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FATE AND IMPACT OF PESTICIDES: NEW DIRECTIONS TO EXPLORE

Integrated modeling of agricultural scenarios (IMAS) to support pesticide action plans: the case of the Coulonge drinking water catchment area (SW France)

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Abstract Non-point source pollution is a cause of major concern within the European Union. This is reflected in increasing public and political focus on a more sustainable use of pesticides, as well as a reduction in diffuse pollution. Climate change will likely to lead to an even more intensive use of pesticides in the future, affecting agriculture in many ways. At the same time, the Water Framework Directive (WFD) and associated EU policies called for a "good" ecological and chemical status to be achieved for water bodies by the end of 2015, currently delayed to 2021–2027 due to a lack of efficiency in policies and timescale of resilience for hydrosystems, especially groundwater systems. Water managers need appropriate and user-friendly tools to design agro-environmental policies. These tools should help them to evaluate the potential impacts of mitigation measures on water resources, more clearly define protected areas, and more efficiently distribute financial incentives to farmers who agree to implement alternative practices. At present, a number of reports point out that water managers do not use appropriate information from monitoring or models to make decisions and set environmental action plans. In this paper, we propose an integrated and collaborative approach to analyzing changes in land use, farming systems, and practices and to assess their effects on agricultural pressure and pesticide transfers to waters. The integrated modeling of agricultural scenario (IMAS) framework draws on a range of data and expert knowledge available within areas where a pesticide action plan can be defined to restore the water quality, French "Grenelle law" catchment areas, French Water Development and Management Plan areas, etc. A so-called "reference scenario" represents the actual soil occupation and pesticide-spraying practices used in both conventional and organic farming. A number of alternative scenarios are then defined in cooperation with stakeholders, including socio-economic conditions for developing alternative agricultural systems or targeting mitigation measures. Our integrated assessment of these scenarios combines the calculation of spatialized environmental indicators with integrated bio-economic modeling. The latter is achieved by a combined use of Soil and Water Assessment Tool (SWAT) modeling with our own purpose-built land use generator module (Generator of Land Use version 2 (GenLU2)) and an economic model developed using General Algebraic Modeling System (GAMS) for cost-effectiveness assessment. This integrated approach is applied to two embedded catchment areas (total area of 360,000 ha) within the Charente river basin (SW France). Our results show that it is possible to differentiate scenarios based on their effectiveness, represented by either evolution of pressure (agro-environmental indicators) or transport into waters (pesticide concentrations). By analyzing the implementation costs borne by farmers, it is possible to identify the most cost-effective scenarios at sub-basin and other aggregated levels (WFD hydrological entities, sensitive areas). Relevant results and

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indicators are fed into a specifically designed database. Data warehousing is used to provide analyses and outputs at all thematic, temporal, or spatial aggregated levels, defined by the stakeholders (type of crops, herbicides, WFD areas, years), using Spatial On-Line Analytical Processing (SOLAP) tools. The aim of this approach is to allow public policy makers to make more informed and reasoned decisions when managing sensitive areas and/or implementing mitigation measures.

Keywords Pesticides · Water management · Integrated modeling · Agriculture · Scenarios · Indicators · Data warehousing

Introduction and context

As EU and national public policies focus more and more on reducing the "risks and impacts" of pesticide use (Lefebvre et al. 2015), political and public debate across Europe is placing greater emphasis on achieving a more sustainable use of pesticides (Hamlyn 2015). Intensive farming has been identified as one main source of diffuse pesticide pollution. France is considered the world's third-largest consumer of plant protection products (PPPs), with an industry turning over some 2 billion euros per year. Climate change is also affecting agriculture in many ways, increasing pest events, and heightening the sensitivity of crops to stress and disease. These changes are likely to lead to an increased use of pesticides (Fisher et al. 2005; Kattwinkel et al. 2011; Howden et al. 2007; Babut et al. 2013). Many of the thousand or so PPPs currently used in France can be transported to freshwaters, generating potentially hazardous residue.

Water quality continues to deteriorate, despite decades of public policy attempting to reverse the decline. Issues relating to pesticides and diffuse pollution are essentially covered by the following two pieces of EU legislation: EU Directive 2009/128/EC (EC 2009a) and the Water Framework Directive (EC 2000). As part of these regulations, EU member states are required to adopt action plans to limit the risks and environmental impact associated with agricultural pesticides. In France, one such action plan is "Ecophyto 2018." Its key aim is to achieve a 50 % reduction in the use of PPP by 2018. Clearly, the less pesticide that is used the lower the risk of transport into waters. Climate and environment also play a major role in this. However, the quantity of pesticide used is not always a clear indicator of toxicity. According to the European Crop Protection Association, the development of new phytosanitary products led to an almost tenfold decrease in mean PPP doses applied by hectare between 1950 and 2000. However, these new products are just as toxic at low doses as their predecessors were in higher quantities (Babut et al. 2013). For this reason, it is essential to encourage farmers to use molecules that have both low toxicity and a low risk of transport into rivers.

France's "Grenelle" laws (implemented following an environmental summit) identified around 500 drinking water abstraction sites as being particularly at risk for non-point source pollution. Various action plans have been developed in these areas, and a number of reports (CGAAER 2014) have highlighted shortcomings in the way areas at risk for water pollution are assessed, as well as the methods by which information from surveys and other sources is used by decision makers to define agro-environmental action plans, aimed at decreasing the amount of pesticides in freshwaters. Water managers need appropriate tools when designing agro-environmental policies, to help them evaluate the potential impact of local mitigation measures on water resources particularly the transport of nutrients and pesticides into water bodies and groundwater. They do not always use appropriate information from monitoring or models when making decisions and establishing environmental action plans: stakeholder participation makes modeling truly adaptive and helps to relate the models with real needs (Voinov et al. 2016).

Mitigation measures such as buffer strips, low-input agricultural systems and organic agriculture are a challenge not only for individual farmers but also for professionals and agricultural experts working in areas where public action is required to protect and restore the quality, e.g., Grenelle water catchment areas. These measures need to suit both the natural and socio-economic conditions of the targeted area. Several authors have highlighted the major challenge of selecting the relevant spatial scale for measurement and analysis of spatially variable economic and bio-physical processes (Van Ittersum et al. 2008; Ewert et al. 2011; Volk and Ewert 2011). Two main issues must be addressed: (i) balancing ecological and socio-economic needs, which calls for a multi-criteria assessment, and (ii) managing multiple scales, i.e., which methods and data resolution are available and appropriate at these scales? What information can be obtained? What is the best way to aggregate indicators and outputs?

One way of dealing with these complex multi-scale problems is through integrated assessment and modeling. A scenario-based approach can stimulate creative ways of thinking that may help stakeholders better adapt to the future by assessing situations and planning actions or to better understand the consequences of potential development of alternative systems (Delmotte et al. 2016). This approach is more important than ever in an environment where complexity and uncertainty are high (Wollenberg et al. 2000).

In this paper, we propose an integrated and collaborative approach to analyzing changes in land use and farming practices, specifically their effects on agricultural pressure and transport of pesticide into rivers and groundwater. First, we present how our integrated framework can answer these questions. We discuss the best way of characterizing the potential environmental impact of agricultural systems and practices within a water catchment area, as part of agro-environmental action plans to restore the water quality in rivers, especially regarding pesticide concentrations. We then focus on evaluating the environmental impact of these practices on pesticide pressure from agriculture (with indicators), on pesticide transport to rivers (using a hydrological model) and finally, calculating the private costs associated with that (economic model).

Next, we describe the Coulonge Saint Hippolyte drinking water catchment area (BAC Coulonge) (SW France) and the likely future evolution of agricultural systems in this study site, as projected in cooperation with agricultural experts, i.e., advisers from agricultural bodies for a specific crop or specific area, and other stakeholders, i.e., local authorities, professionals, public bodies, local counselors, water supply officials. Possible scenarios could include changes in practices and/or agricultural systems (introduction of innovative or organic systems) and the development of buffer zones (applied to some sub-basins or to the whole study area).

A number of scenarios are discussed, and the results obtained through calculation of indicators and the simulations from models are analyzed and compared. We then present a prototype of a dedicated data warehouse, constructed using data available handled around the BAC Coulonge action plan, both from institutional databases and from assessment tools. The purpose of data warehouses is to take vast amounts of data from many internal and external sources and present them in meaningful formats to make better decisions (Nilakanta et al. 2008). Data warehouses provide the basis for management reports, decision support, and sophisticated Spatial On-Line Analytical Processing (SOLAP) and data mining. Following this, we discuss the advantages and limitations of the IMAS framework. Finally, a set of needs covering the development of operational tools and information systems to support water managers with decisions on management strategies to reduce pesticide input to rivers and water table are listed in the "Conclusions and perspectives" section.

The IMAS framework: an integrated modeling framework of agricultural scenarios to help water managers in water catchments

General approach

By nature, integrated assessment must include several dimensions (Jakeman and Letcher 2003). This is particularly true in the case of pesticide action plans, which involve large networks of stakeholders (local authorities, water managers, etc.). This type of assessment draws on a number of different disciplines from the human and natural sciences and covers multiple scales, ranging from the individual plots where pesticides are applied right up to the sub-basins and basins to which they are eventually transported. There is a variety of cascading effects to take into account, as well as a variety of different models and databases for which cross compatibility needs to be achieved.

Collaborative governance is considered to be more appropriate for integrated and adaptive management regimes needed to cope with the complexity of social-ecological systems (Pahl-Wostl 2007). Water governance and management should be seen as part of a broader societal transformation towards sustainability that focuses on a reduction of pressures in river basins instead of mitigating their impacts (Knieper and Pahl-Wostl 2016). We consider as well the work of The Integrated Assessment Society and focus on integrated modeling, considering an interdisciplinary process (agro-geography, hydrology, economy) and a "true" spatial integration taking into account both the economic and environmental impacts of agriculture (Laurent et al. 2007; Matthies et al. 2007; Volk et al. 2008; Vernier et al. 2014). We also develop strong links with stakeholders and water managers. Decision makers (in our case local water managers and the river basin agency) should be given relevant information allowing them to estimate the future state of rivers in the area if mitigation measures were to be implemented in part of the area or the whole area. Our integrated modelling framework for agricultural scenarios (IMAS) combines (Fig. 1) expertise and typologies of agricultural systems within an area with a range of environmental indicators, along with integrated modeling using agro-hydrological (Generator of Land Use version 2–Soil and Water Assessment Tool (GenLU2-SWAT)) and economic models to assess the cost-efficiency of spatialized scenarios. This information is organized into a data warehouse taking into account institutional and field data, as well as scientific and expert knowledge available in the water catchment area.

Scales

According to Wenkel et al. (2013), decision support frameworks should at the very least support spatial and non-spatial data management. In the IMAS approach, common spatial scales are defined and used by the different tools all throughout the project (Fig. 2). The lowest level is the block of plots, where crop rotations and associated practices are modeled and Common Agriculture Policy (CAP) data are available. A classical ArcGIS geoprocessing model makes possible that a block of plot is part of only one sub-basin, which is not always the case in institutional layers. A block of plots (BOP) is homogeneous regarding the crop rotation or permanent crop grown and the practices associated. Its area can be very different depending on rural landscapes and associated systems; the mean area is 2 ha

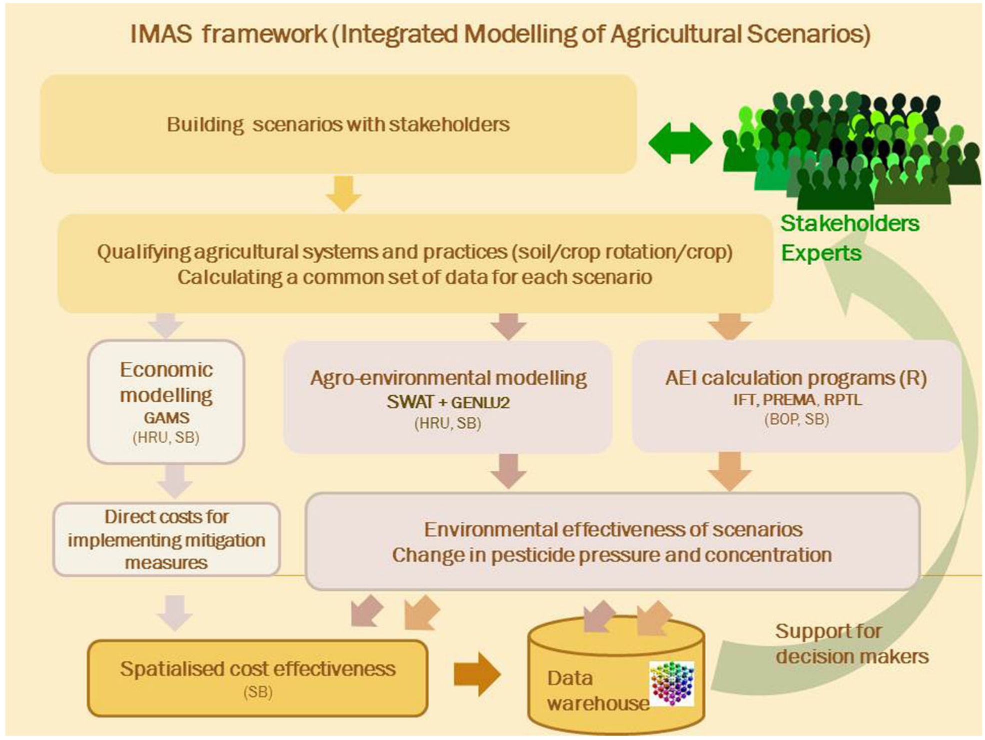


Fig. 1 The IMAS approach developed at Irstea (ETBX, TETIS teams) with local stakeholders

(about 160,000 B.P. in our study site. A link is made between the spatial reference units of all models. The calculation unit for routing the molecules up to the stream is the hydrological response unit (HRU) of the SWAT model. The HRU is a homogeneous unit, a unique combination of land use/soil/slope within a sub-basin. For our study site, it typically covers around 200 ha. This scale is also used by the bio-economic model to calculate the cost of implementing mitigation measures. Global

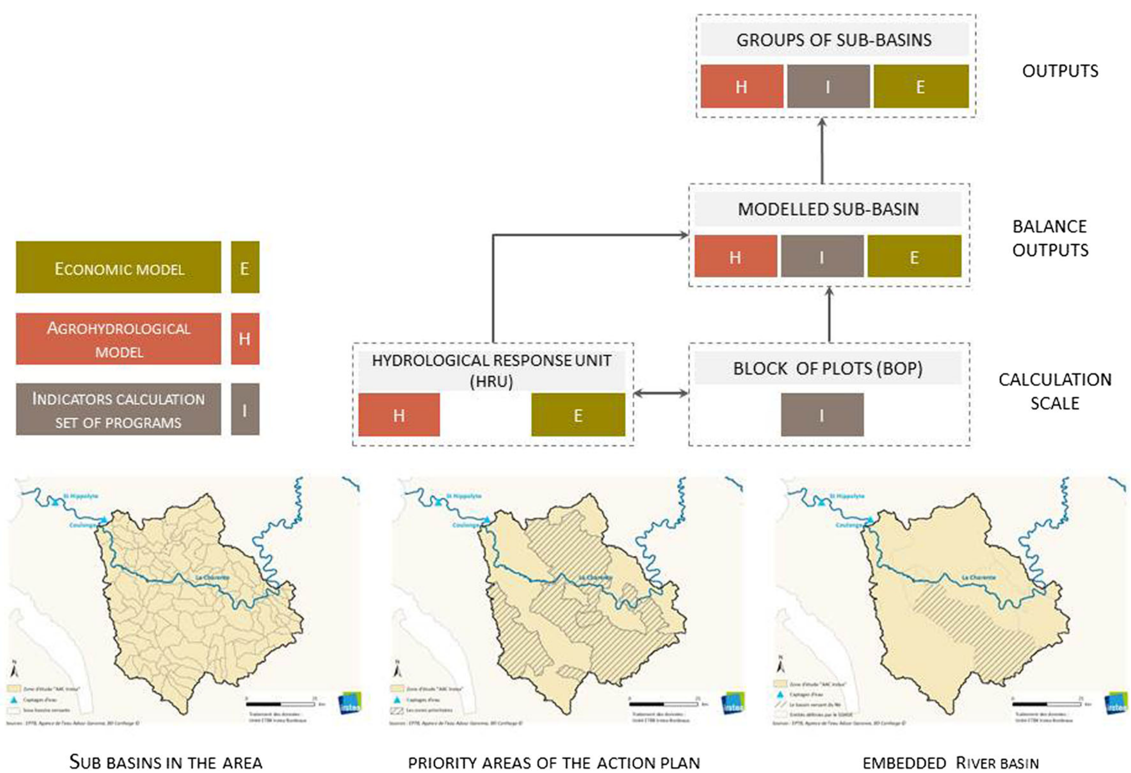


Fig. 2 Spatial scales used in the IMAS approach

discharge and balances (water, pollutants, etc.) are then calculated and returned to the sub-basin and basin levels, which are aggregated levels for the calculation of indicators. The number of sub-basins in the area is chosen based first on the constraints of the hydrological models and second on the coherence of the model with regard to local management of water resources. For instance, our study site, the BAC Coulonge area was divided in 106 modeled sub-basins with an average area of 2000 ha.

