imposition of cross compliance measures, such as measures for the protection of water in Nitrate Vulnerable Zones, can significantly ameliorate compliance with respect to the WFD. Finally, the potential new agri-environmental measures, under the rural development programs, can provide additional incentives to the direction of achieving water quality objectives. Clearly, greater attention is required to the interplay between water quality measures and CAP scenarios (Bartolini *et al.*, 2007).

Additionally, in most studies the integration of economic and biophysical processes is achieved by attaching simple or indirect indicators to the economic analyses. For example the biophysical factors related to productivity are represented by using ad hoc indicators such as dummy variables for the effect of soil types and average rainfall during the growing season (Stoorvogel & Antle, 2001). Similarly, the representation of the environmental damages is by means of technical coefficients related to the levels of production of outputs or consumption of inputs (Flichman, 2002). This results in the poor representation of the complexity of the links between agricultural production and the environment, as it implies linear straightforward relationships between biophysical characteristics of the agricultural environment, the production levels and the environmental impacts. Table 1 depicts some examples of studies on the WFD.

Table 1. Modelling studies on the WFD

Study	**CAP-WFD Interactions**	**Water Resources Indicators**	**Economic Method**
Bartolini *et al.* (2007)	Yes (no cross-compliance)	Nitrogen use	Linear Programming Principal-Agent Model
Blanco (2006)	n/a	Fertiliser use Water Consumption	Positive Mathematical Programming
Martínez & Albiac (2006) Martínez (2006)	n/a	Water Consumption Nitrogen use Soil nitrogen content Nitrogen leaching	Dynamic non-linear programming
Mejías *et al.* (2006)	Yes	Water consumption	Stochastic Dynamic Programming
Gómez-Limón & Riesgo (2004a; 2004b)	n/a	Water Use Nitrogen Use	Multicriteria Mathematical Programing
Bazzani (2005) Bazzani *et al.* (2005)	Yes	Water Use Calculated Nitrogen Balance	Multicriteria Mathematical Programing

3. Bio-economic Modelling Methodology

The case of nitrogen use is a particularly sensitive issue, given that it is one of the most significant factors determining farm productivity and agricultural diffuse pollution. The impact of nitrogen use on crop yields and pollution losses is determined by complex processes controlled by both natural and man-made factors. Climate characteristics, such as rainfall and temperature, and soil types have a critical influence to the nature and rate of nitrogen losses. The amount of nitrogen potentially available for leaching and run-off is also highly affected by crop types and crop rotations. Additionally, the amount, timing, application methods and types of fertilisers used are of major significance. These relationships should be explored and taken into account when analysing the impacts of agricultural production on water resources. This multidisciplinary problem can be overcome by adopting insights from the natural sciences and incorporating them into economic analysis, by means of bio-economic modelling.

Bio-economic models facilitate the integration of socio-economic and agro-ecological information by linking biophysical models to mathematical programming models (MPM). A diagrammatic representation of a bio-economic model is given in Fig. 1. The MPM describes farmers' production and management decisions. The objective function states the farmer's objectives, which are optimised subject to a set of explicitly defined technical, agronomic, economic and institutional constraints. The biophysical model describes the relevant production and environmental processes. It is thus used to establish agronomic and environmental pollution relationships, which serve as an input to the MPM. The selected agricultural activities simulate how the farmer's goals described by the objective function could be achieved (Janssen & van Ittersum, 2007), while the socio-economic and environmental effects resulting from the selected activities are reported.

