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Development of a watershed model for Cataloniato manage and reduce diffuse pollution

Fayçal Bouraoui, Angel Udias, Marco Pastori, Alberto Aloe

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Development of a watershed model for Catalonia to manage and reduce diffuse pollution

Final Report

JRC 31266-2009-02

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1. INTRODUCTION

BACKGROUND INFORMATION

In surface water bodies, the increase in nutrient concentration above the natural background levels enhances the productivity, causing the phenomenon of eutrophication (Nixon, 1995). Eutrophication has been identified as a major cause of impaired water quality of rivers, lakes and estuaries (EEA, 2001). Agriculture is considered the main responsible for nitrogen enrichment in water bodies (Kronvang et al. 1995; Larsen et al. 1999), while in the case of phosphorus, the households and industry wastewater discharges and the soil erosion are the principal sources of pollution (EEA, 2001). In Western Europe, agriculture is the main source of nitrogen loading to water bodies while agriculture and households contribute the most to phosphorus loading. The contribution of agriculture to nutrient loading into surface waters is highly variable ranging from more than 80% in Denmark to less than 30% in Finland for nitrogen and from more than 40% for Germany and Finland to about 17% for Belgium and United Kingdom for phosphorus (OECD, 2001).

To control and reduce pollution coming from nutrients, the EC has been setting stringent regulations. In 1991 the European Economic Community adopted the so called Nitrate Directive (91/676/EEC) and the Urban Waste Water Treatment Directive (91/271/EEC). In 2000, the European Commission adopted the Water Framework Directive 2000/60/EC (CEC, 2000) to establish a framework for the Community action in the field of water policy. With the WFD the water quality issue is tackled in a comprehensive way, integrating the previous regulations. The directive aims at protecting and enhancing the status of water resources and promotes a sustainable water use based on a long-term protection of the available water resources.

The enforcement of the WFD raises new challenges for the research and managerial community and models have been identified as the tools that can contribute to fulfill the requirements stated in the policy framework. In the case of nitrogen and phosphorus pollution, this involves the analysis of the role of the different sources (point and diffuse) in the nutrient export from the river basin.

As the total load of nutrient coming from point sources has severely dropped, emphasis has been put on controlling diffuse sources. Combating diffuse pollution from agriculture is complicated due to the temporal and spatial lag between the management actions taken at the farm level and the environmental response (Schröder et al., 2004). Beside the correct identification and quantification of sources, cost-effective nutrient mitigation requires the delineation of critical source areas, which contribute disproportionate amounts of nutrients to receiving waters. According to Dickinson et al. (1990), targeting and prioritizing diffuse pollution control has the potential to triple pollutant reduction, is financially attractive, and minimizes the extent of area affected negatively by restrictive land practices.

As water is a limited resource in Mediterranean countries it can generate conflict between the stakeholders. Indeed, availability and development of water resources need to consider requirements of households, irrigation, recreational needs, cost, in a context of global climate change and increasing water pollution. In general, natural resource development, use, and management decisions involve multiple conflicting objectives and criteria, and incommensurable units for measuring goods and services.

Natural resource managers must balance conflicting objectives when developing land and water management plans, as the exploitations of these resources are mutually conflicting. The extension of irrigated area is justified by its important role in the development and diversification of agricultural production. However, the intensification of the agricultural activities may lead to the pollution of water resources due to an excessive use of agrochemicals.

Selecting the best combination of management alternatives from numerous objectives is difficult and challenging. Multi-Criteria Decision Models (MCDM) provide a systematic approach for comparing tradeoffs and selecting alternatives that best satisfy the decision maker's objectives.

THE CASE OF CATALONIA

In this context, UTE DMA Gestio on behalf of the Catalan Water Agency (ACA) requested the JRC the transfer of GIS-EPIC, one of the modelling tools maintained by the JRC Rural, Water, and Ecosystems Resources Unit to help managing diffuse losses and elaborating scenarios of land use and land management in view of a sustainable use of natural resources in the region of Catalonia. The elaboration of the scenarios is evaluated through the use of a multi-criteria system linked to the EPIC model.

The tool could be summarized as follows:

- **Database**. The EAGLE European geodatabase holds all the necessary data (soil, meteorological, crop management, etc.) to perform EPIC simulations. A specific data model was designed, using the ESRI ArcGIS geodatabase environment, in order to structure all the relevant data (geographic and tabular) to perform EPIC modelling at regional or European scale.
- **EPIC model**. EPIC is a continuous simulation model that can be used to determine the effect of management strategies on agricultural production and soil and water resources. The drainage area considered by EPIC is generally a field-sized area, up to 100 ha (weather, soils, and management systems are assumed to be homogeneous). The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control. Within the EAGLE context, EPIC represents the logic tier where data input are processed to obtain relevant information for the specified study area.

- **GIS Interface**. This is an ESRI ArcMap customization that allows the use of EPIC using data stored in the previously described geodatabase through an intuitive GIS interface.

- **Genetic algorithm MOEA**. It is an iterative search algorithm that is based on the principles of evolution.

OUTCOME AND DELIVERABLES

The report describes the work performed in the frame of contract Reference JRC 31266-2009-02 titled “The development of a watershed model of Catalonia to manage and reduce diffuse pollution”. This reports summarizes the work done based on continuous interactions with representatives from UTE DMA and the ACA (Catalan Water Agency). The request was to produce a modelling and database template to be continuously populated with updated data by ACA. The study contract delivered:

- A database including all major data required to run a bio-physical model such as EPIC and it adaptation to the region of Catalonia
- Transfer of the GIS modelling tool for application in the region of Catalonia
- Support to the regional implementation of the tool
- Run basic EPIC simulation for the region of Catalonia
- Integrated EPIC model with a Multi Criteria Analysis tool as applied to Catalonia

The report will be structured in two parts. The first part summarizes the tools including model description, database development, transfer and implementation for the region of Catalonia. The second part is dedicated to the model application.

The database and the models have been delivered to the contractor during the reporting period, and they are also attached to this report. The JRC also hosted and trained staff from the contractor to the use of the integrated modelling tools. The progress of the project also benefited from a collaboration between the JRC and Rey Juan Carlos University, Madrid. In this context Prof. Angel Udias, expert in multi-criteria modelling performed a 6 months stage at the JRC. During this period several case studies for the different catchments of the Catalonia have been run and are presented in this report. The results of these studies show the great advantage of the integration of the tools developed by the JRC and the University of Rey Juan Carlos. These integrated tools will be useful to ACA as a basis for further development and application in the implementation of measures aiming at controlling emissions of nitrogen and phosphorus from agriculture. The JRC is available to support ACA or UTE DMA staff should they need help in the application of the modelling software and database.

2. GIS EPIC FOR CATALONIA

MODEL DESCRIPTION

The EPIC model as delivered to the contractor is described in details in Annex I.

DATABASE FOR CATALONIA

OVERVIEW

The most relevant aspects that drove the database design are listed below:

- geographical bidimensional units supporting EPIC runs are based on a 10 km grid
- original available input soil data (1 km resolution) were aggregated to the mentioned grid (10 km resolution),
- available input meteorological data (50 km resolution) should be spatially linked to the mentioned grid, and
- available landuse data (1 km resolution) was tabulated based on the mentioned grid to obtain area values of landuse classes as 10 km grid cell attributes.

Because EPIC runs on a specific landuse type, crop specific EPIC simulation can be achieved by modelling site units based on their crop specific attribute (crop type and geographical extent). As a result, each site unit is composed of crop specific subunits which are the atomic input for EPIC simulation (Figure 1). Subunits can be limited to the most predominant crops, resulting in simulation time saving, or can be used in full to model each crop contained into the specific 10 km run unit.

Figure 1 shows an example of crop specific subunits for a site (10 km square cell) that contains maize, rice, durum wheat and a non agricultural portion where EPIC modelling is not performed. Subunits can be seen as fictitious crop fields of a size which is the total crop area within the 10 km site cell with an undefined spatial location within the site cell having the soil, meteorological, topographic attributes of the whole site cell.

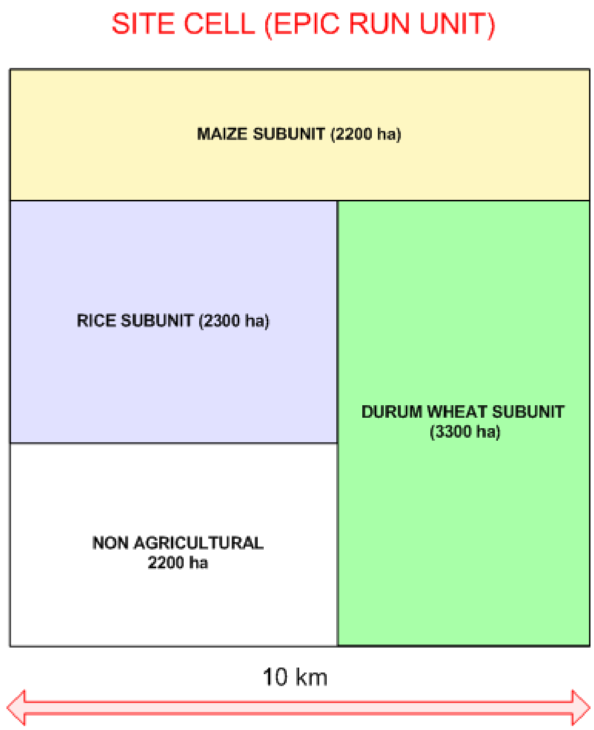


Figure 1. Crop specific run subunit

This conceptual model allows performing EPIC modelling based on the mentioned subunits re-aggregating back the results to run unit level. The previously illustrated conceptual model was implemented into an object relational data model within the context of the ESRI ArcGIS personal geodatabase.

INPUT DATA

Preliminary remarks

One of the problems encountered during the execution of the project has been the lack of data provision from the ACA side for achieving some of the objectives defined by the contract. In particular, ACA was in charge of providing detailed information on land use distribution and crop management schemes so that the JRC could tailor the European database to the specific conditions of Catalonia. The required data became available end of October 2010, well after the end of the project. So it was no longer possible to adapt the database on time and include this new data in this project as most of the simulation and optimization work was already finalized. Consequently, only the weather files provided on time by ACA were updated.

Soil Data

Most of the soil data required to run EPIC were derived from Pan European soil data provided by the JRC's European Soil Bureau Network (ESBN) (Jones et al., 2004) and contains:

- Soil Geographical Database of Europe (SGBDB),
- Soil Profile Analytical Database of Europe (SPADE),
- Hydraulic Properties of European Soils (HYPRES) database linked to the SGDBE, and
- Pedo-transfer Rules (PTR) database.

Soil data for were derived using the SMUs and 1 km x 1km soil raster data. The ESBN has created a series of 1 km x 1 km soil rasters including topsoil organic carbon content that has been calculated using a refined pedo-transfer rule derived from the European Soil Database, an extended CORINE land cover dataset, a digital elevation model (DEM) and mean annual temperature data (Jones et al., 2004). Additional data were provided as an ESRI grid raster dataset including the following layers:

- Topsoil sand content (%): SLP_SAND,
- Subsoil sand content (%): SLP_TDSAND,
- Topsoil silt content (%): SLP_SILT,
- Subsoil silt content (%): SLP_TDSILT,
- Topsoil organic carbon content (%): OCTOP_GRID,
- Topsoil cation exchange (cmo /kg soil): SLP_CECTOP,
- Subsoil cation exchange (cmo /kg soil): SLP_CECSUB,

A map of the aggregated soil clay content is displayed in Figure 2.