Cost-effectiveness analysis is particularly useful in comparing mitigation measures by providing a rationale for decisions to be taken at "agricultural district" level for drinking water abstraction. The cost-effectiveness of mitigation measures is assessed both as a ratio of cost-differences for farmers, and either the reduction of pressure and potential risk of pesticide transport to rivers, estimated by the indicators, or reduction in the simulated concentration of pesticides in freshwater. These combined calculations make it possible to identify the most cost-effective scenarios for each sub-basin and for the whole watershed. Compared to existing integrated approaches, the IMAS one has the following three main advantages:

- All the assessment tools, i.e., the R programs for the calculation of indicators, the SWAT and economic models, the SQL database for upload of indicators and outputs of the models into the data warehouse, use the same dataset characterizing the location of crops and associated crop management sequences, for a given scenario
- All assessment tools take into account the dynamics of agriculture, 6-year crop rotations changing through scenarios (lengthening or adding new crops, changing from a conventional system to an organic one)
- Calculation and outputs are provided at coherent spatial scales and combined indicators and models.

The following is a description of all the models and assessment methods, which are combined to make up the modeling element of our integrated approach.

Models and assessment methods

Constructing "modeled" agriculture in the area

The first step in the IMAS method is to characterize and model agricultural systems and practices in the studied area, from an environmental point of view, i.e., what could be the potential impact of agriculture on water resources, regarding its characteristics. A cropping system can be defined by the crop rotation and also the management sequence associated with each crop. The crop management sequence is a succession of actions with a temporal and spatial coherence (Meynard et al. 2001), as the management sequence of a crop depends on the preceding crop and results from decision processes applicable to areas greater than a single field (Jouve 2006). The spatial distribution of cropping systems can be explained by environmental factors—mainly soil, water, and biodiversity-and technico-economic factors (Bürgi et al. 2004; Dalgaard et al. 2003; Murgue et al. 2016). Therefore, even if the influence of these factors can be lessen in some specific European contexts, we consider that the decision to grow crops in a specific sequence is made based on environmental, socio-economic, and agronomic constraints (Castellazzi et al. 2007). Assessing the potential impact of agricultural systems and practices in a protected area calls for a characterization of crop rotations and associated farming practices linked to agricultural systems and soils in a spatialized way. Soils are used as criteria both by authors (Clavel et al. 2011) and local agricultural experts.

Our approach for assessing a modeled vision of current agriculture in the area (Fig. 3) uses a typology based on type of soil and associated crop rotations or permanent crops. The typology is carried out using institutional data, such as censuses and CAP data, as well as expert advice from stakeholders and data from surveys conducted in the area. We consider a 6-year standard crop rotation, which enables to manage all the current systems, but this could be more or less, depending on the context. A crop rotation can be irrigated or not, and in case of monoculture—for instance, irrigated maize—the crop is repeated six times to reach the temporal standard. The goal of this approach is to provide a dynamic view of agriculture as close as possible to reality. Considering the typology of soil/crops, each BOP is given a crop rotation—or permanent crop—and associated crop management sequence by R programs specifically developed to build land use layers. The process takes in account the "real" crop affected on the block of plots for year 1 (from CAP data) and the total area for a crop in the global area, using data from the French Agricultural Census.

Building scenarios with stakeholders

Our approach is scenario-based approach; firstly, a reference scenario describes the most likely evolution of the system resulting from present trends (Claessens et al. 2009; Mitchell et al. 2016). Alternative scenarios are intended to function as a combination of future trends in crop area (increase, decrease, or change), mitigation measures, and management options. In our study, we worked with local stakeholders to establish a reference scenario, considering both conventional and organic farming systems. Local stakeholders can be placed into the following three main categories: local authorities in charge of implementing European or French policies in the area, farmers, and their representatives; water managers in

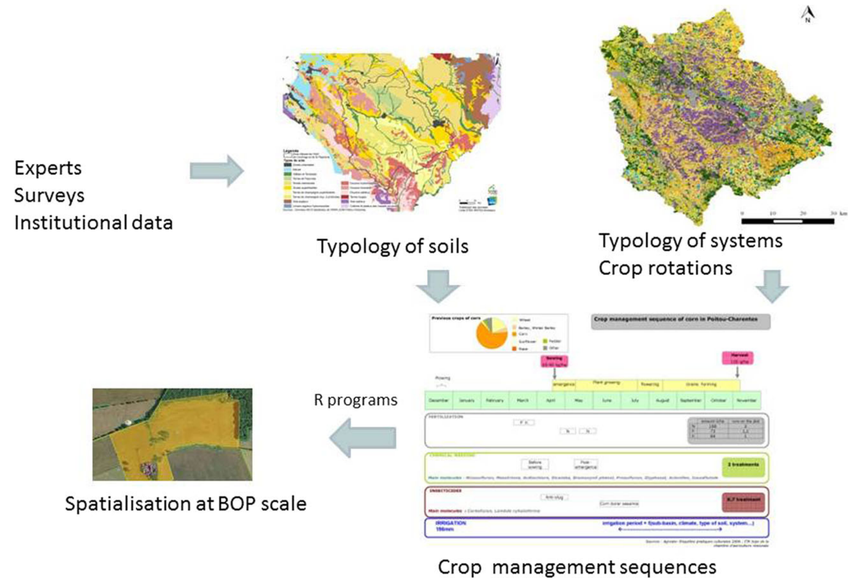


Fig. 3 Assessing agriculture systems and associated practices

charge of restoring/improving water quality and the river basin agency; and responsible for coordination and funding. We created a focus group (about ten persons) composed predominantly of experts of agriculture in the area or advisers for specific crops (vineyards, cereals…) or specific agronomic contexts. These people agreed to attend meetings on a monthly basis during the period dedicated to the detailed description of reference and alternative scenarios. Besides consultation with the participant group (local managers), we performed dedicated surveys with agricultural experts and a set of farmers, with the aim of verifying the relevance of our model. We then created a set of hypothetical scenarios, in which several agro-environmental measures (such as buffer strips) or changes in crop rotations and practices were applied at sub-basin level (Fig. 4).

For each scenario, a common dataset is used to calculate indicators, and data are fed into an agro-hydrological model (SWAT) and an economic model (using General Algebraic Modeling System (GAMS)), the latter being used to calculate the costs of implementing each scenario.

Evaluating the environmental impact of scenarios using indicators

A successful implementation of mitigation measures can only be achieved through a greater understanding of the interactions between land use (pesticide pressure) and the environment. One way of doing this is to calculate agro-environmental indicators (AEIs), which account for both pressures from agriculture and human activities and the vulnerability of surrounding ecosystems. An indicator can be seen as something that provides a clue to a matter of larger significance or makes perceptible a trend or phenomenon that is not immediately detectable. Composite indicators (aggregation or combination of a set of indicators) can be used to summarize complex or multi-dimensional issues in view of supporting decision makers (EU Commission 2014). Relatively simple to use, indicators may be particularly useful when resources and data are limited (Feola et al. 2011). The key purpose of an indicator is to enable a decision maker, who is not necessarily a scientist, to assess the potential impact of mitigation measures and make informed decisions. However, in practice, many indicators are misleading, out of context, lacking in scientific precision, based on misleading proxies of risk, or insufficiently validated (Bockstaller et al. 2009; Yli-Viikari et al. 2007). As a consequence, there is still a need for the development of a framework allowing optimization and harmonization of the use of pesticide risk indicators in the European Union (Reus et al. 2002).

In our approach, we use several AEIs, mainly evaluating the intensity of practices and the pesticide pressure at the river basin scale. Because there is no institutional indicator available at this scale for evaluating potential risks of transfer to freshwaters, we developed a specific one, the localized potential risk of transfer (LPRT) indicator, using previous studies (Vernier et al. 2014) and available local expertise.

The indicators chosen for the study with stakeholders are described below.

1. *The IFT indicator (treatment frequency indicator)* is adapted from the Danish IIT (Champeaux 2006). A treatment index also exists in Germany (Sattler et al. 2007). It estimates the frequency and doses of PPP applied in an area, compared with officially permitted doses. It is calculated in the case study at

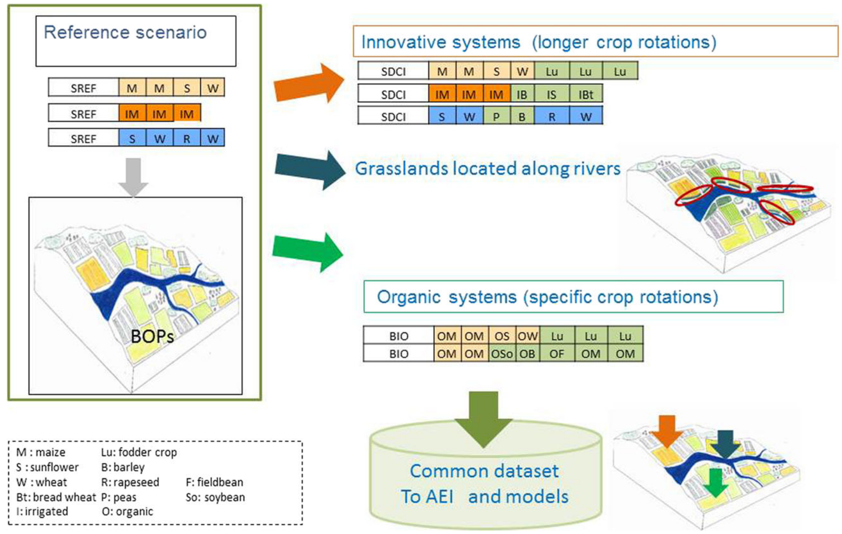


Fig. 4 Design and spatialization of reference and alternative scenarios

the BOP scale and then aggregated to all spatial scales as defined with stakeholders (sub-basin, group of sub-basins, priority areas—the latter being among the most sensitive to diffuse pollution defined in the diagnosis step of the action plan). It is largely used in agro-environmental action plans (Ecophyto 2018 national action plan, DEPHY farm network, etc.), and regional standards have been set throughout France. Despite the fact that it is possible to adjust the composition of a PPP (multi-molecule) to lower its value, the IFT indicator remains the benchmark indicator in current agro-environmental action plans.

where BOP is the block of plots, SB is the sub-basin, T is the 6 years for crop rotation, and P is the total product applied.

2. *The PREssure in one specific Active Matter (PREMA) indicator* estimates the quantity of specific molecules applied to an area (in grams per hectare). It is calculated at the block of plots scale and then aggregated at the subbasin scale. The advantage of PREMA is that it can be compared more easily to the transport of molecules into rivers estimated through monitoring orhydrological models. Monitoring the amount of molecules applied is one of the goals of the Ecophyto action plan.

$$\mathrm{IFT\,BOP} = \sum_{p=1}^{P} \frac{\text{applied dose}}{\text{authorized dose for the crop}} \times \frac{\text{total sprayed BOP area}}{\text{BOP area}} \qquad \mathrm{IFT\,SB} = \frac{\sum_{t=1}^{T} \text{IFT BOP} \times \text{BOP area}/T \text{ within the subbasin}}{\sum \text{total BOP area within the subbasin}}$$

$$\mathrm{PREMA\,BOP} = \frac{\sum \text{appliedquantityofactivematter (g)}}{\text{total BOP area (ha)}} \qquad \mathrm{PREMA\,SB\,(for\,one\,molecule)} = \frac{\sum_{t=1}^{T} \text{PREMA BOP} \times \text{BOP area}/T \text{ withinthesubbasin}}{\sum \text{total BOP area withinthesubbasin}}$$

where BOP is the block of plots, SB is the sub-basin, and T is the 6 years for crop rotation.

3. *The LPRT indicator* is a composite indicator, specifically developed within the project, combining vulnerability of spatial homogeneous units and pesticide pressure from human activities. On the one hand, pesticide pressure is represented by IFT indicators (herbicide and non-herbicide). On the other hand, global vulnerability is represented by slope, vulnerability to lixiviation and runoff, and distance to rivers. Classes of vulnerability of soils to lixiviation and runoff are known from previous studies in the area. The selected variables are analyzed through multiple factor analysis (MFA), a factorial method devoted to multiple groups of variables collected on the same observations. The main idea of MFA (for only groups of numerical variables) is to normalize each group of variables by dividing all the variables by the first eigenvalue coming from the principal component analysis (PCA) of the group. After that, MFA consists in applying a classical PCA on all weighted variables taken together. Initially, this method was developed by Escoffier and Pagès

(1983) for groups containing numerical variables, then for groups containing categorical variables. This method was later improved to deal simultaneously with groups of solely numerical and categorical variables (Bécue-Bertaut and Pagès 2008). Recently, an extension of the method called MFAmix, which is implemented in an R package available on the CRAN, has been developed for groups containing mixture of numerical and categorical variables (Labenne et al. 2013; Chavent et al. 2014). This approach is particularly useful for constructing the LPRT composite indicator, since it enables the two groups of variables to be balanced, namely, sensitivity and pressure. The first principal component generated by MFAmix is set as the value of the indicator. Following this, a complete hierarchical clustering is obtained using an agglomerative algorithm, which at each stage amalgamates a pair of clusters which leads to minimum increase in the total within-cluster sum of squared distances (Ward 1963). This method seeks to build a hierarchy of clusters; it allows the identification of several groups, each corresponding to different levels of potential risk of pesticide transport. The values of thresholds obtained for the set of data, corresponding to the reference scenario, are retained for all scenarios (true for all indicators used).