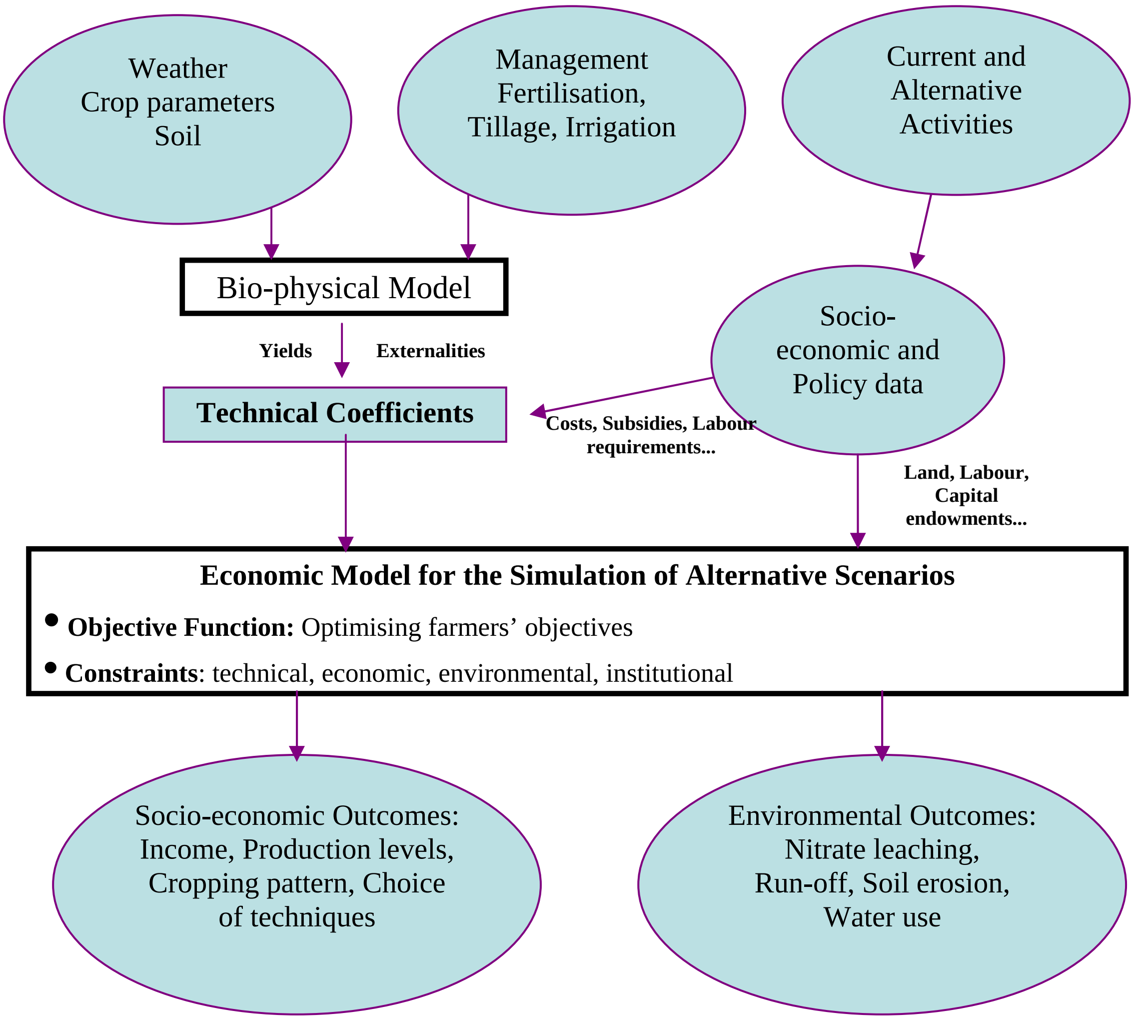

Figure 1. Scheme of a Bio-Economic Model
Adapted from Ghali (2007) and Flichman (1997)

3.1 The Estimation of Production and Pollution Functions

The incorporation of information regarding production and pollution functions into the framework is of central importance. There are a variety of ways for the estimation of such functions. The econometrics approach uses time series or cross-section statistical data which are adjusted to "a priori" defined mathematical functions (Flichman, 1997). This approach for estimating production functions is subject to limitations, summarised by Flichman (1997). Another approach is to use site- and situation-specific data from agronomic experiments for constructing engineering production functions (*ibid*). Therefore, changing any of the weather, soil, and/or cultivar parameters, would involve repeating a whole experiment (Steduto, 1997). Similar problems arise regarding management, as data will exist only for the management practices that were actually used at the time of the experiment. It is difficult to analyse separately the effect on crop growth of fertilisation, irrigation, weather, soil type, previous crop in the rotation, etc. (Flichman, 1997), which adds to the problem. These issues are even greater in the case of pollution. The diffuse nature of the phenomenon and the time lags between nitrogen applications and nitrogen losses makes it difficult to establish a clear relationship between all the interacting factors and the resulting losses, even if sufficient experimental data exist. When analysing agricultural production in relation to water pollution, alternative techniques and varying levels and timing of fertilisation and irrigation need to be assessed. Given the challenges described, the use of agronomic simulation models can be a viable and reliable alternative, overcoming the scarcity of consistent data and approaches for the estimation of accurate production and pollution functions.

3.2 The Biophysical Component: Cropping Systems Simulation Model

Agronomic simulation models deal with the effects of weather, soil types, inputs, management practices, and their interactions on agricultural productivity and yields. In addition, they can provide information on specific environmental attributes of different agricultural activities, using the same input parameters. Effectively these models consist of a set of non-linear mathematical equations describing the complex biophysical processes that take place within the agricultural system. The selection of the appropriate agronomic model for each particular case is not a straightforward task (Saraiva, 2006). A distinction can be made between single-crop and multi-crop models. As Steduto (1997) stated, the single-crop models differ in the input/output variables selected. Clearly, that makes multi-crop models more appropriate for bio-economic modelling applications. The same input parameters are required, while consistent output is provided for the wide range of crop activities that are included in the economic model. Additionally, the responsiveness of the model to the target decision variables is a significant factor. Given that dynamic process models handle a limited set of agronomic decisions, the model chosen should not constrain the decision options that would like to be considered (Hansen, 2002). Availability and quality of model data have also to be considered, as they are often found to be a constraining factor (Bouman *et al*., 1996).