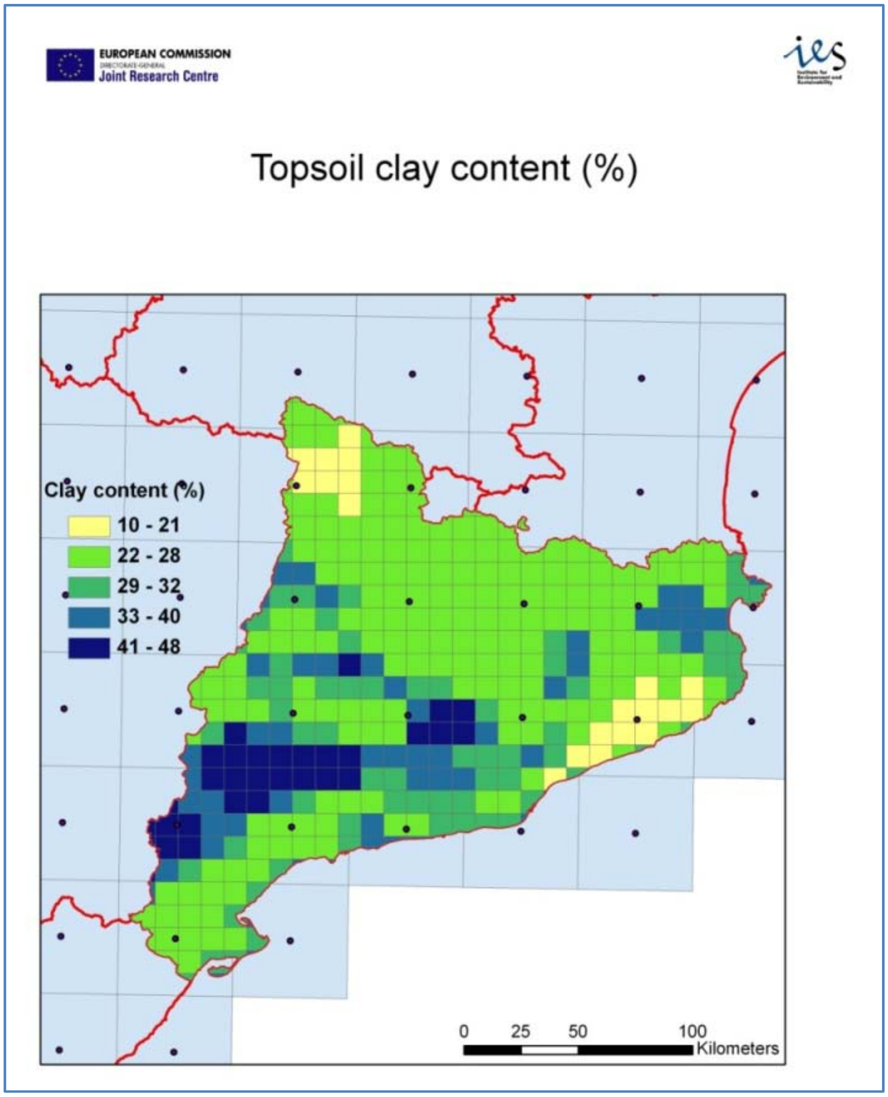


Figure 2. Top soil clay content (%) for the region of Catalonia.

Topographic data

Digital elevation data were provided by Institute for Environment and Sustainability at the Joint Research Centre as a pan European DEM based on SRTM (Shuttle Radar Topographic Mission) data. Data were obtained in ESRI grid format with a resolution of 90 m in Lambert Azimuthal Equal Area projection based on ETRS 89 datum (ETRS_89_LAEA). The DEM was used to discretize Catalonia into nine river basins displayed in Figure 3, and whose main characteristics are given in Table 1.

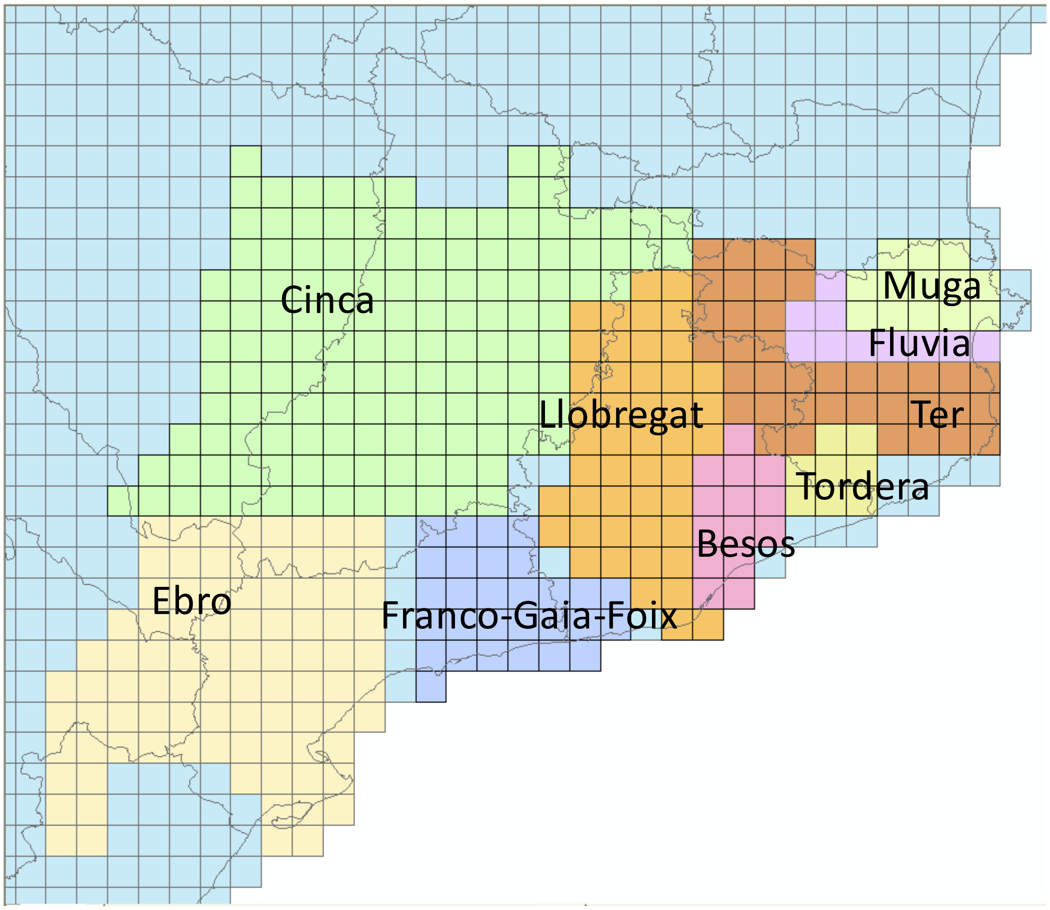


Figure 3. Map of the major river basins in Catalonia

Table 1. Main characteristics of the inner Catalan river basins

	Muga	Fluvia	Ter	Tordera	Besos	Llobregat	Foix	Gaia	Franco
A (km^2)	863	1008	2989	879	1029	5045	319	429	828
Length(km)	67	104	212	59	52	163	45	67	60
P($mmyr^{-1}$)	807	859	828	770	643	675	573	563	575
Q(m^3s^{-1})	3.3	9.4	17.1	7.2	6.8	19.3	0.3	0.3	1.1

A: surface, L: Length, P: precipitation; Q: natural average annual inflow

Landuse data

For the construction of a land use map two approaches were used, both based on FSS (Farm Structure Survey / Eurostat) statistical crop area data and Corine Land Cover 2000 (Mulligan et al., 2006). In the first approach that covers EU15, FSS data on crop areas were spatialised using the Corine Land Cover 2000 preserving the surface covered by each crop reported by

FSS (Grizzetti et al. 2006). For illustration purposes, the spatial extent of the barley (dominant annual crop in Catalonia) in 2000 is shown Figure 4. The list of the major crops considered is given below in Table 2.

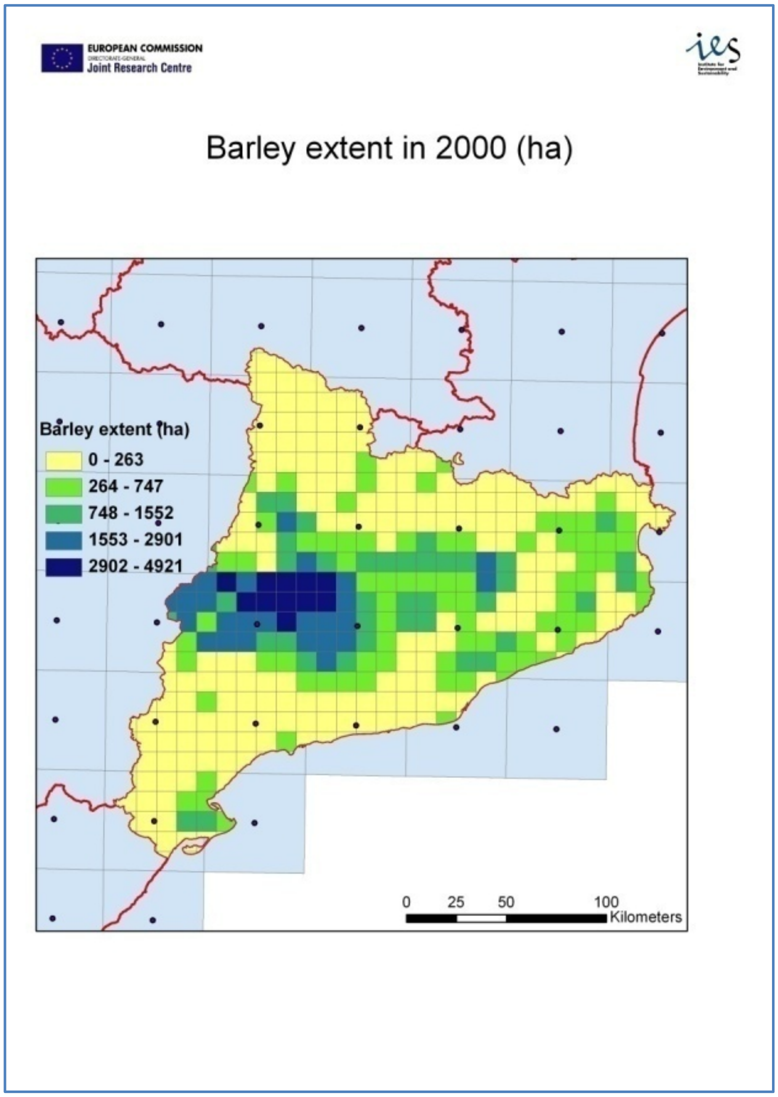


Figure 4. Barley extent (ha) for the region of Catalonia in year 2000.

The distribution of crops within the major river basins of Catalonia is summarized below in Table 3

Table 2 Major crops considered in the EPIC runs

DESCRIPTION	EPIC_CODE	EPIC_NAME
Common wheat and spelt	SWHT	Spring wheat
Maize	CORN	Corn
Rice fields	RICE	Rice
Olive plantations	OLIV	Olive trees
Durum wheat	WWHT	Winter wheat
Rye	RYE	Rye
Barley	BARL	Barley
Oats	OATS	Oats
Pulses - total	GRBN	Green beans
Potatoes	POTA	Potatoes
Sugar beet	SGBT	Sugar beets
Fodder roots and brassicas	SPOT	Sweet potatoes
Rape and turnip	RAPE	Rapeseed
Sunflower	SUNF	Sunflowers
Soya	SOYB	Soybeans
Other oil-seed or fibre plants	CANA	Canola argentine
Under glass:fresh vegetables; melons; strawberries	CRRT	Carrots
Forage plants - temporary grass	SGHY	Sorghum hay
Green maize:other green fodder:forage plants	CSIL	Corn silage
Vineyards - quality wine	GRAP	Grape
Fruit and berry plantations - total	APPL	Apple trees
Pasture and meadow:permanent grassland and meadow	SPAS	Summer pastures
Vineyards - other wines	GRAP	Grape
Vineyards - table grapes	GRAP	Grape
Vineyards - raisins	GRAP	Grape
Olive plantations - table olives	OLIV	Olive trees
Rough grazings:permanent grassland and meadow	SPAS	Summer pastures
Citrus plantations	CITR	Citrus trees
Other permanent crops	APPL	Apple trees
Permanent crops under glass	APPL	Apple trees
Tobacco	TOBC	Tobacco
Hops	TOBC	Tobacco
Cotton	COTS	Stripper cotton
Outdoor:fresh vegetables; melons; strawberries	TOMA	Tomatoes

Table 3. Extension of each crop in each basin (ha) in Catalonia

	Muga	Llobre	EbroC	EbroSC	Ter	Tord	Besos	Fluvia	F-G-F	%
APPL	997	2186	44878	62571	205	15	484	1337	24333	12.10%
BARL	2912	20953	14566	174864	13416	2370	8171	4000	6940	21.91%
CITR			1426						3642	0.45%
DWHE			2426	2151						0.40%
GRAE	5199	10821	77040	132506	11411	1821	472	4333	5544	22.00%
GRAI	7497	12109	22398	42752	16727	2771	1373	6429	1395	10.02%
LEFO			10							0.00%
MAIZ	1701	169	17	23670	1465			2507		2.61%
OATS		155	314		262		204			0.08%
OCRO			883						2641	0.31%
OFAO	527	1207		1533	1422	187	1603	491	2	0.62%
OFAR	1937	5147	590	54639	5929	1264	1996	2244	3	6.51%
OLIV	579	975	86818	12547	234				774	9.00%
PULS				59						0.01%
RICE			18606		610					1.70%
SUNF	27			1288	135	11				0.13%
SWHE	2696	11102	6133	42370	9493	1736	4540	3063	1991	7.34%
TABO			775							0.07%
TOMA		97	1876		19				666	0.23%
TWIN	1012	9717	9717	2500			146		22989	4.07%
TWIO	121	307	1073						3569	0.45%
TOTAL	**25205**	**74945**	**289546**	**553450**	**61328**	**10175**	**18989**	**24404**	**74489**	
%	2.23%	6.62%	25.57%	48.87%	5.42%	0.90%	1.68%	2.15%	6.58%	

Climate data

The initial data included in the EPIC data base was provided by AGRi4CAST (MARS Unit-JRC). The data was then updated by local climate data Agencia Catalana de L'Agua that consisted of daily records of precipitation and temperature.