The temporal scale used for all indicators is the 6-year crop rotation; indicators are actually calculated each year, then for the 6-year crop rotation. Single crops are repeated when necessary ("MMMMMM" for maize monoculture). The calculation of AEI at several spatial scales estimate the "transitional" efficiency of the alternative scenarios in comparison with the reference scenario, given by the decrease in the pesticide pressure (IFT and PREMA indicators) or the decrease in the potential risk of pesticide transport (LPRT composite indicator) (Fig. 5). A one-sample Student's test is used to compare the mean value of the indicator obtained on the alternative scenario to the corresponding value for the reference scenario (Lehmann and Romano 2005).

While this is already important when deciding "where and how" to imply mitigation measures, decision makers are also calling for greater functionality, including ways to estimate the impact of scenarios on pesticide concentration in rivers. This can be estimated with another tool, agro-hydrological modeling.

Modeling the transport and fate of pesticide to rivers with the SWAT-GenLU2 model

While there are some models to simulate pesticide fates at field scale, fewer tools accomplish the same task at river basin

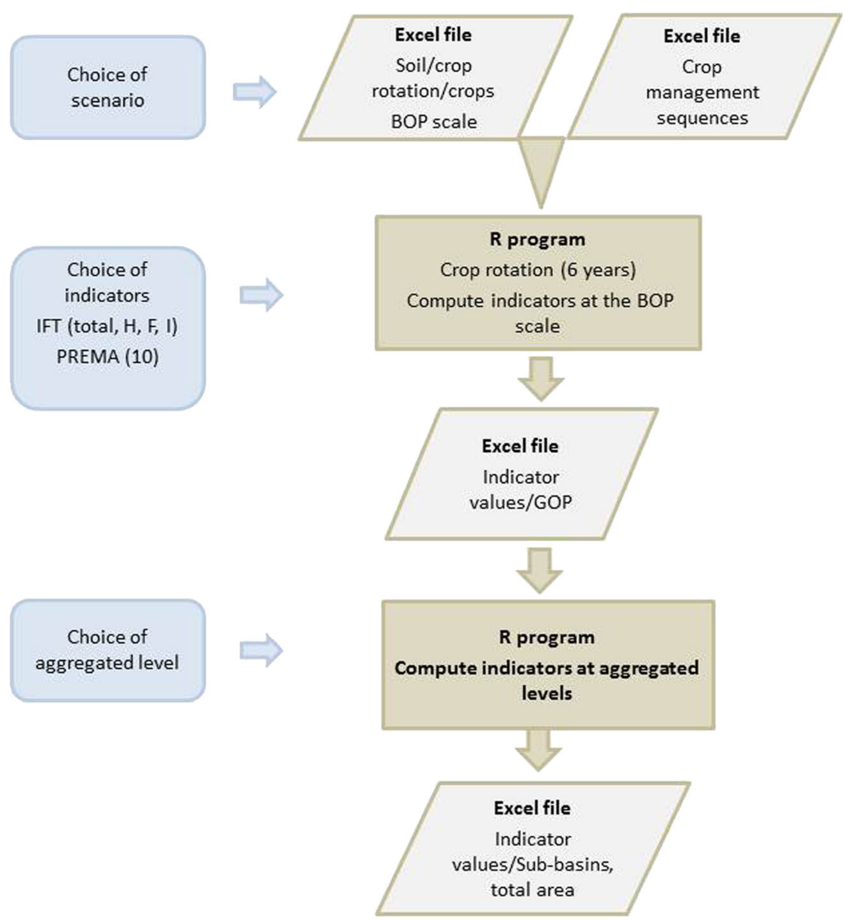


Fig. 5 Methods for computing the AEI indicators at different spatial scales

scale (Babut et al. 2013). Modeling is more complex in this case, because in larger watersheds, territories do not directly contribute to pesticide inputs into surface water, and so-called critical source areas can provide most of the contaminant load in those waters (Freitas et al. 2008; Frey et al. 2009). In an ideal world, models would be fully distributed and would account for the influence of landscape characteristics such as hedges and man-made structures (Doppler et al. 2012), processing huge amounts of data. However, such models are not currently available at watershed scale.

A compromise therefore needs to be struck in terms of processing time when considering large and extensively monitored territories. In this context, we chose the continuous time step and semi-distributed SWAT as the most appropriate model to evaluate long-term (20 years) impacts of PPP spraying on soils and water bodies from complex agricultural scenarios at the large river basin scale (Arnold et al. 1998; Santhi et al. 2001). This modeling approach allows identification of the most contributive areas within a given zone, where mitigation measures could be the most efficient, in terms of decreasing the amount of pesticide concentration in rivers. The impacts of alternative scenarios are quantified compared with the reference scenario. The model is able to run various input scenarios including measures such as reduced pesticide spraying or fertilization, filter strips, active matter, or crop substitution and lengthening of crop system rotations.

The SWAT model can route a set of ten molecules for each management schedule. These molecules (active matters associated to PPP) were chosen in collaboration with local stakeholders as “witnesses,” depending on use and monitoring results in the protected area and chemical and physical features of the molecules. Calculations (yields, inputs/outputs) are carried out at the HRU scale.

This model is a physically based watershed-level continuous daily step calculation model. The calculation unit (crop yields, inputs/outputs) is the HRU, which is a homogeneous unit (unique combination of land use/soil/slope), within a sub-basin (Fig. 6). The HRUs are not fully distributed within the sub-basin. Assessment of impacts by the SWAT model is carried out at the sub-basin/basin scale. For each alternative scenario, variations in pollutant concentrations, fluxes, and water balance are estimated at each sub-basin outlet inside the modeled area. Pesticide

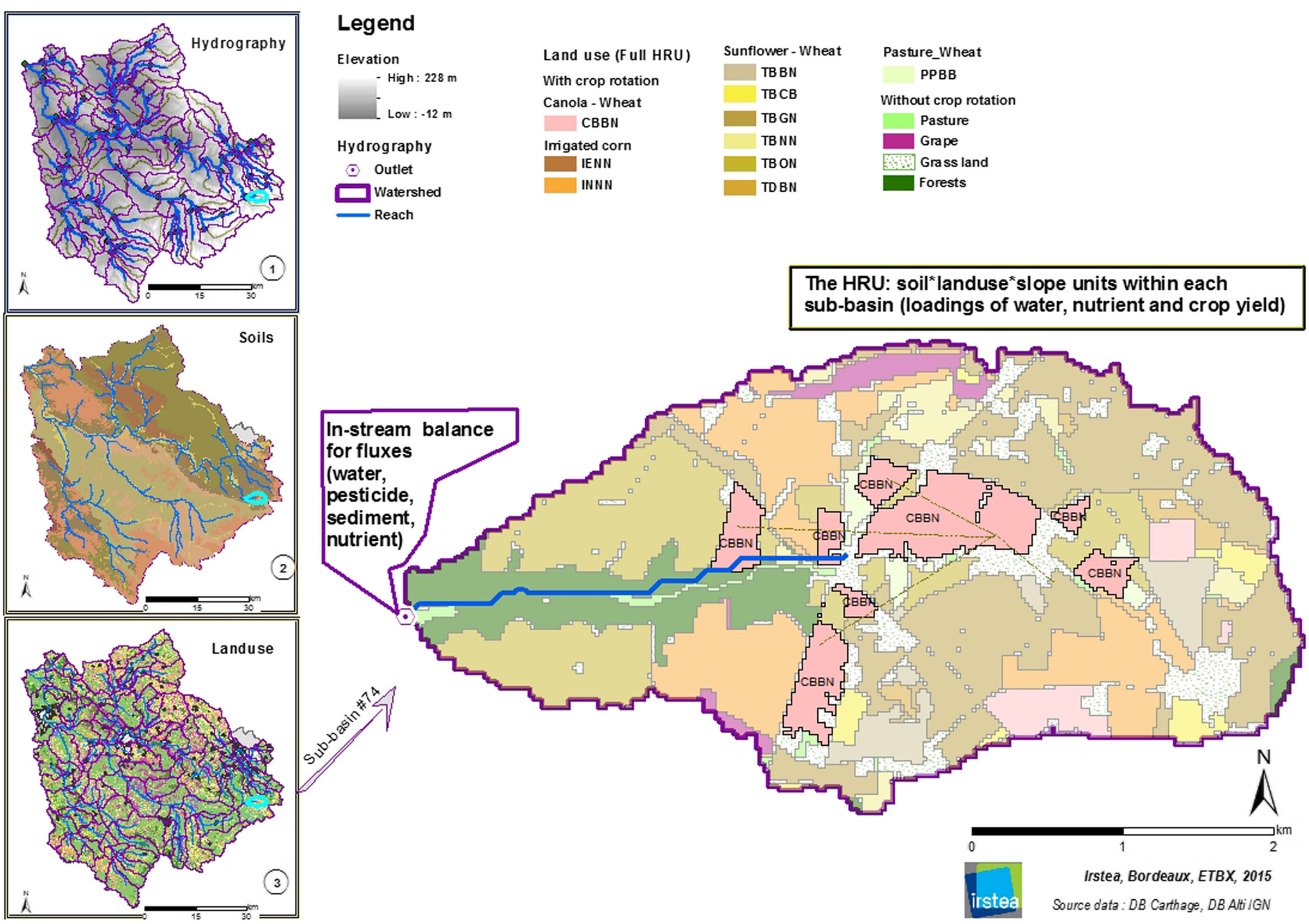


Fig. 6 Spatial scales of calculation and outputs (SWAT model)

concentrations are calculated based on the amount of dissolved pollutant loads divided by the water outflow simulated at each sub-basin outlet from the ten latest years of simulation.

A specific module, the GenLU2, was developed at Irstea Bordeaux (Fig. 7) as part of this work. This module improves and expands the scope of GenLU1 (Bordenave et al. 2009), which was developed in a previous work. GenLU2 is able to handle the common dataset of spatialized crop rotations and connected practices defined for each scenario. It can schedule and manage the variability of crop management sequences, introducing temporal variability in dates of farming operations, particularly pesticide spraying, which is a controlling factor of pesticide transfers (Boithias et al. 2014). The parameters of the SWAT model were adapted to suit French crops and crop rotations grown within the studied area, which is a key factor in correctly estimating yields at the HRU scale.

The model was calibrated using multi-site and multi-objective calibration methods (SUFI2 and PEST) in the four available official gauging stations within the BAC Coulonge area. Two gauging stations were used so as to enter the inflows and incoming nitrate and pesticide concentrations into the basin inlet of the modeled area. Quality stations were used. There was a 19-year simulation period, including a 2-year warm-up period, and 5- and 4-year calibration periods, depending on the available observed data at each station.

Two calibration approaches were tested to assess the performance of the over-parameterized semi-distributed SWAT model. This involved two multi-objective evolutionary algorithms CMAES from PEST and SUFI-2 from SWAT-Calibration and Uncertainty Procedures (CUP) (Abbaspour et al. 2007). The aim was to evaluate their ability to deal with equifinality and uncertainty on a poorly gauged basin. Both methods are structurally very different; one handles a large number of parameters that can be calibrated at the calculation unit level (PEST), whereas the other deals with a limited number of the most sensitive parameters that have been previously selected performing a sensitivity analysis (SWAT-CUP). The principle of parsimony in parameter calibration was tested with SWAT-CUP in relation to the principle of dominance (Efstratiadis and Koutsoyiannis 2010).This is an important point we will discuss in a separate paper focusing on hydrological modeling.

The objective functions and quantitative criteria used to evaluate the model's replicability were Nash-Suttcliffe efficiency (NSE) (Eq. 1) and the coefficient of determination r^2 (Eq. 2).

$$\mathrm{NSE} = 1,0-\frac{\sum_{i=1}^{n}\left(Q_{i.\mathrm{obs}}-Q_{i.\mathrm{sim}}\right)}{\sum_{i=1}^{n}\left(Q_{i.\mathrm{obs}}-Q_{\mathrm{obs}}\right)^2} = 1,0-\frac{\mathrm{MSE}}{\partial_0^2} = 1,0-\frac{(\mathrm{RMSE})^2}{\partial_0^2} \tag{1}$$

$$r^2 = \frac{\left[\sum_{i=1}^{N}\left(Q_{i.\mathrm{obs}}-Q_{\mathrm{obs}}\right)\left(Q_{i.\mathrm{sim}}-Q_{\mathrm{sim}}\right)\right]^2}{\left[\sum_{i=1}^{N}\left(Q_{i.\mathrm{obs}}-Q_{\mathrm{obs}}\right)^2\right]\left[\sum_{i=1}^{N}\left(Q_{i.\mathrm{sim}}-Q_{\mathrm{sim}}\right)^2\right]} \tag{2}$$

Qualitative criteria were also taken into account through collaborative work with stakeholders (agricultural institutional local entities and regional water managers). Once the environmental efficiency of scenarios has been assessed by the AEI and the SWAT model, it is now important to consider an economic input for ranking potential mitigation measures.

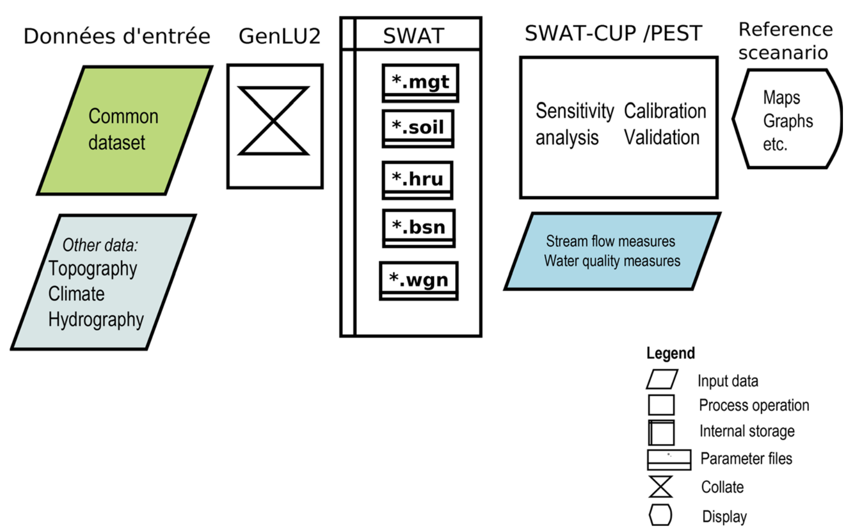


Fig. 7 Agro-hydrological modeling with SWAT and GenLU2

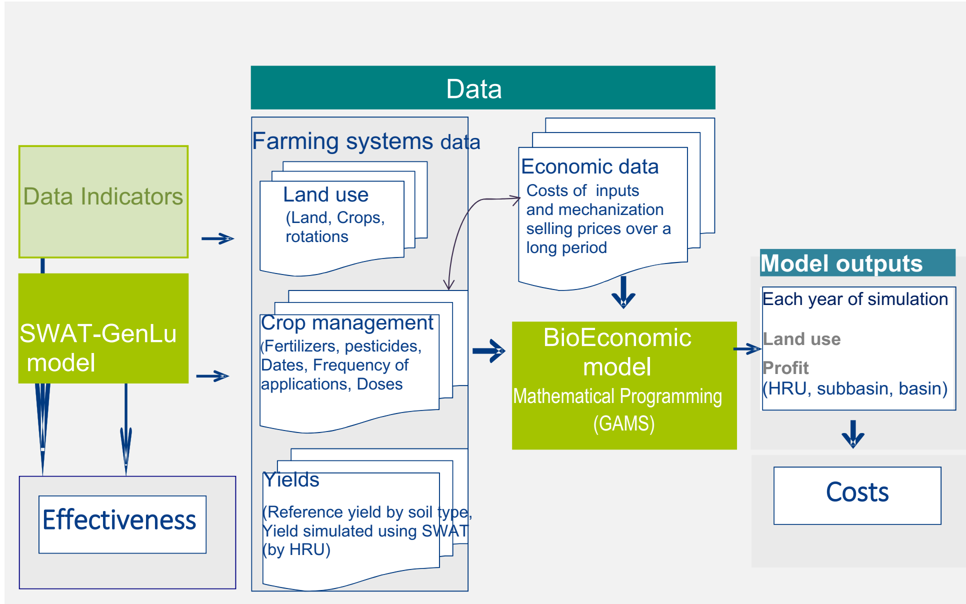


Fig. 8 The economic model—calculation at the HRU level

Evaluating the costs for farmers with an economic model

When choosing mitigation measures, it is assumed that selected measures will be effective. Their effectiveness can be then assessed by the use of indicators for transitional goals (i.e., effect on the pressure on the environment, freshwaters or land resources, on the practices intensity as defined before[1] or on the risk of pollutant transfer into water bodies). However, models are required to assess the impacts of land use scenarios on effective pesticide transfer to assess final goals (impacts). While two measures may reduce pollution with equal effectiveness (assessed by the impact on pressure or on transfers), their respective costs will be different, given that marginal costs for implementing are not the same. In addition, costs may also vary for the same measure applied at different locations.