CropSyst was identified as the most appropriate crop model for the needs of this research. It is a multi-year, multi-crop, daily time step, simulation model that simulates an array of biophysical processes taking into account climatic characteristics, soil types, crop characteristics, and farming management options such as crop rotation, cultivar selection, nitrogen fertilisation, irrigation, tillage operations and residue management. The simulated processes include crop growth, nitrogen leaching and run-off, and soil erosion. CropSyst offers an extensive menu of options for inorganic and organic fertilisation, as well as a wide range of choices regarding the applied amount of nitrogen, the source of nitrogen, and the application method. It has been widely used to analyse the effects of alternate fertilisation practices on crop growth and the associated environmental effects (e.g. Morari *et al*. (2004); Belhouchette *et al*. (2004); Sadras (2002); Le Grusse *et al*. (2006)). In Scotland, it is one of the few models that have been used for integrated ecological-economic analyses in relation to agriculture. It is part of the LADSS integrated modelling framework, simulating whole farm systems (LADSS, 2005). Additionally, Rivington *et al*. (2007) and Hanley *et al*. (2005) used it to explore the impacts of climate change on agriculture. In the current research, it will be used to mathematically express the input-output technical/environmental coefficients in relation to yield, nitrate leaching, nitrate run-off and soil erosion.

3.3 The Economic Component: Farm System Simulator – Mathematical Programming

Economic models based on mathematical programming have been widely used for agricultural economics policy analysis. Often MPMs are identified as normative/mechanistic models, while econometric models as positive/empirical models (Flichman, 1997)[1]. Nevertheless, mechanistic bio-economic MPMs can be used in a positive way (Janssen & van Ittersum, 2007; Flichman, 1997). In the agronomic/environmental space, this can be facilitated by high levels of technical specification, along with the coupling to biophysical modelling (Flichman, 1997). In the socio-economic space, further insights regarding the representation of farmers' behaviour, can be provided by a more sophisticated formulation of the objective function, departing from the typical linear programming profit maximisation approach.

FSSIM-MP has been developed as a positive mechanistic bio-economic MPM[2]. The non-linear objective function represents expected income and risk aversion towards price and yield variations (van Ittersum *et al.*, 2007). The model is calibrated using the risk approach, and subsequently complemented by an extension of the PMP approach (Howitt, 1995)[3], inspired by Röhm and Dabbert (2003) (Flichman *et al.*, 2006). The model has a high technical specification and is coupled with a biophysical model. The definition of the agricultural activities is multi-dimensional. Thus the different factors affecting the agricultural activities can be simultaneously taken into account. Given this approach, the production activities can be specified as discrete and independent options, whether they refer to different crop or livestock activities, to different technologies for the same activity, or to variations of the same technology (Ruben *et al*., 1998). This allows one to deal with a wide range of production activities, with differences in the levels of inputs, management practices, etc., when the other complementary factors are constrained. Additionally, crop activities are defined as rotational activities, which can have significant effects in terms of crop growth and residual nitrogen, rather than individual crop activities. The definition of the activities as rotations facilitates the conceptual and practical integration of biophysical and economic modelling, because it allows the effects of the previous crops to be considered in a consistent manner by both the biophysical and the economic model.

FSSIM-MP follows a joint production approach using discrete production/pollution functions for the incorporation of production and environmental information. Effectively, the agricultural activities are defined as vectors of technical/environmental coefficients describing the inputs, the outputs and the environmental effects (Ruben *et al.*, 1998). Other predominant approaches for the inclusion of environmental impacts of agricultural activities into economic modelling involve the incorporation of pollution functions or of cost functions as a proxy for environmental damages[4]. The estimation of continuous pollution functions and their incorporation into economic modelling has often been criticised in the literature. This is because continuous production functions cannot adequately capture the synergistic effects that can result from interactions between inputs (Kruseman & Bade, 1998; Ruben *et al.*, 1998) and biophysical factors[5].

---

[1] Janssen & van Ittersum (2007) provide a clear definition of the terms.
[2] A detailed analysis of FSSIM-MP can be found in www.SEAMLESS-IP.org.
[3] PMP is a methodology that adds quadratic cost terms to the objective function, ensuring that the model outcomes in the base run calibrate exactly to the observed production levels (Janssen & van Ittersum, 2007).
[4] This approach facilitates the optimisation of environmental targets, since monotonous convex function behaviour that can be minimised is assigned to externalities.
[5] A more extensive analysis of the issue can be found in Flichman & Jacquet (2003).

