Cost-effectiveness analysis for controlling water pollution by pesticides using SWAT and bio-economical modeling

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Plan

- Context
- Methodology + Case study
- Effectiveness assessment (SWAT)
- Costs assessment (Bioeconomic model)
- Main results
- Conclusion

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Protection of surface waters quality requiring measures


Compliance with the Water Framework Directive (WFD) implying a reduction in the impact of agricultural pressures

Public participation in water management required in international conventions that should be meaningful when issues are complex and uncertainties high (United Nations, 2000; Aarhus Convention, 1998; World Water Commission, 2000; WFD, 2000)

→ Agri-environmental measures defined at National or Regional level can lead to extremely different results in terms of implementation costs and environmental effectiveness
Cost-effectiveness analysis (CEA)

Government and Water agencies have to manage limited budgets allocated to the implementation of measures.

CEA to be used to select combinations of measures at the water body and river basin level allowing for the attainment of the desired ecological objectives at the lowest costs for society (WATECO)*

→ Use of modeling tools for analyzing the different impacts and costs of environmental policy measures
  - Could help define least costs programmes
  - Long periods of time
Cost-Effectiveness Analysis (CEA) framework

**Scenarios**
measure or combination of measures

**Economic component**
Mixed integer Linear Programming model
(commune level)

**Cost assessment of implementing measures**
(Commune then sub river basin level)

**Environnemental component**
Soil and Water Assessment Tool model
(management practices defined at the commune level)

**Effectiveness assessment of mitigation measures**
on reduction of pesticides concentration at the outlets
Region water basin, Catchment, Sub-basins levels

**Spatially distributed Cost-Effectiveness Analysis**
of scenarios at the sub basins and catchment level

Stakeholders

Targeting action programmes

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Effectiveness of mitigation measures with SWAT
Case study

- The Gers river basin (sub basin of the Garonne river basin) in the South-western part of France

- Upstream part (UGRB) from Lannemezan plateau to the Roquelaure drinking water collection point

- 17 small rivers and streams (9000 km²) with extremely small water catchment areas (Côteaux de Gascogne)

- Hydrological processes characterized by superficial water transfers fed by shallow water tables with limited capacity

→ link canal (the Neste canal) created to improve water flows
Case study streams

- 5 points for the abstraction of Drinking Water (30 000 hab.) with recurring problems of water quality relating to pesticides
  - 65% of water samples with concentrations > 0.1 μg/l for individual pesticide
  - and 29% with concentrations > 0.5 μg/l for total pesticides
UGRB covers 47000 ha (470 km²) mainly dedicated to Agriculture
34000 ha (72% of the area)
- 700 farms on 55 communes

- mainly Cash crops
- Some Breeding activities suckler farming systems

80 % cropping pattern
- Corn for grains or silage southern part
- spring and winter wheat
- durum wheat
- Sunflower northern part
- Permanent and temporary grassland
Case study soils

- Alluvium
- Colluviums
- Loamy clayey soils
- Clayey soils

Soils types of different characteristics such as

Streams
Subbasins
Soils classes
- Alluvium
- Colluvium
- Loamy soils
- Brown clay loamy soils
- Brown soils and molasse
- Urban
Define areas with homogeneous characteristics of identified crop rotations (PCA, CA)

Crops rotations further improved from land cover data by applying
→ Agronomical decision rules
→ A random spatial function, producing as many HRUs as there are different types of crop rotations

and creating tables with practices (SWAT tables mgt1 and mgt2) for each HRU from average practices by crops constituting the crop sequence

Dates of management practices within periods are generated randomly from identified average values.
## Mitigation measures

<table>
<thead>
<tr>
<th>Measures applied</th>
<th>Implementation in the SWAT model</th>
</tr>
</thead>
<tbody>
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<td><strong>applied on the whole upstream area</strong></td>
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<td>SGL_GA</td>
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</table>

- **Measures proposed by the French Rural Development programm**
  - Effective on water quality
  - As the most likely to be accepted and implemented by farmers

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Effectiveness assessment using the SWAT model

- Assessment over a 25-years period with measures being applied each year
- Average values of pesticide concentrations calculated on the ten last years basis for the modeling period
- Effectiveness is considered in terms of the relative reduction of average concentration of total pesticides following measure implementation

Use of the values from the SWAT main channel output file (.rch)

\[ \text{Effectiveness}\% = 100 \times \left(1 - \frac{[C_s]_{\mu g l^{-1}}}{[C_0]_{\mu g l^{-1}}} \right) \]

- Variability in effectiveness between sub basin is calculated on the difference between inflows concentration and outflows concentration

\[ [C_0]_{\mu g l^{-1}} \] Average concentration over the ten last years of hydrological simulation
\[ [C_s]_{\mu g l^{-1}} \] Baseline concentration
The SWAT model was calibrated and validated using observed discharge data.