The heterogeneity of farming systems is addressed by using bio-economic modeling to appraise the marginal and total costs of implementing measures. Traditionally, due to difficulties caused by data availability, "representative" (average) farms and "type" (modal) farms are modeled. When these are used, geographical information on farm plots and management practices is lost. We overcome these problems by working on farming systems and calculating costs at the HRU level, which is the spatial unit used by SWAT to calculate flows of water, nutrients, and pesticides.

The economic model (Fig. 8) uses yields estimated at HRU level from the SWAT model and the estimated variable costs determined by crop management practices and sequences. Developed with GAMS (Brooke et al. 1988), the economic model simulates the use of agricultural land in each HRU. It is assumed that farmers are "price takers" (i.e., they have no effect on sales or purchase prices) and that they seek to maximize their profit. The objective function of the economic model is therefore the maximization of the expected utility (i.e., here the gross margin (GM) as no allowance related to risks are taken into account) in choosing or not to implement a particular measure. In addition to the decision variables corresponding to crops and standard practices, measures are introduced into the bio-economic model as new decision variables which correspond either to changes in land use (new crops, catch crops, meadows, strips grass) either to changes of practices (e.g., reduced use of pesticides or fertilizers) and by adding, if necessary, additional constraints (longer rotation, crop diversification). We point out here that data used for the SWAT model and with the economic model are exactly the same.

The yearly direct total cost (TC) of implementing a scenario within a SB is then calculated as follows:

$\mathrm{TC_{SB}} = \pi^*_{1,\mathrm{SB}} - \pi^*_{2,\mathrm{SB}}$ with $\pi^*_{1,\mathrm{SB}} = \sum_{\mathrm{HRU}=1}^{n} \pi^*_{1,\mathrm{HRU}}$; $\pi^*_{2,\mathrm{SB}} = \sum_{\mathrm{HRU}=1}^{m} \pi^*_{2,\mathrm{HRU}}$ and for the whole basin, $\mathrm{TC}_B = \sum_{\mathrm{SB}=1}^{p} \mathrm{TC_{SB}}$ with $\pi_{1,\mathrm{HRU}} = \sum_c \left(y_{c,1,\mathrm{HRU}} \times p_c - cv_{c,1}\right) \times X_{c,1,\mathrm{HRU}}$; $\pi_{2,\mathrm{HRU}} = \sum_c \left(y_{c,2,\mathrm{HRU}} \times p_c - cv_{c,2}\right) \times X_{c,2,\mathrm{HRU}}$

where

$\prod_{\mathrm{HRU}}$	Profit gained by HRU for adopting ($\pi_{2,\mathrm{HRU}}$) or not ($\pi_{1,\mathrm{HRU}}$) the changes driven by the scenario
HRU	Hydrologic Response Unit

[1] Practice intensity is defined the same way as mentioned in precedent section for indicators and the SWAT model; depending of the crops defined in the scenario, this could be the quantity of fertilizers per hectare, the type and quantities of pesticides applied/hectare, rotation relationships, technical and/or cultivation practices, no-till farming, etc.

C	Crop
$X_{c,1,\mathrm{HRU}}$	Land use (ha) for crop c and practice 1 within a HRU
$y_{c,1,\mathrm{HRU}}$	Yield of crop c (tons of grains or dry matter ha^{-1}) by crop, practice 1, and HRU
p_c	Price of commodities for crop c (€ ha^{-1})
$cv_{c,2}$	Variable production costs by crop c and practice 2 (€ ha^{-1}).

Effectiveness (in this case, concentration of pesticides) can only be calculated at the outlet of the sub-basin and basin. For indicators, although they are calculated first at the block of plots level, their calculation at the sub-basin and basin levels is needed for comparison with outcomes from the SWAT model. To assess the cost-effectiveness of different scenarios, costs should be calculated at a common spatial scale. The common temporal scale used for calculating total discounted costs of implementation can be either the hydrological simulation period (used for calculating transfers) or the longest rotation period:

$$\mathrm{TC_s} = \sum_{t=1}^{T} \mathrm{TC_B} \times (1 + \mathrm{r})^{-t}$$

TCs : total cost of scenario to be used for the CE analysist : number of years for simulating (longest rotation period)r : discounting rate (0.05) total cost of scenario to be used for the CE analysis; t, number of years for simulating; and r, discounting rate.

In addition to constraints on the availability of farmland (A), irrigated areas or crop rotations requirements were added the following constraints related to the implementation of scenario: quantities of pesticides applied/ha, the rotations relationships, technical and/or cultivation practices, and no-till farming.

More information about bio-economic modeling and how the marginal costs are calculated can be found in Lescot et al. (2013). Ratios (TCB/E) of the discounted sum of yearly costs (TCB) on effectiveness (E) summarize results into single useful quantitative indicators for selecting measures.

However, these ratios calculated at different scales need to be handled carefully, because of the deterministic approach fused in their computation, especially since the risk or uncertainty attached to commodity prices and yields have not been taken into account.[2]

Providing efficient information systems for decision support in pesticide action plans

To help local managers to bring surface water back to "good biological status" and to preserve a quality of the resource suitable for drinking water supply, decision makers need information systems combining data and scales about the quality of water resources, as well as the environmental and economic impacts of human practices. To this end, the wishes of local managers should be better taken in account by public bodies and researchers. These systems have also to deal with scarcity and data uncertainty. For instance, at regional level, basic data such as agricultural land use, soil characteristics, or pesticide concentrations from regional monitoring are not easy to obtain or even not available at relevant scales. Pre-processing these data (cleaning, making typologies or groups, merging or carefully aggregating) is often necessary (Vernier and Miralles 2015). However, the information system calls for a number of parameters to be processed, river basin characteristics , localization of systems and associated crop management sequences, indicator values at various aggregated levels, values of concentrations simulated by the SWAT model, and costs estimated by the economic model for each sub-basin and each scenario. This represents a huge amount of data—possibly running into hundreds of thousands of BOPs for each scenario—which must be readily available to decision makers. By better structuring available information, a range of relevant spatialized "indicators in every sense"—AEI, thematic aggregated values, and estimations from the models—can be generated to assist public decision makers (river basin agencies, water managers, local authorities) (Vernier et al. 2015).

Agricultural and environmental Information Systems (IS) and Decision Support Systems (DSS) are two complementary approaches, whose combined use facilitates information management and decision making in numerous applications for agriculture and the environment (Pinet et al. 2015). Such environmental information systems can benefit from spatial data warehouse technology (Schneider 2008; Pinet et al. 2010). Data warehousing has proved useful in creating decision-making tools for agro-environment action plans and evaluating "ex-ante" the potential impacts of the evolution of agriculture and specific cubes have been implemented (Vernier et al. 2013). Using this technology, it is possible to manage huge amount of data and define analytical perspectives with stakeholders. It also allows the generation of maps/graphs presenting indicators and results from modeled scenarios, using one or several cubes (Fig. 9). A cube is a set of data that is usually constructed from a sub-set of a data warehouse and is organized into a multi-dimensional structure defined by a set of dimensions (hierarchies) and measures (values). The dimensions of the cubes can be temporal (month, year, all years, etc.) spatial (outlets, BOP, sub-basins, etc.), or thematic (type of crops, type of chemicals—herbicide, fungicide, insecticide), and they are all defined alongside stakeholders. The use of an intermediary SQL database makes it possible to save all the source information and to build or re-build cubes as necessary.

We have seen how the IMAS framework can be used to model agricultural systems and practices, define alternative scenarios, calculate AEIs to estimate their impact on the pressure from agriculture, use GenLU-SWAT to estimate the associated

[2] Prices of commodities from organic farming are less affected by market fluctuations than prices of products from conventional farming.

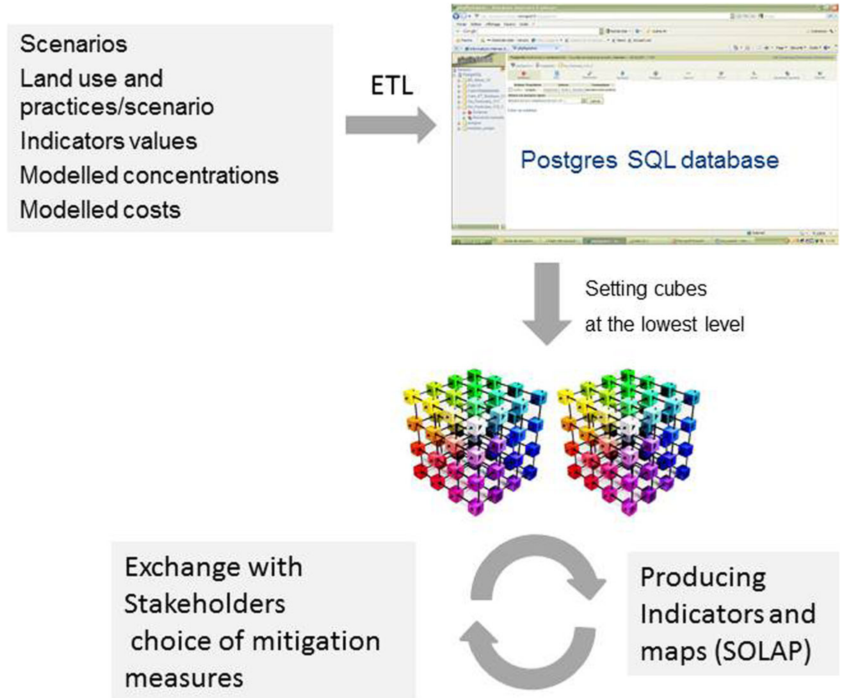


Fig. 9 Integration of relevant information in a data warehouse for stakeholders and decision makers

fate and transport of pesticides to rivers, use an economic model to estimate the cost/efficiency of scenarios, and finally organize all the information provided using data warehousing. The following is an example of how applying the IMAS framework to drinking water catchments in the SW of France.

Application of the IMAS framework for assessing the impact of agriculture changes on the pesticide pollution in rivers

The case study: the BAC Coulonge Saint Hippolyte in the Charente river basin (SW France)

The case study took place in the Charente river basin in southwest France (Fig. 10). The Charente river basin (10,000 km^2) is linked to the Pertuis Charentais Sea by a large tidal influence. Agriculture has a strong impact on the quantity and quality of freshwaters and influences the salinity and quality of coastal waters; both of which are needed for oyster farming and tourism (Mongruel et al. 2011). Currently, only 42 % of the water bodies in the Charente river basin satisfy the 2015 the requirements laid down in the Water Framework Directive (WFD), namely, achieving "good" ecological status (36.5 % in 2021 and 20 % in 2027). This is due to high levels of agricultural non-point pollution (nitrates, suspended matter, and pesticides) and frequent water shortages.

The IMAS approach was first implemented on the Né watershed (Vernier et al. 2014) and then on the wider area of Coulonge drinking water catchment (Vernier et al. 2015). It shows first the possibility to apply the methods at embedded scales (intermediary and large watershed) and then the robustness of the method, confronting the results obtained on the same Né watershed in the both projects. Sixty-six kilometers long, the Né is a tributary of the Charente River. The Né watershed spans some 30,000 ha. The crops found upstream are mainly cereals, while viticulture prevails in most of the downstream area. One of the main reasons for selecting this basin is that it has been designated by the French Authorities as a pesticide-sensitive area and targeted for several agro-environmental action plans (local action plan since 2007). It is quite representative of the main crops and soil types present in the wider area. The Né watershed is embedded in the Coulonge Saint Hippolyte drinking water catchment area, named from the two water uptakes of Coulonge and Saint Hippolyte (Fig. 10).

These two water catchments are considered a protected area because they provide drinking water for the city of La Rochelle as well as a large part of the Charente-Maritime coastal zone (13 M m^3 uptake/year and 290,000 people provided with water). At monitoring points, concentrations in pesticide, especially glyphosate and its degradation product AMPA, along with now banned molecules such as atrazine and associated products are often higher than the official norms for drinking water (0.1 μg/l for one molecule and 0.5 μg/l for all molecules). The institutional area of the action plan based on administrative borders (communes) is around 255,000 ha, while the hydrological

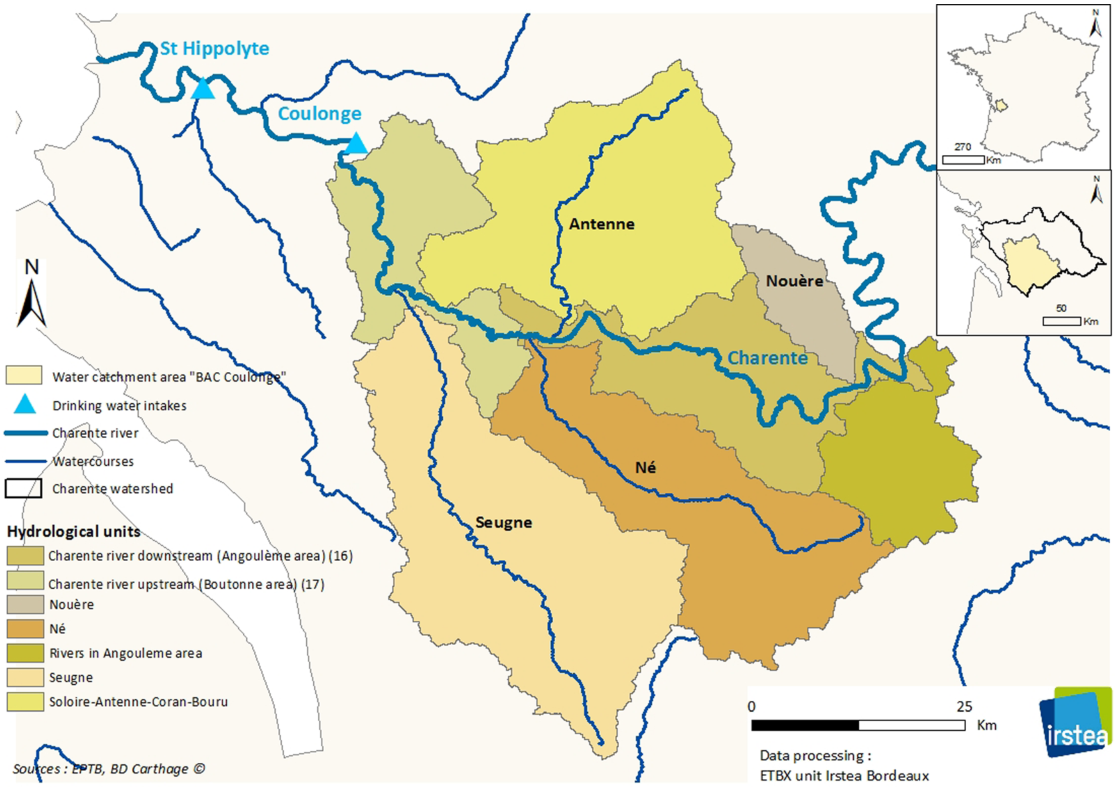


Fig. 10 Embedded river basins in the Charente river basin (sources River basin agency–EPTB Charente–Irstea, ETBX)

area of influence is around 360,000 ha; 69 % of which are made up of arable land. It covers some 260,000 ha of crops and vines. A wide range of crops are grown, with the main ones being sunflower (19 %), vines (22 %), maize (15 %), and wheat (24 %). About 8 % are grasslands. Local vineyards are famous for producing Cognac liqueur. Productive agriculture (99 %) in the area uses a wide range of pesticides, while organic farming (1 % of the total area) is concentrated in about one thirds of the modeled area with various cropping systems. The vineyards consume the highest amount of pesticides per hectare. Pesticide fluxes are transported from the small upstream watersheds into the river network and then out towards the coast.