GIS EPIC INTERFACE FOR CATALONIA

The EAGLE GIS interface was designed as an in-process server component (dll), developed into Microsoft Visual Basic 6 environment, to be plugged into ESRI ArcGIS. Main system requirements to use EAGLE server component can be listed as follows:

- Windows XP / Windows 2000/2003,
- ESRI ArcGIS 9.0 or higher,
- Microsoft Access 2000 or higher.

Once the server is properly registered, the ESRI ArcMap user interface is added with a new toolbar representing the user interface.

3. MULTI-CRITETIA DECISION ANALYSIS (MCDA)

MCDA IN AGRICULTURAL MANAGEMENT

In many European regions, increasing water shortage and extreme weather events such as summer droughts during the cropping season may cause more frequent yield loss and instabilities, and make areas less suitable for traditional crops. Hence, adaptation strategies for agricultural water resource management are needed to cope with the expected change in climatic conditions, taking into account possible increases in costs for supplemental water. These may include adjustments of crop rotations (e.g. shifting from high to low water-demanding crops) and of production intensities, use of reduced (or no) tillage, integration of cover crops, adoption of irrigation with efficient technologies and choice of water sources, retention of water in reservoirs (e.g. rainwater harvesting), introduction of suitable landscape elements to reduce runoff, or changes in stocking rates and livestock types.

Farmers who have sufficient access to capital and technologies should be able to continuously adapt their farming system by changing crops, adopting irrigation and adjusting fertilization (Easterling and Apps 2002). However, in connection with climate change this might intensify existing impacts on the environment and lead to new conflicts between ecosystem services (Schröter et al. 2005, IPCC 2007). For example, increased water use for irrigation could conflict with water demands for domestic or industrial uses, and lead to negative ecological implications (Bates et al. 2008). Also, soil loss through erosion may increase due to climate change, an effect which could be aggravated through changes in land management (Lee et al. 1999). To prevent continued degradation of natural resources, policy will need to support farmers' adaptation while considering the multifunctional role of agriculture (Olesen and Bindi 2002). Hence, effective measures to minimize productivity losses and preserve finite natural resources need to be developed at all decision levels, and scientists need to assist decision makers in this process (Salinger et al. 1999).

Multi-objective optimization (MOO) methods in connection with biophysical models have shown great potential for addressing such issues of opposing management goals (Ines et al. 2006, Bryan and Crossman 2008, Higgins et al. 2008, Sadeghi et al. 2009, Meyer et al. 2009, Whittaker et al. 2009 and Latinopoulos 2009). Bryan and Crossman (2008) developed an optimization-based regional planning approach to identify geographic priorities for natural resource management actions that most cost-effectively meet multiple natural resource management objectives. Higgins et al. (2008) applied a multi-objective integer programming model, with objective functions representing biodiversity, water runoff and carbon sequestration. Sadeghi et al. (2009) applied an optimization approach to maximize profits from land use, while minimizing erosion risk. Meyer et al. (2009) coupled SWAT (Soil and Water Assessment Tool) with an optimization routine to determine optimum farming system patterns to reduce nitrogen leaching while maintaining income. Similarly, Whittaker et al. (2009) applied SWAT in connection with a Pareto optimization approach considering profits from land use and chemical pollution from farm production. Latinopoulos (2009) applied optimization to a problem of water and land resource allocation in irrigated agriculture with respect to a series of socio-economic and environmental objectives.

For this work, we propose a MOO (Multi-Objective Optimization) that defines the conflicting objectives on management agricultural and watersheds resources. In the next section we describe the methodological approach used to select the most efficient agricultural practices while preserving water resources and maintaining the productivity of the agricultural holdings.

Description of the Methodology

In this study we apply a Multi Criteria evolutionary base methodological approach for identifying optimum adaptation strategies for agricultural land management with respect to multiple ecosystem services. These include not only food production but also water regulation, soil protection and nutrient cycling. This methodology applies a multi-objective optimization routine that integrates a biophysical model and a multi criteria mathematical optimization method. A relatively large number of criteria have to be considered for assessing the complex interactions between water and land use activities. MOOs are appropriate tool for this purpose. Considering the variety of stakeholders, a balancing of interest of various groups could be very difficult. The proposed approach is capable of providing a platform for public discussions of alternative measures or management decisions among stakeholders.

The integration of MOO with biophysical models makes it possible to consider simultaneously crop nutrient uptake, the leached fraction of fertilizers, and soil erosion. These estimates provide decision-makers with information about the environmental impacts of real and simulated farm management practices. The biophysical model used in this study is the Erosion-Productivity Impact Calculator (EPIC) (described in Annex I).

A genetic algorithm was used in this assessment as this type of approach has proven to be highly suitable for addressing complex combinatorial problems in many previous applications (Udías et al., 2007, Kuo et al. 2000, Ines et al. 2006, Whittaker et al. 2009, Liu 2009). It is an iterative search algorithm that is based on the principles of evolution (Goldberg 1989). The genetic algorithm used in this study will be referred to as MOEA. The integration of the MOEA and EIC is illustrated below in Figure 5.

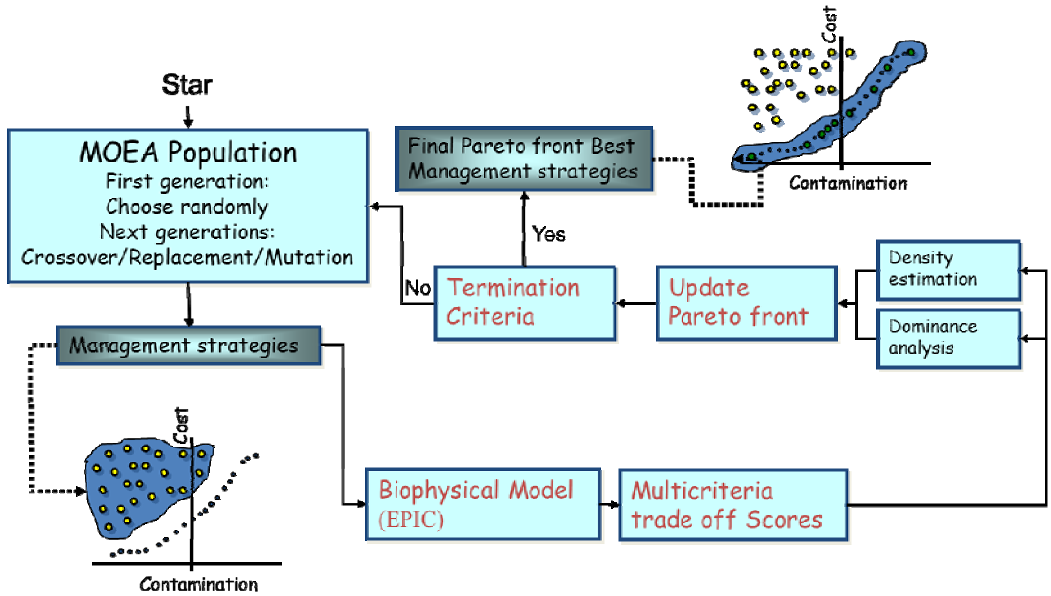


Figure 5. Flowchart of the MOEA- EPIC integration as applied to Catalonia

The key idea is to maximize farmers' returns and minimize water and fertilizer consumption and also minimize the nitrates leaching and percolated to preserve the quality of soil and water resources. The MOEA integrated with EPIC generates the trade-off curves between all the different objectives. These trade-off curves will help determine the opportunity costs of reducing nitrate pollution without increasing the environmental drawbacks. This is done usually by analyzing the Pareto front (Figure 6).

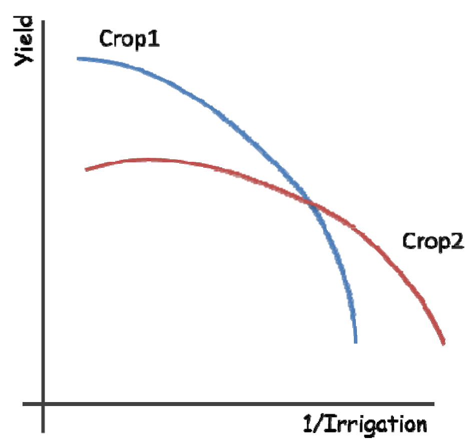


Figure 6. Example trade-off visualization analysis to help in the management decisions

Exploration of the Pareto frontier helps decision maker to understand the criterion tradeoffs and to identify a preferred criterion point directly at the Pareto frontier (the goal point).

Application of the Methodology to Catalonia

Trade-offs between maximum crop production, minimum water and fertilizer use and minimum nutrient leaching are investigated. The methodology is applied to identify optimum land management patterns in the major catchment in Catalonia. Preliminary results are presented to illustrate the optimization method and possible outcomes.

1. **Objectives:**

- maximize production,
- minimize irrigation,
- minimize fertilizer application,
- minimize the nitrate leached,
- minimize nitrates found in runoff.

2. **The decision variables:** In this first approach, the MOEA model controlled only 7 variables of EPIC, all concerning irrigation and fertilizer applied to each crop.

- BIR irrigation trigger,
- VIMX maximum annual irrigation volume allowed,
- ARMN minimum single application volume allowed,
- ARMX maximum single application volume allowed,
- BFT0 auto fertilization trigger,
- FNP fertilizer application variable,
- FMX maximum annual N fertilizer application for a crop.

MOEA runs EPIC model for several combinations, improving the solutions until it finds the effective strategies, i.e. the values of the variables that yield target output belonging (or very close) to the Pareto front (see Figure 7).

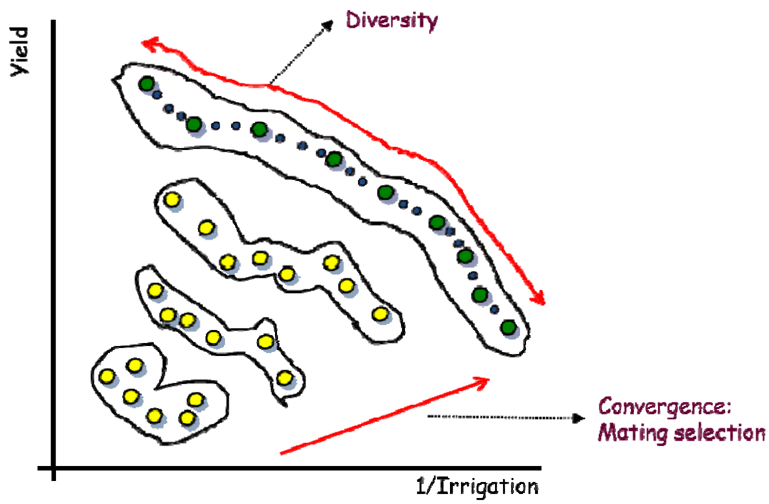


Figure 7. Example of convergence to the Pareto optimal front.

Figure 8 (right) illustrates the Pareto front considering two goals simultaneously: production and irrigation. The integrated tool find quasi optimal front in very few executions of the EPIC model of a watershed (approximately 40). In the same figure (small blue points), we display the result of running EPIC model more than 500 times selecting the value of decision variables in a random way. This way we could determine an approximation of the Pareto front, however the process is obviously more computationally intensive.

When increasing the number of objectives, the combinations of variables that give Pareto optimal solutions increase exponentially. So the advantage of applying this integrated tool is the guarantee to find the Pareto optimal front in a few runs of the EPIC model and explore properly the entire solution space. Once the tool has generated the efficient front (Pareto), it is possible to consider which management options to consider to achieve the desired results. The Pareto frontier allows the decision or policy makers to visualize the full range of optimal possibilitie, facilitates dialogue to reach an agreement between all the stakeholders.