4. Spatial and Temporal Scale Approaches and Methodology

The problem of selecting the appropriate spatial and temporal scale of analysis for bio-economic modelling is linked to two main concerns. First, the wide arrays of agronomic/environmental and economic processes, between which the causal relationships have to be established, operate at different spatial and temporal scales. Crop production and environmental processes take place at the field level on a daily basis. Farmers make their main cropping decisions at the farm level on a seasonal or yearly basis, while some management decisions, such as fertilization, are made on a daily or weekly basis. Second, while the integration of biophysical and economic models typically occurs at a highly disaggregated level so as to capture biophysical and economic behaviour heterogeneity, policy making is interested in larger units of analysis, such as the river basin or the regional/national level, and in the long-term effects of environmental and agricultural policy regulations.

4.1 Spatial Scale

There are typically three approaches to spatial scale. The first involves modelling a single farm or few representative farm types. The farm-level approach is appropriate for primary policy analysis, as it is the level at which the actual decisions about cropping patterns, production intensity, etc. are made (Falconer & Hodge, 2001). However, this level of analysis provides little information to policy makers who are interested to the aggregate results of policies. The second approach involves modelling the whole area of interest as a single farm. This overstates flexibility of resources by ignoring farm boundaries and resource ownership, while totally ignoring the behavioural heterogeneity of the different farmers in relation to their resources and production patterns. A third approach that retains the merits of the first approach while overcoming the drawbacks of the second, involves modelling average farms and upscaling to the whole study area. This is sufficiently more complex and data demanding that the other two approaches, as it requires aggregation or disaggregation and up- and down-scaling of information between the levels of biophysical and economic relationships (Bouman *et al*., 1999) and then of these relationships at the catchment/river basin level.

In this study the third approach will be pursued. The land and farms of the area under study will be divided into homogenous units, the different processes modelled at the appropriate level, and then up-scaled through aggregation procedures. The land and farm typology will be based on the criteria/variables to which the results show significant sensitivity and will be developed on the principle of maximising the heterogeneity between types and minimizing it within types. A sensitivity analysis will be carried out with CropSyst to determine the most appropriate variables to represent soil productivity and drainage properties. The farms will be distinguished into types according to size, production pattern, and production intensity, by means of cluster analysis.

4.2 Temporal Scale

Procedures that link different temporal scales of analysis offer a better representation of the agricultural system compared to approaches that use a single scale. As biophysical modelling aims at capturing the natural processes, while economic modelling farmers' decision making, typically the former are modelled on a daily basis, while the latter on a seasonal or yearly basis (Vatn *et al*., 2006).

A more explicit representation of the time dimension of economic models can be provided by using dynamic models that capture some of the decision variables as functions of time (Blanco Fonseca & Flichman, 2002), as opposed to static models, which model a period with one time step. A special category of dynamic models is recursive models, where the results of each decision period have an influence on the decisions to be taken on the following decision period (Belhouchette *et al*., 2004)[6].

Although the economic model used in this research, is a comparative static one, some dynamic aspects are taken into account, as the activities are defined as rotations and the biophysical model is run for a sequence of years. Consequently, the long-term effects of crop selection and management practices, in relation to soil nitrogen stock and the associated nitrate leaching are taken into account explicitly by the biophysical model and implicitly by the bio-economic model. Nevertheless, this approach does not allow a close representation of the feedbacks between the biophysical and socio-economic system. This task however is not a trivial one, which probably explains why most bio-economic models do not take time explicitly into account (Janssen & van Ittersum, 2007). As Vatn *et al*. (2003) state one would like to model all processes simultaneously and explicitly, but this is hindered by limited understanding of some processes and danger of over-complex and opaque models.

5. Case Study Application

5.1 The Lunan Water Catchment

The case study area is the Lunan Water Catchment, located on the East Coast of Scotland in the region of Angus. The area includes three rivers (Lunan Water, Gighty Water, Viny Water) divided into five water bodies. The Lunan Water Catchment is one of the two priority catchments monitored under the Diffuse Agricultural Pollution Action Plan of the Scottish Environment Protection Agency (SEPA), as it is at risk of not meeting the environmental objectives of the WFD (SEPA, 2007). It is a partly groundwater fed catchment, draining an area of 134km² (SEPA). The whole catchment falls within a designated river nutrient sensitive area and a nitrate vulnerable zone (*ibid*). The land use in the catchment is representative of arable cropping in Scotland (SEPA, 2007), as it consists of intensively arable agriculture with cereal crops, potato and root crop cultivation (SEPA).