Scenarios towards a more sustainable agriculture in the area

We defined some main scenarios applied to the Né watershed (Vernier et al. 2014), referred to as "intensive" (S9), "reference" (S0) (based on the situation from 2006 to 2010), and "widespread BMP" (S2), based on all of the measures defined by stakeholders and water managers (Table 1). A number of sub-scenarios were created, combining localized elements from two of these main scenarios (e.g., for the S3A, 80 % of the effects of the "current" scenario for vineyards coupled with 20 % of organic vineyards). Regarding the BAC Coulonge, as the IMAS method has already been developed, we were able to define a higher number of scenarios ("organic farming," BMP's, buffer strips, etc.) to highlight trend lines and be more helpful to water managers and decision makers (Table 1). These scenarios were approved by stakeholder focus groups. The reference scenario defined in the BAC Coulonge takes in account current organic farming (1 %), while the BIO-2 scenario doubles the organic farming area, which is a common goal in action plans. Other BIO scenarios test the impact of a major increase in organic farming (5 to 36 % of utilized agricultural area) and the specific effects of organic farming on vineyards or field crops for the reduction of pesticide pressure from agriculture (pesticide products sprayed on the area) and transport to waters. The other ranges of scenarios are related to the implementation of innovative crop systems (SDCI) partly or in the total area. These innovative systems are designed by chambers of agriculture to satisfy the objectives of action plans (less spraying products used and lower doses), longer crop rotations, new crops in the rotations, and adapted practices. These scenarios use innovative crop rotations and practices built alongside local agricultural experts and can be combined with current practices (SREF2) or organic farming scenarios (BIO-6). We also defined an intensive scenario (DEPP) focusing on the cattle breeding crisis, which could lead to a decrease in grassland and an increase in maize. As well as for the Eccoter scenarios, the HERB scenarios test the conversion of field crops along rivers to grasslands. In each case, the

Table 1 Scenarios built alongside stakeholders on the Né watershed and the wider area of BAC Coulonge

River basin	Scenarios	Purpose of scenarios
BAC Coulonge	SREF-2	Modeling the majority cropping systems of the BAC Coulonge (including organic farming)
	BIO-1 BIO-2 BIO-3	Illustrate the influence of a gradual increase in organic UAA - BIO-1, doubling organic surface area relative to the initial state - BIO-2, fivefold increase of organic surface area relative to the initial state - BIO-3, 10 % of UAA in organic farming
	BIO-4	Isolate field crops effect for the development of bio, 9 % of UAA field crops in organic farming
	BIO-6 BIO-7	Maximum potential development of organic agriculture. Hypothesis tested; the soil type effect is predominant - BIO-6, 15 % of the total UAA in organic farming - BIO-7, 36 % of the total UAA in organic farming
	HERB-1, HERB-2, and HERB-3	Conversion of crops into grasslands along rivers (buffer strips) consistent with local BMPs. Associated with (1) current systems, (2) innovative systems, or (3) organic farming
	SDCI	Illustrate the influence of a gradual increase in innovative crop management UAA - SDCI-1, 100 % of the total UAA in innovative crop management - SDCI-2, 57 % of the total UAA in innovative crop management - SDCI-3, isolate field crops effect for the development of innovative crop management - SDCI-4, isolate vineyard conversion into innovative crop management - SDCI-5, 20 % of the total UAA in innovative crop management - SDCI-6, 20 % of the total UAA in innovative crop management with 15 % of organic farming
	DEPP	Illustrate the influence of the cattle breeding's abandonment (−15 % of grassland area)
Né watershed	S0	Modeling the current cropping systems of the Né watershed
	S9	More intensive practices
	S1A-S2	Illustrate the effect of environmental measures on field crops (FERTI 01, PHYTO 04) and on vineyards (PHYTO 04) - S1A, 25 % of the total UAA - S2, 100 % of the total UAA
	S3A	Isolate the effect of vineyard conversion into organic farming, 20 % of the vineyards become organic vineyards
	S4	Conversion of crops into grasslands along rivers (buffer strips) consistent with local BMPs

UAA utilized agricultural area

proportion of low-input systems is progressively increased to evaluate the relevant thresholds and reach the goals of current action plans. A set of data is calculated for each, including land use for 6-year rotations and associated crop management sequences. This is then fed into the programs which calculate AEI as well as being inputted into the models.

Results and discussion

Reliability and spatial coherence of the IMAS method

The projection of the typology of cropping systems and practices at BOP and HRU scales and the use of this

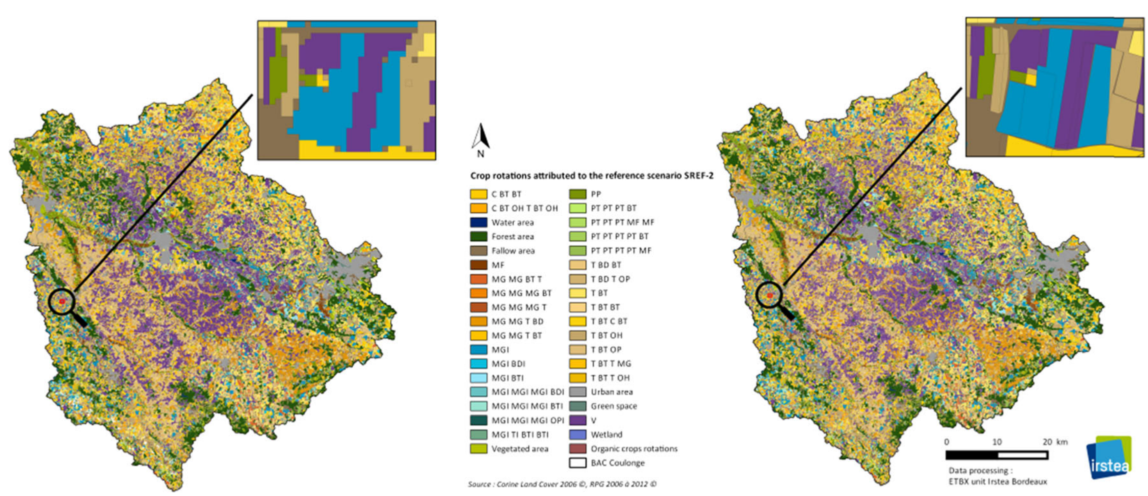


Fig. 11 Modeled land use for the reference scenario, AEI (*left*; BOP scale) and SWAT (*right*; HRU scale)

Table 2 Results of the evaluation of scenarios using indicators

		IFT			PREMA											Nitrogen
		Total	Herbicide	Except Herbicide	Glyphosate	S-metolachlo	Isoproturon	Mancozeb	2-4-MCPA	Metaldehyd	Aclonifen	orpyriphos-e	Tebuconazole	Difufenicanil	All molecules	
BAC COULONGE	SREF-2	6.11	1.74	4.37	475.49	342.11	135.84	642.11	48.74	18.65	334.13	61.31	24.55	10.20	2082.93	124.51
	HERB-1	-	-	=	-	--	-	=	-	--	-	=	=	-	-	-
	HERB-2	--	---	-	---	---	---	=	--	---	---	=	-	--	--	--
	HERB-3	--	---	--	--	---	---	--	--	---	---	--	--	---	--	--
	BIO-1	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
	BIO-2	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
	BIO-3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	BIO-4	=	-	=	=	-	-	NS	-	-	-	=	=	-	=	-
	BIO-6	-	-	-	-	-	--	-	-	--	-	-	-	-	-	-
	BIO-7	--	--	-	--	--	--	--	--	--	--	--	--	--	--	--
	SDIC-1	--	--	-	--	---	---	=	-	--	---	=	-	--	--	-
	SDIC-2	-	-	-	--	--	--	=	NS	-	--	=	NS	-	-	-
	SDIC-3	-	--	-	--	---	---	NS	-	--	---	=	-	--	--	-
	SDIC-4	-	-	-	-	NS	NS	=	NS	NS	NS	=	=	=	=	=
	SDIC-5	=	-	=	-	-	-	=	=	-	-	=	NS	=	-	=
	SDIC-6	-	--	-	-	--	--	-	-	--	--	-	-	--	-	-
BV NE	S0	10.31	1.27	9.04	460.55	126.99	125.57	1548.48	31.64	47.07	240.77	130.38	52.14			
	S9		++	+	+++	++	+	=	=	+++	--	=	+++			
	S1A		-	=	-	=	-	=	=	-	-	-	+			
	S2		--	--	---	-	NS	=	--	NS	---	---	+++			
	S3A		=	-	-	=	=	-	=	=	=	-	-			
	S3B		--	--	---	-	NS	-	--	NS	---	---	+++			
	S4		-	=	=	-	-	=	-	--	-	=	=			

Legend

---	>= 50%
--	[-50%;-25%[
-	[-25%;-5%[
=	[-5%;5%[
+	[5%;25%[
++	[25%;50%[
+++	>50%
NS	not significant
	not modeled

Comparison of means with a Student test

NS : not significant

If significant, range of difference between values of reference and alternative sceanarios

common set of data by all the tools make it possible to analyze the results of scenarios, in terms of values of indicators (pressure, potential risk), SWAT simulations (concentrations, balance), and associated costs.

Table 3 IFT decrease for scenarios within the BAC Coulonge and priority areas of the action plan

	Objective -25% reduction total IFT				Objective -50% reduction total IFT			
	Relative value total IFT total UAA	% SB reaching the objective	Relative value total IFT priority area	% SB of priority area reaching the objective	Relative value total IFT total UAA	% SBV reaching the objective	Relative value total IFT UAA of priority areas	% SB of priority area reaching the objective
SREF-2	6.11	/	6.69	/	6.11	/	6.69	/
SDCI-1	-27.45	69%	-25.60	65%	-27.45	2%	-25.60	0%
SDCI-2	-13.52	32%	-25.68	67%	-13.52	0%	-25.68	0%
SDCI-3	-17.81	44%	-15.07	33%	-17.81	3%	-15.07	0%
SDCI-4	-9.75	0%	-10.57	0%	-9.75	0%	-10.57	0%
SDCI-5	-4.43	0%	-8.41	0%	-4.43	0%	-8.41	0%
SDCI-6	-16.88	26%	-18.98	24%	-16.88	13%	-18.98	14%
HERB-1	-9.25	19%	-8.44	16%	-9.25	2%	-8.44	2%
HERB-2	-32.70	77%	-30.39	73%	-32.70	22%	-30.39	12%
HERB-3	-32.76	58%	-26.56	49%	-32.76	38%	-26.56	35%
BIO-1	-0.77	0%	-0.34	0%	-0.77	0%	-0.34	0%
BIO-2	-2.62	1%	-2.06	0%	-2.62	0%	-2.06	0%
BIO-3	-6.19	7%	-5.92	6%	-6.19	0%	-5.92	0%
BIO-4	-3.41	5%	-3.11	2%	-3.41	1%	-3.11	0%
BIO-6	-12.04	25%	-9.81	20%	-12.04	11%	-9.81	10%
BIO-7	-28.87	53%	-23.76	43%	-28.87	33%	-23.76	35%
DEPP	1.19	0%	0.78	0	1.19	0%	0.78	0%

Objective -25%

Decrease or increase total IFT compared to SREF2 scenario

>= -25%

<-25%

increase

Objective -50%

Decrease or increase total IFT compared to SREF2 scenario

>= -50%

<-50%

increase

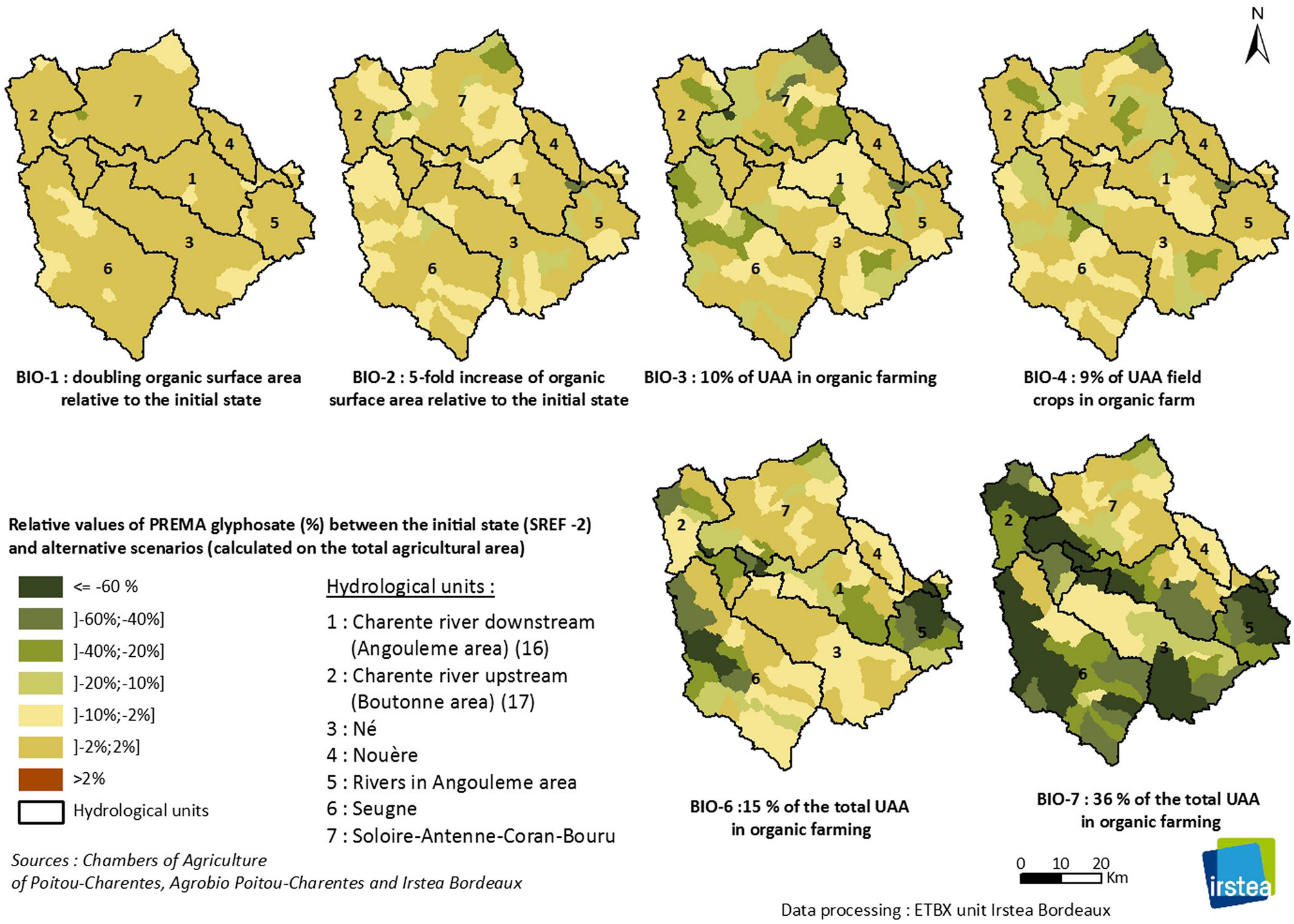


Fig. 12 Impact of alternative organic farming scenarios on the glyphosate pressure in the BAC Coulonge

Figure 11 shows the coherence of the common dataset obtained for the same scenario. The land use is generated for the 161,125 groups of plots and the 3659 HRU defined in the modeled area of BAC Coulonge with a difference of 0.08 % in the cropping area, i.e., 20 ha.