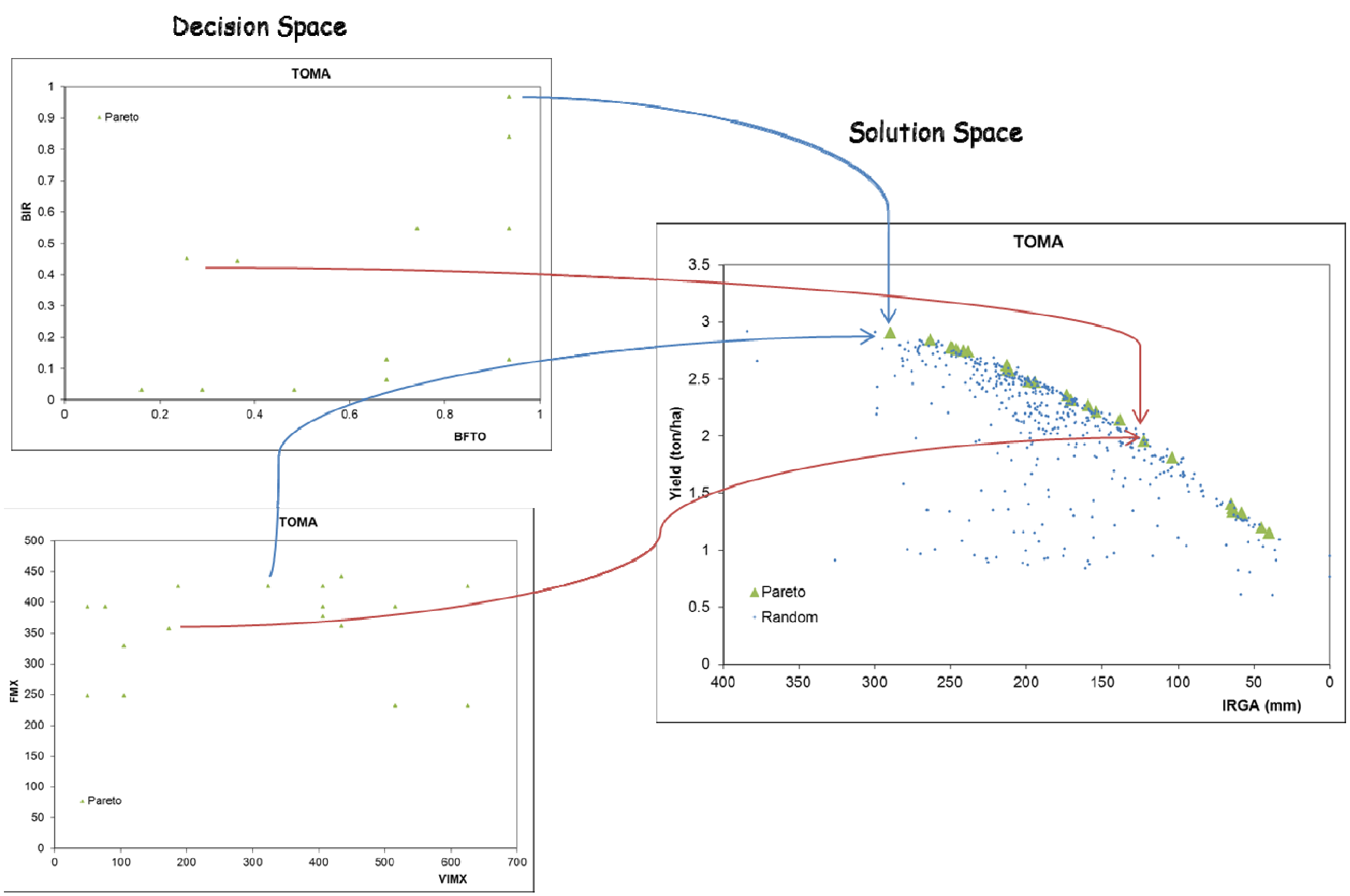


Figure 8. Decision space and solution space relation

When the Pareto front has been generated considering more than two objectives, the display on a plane is not so easy. Most of the results presented in this report were generated considering 4 or 5 objectives simultaneously. In that case we include paired figures with the two different objectives considered (Figure 9).

Figure 9 (left) illustrates the Pareto front obtained considering two objectives: minimizing water consumption and maximize production. The right panel illustrates the Pareto front obtained considered four objectives simultaneously: maximizing yield, minimizing irrigation, minimizing fertilization and minimizing nitrates percolation. The points highlighted in red (right panel) illustrate a non efficient solution according to three criteria simultaneously (i.e. irrigation, fertilization and yield). Special visualization tools (Lotov, 2005) exists to examine Pareto fronts up to 5 objectives simultaneously.

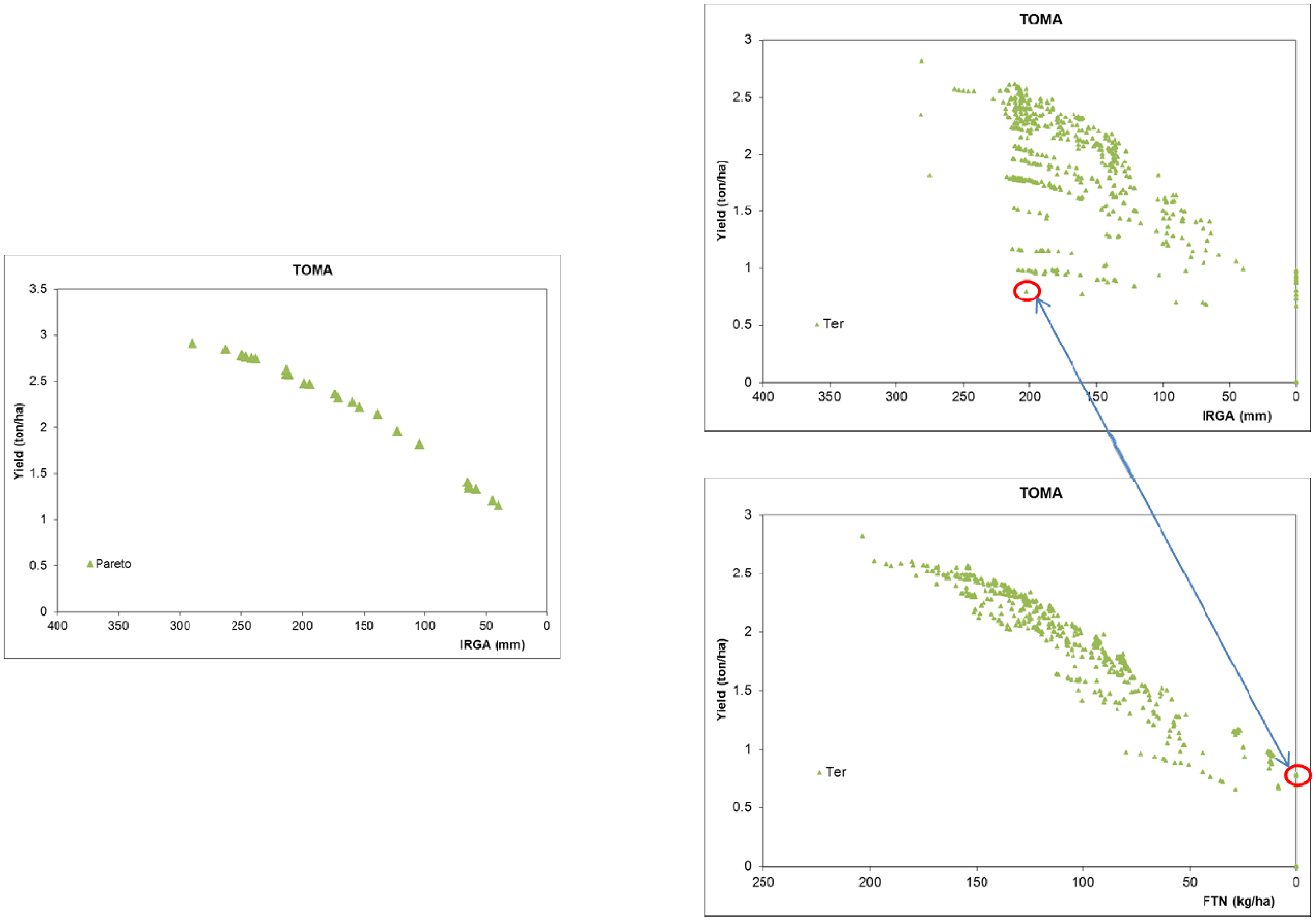


Figure 9: Pareto front considering 2 objectives (left) and considering four objectives.

4. APPLICATION IN CATALONIA

In some Mediterranean countries 80% of the available water is being used in the agricultural sector. Sustainability and quality of water resources are also major issues in the Mediterranean countries. Erosion and sediment transport are causing dams to silt up, reducing water storage capacity and water availability. Nitrate pollution is also an issue of concern for dams and groundwater. Problems of eutrophication due to excess phosphorus are significant (Torrecilla et al., 2005). These problems are also affecting the Catalonia region, where agriculture is the major water user (Figure 10).

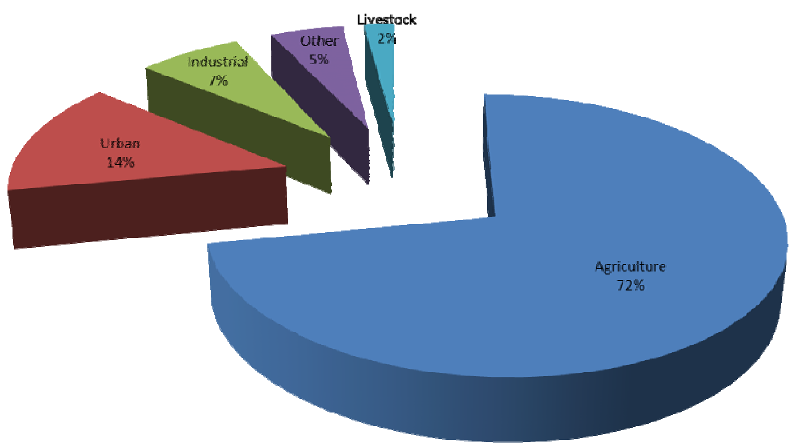
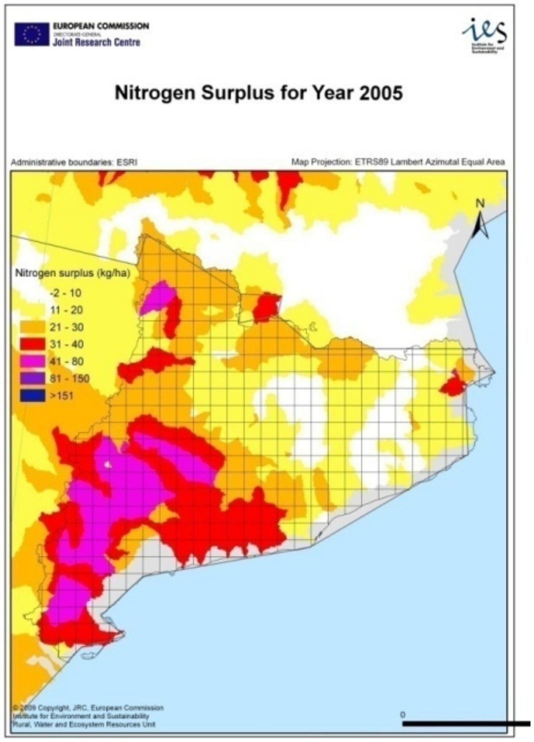
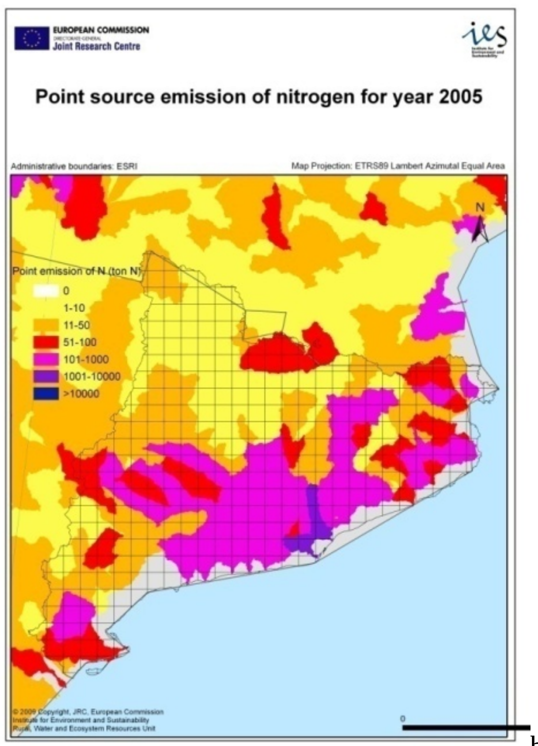


Figure 10. Catalonia sectorial water uses distribution

Agriculture is also a major contributor to diffuse nutrient losses in surface waters. We performed source apportionment, i.e., allocate nutrient loads measured in the streams to various sectors of activities using a statistical model (Grizzetti et al., 2008). The nitrogen surplus and point sources for the region of Catalonia are displayed Figure 11a and Figure 11b, respectively.



a)



b)

Figure 11. Estimated itrogen surplus (kg N/ha of total land) (top graph) and point source emission in surface water (ton N) (bottom graph) for the region of Catalonia for year 2005.

The contribution of diffuse sources, including agriculture to total nitrogen load in Catalonia surface water is displayed in Figure 12. Usually diffuse losses contribution to total nitrogen load tend to dominate in the inland part Catalonia where the most intensive agriculture and animal breeding is found, while point sources are more dominant along the coast. It is thus of critical importance to dispose of tools that allow to quantify the agriculture contribution to total nutrient losses and that can be used to elaborate scenarios of sustainable use of land and natural resources, water in particular.