Bio-economic modelling is associated with high data intensity. Table 2 depicts the main data sources that are used for this study. Except from the conceptual and methodological integration, integration of data available at administrative and physical boundaries is also necessary. A particularly challenging and data demanding, albeit crucial, task remains the spatial allocation of the farms within the landscape, which is necessary for matching the soil types with the farm types. The catchment is situated within an area of 12 agricultural parishes. Highly disaggregated data on the individual farms of the agricultural parishes have been obtained. However, this data are not spatially explicit, except from the information on the parish within each of the farms is located. Given the soil heterogeneity within the parishes, this information is not sufficient. For the achievement of this task spatially explicit

[6] An overview of different types of dynamic models, including recursive models, intertemporal models, and dynamic recursive models is provided by Blanco Fonseca and Flichman (2002).

land use data are needed as an intermediary variable[7]. This will also be necessary for separating the farms of the 12 parishes that fall within the catchment from the rest of the farms.

Table 2. Data Sources

Data Source	Information	Use
June Census Data	Farm Data: Observed activity levels, land ownership and labour use for each of the individual farms of the agricultural parishes of the area	Farm Classification, FSSIM-MP Calibration
EARWIG Weather Generator	Climate Data: Daily values of precipitation, max and min temperature, solar radiation, and approximate windspeed for the Lunan Water Catchment	CropSyst Simulations
Scottish Soils Knowledge and Information Base (Macaulay Institute)	Soil Data: Soil texture, drainage description, permanent wilting point, field capacity, organic matter content, and pH, for each of the soil series present in the catchment. Spatial allocation of soil series within the catchment	CropSyst Simulations, Soil Types Classification, Linkage of Farm Types and Soil Types
Scottish Fertiliser Survey, RB209 Report	Fertilisation Data: Timing and amount of fertiliser applications	CropSyst Simulations, FSSIM-MP Simulations
Farm Management Handbook	Cost Data on crop activities	FSSIM-MP Simulations
Expert Opinion	Fertilisation Data (validation) Cost Data (differentiation for various practices) Other Management Data (tillage, sowing, harvesting)	CropSyst Simulations, FSSIM-MP Simulations

5.2 Scenarios and Measures

The scenarios needed to analyse the potential for reduced nitrate losses can either consist of individual measures or packages of a combination of measures. A wide array of measures can be proposed, including regulatory instruments, economic instruments, and managerial measures. Table 3 depicts some examples. The measures can be assessed by their effectiveness and efficiency. The effectiveness of a policy measure can be measured by the level of achievement of the objective that this measure is targeting, and efficiency by the costs involved in achieving the objective (Flury *et al.*, 2005). Combining these two attributes ensures that the cost-effectiveness of measures is taken into account, as dictated by the Directive. However, the measures can differ in their impact on individual farms, depending on their resource endowments, their location and their production orientation. Therefore these distributional effects should not be neglected.

The different measures will be evaluated under various policy scenarios. These will be formulated against the policy drivers that are already in place. Although the WFD is one of the main policy drivers in relation to our study, no specific scenario can be formulated as the relevant River Basin Management plan will not be released till 2009. However, the possible measures that might be adopted

[7] Such data are difficult to obtain due to confidentiality reasons. It might be necessary to make some broad assumptions on where the farms are situated, followed by a sensitivity analysis.

Table 3. Measures for the Reduction of Nitrate Losses

Measure	**Description**
A. Economic Instruments	
Tax on pollution emissions	Charges per kg of emissions
Tax on fertiliser inputs	Tax on inorganic fertiliser inputs
B. Regulatory Instruments (quotas, standards)	
Standard on pollution emissions	Standard on the allowable level of pollution emissions per ha
Quota on nitrogen input (average per ha)	Maximal fertilisation threshold as an average per ha
Quota on nitrogen input (specified per activity)	Maximal fertilisation threshold for each of the activities
Best Management Practices	
Catch crop obligations	Land requirement on catch crops/grass cover
Manure storage requirement	Adequate storage requirement for manure
Tillage obligation	Abandon autumn tillage
Animal feeding	Feeding practices reducing excretion
Ploughing obligations	Early ploughing shortly after harvest
Split fertilisation	More fertiliser applications of smaller doses
Stocking density restrictions	Reduced stocking density

under the WFD implementation will be analysed. The other two main policy drivers that influence water pollution from agricultural sources are the Nitrates Directive and the Common Agricultural Policy. The year 2002 was chosen as the base year, as it was prior to the introduction of the Nitrate Vulnerable Zones (NVZ) regulations and the implementation of the 2003 CAP Reform and was devoid of any major policy changes that could significantly affect the agricultural sector and by consequence the farmers' production decisions. The Agenda 2000 regulations will be incorporated in the base year scenario. The CAP Reform 2003, introduced in Scotland in 2005, will be the subsequent scenario. This deals with the introduction of the single farm payment, cross-compliance and modulation. A major cross-compliance measure in Scotland is the compliance with the NVZ regulations, introduced in 2003.