Calculation of indicators to estimate pesticide pressure and potential risk of pesticide transport to rivers

Reference practices were enlarged to encompass other types of soil and other agricultural systems in the wider BAC Coulonge area, which explains the differences in indicators for the reference scenario. The difference in pesticide pressure from agriculture (estimated through PREMA indicators) and intensity (estimated by IFT indicators) can be explained by a larger crop area in the BAC Coulonge (higher IFT herbicide) and a higher value for IFT fungicide and insecticide in the Né watershed due to a larger area of vineyards. Table 2 presents the results of comparison of means completed with a Student's test, between alternative and reference scenarios. In the Né watershed, the most effective Eccoter scenarios are S2—the entire basin with BMPs—and S3B—with 20 % organic vineyards—allowing a strong reduction of the IFT value (till 47 % for the IFT herbicide and 39 % for the IFT insecticide and fungicide). This decrease is only 5 to 10 % for mixed scenarios (25 % of the area with BMPs). The intensive scenario significantly increases the value of the IFT indicator (more than 40 %), although representing only a few more treatments each year. Similar results were obtained with the SDCI scenario in the BAC Coulonge area. For instance, scenarios SDCI1 and SDCI3 lead to a decreased IFT of 25 to 50 % as well as the PREMA values for high-priority molecules such as glyphosate and metolachlor. In both cases, we can conclude that a large spread of BMPs and innovative practices in a protected area can have a significant impact on reducing pesticide pressure and satisfying goals laid down in local action plans (decrease from 25 to 50 %).

The results are similar for the case of an increase in the crop area dedicated to organic farming. Pesticide pressure can be decreased (IFT and PREMA) with a significant area (more than 10 %) dedicated to organic farming. The difference is that organic farming drastically reduces the spraying of pesticides in the area, while innovative practices decrease the most unwanted molecules (glyphosate, metolachlor), currently

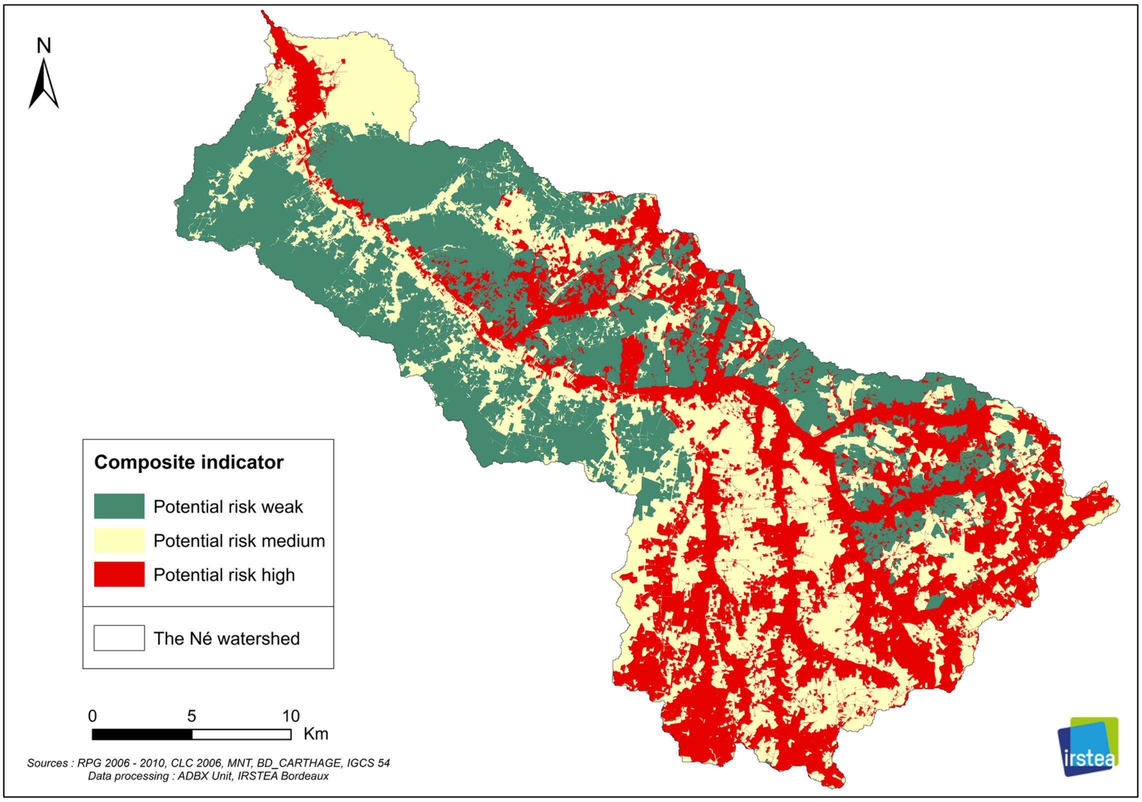


Fig. 13 Results of the composite indicator calculated on the Né watershed on the reference scenario

ever-present in the monitoring, but substitute these molecules with other ones in crop management sequences.

The benefit for water resources is not the same. The goal of current action plans (a reduction of 25 to 50 % of the pesticide pressure) can be achieved through a significant increase in organic farming (BIO-6 and BIO-7)—scenarios which consider the effects of soil, leading to a significant reduction in pesticide pressure—or with the requirement of low inputs and innovative agro-systems on the total area (Table 3). In the case of organic farming, better results are obtained with a smaller cultivated area within low-input systems.

The use of the sub-basin scale as the output for AEI and models makes it possible to identify the most effective scenarios for each sub-basin or group of sub-basins, for instance, priority areas or a specific hydrologic unit such as the Né watershed (Table 3 and Fig. 12). Table 3 shows that the best scenario is not the same for the total area and a specific set of sub-basins; a scenario can reach the goal of a 25 % decrease in pressure on the total area while being more efficient for some sub-basins. A scenario (for instance, SDCI2) can reach the goal of a decreased pressure of 25 % in priority areas but not for the total BAC Coulonge area. Water managers can use these results to implement a specific scenario in some sensitive areas or to choose the best scenario to decrease pressure, depending of the location. Figure 12 shows the decrease in glyphosate pressure, depending on the cultivated area dedicated to organic farming.

The composite indicator LPRT (Fig. 13) could prove helpful in selecting the most sensitive areas, where measures should be applied when focusing on a specific location in the area (for example, highly sensitive zones).

Table 4 Calibration and validation values (flow discharge)

	Calibration				Validation			
Sub-basin	*p* factor	*r* factor	r^2	NSE	*p* factor	*r* factor	r^2	NSE
Q-Sub_23	0.61	1.14	0.48	0.45	0.07	0.31	0.63	0.32
Q-Sub_26	0.81	0.31	0.83	0.81	0.23	0.25	0.74	0.55
Q-Sub_54	0.82	1.21	0.6	0.43	0.26	0.49	0.63	0.5
Q-Sub_59	0.76	0.77	0.49	0.46	0.09	0.2	0.59	0.27

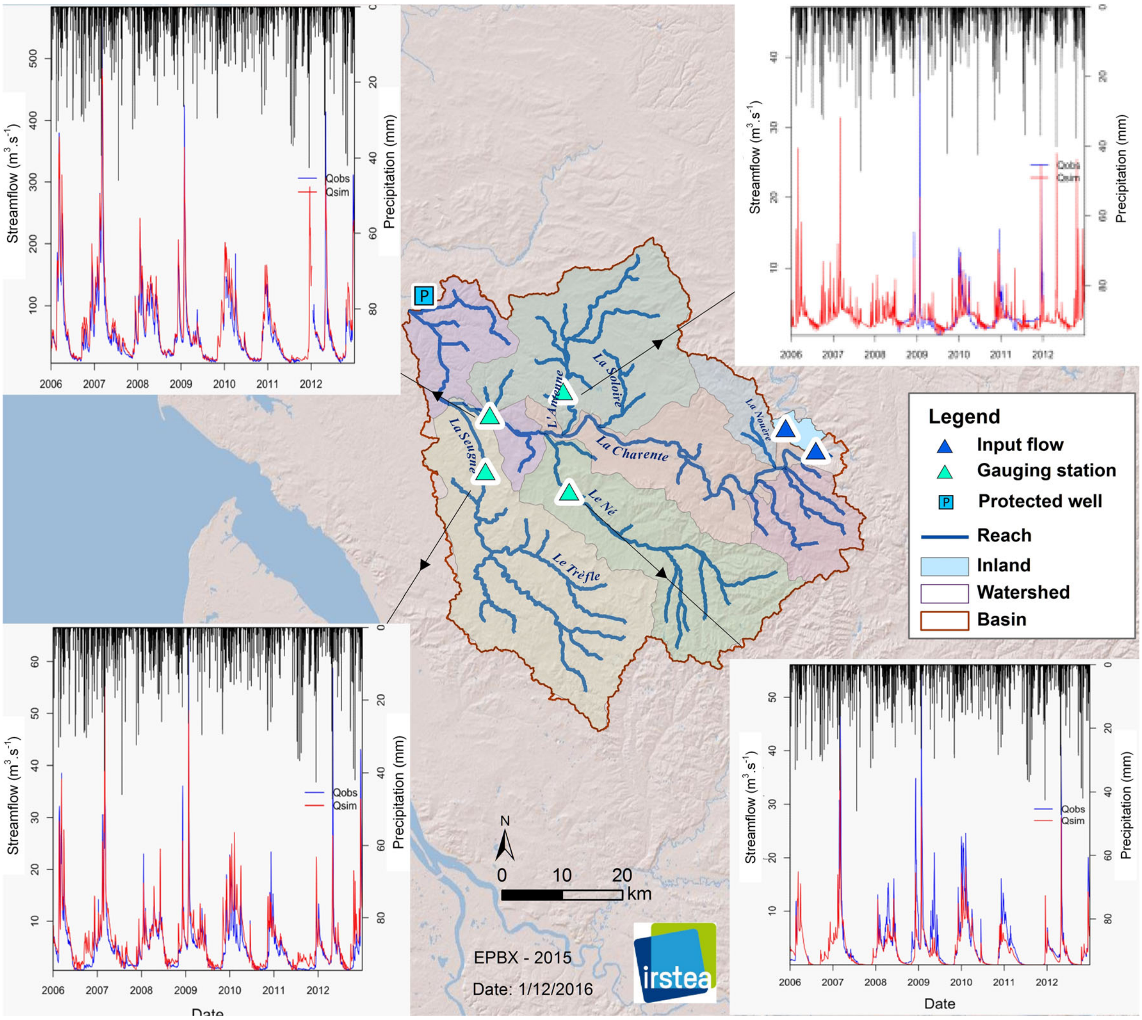


Fig. 14 Calibration of the SWAT model within the BAC Coulonge area

Specific actions can be carried out with farmers (modifying crop area and spraying practices, for instance), targeting mitigation measures whose implementation has the greatest influence on budget decisions. Of the area, 16 % are classified as a high potential risk of transfer to waters, where 30 % have a medium risk and 55 % a lower risk. These percentages do not vary significantly for the most effective scenario (S2), 15.4 % high, 28.9 % medium, and 55 % low, respectively. In its current version, the LPRT indicator is still not able to identify differences in potential risk between two scenarios with a relevant change in practices, as the weight resulting from the natural characteristics is too high. A further version is to be developed to improve the sensitivity of the indicator.

Table 5 Results of the SWAT simulations for the scenarios defined for the BAC Coulonge

	Glyphosate	S-metolachlor	Isoproturon	Mancozeb	2-4-MCPA	Metaldehyd	Aclonifen	hlorpyriphos-eth	Tebuconazole	All molécules
SREF-2	0.521	2.650	0.095	0.016	0.081	0.087	1.090	0.007	0.014	4.561
HERB-1	NS	-	NS	+	-	-	NS	=	NS	-
HERB-1 5m	-	-	-	NS	-	-	-	=	=	-
HERB-1 10m	-	-	-	NS	-	-	-	=	-	-
HERB-1 15m	-	-	-	NS	-	-	-	=	-	-
HERB-1 20m	-	-	-	NS	-	-	-	=	-	-
BIO-1	NS	=	=	NS	=	=	=	NS	NS	NS
BIO-2	=	=	=	-	=	=	=	-	-	=
BIO-3	-	-	-	-	-	-	-	-	-	-
BIO-4	=	-	-	NS	-	-	-	NS	NS	-
BIO-6	=	-	-	NS	-	-	-	NS	NS	-
BIO-7	---	---	---	---	---	---	---	---	---	---

Legend

+	[5 %; 10 %[
NS	Non significant
=	{-5 %; 5%[
-	[-25 %; 5 [
--	[-50 %; -25 %{
---	>= -50 %

Simulation of pesticide transfers to rivers associated with scenarios

Calibration and validation

The SWAT-GenLU2 model was firstly calibrated on hydrological stream flows over a 20-year simulation period (Nash-Suttcliffe efficiency criteria 0.8), which measure data was the more reliable on the Né river basin. Then, the quality parameters for pesticide fate and transport of the ten selected molecules have been adjusted in confronting simulated concentrations with measured ones. Some “soft data” or qualitative knowledge (Seibert and McDonnell 2002) about the behavior of the basin have been incorporated in the calibration and validation processes. This qualitative data has been outcome by the chamber of agriculture and local hydrologists thanks to a continuous 3-year dialog. This qualitative data helped us specify reliable parameter boundaries for soil water capacity and texture, hydrological behavior of groundwater, and overall hydrological behavior of the basin set in a karstic soil and provided us with the reliability of measures at some gauging stations.

“If performance is unsatisfactory, then different data, calibration procedures, and/or model structures should be considered” (Bennett et al. 2013), but model calibration is satisfactory (NSE above 0.8); a good or “acceptable” for SWAT performance corresponding according to the literature is an objective criterion of the NSE, which has to be >0.75. Some authors emphasize that validation with quality criteria is also needed (Bennett et al. 2013). The work presented here has led to modeling workshops at the request of the end-users, i.e., water managers.