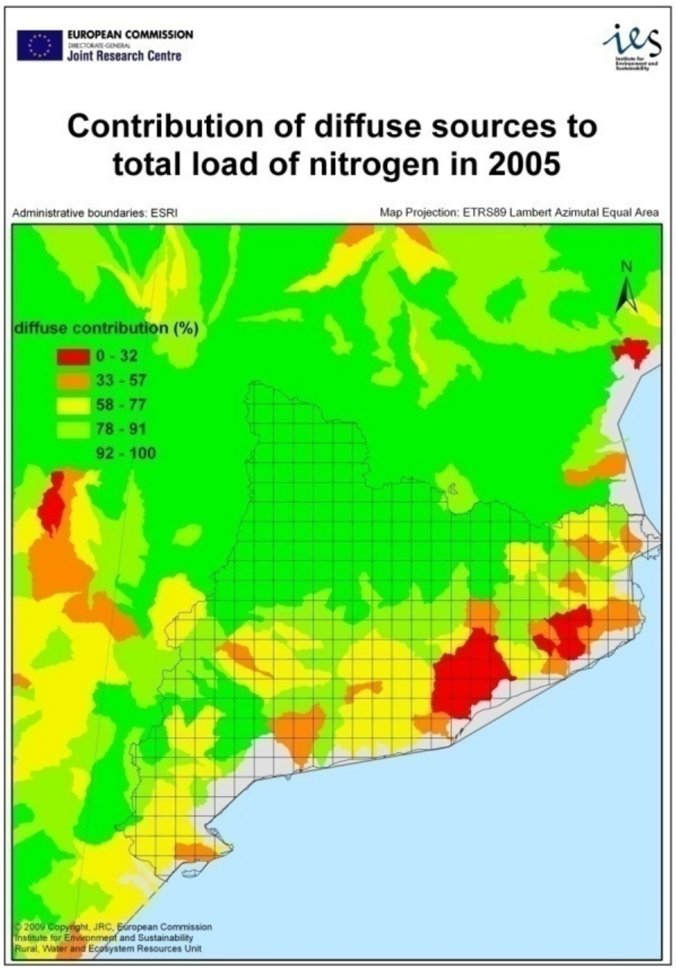


Figure 12. Estimated contribution of diffuse losses to total nitrogen load in Catalonia surface water.

EXAMPLES OF APPLICATION OF THE COUPLED MOEA - EPIC TOOLS IN CATALONIA

Before using the coupled MOEA-EPIC system in Catalonia, a preliminary run of EPIC was performed to understand how EPIC performs under optimal condition and if it produces reasonable results under the most favourable conditions. Indeed, the coupled system is exploring the whole space of possible solution and EPIC thus has to produce reasonable results in order to produce realistic scenarios. Details concerning crop yield validation and irrigation and nutrient requirements can be found in Van derVelde et al. (2009), and Wriedt et al. (2009).

In the case of maize the crop yield is linearly well correlated with fertilization and irrigation practices (Figure 13). As expected, the crop yield is much higher with more fertilizer and irrigation, and the limiting influence of these elements for maize is much more evident than for other crops. All the points showed in these figures are the results of the optimization process and in this way they represent optimal agricultural practices.

Nitrogen is a key limiting factor for maize in all the Catalan basins considered (the cloud of point is very narrow) while irrigation can be a limiting factor, but if not linked with good fertilization practices it can be inefficient (see highlighted area in Figure 13, left panel). When considering the impact on water quality one can identify areas where it is possible to increase the yield with minimal impact on the environment (see highlighted area in Figure 14). For example the Fluvia basin seems to have the highest nitrogen losses into surface water, while the SegreCinca seems to have more capacity to protect surface waters, even with higher input of fertilizers and irrigation

.

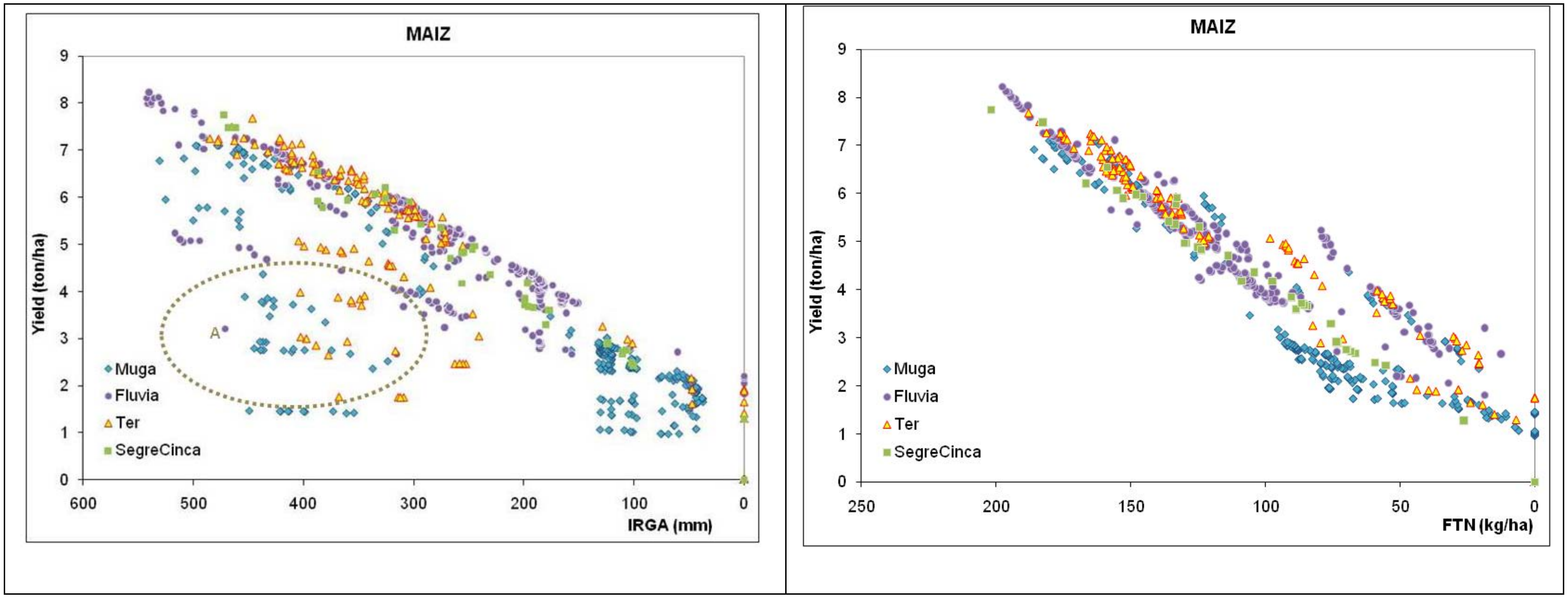


Figure 13. Yield vs. irrigation (left) and yield vs. fertilization (right) optimized points for maize, for the major Catalan basins.

To transfer the previous analysis into real practices requires a further step by associating an economic cost to each potential scenario, approach not considered so far in this application. Indeed, it is possible to define the economic values derived by higher yields (income), higher fertilization and irrigation (outcome) and by the impacts on the environment (economic valuation) in order to select the most sustainable alternatives in terms of cost and agro-environmental practices for each basin according to different end user's specific needs.

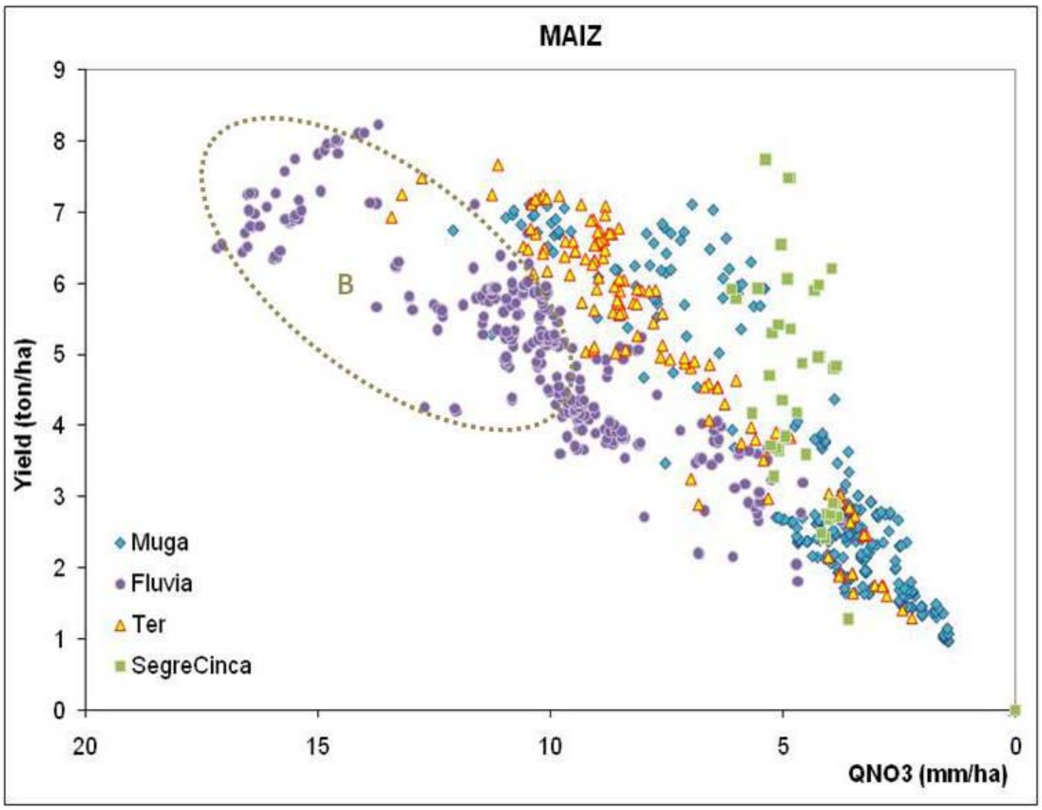


Figure 14. Yield vs. nitrate losses in surface water graph for maize.

Barley is another important crop for the Catalonia region. Under normal agriculture practices, barley is not irrigated. For the smaller additions of N fertilizer, there is a linear relationship between the yield of barley and the fertilizer inputs. Then it seems that the yield reaches a plateau where additional nitrogen inputs do not have any impact on the yield (Figure 15).

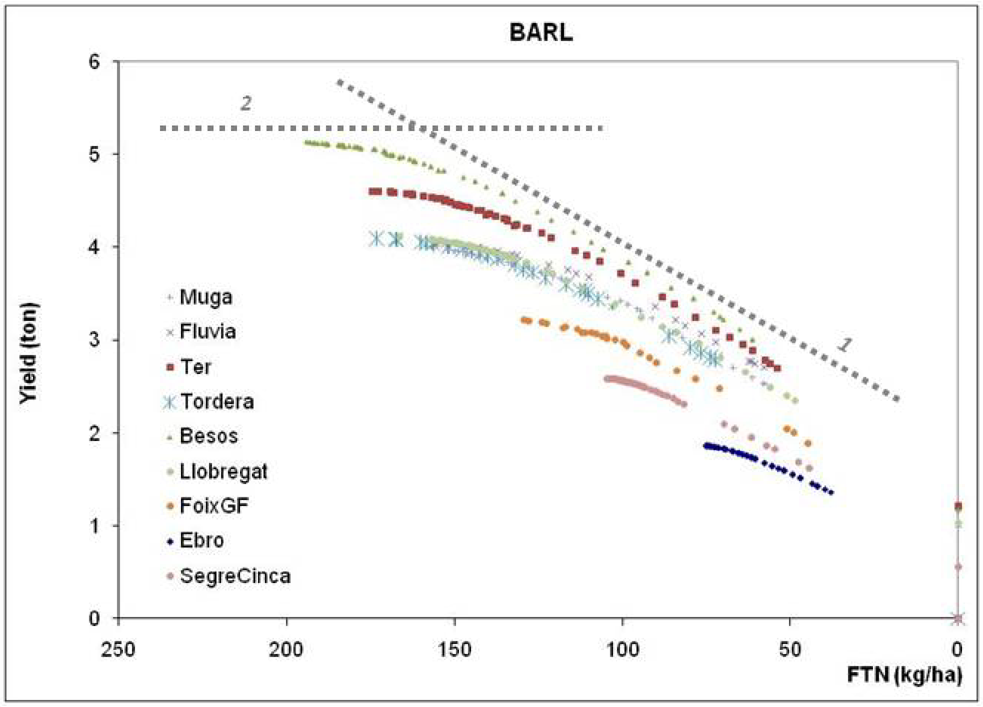


Figure 15. Yield vs. nitrogen fertilization graph for crop barley.

The yield/fertilization figure identifies Besos and Ter basins as the most productive for barley, or at least the basins where it is more probable to have a high increase in the yield following an increase in the fertilization.

Nitrogen losses increase both for surface and in percolation water. It is quite clear that the Tordera basin is affected more by groundwater quality than nitrate losses in surface runoff which are rather limited. Considering the case of SegreCinca basin, the optimal yield production is around 2.5 ton ha^{-1} y^{-1}, with a fertilizer input around 90 kg N ha^{-1}. Any addition beyond that point does not increase the yield while increasing significantly nitrate losses in the surface and leaching waters.