These consist of the Action programme for Nitrate Vulnerable Zones (Scotland) Regulations 2003 (SSI 2003 no 51). The related measures can be broadly classified as a) restrictions on the quantity of N applied; b) restrictions on the timing of N applications; c) manure storage requirements; d) record-keeping requirements; and e) other restrictions on N application. The NVZ regulations will be first modelled as a separate scenario and then combined with the other CAP 2003 Reform regulations[8]. The scenario will look at both the current regulations and the modified regulations that were the result of consultation by the Scottish Executive[9]. A greater flexibility concerning the closed periods will be allowed, given that this is a major concern of farmers. Although the NVZ regulations are enforced, they will be modelled as a scenario, due to several reasons. First, the NVZ regulations are still open to discussion, as there are concerns related to their effectiveness from the regulator’s point of view, and concerns on their economic impacts from the farmers’ point of view. Additionally, full compliance

[8]The modular nature of FSSIM-MP largely facilitates the modelling of combined scenarios. The various scenarios can be written in separate GAMS files, and activated or deactivated by turning the relevant “include” commands on and off.

[9] In February 2007, the Scottish Government, after evaluating the current Action Programme as insufficient, have consulted on a number of modifications to it (Scottish Executive, 2006).

with the regulations is probably unrealistic, so activities and management practices not allowed by the regulations should also be considered.

6. Concluding Remarks

Combining biophysical and economic models into a single analytical framework can greatly assist policy making. The use of biophysical models can provide crucial insight into the production and pollution functions, which is a necessary condition for their effective incorporation into economic models. Subsequently, bio-economic modelling can facilitate the comprehensive representation of the agricultural system, offering the opportunity to simulate the effects of policy scenarios on agricultural production and the associated economic and environmental impacts. The methodological approach offers significant advantages for WFD implementation purposes. It allows a detailed exploration of the combined costs and effectiveness of measures, while considering the distributional effects on different farm-types. This is achieved at two spatial scales: the farm scale that offers a better representation of farmers' actual behaviour and the catchment scale that allows consideration of the aggregate policy impacts. Additionally, the approach permits taking into account farmers' adaptability to the potential WFD measures and other policy drivers influencing agricultural production, such as the CAP. This feature is of importance, as ignoring it can lead to a mis-estimation of the expected costs and environmental improvements.

Although the methodological approach offers great advantages, it is associated with high data intensity and time requirements. Therefore, it would be unrealistic to suggest that it could be applied to a great number of river basins. Still, its use for representative case studies is useful, since it can provide a greater understanding of the agricultural system processes and the potential implications of different measures. These processes are significantly variable for different socio-economic and physical environments and great heterogeneity can be found even within small catchments. Although the establishment of detailed measures for different areas and farm types would be associated with high transaction costs, it is important to be aware of the differential impacts. Finally, it should be acknowledged that models are eventually the simplification of a reality subject to uncertainty related to both actors' behaviour and ecological processes complexities. Therefore, model validation, public participation and a close monitoring of the actual effects of policies should be pursued to the greatest possible extent. At the same time, it is necessary to explore the system in depth through an interdisciplinary approach that can broaden our understanding, and possibly our predictive capacity.

Acknowledgements

The authors wish to acknowledge the funding from RERAD.
Part of the work presented benefits from the SEAMLESS integrated project, EU 6th Framework Programme for Research Technological Development and Demonstration, Priority 1.1.6.3. Global Change and Ecosystems (European Commission, DG Research, contract no. 010036-2; www.seamless-ip.org).

References

Bartolini, F., Gallerani, V., Raggi, M. and Viaggi, D. (2007). Implementing the Water Framework Directive: Contract design and the cost of measures to reduce nitrogen pollution from agriculture. *Environmental Management* 40: 567-577.

Bazzani, G.M. (2005). A decision support for an integrated multi-scale analysis of irrigation: DSIRR. *Journal of Environmental Management* 77: 301-314.

Bazzani, G.M., Di Pasquale, S., Gallerani, V., Morganti, S., Raggi, M. and Viaggi, D. (2005). The sustainability of irrigated agricultural systems under the Water Framework Directive: first results. *Environmental Modelling & Software* 20: 165-175.

Belhouchette, H., Blanco M. and Flichman G. (2004). Targeting sustainability of agricultural systems in the Cebalat irrigation district in Northern Tunisia : An economic perspective using a recursive stochastic model. 13th Annual European Association of Environmental and Resource Economics Conference, Budapest, Hungary, 25-28 June. http://eaere2004.bkae.hu/download/paper/blanco1paper.doc. Accessed 27 October 2006.

Blanco, M. (2006). Sistema de ayuda a la decisión para estimar efectos ambientales y socioeconómicos del precio del agua. Enforque basado en PMP. International Workshop Hydro-economic modelling tools for implementation of the EU Water Framework Directive, Valencia, Spain, 30-31 January.