For the wider BAC Coulonge area, our results were sufficient to flow discharge using PEST. For the four gauging stations, the results of calibration with PEST are satisfactory (NSE above 0.8) at the gauging station located on the outlet of the sub-basin (SBV) no. 26 (cf. Table 4), which corresponds to the flows of main river Charente (cf. Figure 14). Calibration was less acceptable at Seugne station (located downstream) and reasonable for the two other gauging stations. One of the both presenting not sufficient measured data (located on the SBV no. 59) and the other (located at the station R4122522 on SBV no. 54) made of data that comes from a “virtual hydrological basin”; i.e., these institutional data are recalculations of three stations that are no longer in active use. The results of calibration/validation with SUFI-CUP on the embedded basin of the Né river and the calibration at the same station R4122522 have been better with (i) calibration (2001–2005) results with r^2 0.80 and NSE 0.75 and (ii) validation (2008–2010) with r^2 0.55 and NSE of 0.51.

These difficulties are essentially due to two main factors: (i) lack of continuous time series for observed data on three of the four gauging stations and (ii) pesticide concentrations from monitoring result from real agriculture within the area, whereas the outputs of the model result from the agriculture modeled from the reference scenario.

The physico-chemical features used by the model for transport and fate of the molecules have been adjusted with PEST in regards to the available measured concentrations. The difficulties are to use scarce measured (from 2 to 6 hourly measures by year) that have begun recently (2006) to fit the daily simulated concentrations. The confrontation of average simulated vs observed pesticide at quality stations were at the same levels for most of the molecules, except for Metolachlor whose measured concentrations are lower. The simulated molecule is S-Metolachlor, as Metolachlor is no longer in use. Despite the uncertainty due to input data, the model proved efficient not in predicting exact concentrations but in predicting a tendency in terms of reductions/increases in concentrations for long-term mitigation measure scenarios when compared to the baseline scenario.

Results of scenarios

Table 5 presents the results of simulation for scenarios linked to the development of organic farming within the BAC Coulonge or the conversion of crops into grasslands along rivers. HRUs are not fully distributed within the sub-basin. We consider this is a limitation of the model. This does not affect the limit, as we selected the relevant HRUs (the ones set close to streams). The SWAT built-in buffer strip or vegetative filter strip (VFS) incorporates a distance function but also velocity and bio-physical functions, allowing it to act as a surrogate physical and bio-chemical barrier between the water course and sources of pollution (agricultural plots). All functions simulate processes at the HRU-scale trapping sediments, plant nutrients, organics matter, and chemicals such as pesticides when runoff flows through this area (Gharabaghi et al. 1998; Brown et al. 2004; Lacas et al. 2005). Some researchers have improved this native BMP in extending the processes in the infiltration part and by adding a part describing sedimentation in the filter strip (Gevaert et al. 2008). Our results show that the most environmentally efficient scenarios are those involving vegetative filter strips and crop conversion to pastures (HERB-1 family) and the organic scenarios from BIO-3 to BIO-7 when considering all molecules.

Figure 15 shows a comparison between the nine cumulative pesticide inputs for the reference scenario and for the BIO-6 scenario. The main pesticide pressure, located in the Né river basin, has strongly decreased with the mitigation measures set in scenario BIO-7. Firstly, we can conclude that, despite complex mechanisms of pesticide transfer at the watershed scale, a strong decrease in pressure leads, on the long term (20-year modeling by the SWAT model), to a strong decrease in concentrations in the rivers. More specifically, we can see that there is a visible relationship between input and outputs in some areas, such as the Seugne and Né river basins (SW part of the area), whereas for other hydrologic units, the relationship is more complex, as is the case for the Antenne Soloire in the northern part. This can be explained by the river-groundwater dynamic features for the northern part and on the upstream of the BAC Coulonge (Touvre, Tardoire) within the karstic zone on of the BAC and by the dilution factor as for the Charente River in its medium part. Although all results of the simulations have yet to be analyzed, we can conclude that some scenarios (BIO-3 to BIO-7) would, if implemented, lead to a drastic reduction in both pressure and concentrations in rivers within the BAC Coulonge.

In the Né watershed, embedded in the BAC Coulonge, the most effective scenarios for reducing pesticide concentrations were S2 (the entire basin with BMPs) and S3B (all BMPs with organic vineyards) with a decrease of 4 μg/l on average for all the molecules (Table 6). However, these scenarios were more “extreme” than those defined on the BAC Coulonge area. The mixed scenarios (S1A or S4) led to a lower efficiency (−2.5 % μg/l on average).

The cost-effectiveness of scenarios, considering the reduction of pesticide pressure or transportation of the ten witness molecules into rivers

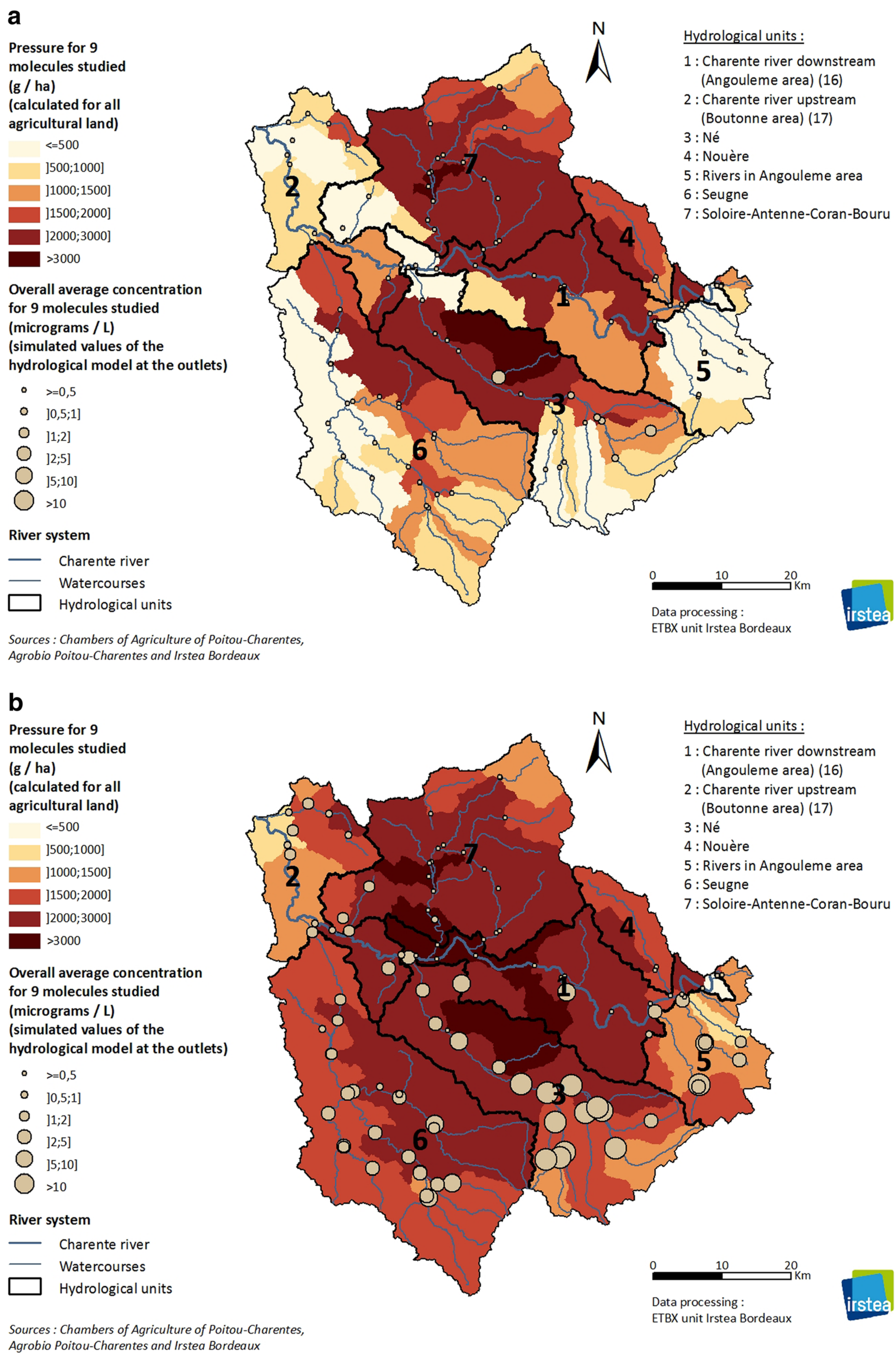
Costs initially computed at the HRU level are then added together at sub-basin level. This makes it possible to compare the costs of different scenarios to their effectiveness calculated by reduction in pressures or transfers at the sub-basin level, eventually identifying the most cost-effective zones. Results show that it is possible to classify scenarios based on their cost-effectiveness, which can be represented graphically either with maps representing spatially distributed cost-effectiveness ratios or scatterplots allowing for rational discussion between stakeholders. Result presented here show cost-effectiveness of HERB-1 (buffer strips) and BIO-6 scenarios, regarding pesticide pressure or transfer (Fig. 16). Sub-basins represented in red to orange colors characterize the zones where implementing a given scenario is the less cost-effective (high costs and low effectiveness), while sub-basins in green represent the sub-basin, where applying scenarios are the most cost-effective. Sub-basins in yellow denote basins where the scenario can be implemented with no costs or can even prove profitable, while effectiveness is very limited. Sub-basins where implementing scenarios is totally ineffective are represented in white. For these, comparisons can be made only for costs.

The results presented here are related to organic farming development and buffer strips. Because work is still in progress for the wider area of Coulonge, a number of scenarios have yet to be classified. Therefore, we can see that the buffer strip scenario (HERB-1) has a good cost/effectiveness as well as the BIO-6 scenario, which allows a significant reduction in pesticide pressure and concentrations in rivers. These results are consistent with those obtained for the Né watershed, where S3B (BMPs combined to organic farming) and S4 (grasslands on the river banks) were part of most cost-effective scenarios. They highlight the spatial heterogeneity of costs and effectiveness (pressure vs transfer) and argue for focused and spatialized action plans.

A prototype of a data warehouse for decision makers to analyze and choose the mitigation measures

Through a number of workshops with the research team and stakeholders (focus group on a monthly basis and dedicated meetings), it was possible to construct a conceptual model, defining requirements in terms of analyses, aggregations, and outputs. The conceptual model was formalized in Unified Modeling Language (UML) but actually began by drawing and correcting on a paper board. We re-use some parts of the EIS pesticide conceptual model, built with Irstea teams in a previous project (Vernier et al. 2013). This step is crucial because it makes it possible to define the lines of enquiry used by stakeholders, represented by the focus group. At this time, all the data linked to the reference scenario have been uploaded into the database and the process is ongoing for alternative scenarios. Cubes, tables, and maps can be obtained with a single click. Figure 17 gives an example of the SOLAP interface, which allows one-click display of the values of desired indicators for groups of sub-basins or for the total area (the sub-basins of the Né in the example). On the left, we can see all the cubes (sub-sets created within the data warehouse) available for requests. This can be for one specific year or all years, for one specific crop or a type of crops, and for field crops or vineyards. The request can also be for a specific molecule or range of molecules (in Fig. 17, glyphosate and S-metolachlor). Data mining allows individual values obtained for BOP to be downloaded. The opposite is possible, from a specific sub-basin to a larger watershed and then the total area. The requests are made possible by the previous construction of the cubes (an example in Fig. 18). If an axis of analysis is missing, a new cube can be built from the SQL database. The update of data (new soil occupation, new scenarios, etc.) is first made in the

Fig. 15 Evolution of glyphosate pressure and concentrations into the rivers for reference and BIO-7 organic farming scenario in the BAC Coulonge area ▶


a
Pressure for 9 molecules studied (g / ha) (calculated for all agricultural land)
<=500
]500;1000]
]1000;1500]
]1500;2000]
]2000;3000]
>3000
Overall average concentration for 9 molecules studied (micrograms / L) (simulated values of the hydrological model at the outlets)
>=0,5
]0,5;1]
]1;2]
]2;5]
]5;10]
>10
River system
Charente river
Watercourses
Hydrological units
Sources : Chambers of Agriculture of Poitou-Charentes, Agrobio Poitou-Charentes and Irstea Bordeaux
N
Hydrological units :
1 : Charente river downstream (Angouleme area) (16)
2 : Charente river upstream (Boutonne area) (17)
3 : Né
4 : Nouère
5 : Rivers in Angouleme area
6 : Seugne
7 : Soloire-Antenne-Coran-Bouru
0 10 20 Km
Data processing : ETBX unit Irstea Bordeaux
irstea
b
Pressure for 9 molecules studied (g / ha) (calculated for all agricultural land)
<=500
]500;1000]
]1000;1500]
]1500;2000]
]2000;3000]
>3000
Overall average concentration for 9 molecules studied (micrograms / L) (simulated values of the hydrological model at the outlets)
>=0,5
]0,5;1]
]1;2]
]2;5]
]5;10]
>10
River system
Charente river
Watercourses
Hydrological units
Sources : Chambers of Agriculture of Poitou-Charentes, Agrobio Poitou-Charentes and Irstea Bordeaux
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5 : Rivers in Angouleme area
6 : Seugne
7 : Soloire-Antenne-Coran-Bouru
0 10 20 Km
Data processing : ETBX unit Irstea Bordeaux
irstea

Table 6 Results of the SWAT simulations for the scenarios defined for the Né watershed

	Glyphosate	S metolachlor	Isoproturon	Mancozeb	2-4-MCPA	Metaldehyd	Aclonifen	Chlorpyriphos ethyl	Tebuconazole	Acetochlor
S0	*0.10*	*3.01*	*0.15*	*0.02*	*1.37*	*0.53*	*0.02*	*0.02*	*0.81*	*1.37*
S2	-	--		--	---		---	---	++	
S9	+++	--	+++	-	=	+++	---	=	+++	-
S1A	-	-	-	-	--	-	-	=	=	=
S3A	+	-	=	-	=	=	=	--	--	=
S3B	---	-		-		---	---	---	--	
S4	=	-	=	-	=	--	--	=	=	=

Legend	
+++	>= 50 %
++	[25% ; 50%[
+	[5% ; 25%[
=	[-5% ; 5%[
-	[-25% ; -5%[
--	[-50% ; -25%[
---	< -50 %
	not modeled

database, and then, the cubes have to be reconstructed. These processes can be done automatically with ETL[3] software such as Talend. Work is still being done on the system to include all scenarios in the database and in the cubes and to test the interface tool in the "real conditions" of stakeholder meetings. The prototype is considered of interest by stakeholders and a further step is to use it in a real context, once all the scenarios uploaded.

Discussion

IMAS-integrated modeling focuses on surface waters and aquifers, which are also its main areas of specialization. For groundwater, another program is underway in parallel with the BRGM (French institute dealing with groundwater quantity and quality) to introduce a coupled use of two models (SWAT-GenLU2 from Irstea and Marthe from BRGM) to estimate the impact of agricultural scenarios on groundwater quality. When presenting the IMAS framework, we highlighted three major advantages that we will discuss now in light of current results of the BAC Coulonge and its embedded sub-basin, the Né watershed.