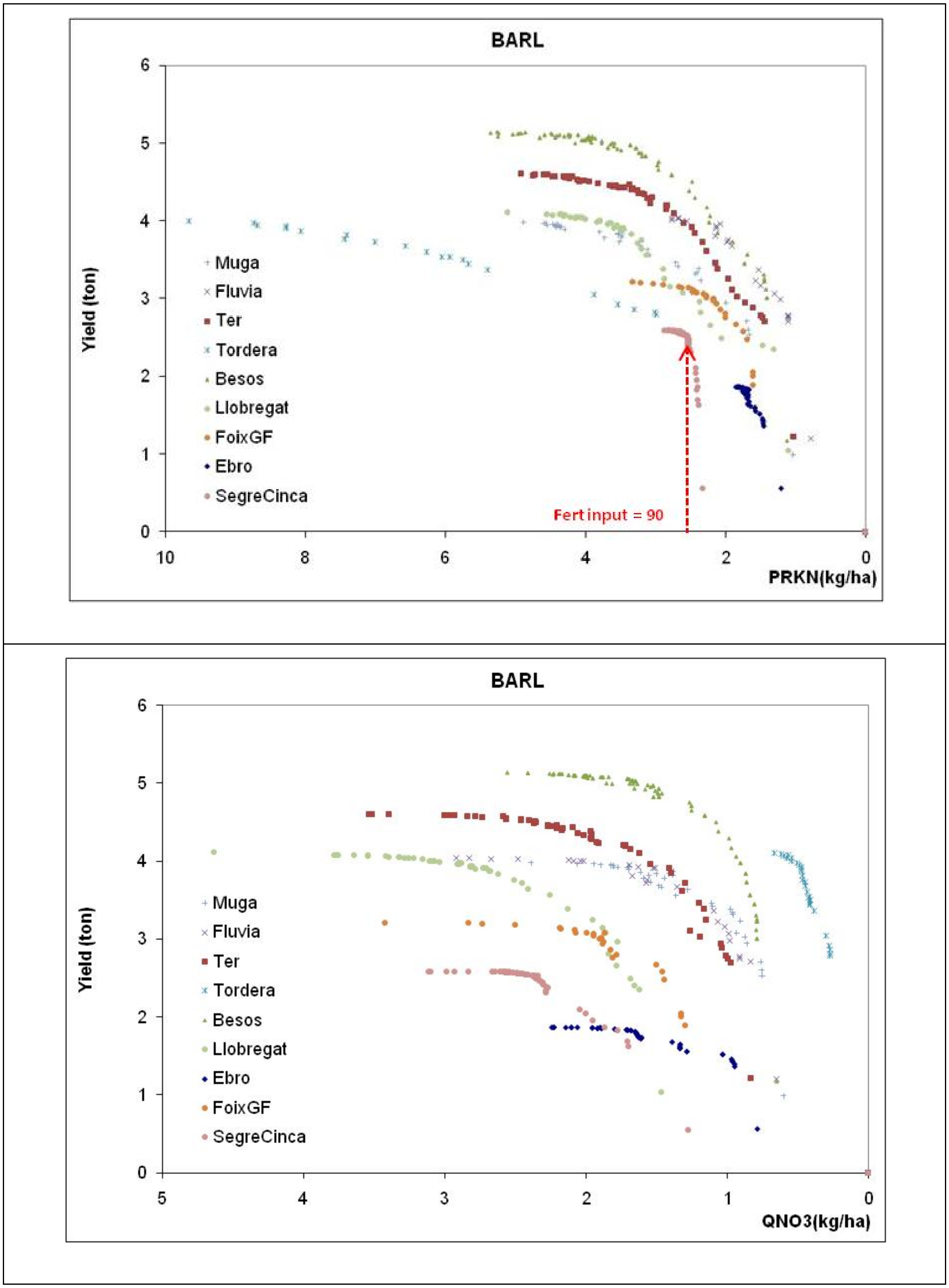


Figure 16. Yield vs nitrogen in surface and leaching water graph for crop barley.

5. EXAMPLES OF APPLICATION FOR ASSESSING THE IMPACT OF POTENTIAL CLIMATE CHANGE IN CATALONIA

The reported tools allow also assessing the potential impact of various climate scenarios on crop water and nutrient requirements. Eighteen high-resolution grids on monthly climate coming from the combination of five Global Climate Models (GCMs) and four emission scenarios (based on assumptions of demographic, industrial, technological developments) were obtained from Tyndall Centre for Climatologic Research (Mitchell et al, 2004). The combinations available for the GCMs and emission scenarios are summarised in Table 4.

Table 4. Combination of GCMs and scenarios used

SRES GCM	A1F1	A2	B1	B2
CGCM2 (Flato and Boer, 2001)	X	X	X	X
CSIRO2 (Gordon and O’Farrell, 1997)	X	X	X	X
ECHAM4 (Roeckner et al., 1996)	Same as A2	X	X	Same as B1
HadCM3 (Mitchell et al., 1998)	X	X	X	X
PCM (Washington et al., 2000)	X	X	X	X

All scenarios derive from the Special Report on Emission Scenarios (SRES; IPCC, 2000). Based on an extensive literature review of global and regional scenarios, a set of four families (A1, B1, A2, B2) with 40 emission scenarios based on potential population, economic and structural and technological changes were developed, covering from the 5th to the 95th percentile of the global energy related greenhouse gas emission reported in literature (Figure 17).

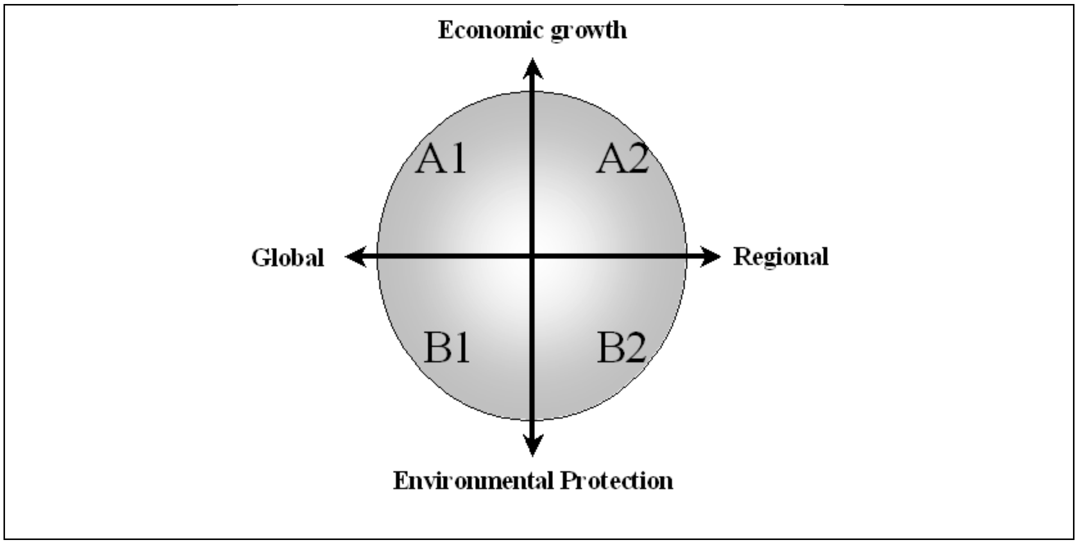


Figure 17. Characteristics of the various climate change scenario storylines

The A scenarios are more economical growth driven, while in the B scenarios the emphasis is put on the protection of the environment. The “1” scenario assumes more globalisation while the “2” scenarios are based on regionalisation.

- The A1 family of scenarios is based on rapid economic growth, an increase in population until the mid-century and a decrease thereafter and the introduction of new and more efficient technologies. The scenario A1F1 puts more emphasis on fuel intensive energy source.
- The A2 scenario is characterised by a heterogeneous, market-led world with high population growth. Economic development is oriented regionally and income growth and technological changes are regionally diverse and slow.
- B1 has the same low growth population as A1 but is characterised by global cooperation and regulation leading to a converging world. Clean and efficient technologies are introduced.

- B2 scenario puts emphasis on environmentally, economically and socially sustainable locally oriented pathways. The technological changes are slower and more diverse than in the A1 and B1 scenarios.

The results obtained running EPIC were analyzed by determining for each climate change scenario, AF1 and B2 in particular (the two most extreme scenarios), the GCMs agreement expressed as the number of GCMs inducing the same level of deviation, notably the number of GCMs inducing an increase or decrease by more than 10% of the considered model output. The agreement varies from 1 to 5 for both the increase and the decrease predictions.

The potential changes in precipitation and potential evapotranspiration (PET) for the whole Europe are summarized in Figure 18 and Figure 19, respectively.

Under the two extreme scenarios, there is a tendency for Catalonia, to receive less water than under current conditions, more pronounced for the A1F1 scenario. However, there is no certainty on the agreement among the different GCMs. It seems that in the two scenarios, Catalonia will be less affected by changes in precipitation (total amount) than central Spain. Concerning PET, under the A1 scenario all GCM predict a strong increase in the evaporative demand for the whole Catalonia. For the B1 scenario no agreement could be detected (Figure 19).

The impact of these potential changes is illustrated for all crop production for the region of Catalonia for both A1 and B2 scenarios in terms of yield and water stress (proxy for irrigation requirement), and also for wheat in particular for the A1F1 scenario in terms of yield (Figure 19, Figure 20, Figure 21, and Figure 22).

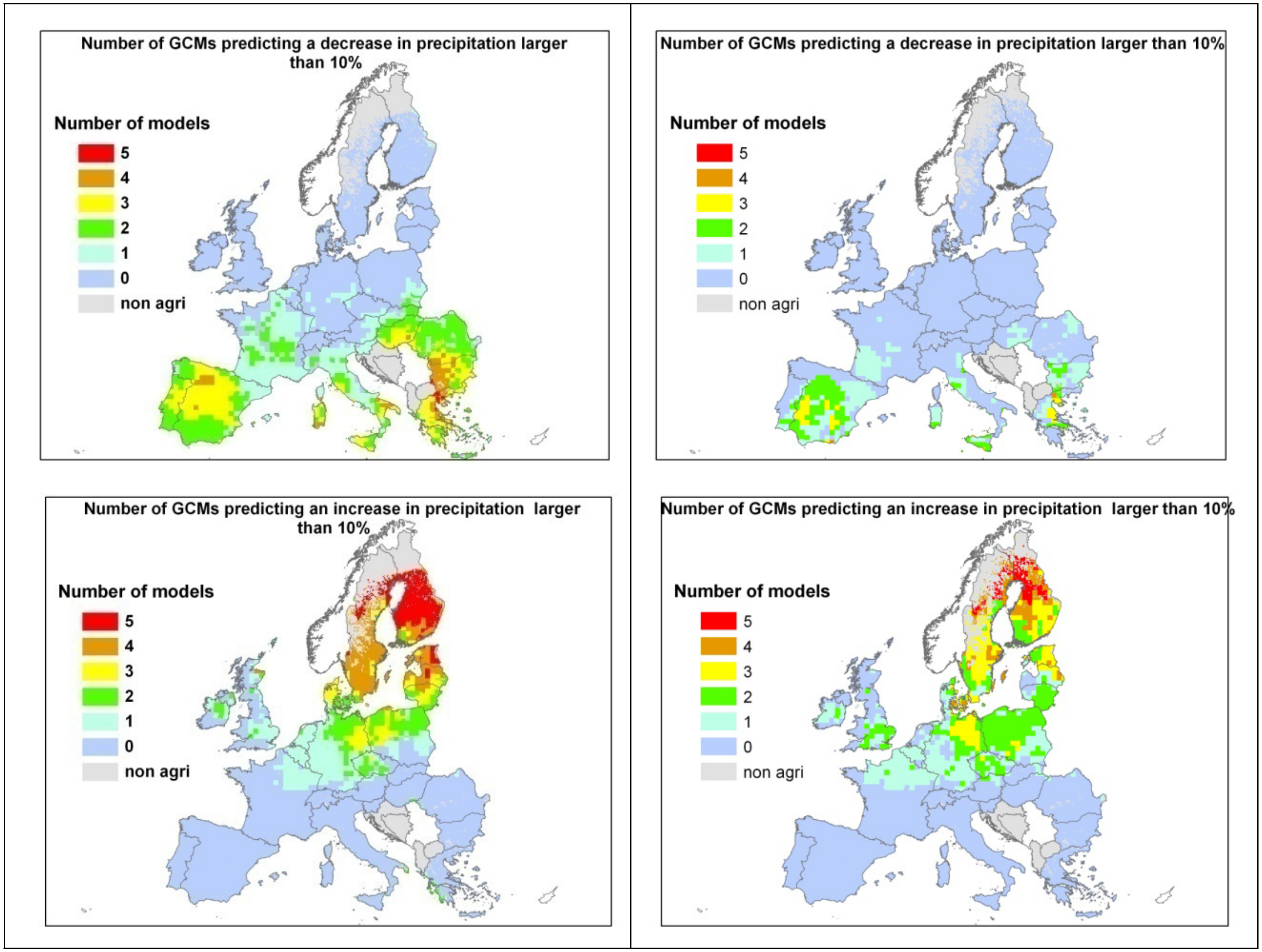


Figure 18. GCMs agreement for predicted changes in annual precipitation for the A1 scenario (left graph) and the B2 scenario (right graph).