- Irrigation water needs calculated with SWAT & Quantities of water withdrawal is validated in comparison with data surveys on irrigation water applied on irrigated crops (doses and frequencies)

- Uncertainties
  - on the actual irrigation doses
  - on the management of low waters by water supplies from the Neste canal (yearly amount of water supply available from reports)
  - could explain discrepancies on daily simulated and observed values
Calibration/validation statistics for stream flows

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<th>Date</th>
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<th>Measured Data</th>
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<td>9/28/2005</td>
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**Discharge Q(m³)**

**Calibration period (1985 to 1995)**
- $R^2$ = 0.80
- NSI = 0.65
- Specific discharge $Q_s$ (liter per second per square km)
  - Measured $Q_{obs}$ = 5.44 l/s/km²
  - Simulated $Q_{cal}$ = 5.40 l/s/km²

**Validation period (1995 to 2005)**
- $R^2$ = 0.72
- NSI = 0.63
- Specific discharge $Q_s$ (liter per second per square km)
  - Measured $Q_{obs}$ = 5.44 l/s/km²
  - Simulated $Q_{cal}$ = 5.40 l/s/km²

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 Verification/Calibration of pesticides

- SWAT model has been implemented on the whole Côteaux de Gascogne zone then calibrated in order to reproduce total yearly pesticides concentration (1.2 µ g/l) at the upper stream watershed outlet (Roquelaure measurement point)

- Concentrations of pesticides analyzed on
  - 4 measurements points alongside the Gers river (within the project)
  - 5 points (tapping for Drinking Water Supply)
  - 15 measurements points out on the main rivers of the Gascogne Côteaux zone from 2005 to 2008 (from another study by Cemagref)

  → Frequency of sampling (4 to 5 measurements per year) to low for precise daily or monthly calibration and/or validation

  → Used nevertheless for verification by comparing on the same points of the streams, the ranking of the yearly average measured and simulated concentrations (total pesticides)
Pesticides run-offs modeling

- Water analyses show that 4 molecules represent 80% of the total pesticides concentration
  - Herbicides (Glyphosate, S-Metolachlor)
  - Insecticide (Carbofuran)
  - Fungicide from the triazole group (Tebuconazole)

- Set of Active Substances applied + frequency of their use (survey carried out on 50 farms within the watershed area) for each crop

- Spraying practices within the watershed are compared to the average practices set at the regional scale from a much wider sample of farms

→ Reduction of the number of applied active substances to the **molecules the most widely used + average dose** (arithmetic mean) applied by farmers
When a chemical class is widely applied

- fungicides (Sulfonylurea, Triazole and Strobilurin groups)
- herbicides with a mix of 3 or 4 active substances sulfonylurea

→ **new “Average Active Ingredient” (AAI)** for its physical and chemical properties (Koc, DT50 and solubility)

  weighted by their relative concentration in the pesticide used
  *(for a mix of active substances)*

→ we defined an **average application rate** calculated as the average application rate weighted by its frequency of use

→ Simulations are carried out for each of these 4 AAI
  the sum of their daily concentrations simulated with SWAT used as results
Average simulated concentrations and measures differ sometimes heavily but → the ranking of the simulated measurements points match exactly the ranking of measured points for all the points of the watershed

- Differences between simulated and measured concentrations do not imply that model calibration is wrong because of the uncertainty on the measurements themselves (pertaining to their frequency and the number of values within a month and year)
### Results for Effectiveness

<table>
<thead>
<tr>
<th>Implementation</th>
<th>Scenario</th>
<th>Measures</th>
<th>Total concentration $\mu$g/l (outlet)</th>
<th>Effectiveness (% reduction)</th>
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<tbody>
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<td>1.2</td>
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<td>0.85</td>
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<td>upstream part</td>
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- **Measure applied on the zones with priority**
- **Measure applied on the whole area of the upstream part**

- **Pesticide loss may be effectively decreased by implementing measures**
- **Best results: restoration measures like riparian grass buffer strips**
  varying however when applied in priority zones or in the entire GA area

- **Switching from chemical weeding to mechanical weeding could have an immediate effect on pesticide loads**
  enhanced when the measure is applied on the whole upstream area (MW_GA)
  explained by the type of chemicals detected at high concentrations (mainly herbicides)
Results for Effectiveness

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<td></td>
<td>5  SGL_GA</td>
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Measure applied on the zones with priority
Measure applied on the whole area of the upstream part

relative inefficiency of other changes in management practices (catch crops, changes in crop rotation schemes)

$\rightarrow$ Concentration objective of 0.5$\mu$g l$^{-1}$ is never reached excepted for one scenario
$\rightarrow$ Combination of agri-environmental measures may be more effective but need first to be assessed

For a given measure, effectiveness nevertheless varies widely between sub basins within the watershed
Costs results

Effectiveness assessment at the sub river basin level measure: riparian buffer strips 2x10m
Zones with priority

Effectiveness assessment at the sub river basin level measure: switching from chemical weeding to mechanical weeding
Whole upstream area

Effectiveness assessment at the sub river basin level measure: modification of crop rotation schemes
Whole upstream area

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Costs assessment

Costs of mitigation measures
Marginal costs of mitigation measures are not equal. Theoretically possible to obtain the same level of water pollution reduction at lower cost by shifting from high-costly measures to lower-costly measures.