All assessment tools take into account the dynamics of agriculture, 6-year crop rotations changing through scenarios (lengthening or adding new crops, changing from a conventional system to an organic one). This dynamic view allows a better evaluation of the impact of agricultural systems and their "translation" in the field through crop rotations. Crop models are designed to operate at the plot and field scale, and establishing guidelines for their application at larger scales is an ever-evolving area of research (Ewert et al. 2015), and we think that the use of typologies to describe agriculture in the area, linked with a specific interface to the models, is quite effective; the yields calculated at the HRU scale match correctly to regional ones. The approach by soil type proved successful in southwestern France, where soils remain a main driver used by farmers and advisors in choosing crops, rotations, and practices. To some extent, soils impact crop yields as well. This soil factor may however be less relevant in some other European contexts.

The key limitations affecting crop models in integrated assessment models are low data availability and integration (Ewert et al. 2015). Spatial data on land use by agriculture, types of soils, and agricultural systems obviously need to be improved at regional level. This called for a pre-processing of data and extensive stakeholder involvement through focus groups to share a common and spatialized vision of agriculture.

Using the indicators of total spraying amounts (PREMA) or intensity of practices (IFT), it was possible to classify a lot of scenarios. However, this is an intermediary efficiency. The composite indicator (LPRT) would be better suited to estimating the potential risk of pesticide transport to rivers. This nevertheless calls for some improvement, because the weights of structural variables are still too high when compared with variables representing pesticide spraying practices. We consider that it is helpful for specific actions on the farm to be engaged in the most sensitive areas for the transport of pesticides.

All the assessment tools of the IMAS framework use the same dataset, which characterizes the location of crops and associated crop management sequences, for a given scenario. However, there is still a problem with the selection of HRUs for alternative scenarios. HRUs have no spatial reference within a given sub-basin, but as they have defined by crossing soil type and land use (and practices) in addition to the elevation, HRU captures the heterogeneity of the environment where crops are calculated.

The authors recognize that farm size plays an important role in production costs and that this is not

[3] ETL is short for extract, transform, load, and three database functions that are combined into one tool to pull data out of one database and place it into another database. ETL is used to migrate data from one database to another to form data marts and data warehouses.

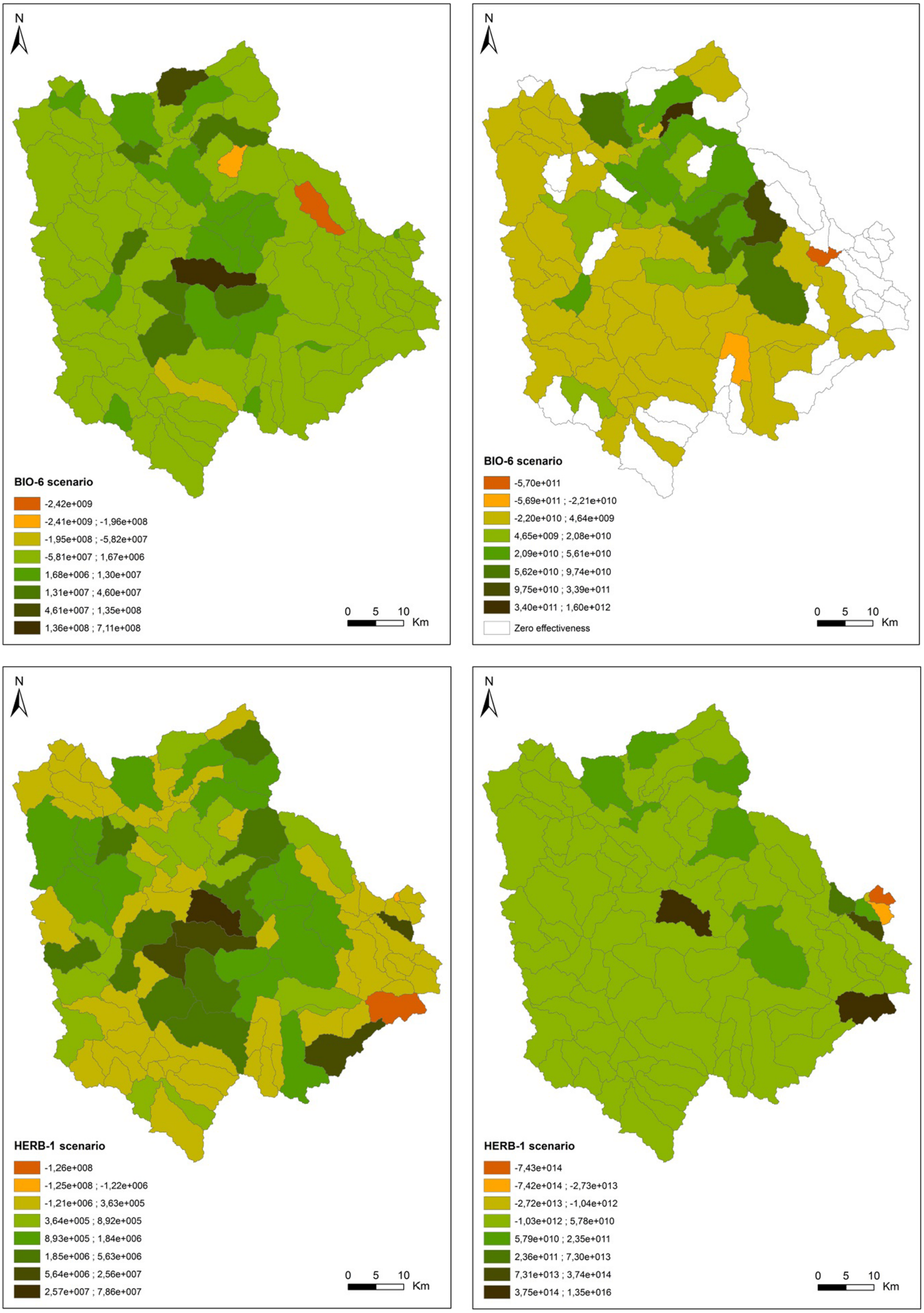

Fig. 16 Cost-efficiency maps for organic farming (BIO-6) and buffer strip (HERB-1) scenarios, regarding pesticide pressure (*left*) or transfer (*right*)

captured by working on farming systems. However, the size of the HRU plays no role, given that products and operational costs are defined per hectare. Effectiveness of mitigation scenarios (such as concentration of

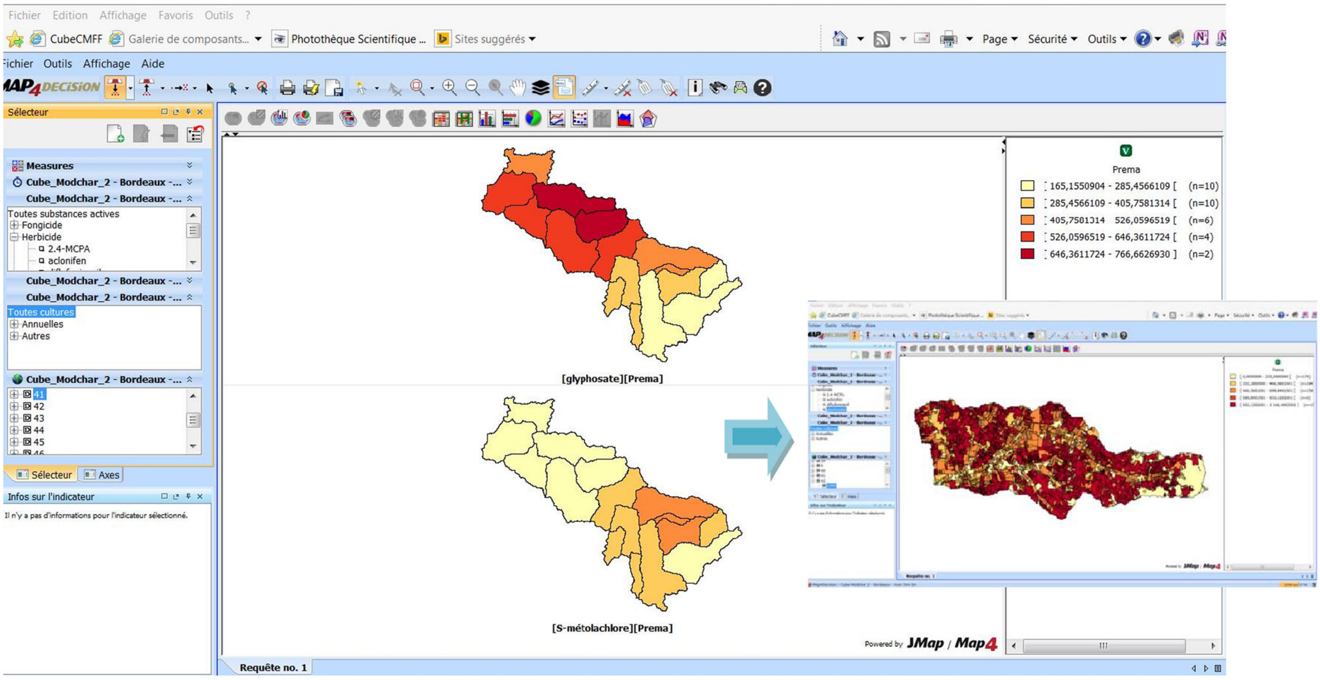

Fig. 17 An example of SOLAP request—pesticide pressure in the Né watershed and link to the associated BOP values

pesticides in waters) can only be calculated at the outlet of the sub-basin and basin. Indicators are calculated at the block of plot level and for comparison with the concentrations at the sub-basin and basin levels).

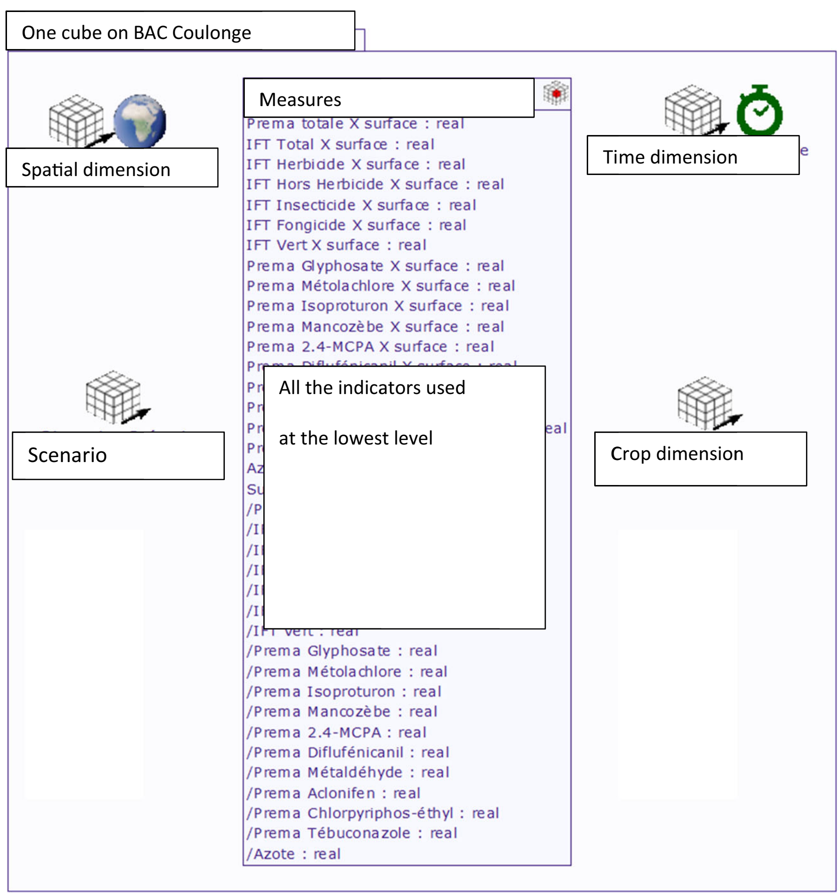

Fig. 18 An example of a cube defined for the BAC Coulonge area. Measures are PREMA indicators and dimensions are scenario, time(year, all years), spatial scale (from BOP to SB and total area), active matter(type of action, all molecules), and crop(type of crop, all crops)

Provided that costs are calculated on these geographical sub-basin or basin common scales, it is possible to calculate and compare the cost-effectiveness of the scenarios. Additionally, the sub-basin has been proven relevant for confrontation of results with observed measures of pesticides in waters and for exchange with the focus group and water managers.

A common temporal scale is also needed for comparing costs and benefits. These could be either the length of the longest rotation or the hydrological simulation period (used for calculated transfers and costs calculated first on a yearly basis) need to be further summed up and discounted.[4]

Implication of using a deterministic approach for calculating costs results in using average costs. Stochastic programming could take into account random factors such as climate, rainfall, or required number of pesticide applications needed. Another important stochastic element in calculating costs is the price variability of commodities. This factor plays a role in computing actual costs of scenario and in assessing the level of involvement of farmers in changes. This issue (that has not been taken into account here) can be addressed by adding a risk factor in the objective function.

Finally, we think that the use of data warehousing to analyze potential impacts of scenarios with stakeholders and support the design and implementation of the action plan is important and makes system more readily usable in a real professional context. The current prototype shows that it is possible to manage all the needed data on the BAC Coulonge.

Conclusions and perspectives

These results show that the IAMS method has proven its ability to assess agricultural scenarios for medium- (Né watershed 30,000 ha) or larger-scale (BAC Coulonge 360,000 ha) watersheds. It was possible at both scales to characterize soils, cropping systems, and their potential evolution in cooperation with agricultural experts, as well as defining relevant indicators or results of models useful in decision making. One interesting result is that AEI can discriminate significantly agricultural scenarios, even if the change is not particularly marked, for instance, when doubling the number of organic farming areas or introducing a slight change in management practices. Another result is the difference and complementarity between the evaluation of scenarios by AEI and by the SWAT-GenLU2 model for the environmental part. Even with the uncertainty within simulations, the model is able to highlight trends in increasing or decreasing concentrations of pesticides in rivers; a scenario can decrease pressure but be not enough effective to decrease pesticide concentrations, depending on natural conditions and transfers. Water managers are very keen to use these elements to evaluate various scenarios. Finally, we showed that it is possible to classify scenarios based on their effectiveness, which is represented either by the values of indicators or the presence or absence of the nine chosen pesticide molecules within the river, along with the costs incurred by farmers for each scenario. The spatial resolution used provides additional information for the implementation of mitigation measures in the area. The choice of the sub-basin proved a key factor in representing the heterogeneity and spatial distribution of efficiencies and associated costs for farmers. Agricultural stakeholders and water managers see this development as a major step, despite the fact that our model does not consider the public costs of the implementation of measures, as action plan managers would ideally like. Our results provide interesting material for science-policy discussions and allow more objectivity in the debate between stakeholders. The long-term timescale used for the simulations allows an interpretation beyond short-term variability, such as annual climate variations and annual variation of agricultural practices. Currently, a scenario is run with the same characteristics all along the modeled period. One future development could be to define long-term scenarios with possible inflections in agricultural practices and climate parameters. This method is also of interest because it provides a multi-criteria evaluation (decrease of pressure, decrease of concentrations, associated costs) of each selected scenario. The participatory process, i.e., discussion with stakeholders, can be taken into account with possible iterations for each scenario to test several assumptions. Another perspective is to apply our method to other large areas, where pesticide action plans are requested and to make our analytical tools available to water managers. Further developments and the BAC Coulonge "complete" data warehouse—beyond the prototype—under construction will prove very useful in achieving this.

[4] As for the choice of the discounted rate, recent analyses of economic data show that the assumption of constant exponential discounting should be modified to take into account large uncertainties in long-term discount rates. A proper treatment of this uncertainty requires that we consider returns over a plausible range of assumptions about future discounting rates. This controversy however concerns only the cost-benefit analysis and in all cases goes outside the scope of this paper.

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