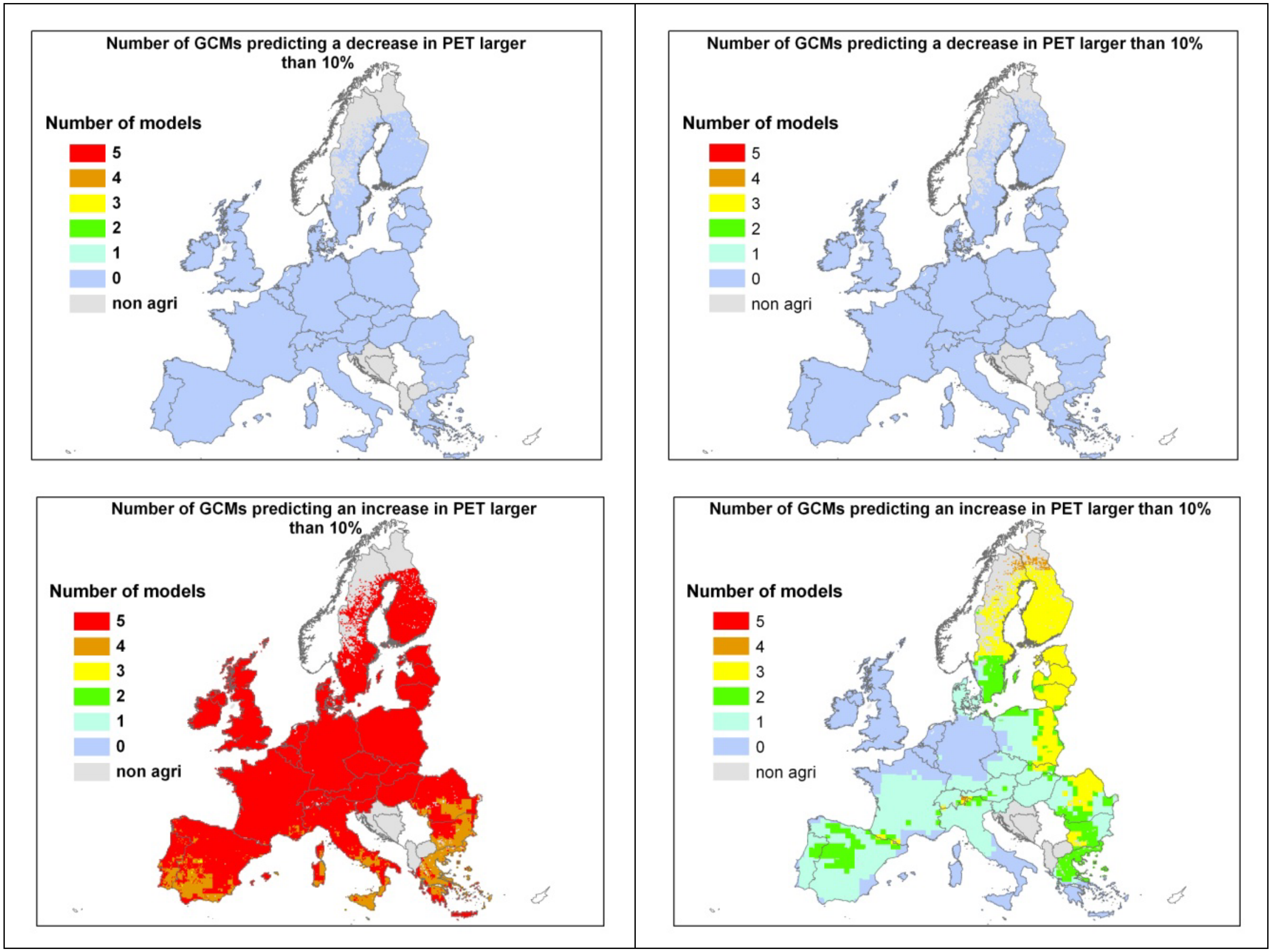


Figure 19. GCMs agreement for predicted changes in annual PET for the A1 scenario (left graph) and the B2 scenario (right graph).

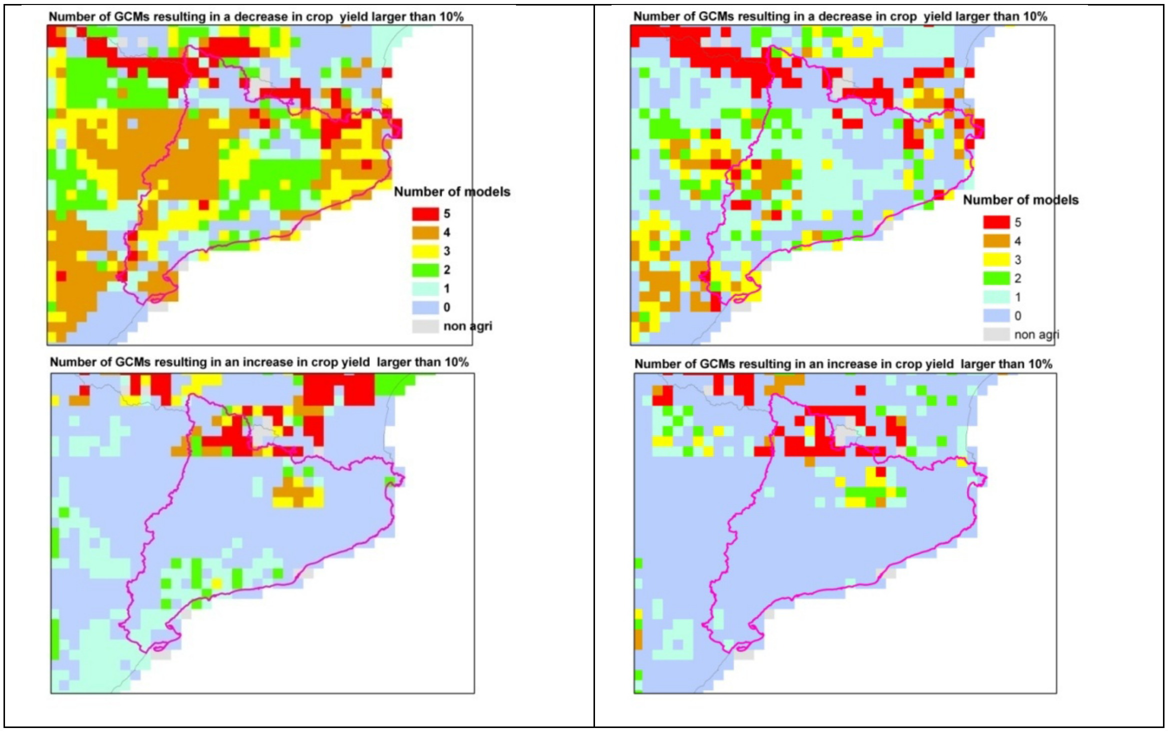


Figure 20. GCMs agreement for predicted changes in annual crop yield (all crops combined) for the A1 scenario (left graph) and the B2 scenario (right graph).

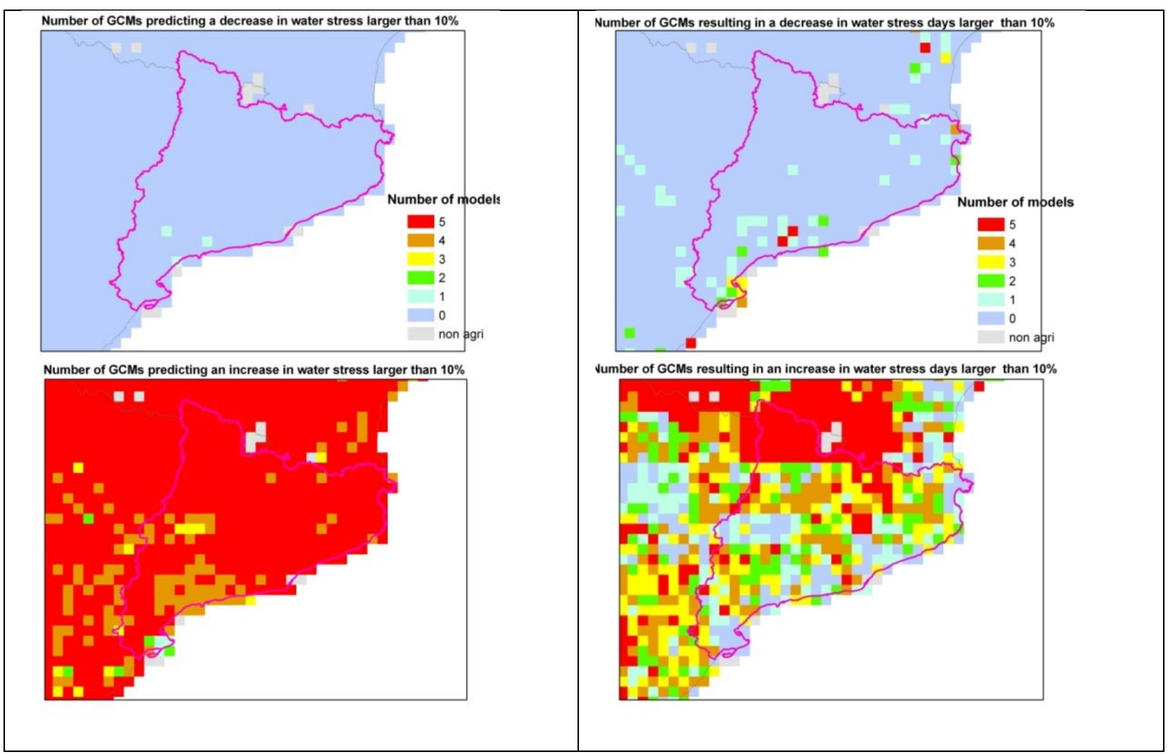


Figure 21. GCMs agreement for predicted changes in annual water stress (all crops combined) for the A1 scenario (left graph) and the B2 scenario (right graph).

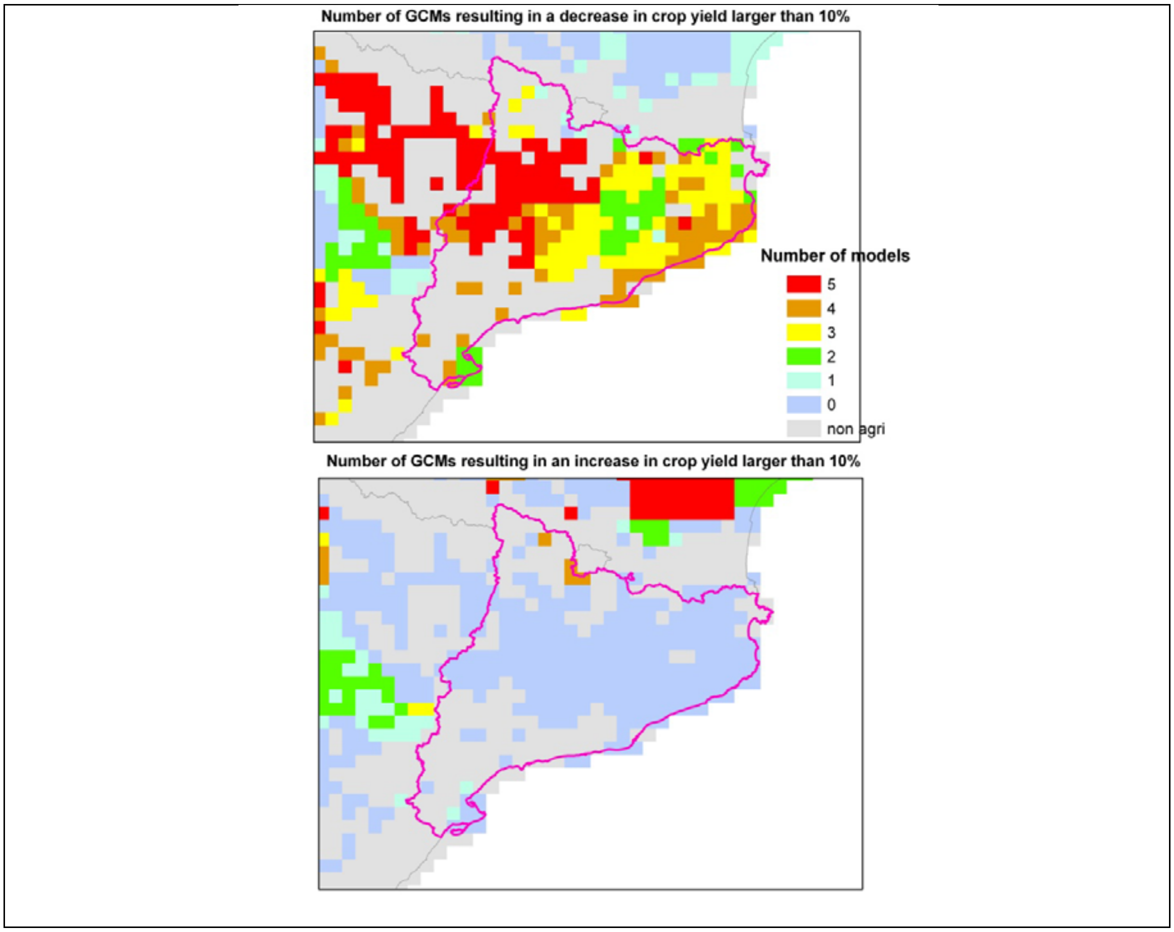


Figure 22. GCMs agreement for predicted changes in annual wheat yield for the A1 scenario.