Blanco Fonseca, M. and Flichman, G. (2002). Dynamic optimisation problems: different resolution methods regarding agriculture and natural resource economics. Working Paper, Universidad Politécnica de Madrid and CIHEAM-Institut Agronomique Méditerranéen de Montpellier, Montpellier.

Bouman, B.A.M., van Keulen, H., van Laar, H.H., and Rabbinge, R. (1996). The School of de Wit crop growth simulation models: A pedigree and historical overview. *Agricultural Systems* 52: 171-198.

Bouman, B.A.M., Jansen, H.G.P., Schipper, R.A., Nieuwenhuyse, A., Hengsdijk, H. and Bouma, J. (1999). A framework for integrated biophysical and economic land use analysis at different scales. *Agriculture, Ecosystems & Environment* 75: 55-73.

Falconer, K. and Hodge I. (2001). Pesticide taxation and multi-objective policy-making: farm modelling to evaluate profit/environment trade-offs. *Ecological Economics* 36: 263-279.

Flichman G. (1997). Bio-economic models integrating agronomic, environmental and economic issues with agricultural use of water. *Options Méditerranéennes* Sér.A /31: 327-336.

Flichman, G. (2002). Building Agro-Environmental Indicators by the Integration of Biophysical and Economic models for Assessing Sustainability of Agricultural Trade Liberalisation. SIAP Workshop Methodological Tools for Assessing the Sustainability Impact of the EU's Economic Policies, with Applications to Trade Liberalisation Policies, Brussels, Belgium, 7-8 November. www.cepii.fr/anglaisgraph/communications/pdf/2002/siap1102/flichman.pdf. Accessed 15 November 2006.

Flichman, G. and Jacquet, F., (2003). Couplage des modèles agronomiques et économiques: intérêt pour l'analyse des politiques. *Cahiers d'Économie et Sociologie Rurales* 67: 1–20.

Flichman, G., Donatelli, M., Louhichi, K., Romstad, E., Heckelei, T., Auclair, D., Garvey, E., van Ittersum, M., Janssen, S. and Elbersen, B (2006). Quantitative models of SEAMLESS-IF and procedures for up-and downscaling, SEAMLESS Report No.17, SEAMLESS integrated project, EU

6th Framework Programme, contract no. 010036-2, www.SEAMLESS-IP.org, 112 pp, ISBN no. 90-8585-044-4.

Flurry, G., Gotsch, N. and Rieder, P. (2005). Site-specific and regionally optimal direct payments for mountain agriculture. *Land Use Policy* 22: 207-214.

Ghali, M.A. (2007). Un modèle bioéconomique d'exploitation pour l'analyse de l'écoconditionnalité et des mesures agrienvironnementales de lutte contre l'érosion - Cas du Lauragais. Unpublished MSc Thesis. Montpellier, CIHEAM-IAMM.

Gómez-Limón, J.A. and Riesgo, L. (2004a). Irrigation water pricing: differential impacts on irrigated farms. *Agricultural Economics* 31: 47-66.

Gómez-Limón, J.A. and Riesgo, L. (2004b). Water pricing: Analysis of differential impacts on heterogenous farmers. *Water Resources Research* 40 W07S05 doi:10.1029/2003WR002205.

Hanley, N., Oglethrope, D., Swales, K. and Tinch, D. (2005). *Predicting the Distributional Impacts of Climate Change on Agriculture.* European Association of Environmental and Resource Economists 14th Annual Conference, Bremen, Germany, 23-26 June. http://www.webmeets.com/EAERE/2005/Prog/viewpaper.asp?pid=201 Accessed 8 September 2006.

Hansen, J. (2002). CLIMAG-West Africa, Harmonisation of Climate Prediction for Mitigation of Global Change Impact in Sudano-Sahelian West Africa, Project EVK2-CT-2000-80001. Deliverable 17, Recommendation from Expert Meeting on Crop Modelling. Plant Research International; Institut d"Economie Rurale, ICRISAT, START.

Howitt, R. (1995). Positive Mathematical Programming. *American Journal of Agricultural Economics* 77: 329–342.

Janssen, S. and van Ittersum, M.K.(2007). Assessing farm innovations and responses to policies: A review of bio-economic farm models. *Agricultural Systems* 94: 622-636.

Kruseman, G. and Bade, J. (1998). Agrarian policies for sustainable land use: Bio-Economic modelling to assess the effectiveness of policy instruments. *Agricultural Systems* 58: 465-481.

LADSS (2005). LADSS, Land Allocation Decision Support System. www.macaulay.ac.uk/LADSS.shtml. Accessed 12 December 2007.