The economic budgeting approach may reflect real world behavior. But budgets may not reflect efficient decisions from an economic perspective.

To derive a meaningful trade-off curve, all economic methodologies need to allow farmers the ability to interchange a variety of optional strategies into the decision making framework.

The methodology of economic optimization is more relevant for cost analysis of mitigation measures. It offers decision makers the possibility to substitute alternative strategies.
Costs assessment

- Representative (average concept) or typical farms (modal concept) is usually the most satisfactory way of modeling farms

- potential bias from aggregating farm-level data or using average/aggregate data at the farm level
- leaves out the spatial distribution of holdings

→ model farms together at the commune level as if they were a single mega-farm

- overstate the flexibility and co-ordination of agricultural productions
- considered appropriate for small areas like communes

→ A model of Agricultural production at the commune level (HRU) is developed in Mixed Integer Linear Programming using GAMS software
Bio-economic modelling

Objective function: \( \text{Max } f_c(X) \)

\[
f_c(X) = \sum_i \sum_p \sum_k (X_{i,p,k,c} \cdot y_{ipk} \cdot p_i) - cv_{i,p,k} + \text{inc}_{k2}
\]

For each \( c \)

- \( c \): commune (commune with at least 10% of its area within the catchment)
- \( i \): crop activities
- \( l \): livestock activities
- \( p \): level of practices intensiveness (intensive, average, extensive)
- \( k \): standard practices \( k_1 \) or with mitigation measure \( k_2 \)
- \( X_{ipkc} \): acreage of the activity with crop \( i \), intensiveness \( p \) and practice \( k \) (ha) within the commune \( c \)
- \( y_{ipk} \): yield of the activity [tons of grains or Dry Matter ha\(^{-1}\)] per crop, intensiveness level and practice type
- \( p_i \): price for grains (€.kg\(^{-1}\)) \( p_l \): price for milk or meat (€.kg\(^{-1}\))
- \( cv_{i,p,k} \): variable costs of production by crop, level intensiveness and type of practice (€.ha\(^{-1}\))
- \( \text{inc}_{k} \): incentive (€.ha\(^{-1}\))
Levels of incentive required to make a measure appear in optimal modeled solutions considered to give the direct costs of its implementation.

When the decision variable (activity with measure) appears in optimum solution, incentive and marginal cost cancel each other out.

Marginal cost (Shadow cost) is regarded to represent the direct cost of the non optimal activity (with measure).

Marginal values indicate how far each activity with measure is from entering the optimal solution.
→ Doesn’t not indicate what would be the optimal level of the activity if it did enter the solution

→ nor does it indicate how the optimal level of other activities currently in the solution would be affected

❖ To determine exactly what changes would occur

→ to alter the model and resolve it, what is done for increasing level of incentives

→ Integration of marginal costs > Total yearly costs

→ Discounted sum of yearly costs > Total Cost over the implementing period
### Costs results

<table>
<thead>
<tr>
<th>Implementation</th>
<th>Scenario</th>
<th>Measures</th>
<th>Total costs (€) - 25 years period</th>
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</table>

- **Wide range of marginal implementation costs**
- **Some measures, depending of their costs per ha implemented (catch crops) or the area implemented (buffer strips) are relatively less expensive to implement on the watershed level**
For a given measure, calculated marginal costs and total costs vary widely between communes as changes are applied to different crops, rotation sequences and farming systems.
<table>
<thead>
<tr>
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<th>Measures</th>
<th>Total concentration ( \mu g/l ) (outlet)</th>
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</table>

- Riparian grass buffer strips
- Switching from chemical weeding to mechanical weeding - Changes to grassland
- Longer rotation schemes – Catch crops
For a given measure, CE ratios of implementing measures vary widely between communes as a result of Effectiveness and Cost variability within the watershed.

Mechanical weeding in replacement of chemical weeding could be then sometimes more Cost-Effective than Grass buffer strips depending on the location where the measure is applied.
Objective: find the changes of crops and practices that will contribute most to achieving goals at minimum costs

- Useful for policy analysis

- By integrating the environmental and the economic issues at diverse spatial and time scale

- Profitably replace more classical approaches based on pressure indicators allowing the integration of the dynamics of the agro-hydrological systems

- Better target the implementation of measures and financial incentives to farmers where appropriate

- CE analysis: Simple educational and communication tool summarizing the outcomes in a single quantifiable indicator for participatory approaches (integrated information needed)
Thanks for your attention

Gracias por su atención
Uncertainty

- Uncertainty at each step of the analysis
  - Uncertainty surrounding environmental goal and parameters
  - Uncertainty surrounding the sources of pollution (PS, NPS)
  - Uncertainty surrounding the choice of the measures defined by Science
  - Uncertainty about the placement for implementing the measures
  - Uncertainty surrounding the Costs and Effectiveness of mitigation measures
    → Sensitivity Analysis with SWAT and Bio economic model

2011 International SWAT Conference, June 15-17, Toledo, Spain