6. CONCLUSION

The ACA and UTE DMA requested the JRC to develop and transfer an integrated modelling tool that could be used in the elaboration and evaluation of management options for reducing diffuse losses of nitrogen and phosphorus from agriculture. The work performed in this study included:

- the integration of the EPIC model with a multi-objective analysis tool to determine agricultural practices in terms of nutrient and irrigation water applications that maximize yield while preserving the environment;
- the transfer of this integrated model and associated database to ACA and UTE DMA;
- applications of this integrated tool in the region of Catalonia.

Even though it was originally envisaged to include in the database more detailed information concerning soil, landuse and climate, due to limited data provision, the update only concerned precipitation and temperature. Additional updates could be performed later on, and the JRC remains available, if needed, to support ACA or UTE DMA in the application of the modelling software and database. The integrated EPIC multi objective analysis tool was applied in all major basins in Catalonia for maize and barley. The integrated tool was also used to assess of potential climate change impact on crop yield, nutrient and water requirements in Catalonia. This integrated tool was shown to be powerful and is fully operational to make management decisions.

This work was preliminary in the sense that it aimed at exploring the potential of coupling bio-physical model and multi-objective programming. Some results were achieved during this work, but the potentialities of the system extend beyond the achievement shown in this report. Indeed, work focused on nitrate in this work, but EPIC is setup to work with other determinands such as phosphorus, pesticides. As a standalone tool EPIC could also be used to assess erosion problems in Catalonia, and also to evaluate alternative management practices such as split applications of fertilizers, crop rotation in order to minimize nutrient and pesticides application, etc.

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8. ANNEX I: EPIC DESCRIPTION

HYDROLOGICAL CYCLE

The EPIC (Erosion-Productivity Impact Calculator; Williams et al., 1995) is a field scale model, originally developed to simulate the long-term effects of soil erosion on soil productivity. A nutrient cycling and pesticide fate routines were added later on. The various developments of EPIC are given by Gassman et al. (2005) and a flow chart of EPIC is given in Figure 23.

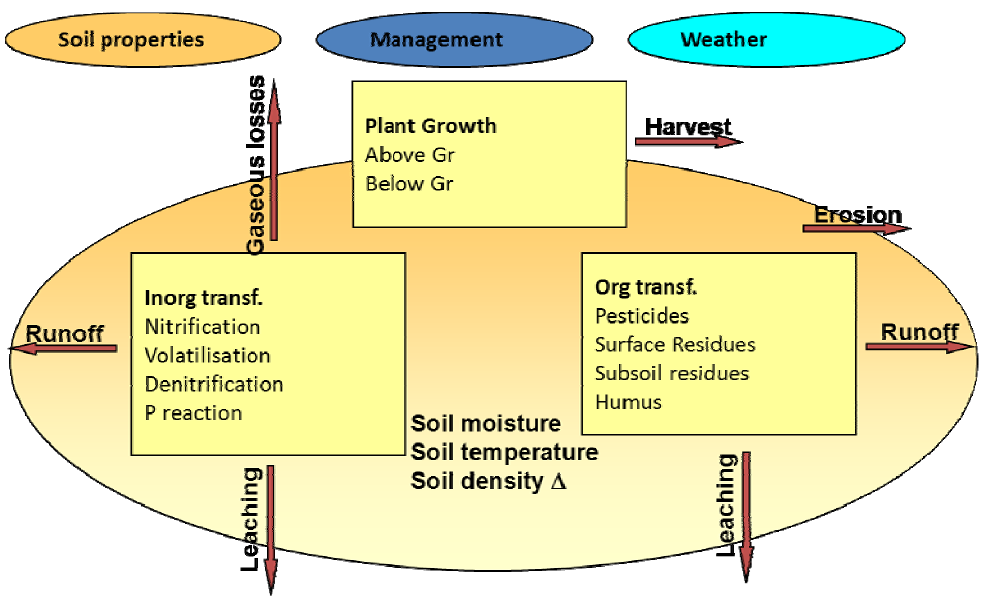

Figure 23. EPIC flow chart

The hydrological model is based on the water balance equation in the soil profile where the processes simulated include surface runoff and infiltration (SCS curve number), evapotranspiration, lateral flow, and percolation. Surface runoff, Q(cm), is related to daily precipitation, P (cm), based on the SCS curve number (U. S. Department of Agriculture, 1972) as follows:

$$Q = \frac{[CN(aP+2)-200]^2}{CN[CN(aP-8)+800]} \tag{1}$$

CN is the curve number, and *a* is a unit conversion factor equal to 0.3937. The curve number for a watershed depends on the antecedent soil moisture content, land use and treatment practices, the hydrologic surface conditions and the hydrologic soil group.

Potential evapotranspiration can be computed, based on data availability, using one of the following methods: Penman (1948), Penman-Monteith (Allen et al., 1989); Priestley Taylor (Priestley and Taylor, 1972), and Hargreaves (Hargreaves and Samani, 1985). Evapotranspiration is determined using the Ritchie's approach (Ritchie, 1972). Potential soil evaporation and plant transpiration are partitioned based on the leaf area index (LAI) and the above ground biomass (CV, kg/ha). Potential soil evaporation, E_S, (cm) is determined as:

$$E_S = E_0 e^{(-5.10^{-5}\ CV)} \qquad (2)$$

where E_0 is the potential evapotranspiration (cm). The potential plant transpiration, E_{P0} (cm), is determined as a function of E_0 and LAI (Ritchie, 1972):

$$E_{P0} = \frac{E_0\ LAI}{3} \qquad \text{for} \quad 0 \le LAI \le 3 \qquad (3)$$

If LAI is larger than 3, potential plant transpiration is taken as the potential evapotranspiration. For any given day, the sum of plant transpiration and soil evaporation cannot exceed E_0. The potential transpiration rate is then distributed in the soil profile based on root distribution.

NUTRIENT CYCLE

EPIC divides the nitrogen into active organic, stable organic, fresh organic, nitrate and ammonium pools. The model simulates mineralisation (transformation from organic to ammonia) from the fresh organic pool associated with crop residue and microbial biomass and from the active organic pool. The contribution of the fresh organic N pool to mineralisation is estimated as:

$$RMN = 0.05\, CNP\, \sqrt{\frac{SW}{FC}\, TF}\;\; FON \tag{4}$$

where RMN is the mineralisation rate (kg/ha/d), FON is the fresh organic N present in the soil (kg/ha), CNP represents the impact of the carbon to nitrogen and carbon to phosphorus ratio on the decomposition rate, SW is the soil water content factor, TF is the temperature factor, and FC is the field capacity (mm/mm). The organic N associated with humus is divided into active and sable pools which are in dynamic equilibrium. The mineralisation from the active pool is calculated as:

$$HMN = CMN\;ON\;(SWF\;TF)^{0.5}\;\left(\frac{BD}{BDP}\right)^{2} \tag{5}$$

where HMN is the mineralisation rate (kg/ha/d), CMN is the humus degradation rate (d^{-1}), BD and BDP are the settled and current bulk density as affected by drainage (t/m^3), and SWF is the soil water factor defined as the ratio of SW and FC.

The second stage of mineralisation is based on a first order kinetics and is a function of soil moisture, soil temperature and soil pH. Volatilisation of applied ammonia at the soil surface is determined simultaneously with the nitrification and is a function of air temperature and wind speed. Volatilisation of ammonia in lower soil layers is function of soil temperature and cation exchange capacity. Denitrification is considered to be a first order process, and is based on the amount of soil organic carbon content and is function of soil temperature and soil moisture.

The cycling of organic P is similar to that described for nitrogen with mineralisation occurring from the fresh organic P and organic P associated with humus. Mineral P is divided into a labile P pool, an active mineral pool, and an inactive mineral pool. Fertiliser P is labile at application and then is transferred rapidly to the active mineral pool. The active and stable inorganic P pools are dynamic, and at equilibrium, the stable mineral P pool is assumed to be four times larger than the active mineral P pool (Sharpley and Williams, 1990).

CROP GROWTH

EPIC uses a daily time step to calculate crop potential growth and crop growth limitation stress factors which include the following constraints: water stress, temperature stress, and nutrient stress. Maximum crop yield is based on the radiation use efficiency. The daily potential biomass increase is calculated as:

$$\Delta B_p = 0.001\ BE\ PAR \tag{6}$$

where B_p is the potential biomass production (t/ha), BE is energy to biomass conversion parameter (kg/ha/MJ/m^2) (function of atmospheric CO2 level), and PAR is the intercepted photosynthetic active radiation (MJ/m^2) estimated based on Beer's law as:

$$PAR = 0.5\ RA\left(1 - \exp^{-0.65\,LAI}\right) \tag{7}$$

where RA is the solar radiation (MJ/m^2), and LAI is the leaf area index. LAI is calculated daily based on heat units. The daily change in LAI is calculated as follows:

$$\Delta LAI = LAI_{\max}\ \Delta HUF\ \left(1 - \exp^{(5(LAI_{i-1} - LAI_{\max}))}\right) REG \tag{8}$$

where LAI_{max} is the maximum leaf area index, HUF is if the heat unit factor, and REG is the minimum of the water, nutrient, temperature, aeration and radiation stress factors. Heat units (HU) on a particular day are calculated during the phenological development of the crop as the average daily temperature in excess of the crop base temperature, and the heat unit index (HUI) as the ratio of the cumulative heat unit divided by the potential heat units:

$$HU_i = \max(0, T_{av} - T_b)\ ; \quad HUI_i = \frac{\sum_{k=1}^{i} HU_i}{PHU_j} \tag{9}$$

where T_{av} is the average daily temperature (°C), T_b is the base crop growth temperature (°C), *i* is the day, PHU is the potential heat unit for crop *j* (obtained as the sum of heat units from normal planting to maturity). The yield is calculated as the product of the harvest index and above ground biomass. The harvest index can however be reduced by water stress, or a shortened growing season and it is thus adjusted accordingly. Perennial crops maintain their root system through cold-induced dormancy, and growth restarts when average air temperature exceeds the base temperature for the crop.

GROWTH CONSTRAINTS

EPIC adjusts the daily potential growth by constraints including the influence of the following limiting factors: nutrients, water, temperature, aeration and radiation. This stress can impact not only biomass production, but also root development and yield. A stress is estimated for each of the limiting factor and the actual stress is taken equal to the minimum stress calculated for each of the constraints. Water stress (WS) is evaluated as follows:

$$WS = \frac{WU}{EP_0} \qquad (10)$$

where WU is the water use. The temperature stress (TS) is estimated as:

$$TS = \sin\left(\frac{\pi}{2}\left(\frac{T_s - T_b}{T_o - T_b}\right)\right) \qquad (11)$$

where T_o is the optimal growth temperature (°C), and T_s is the surface average soil temperature (°C). The nutrient stress (NS) is based on the ratio between the actual and the optimum N and P plant content. The stress factor varies non-linearly between 1 (actual N and P content at optimum level) to zero when N and P contents are at half the optimum level. The nutrient stress factor (NS) is calculated as:

$$NS = \frac{SN_s}{SN_s + \exp^{(3.52 - 0.026\, SN_s)}} \quad and \quad SN_s = 200\left(\frac{\sum_{k=1}^{i} UN_k}{C\ B_i} - 0.5 \right) \qquad (12)$$

where SN_s represents a scaling factor, UN_i is the cumulated nutrient uptake for day i (kg/ha), B_i is the cumulated biomass (kg/ha), and C is the nutrient (N or P) optimal concentration of the crop.

Aeration stress is estimated from the top meter of the soil and is a function of the soil moisture content and porosity. It varies from zero to one when the total soil porosity is filled with water. EPIC also considers pest as a constraint to crop growth. The pest factor is used to adjust the crop yield at harvest. The pest factor is a function of temperature, soil moisture and ground cover. The pest index grows rapidly during warm moist with ground cover and is reduced during cold months. EPIC keeps track of all stress factors and computes a daily sum for each of the factor allowing to monitor the number of stress days (sum for all previous days of the stress factor).

FARMING PRACTICES

The major function of tillage is to mix nutrients and crop residues in the plough depth. The impact of tillage on soil bulk density is also taken into account by considering between tillage operations the settling effect of rainfall events. Bulk density settling is also function of the sand content of the soil. Tillage operations will also affect the ridge heights and also will convert standing residues to flat residues, both processes impacting surface runoff and erosion.

EPIC allows irrigation to occur as sprinkler or furrow irrigation. Application timing and rate may be calculated automatically based on the plant requirement and pre-specified application and timing criteria (such as the minimum numbers of days between two irrigation applications, minimum rate to be applied) or can be specified as exact amount and exact dates of application.

Fertilisation management is similar to irrigation and can be fixed for each crop of can be calculated automatically (timing and quantity) based on pre-specified criteria. Other operations incorporated in the EPIC model include liming to raise the pH to optimum levels.