Le Grusse, P., Belhouchette, H., Le Bars, M., Carmona, G. and Attonaty, J. (2006). Participative modelling to help collective decision-making in water allocation and nitrogen pollution: Application to the case of the Aveyron-Lere basin. *International Journal of Agricultural Resources, Governance and Ecology* 5: 247 – 271.

Martínez, Y. (2006). Instrumentos Económicos para el Control de la Contaminación : Applicación a la Cuenca del Ebro. International Workshop Hydro-economic modelling tools for implementation of the EU Water Framework Directive, Valencia, Spain, 30-31 January.

Martínez, Y. And Albiac, J. (2006). Nitrate pollution control under soil heterogeneity. *Land Use Policy*, 23: 521-532.

Mejías, P., Varela-Ortega, C. and Flichman, G. (2004). Integrating agricultural policies and water policies under water supply and climate uncertainty. *Water Resources Research* 40 W07S03 doi:10.1029/2003WR002877.

Morari, F., Lugato E. and Borin, M. (2004). An integrated non-point source model-GIS system for selecting criteria of best management practices in the Po Valley, North Italy. *Agriculture, Ecosystems & Environment* 102: 247-262.

Rivington, M., Matthews, K.B., Bellocchi, G., Buchan, K., Stöckle, C.O. and Donatelli, M. (2007). An integrated assessment approach to conduct analyses of climate change impacts on whole-farm systems. *Environmental Modelling & Software* 22: 202-210.

Röhm, O. and Dabbert, S. (2003). Integrating agri-environemntal programs into regional production models: An extension of positive mathematical programming. *American Journal of Agricultural Economics* 85: 254-265.

Ruben, R., Moll, H. and Kuyvenhoven, A. (1998). Integrating agricultural research and policy analysis: Analytical framework and policy applications for bio-economic modelling. *Agricultural Systems* 58: 331-349.

Sadras, V. (2002). Interaction between rainfall and nitrogen fertilisation of wheat in environments prone to terminal drought: Economic and environmental risk analysis. *Field Crops Research* 77: 201-215.

Saraiva, J.P (2006). A bio-economic Modelling Approach for Irrigation Water Management: a Methodological Framework Using CropSyst and MCDA. II AERNA Conference, Lisbon, Portugal, 2-3 June. http://aerna2006.de.iscte.pt/lista_completa.htm. Accessed 5 December 2007.

Scottish Executive (2006). Protection of Scotland's Water Environment - Consultation on Proposed Amendments to the Action Programme for Nitrate Vulnerable Zones. Edinburgh, Scottish Executive. http://www.scotland.gov.uk/Publications/2006/11/16095031/0. Accessed 25 October 2007.

SEPA (2007). Press Release 2007: Rural water quality project is up and running *3 Apr 2007 - EXT01-B01*. http://www.sepa.org.uk/news/releases/view.asp?id=513&y=2007. Accessed 7 December 2007.

SEPA. Monitored Priority Catchments Angus Lochs/Lunan Water: Diffuse Agricultural Pollution Action Plan. Unpublished Report, Scottish Environment Protection Agency.

Steduto, P. (1997). Modelling for crop response to water: Physiological aspects. *Options Méditerranéennes* Sér.A /31: 289-312.

Stöckle, C.O., Donatelli, M., and Nelson, R. (2003). CropSyst, a Cropping Systems Simulation Model. *European Journal of Agronomy* 18: 289-307.

Stoorvogel, J.J. and Antle, J.M. (2001). Regional land use analysis: the development of operational tools. *Agricultural Systems* 70: 623-640.

Van Ittersum, M.K., Ewert, F., Heckelei, T., Wery, J., Olsson, J.A., Andersen, E., Bezlepkina, I., Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A.E., van der Wal, T., Wien, J.E. and Wolf, J. (2007). Integrated assessment of agricultural systems – A component-based framework for the European Union (SEAMLESS). *Agricultural Systems*, in press.

Vatn, A., Bakken, L., Bleken, M., Baadshaug, O.H., Fykse, H., Haugen, L.E., Lundekvam, H., Morken, J., Romstad, E., Rørstad, P.K., Skjelvåg, A.O., Sogn, T., Vagstad, N.H., and Ystad, E. (2003). ECECMOD 2.0 – An interdisciplinary research tool for analysing policies to reduce emissions from agriculture. Report no. 3/2002, Agricultural University of Norway, Aas. www.nlh.no/forskning/mildri/publikasjoner/ececmod_doc.pdf. Accessed 4 March 2005.

Vatn, A., Bakken, L., Bleken, M.A., Baadshaug, O.H., Fykse, H., Haugen, L.E., Lundekvam, H., Morken, J., Romstad, E., Rørstad, P.K., Skjelvag, A.O., and Sogn, T. (2006). A methodology for integrated economic and environmental analysis of pollution from agriculture. *Agricultural System*, 88: 270-293.