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Integrating local knowledge and biophysical modeling to assess nitrate losses from cropping systems in drinking water protection areas

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ABSTRACT

Addressing the issue of agricultural pollution in water protection areas (WPA) requires assessing the impact of agricultural activities at regional scales. However, current water quality modeling studies often neglect the agronomic concept of a cropping system and interactions with soils. This paper presents a participatory assessment framework involving local experts in building a shared diagnosis of nitrate losses from cropping systems in a WPA. It includes a co-designed typology of landscape units and participatory assessment of nitrate losses with the modeling software Syst'N. Results show that characteristics of cropping systems depended on soils and that nitrate losses were highest in shallow soils. Intercrop periods were identified as critical periods for nitrate leaching, which demonstrates the importance of considering pluri-annual crop rotations rather than individual crops. The framework is generic for a modeling approach based on the involvement of local experts, who define their functional system in an agronomically sound way.

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Software availability

Name of software: Syst'N
Computer development: Pascal Dubrulle, Aurélien Dupont
Contact information: Virginie Parnaudeau: virginie.parnaudeau@rennes.inra.fr
Hardware required: PC running Microsoft® Windows
Availability and cost: prototype version of the software and documentation available freely at http://www.rmt-fertilisationetenvironnement.org/moodle/course/ after registration (in French)
Program language: C++
Program size: 24MB
Year first available: 2013

1. Introduction

In recent years stakeholder–scientist relationships have shifted from unilateral knowledge transfer to two-way communication of knowledge and information (Eshuis and Stuiver, 2005; Krueger et al., 2012; Oliver et al., 2012; Reed et al., 2014). Scientific knowledge is often viewed as formal, objective and decontextualized, while local knowledge is informal, implicit and context-dependent (Ingram, 2008; Raymond et al., 2010). By its explicit nature, scientific knowledge is well suited for integration into biophysical models but, when developed and applied by scientists alone, such models often lack information from the "real world" to be useful for improved environmental management. Hence, integrating scientific and non-scientific knowledge offers a lot of promise in environmental management to preserve the rigor and accuracy of scientific methods while ensuring relevance in the context of application (Reed, 2008; Reed et al., 2008).

Addressing the issue of nitrate pollution in agricultural areas requires integration of two spatial levels (van Ittersum et al., 2008; Gascuel-Odoux et al., 2009a, 2009b; Belhouchette et al., 2011): i)

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the water protection area (WPA), i.e. the spatial level at which water quality is evaluated, hence the most relevant for public decision makers; and ii) the field or farm levels, i.e. the levels at which pollution is generated and can be controlled and at which farmers make decisions. The concept of a cropping system (Sebillotte, 1974) is a useful framework to analyze interactions between crops, their succession order and the crop management plan associated with each crop. Recently, a new discipline called landscape agronomy (Benoit et al., 2012) has emerged to extend the cropping system concept, originally developed for a small number of fields, to regional scales such as WPA. A regional scale assessment cannot consist of exhaustively analyzing the cropping system of each individual field because: i) information about soil, climate and agricultural practices is generally not available at that scale and ii) the amount of information produced would be too large to be useful to help stakeholders improve environmental management. A variety of methods have been developed to describe cropping systems at regional scales (see Leenhardt et al. (2010) for a review), including stochastic modeling such as Markov chains (Mignolet et al., 2004; Salmon-Monviola et al., 2012), decision trees (Sorel et al., 2010) and use of farm decision models (Le Gal et al., 2010; Vayssières et al., 2011; Moreau et al., 2013). In most cases, description and location of cropping systems at regional scales is performed by scientists alone. The role of stakeholders is often quite nominal: their contribution is often limited to providing input data for the biophysical model when existing agricultural databases are insufficient (Voinov and Bousquet, 2010). Stakeholders sometimes participate when defining the scenarios to be tested (e.g. implementation of a regulation), but collaboration between stakeholders and scientists usually does not go further than a “transformation … to convert narrative information into a quantitative form …, thereby enabling scientists to apply computer models” (Leenhardt et al., 2012). Generally, the lack of involvement of local stakeholders results in modeling outcomes that are not understandable to them or that do not help to answer their questions; hence, they cannot lead to improved environmental management.

Participatory approaches, in the broader sense of the term, encompass a wide range of assessment and modeling activities to articulate different forms of knowledge and opinions (Voinov and Bousquet, 2010; Carr et al., 2012; Reed et al., 2014). The normative rationale of participation rests upon the idea that confronting different opinions should be part of a democratic process (Reed, 2008). Krueger et al. (2012) also emphasize two pragmatic benefits of participation: i) improved environmental management as a result of good articulation between different forms of knowledge and opinions and ii) improved acceptance of participation outcomes, which eases implementation of policy (Souchère et al., 2010). The normative argument implies involving many stakeholders with a diversity of values and interests. Yet, working with many stakeholders is arduous in a co-construction process; thus, it often results in extractive use of participation, degrading the quality of participation (Voinov and Bousquet, 2010; Hare, 2011). Hence, engaging a few well-identified local experts has sometimes proven to be more effective in solving environmental management problems (Reed, 2008; Raymond et al., 2010).

In this paper, we sought to integrate a higher level of participation from local experts than what is usually done in modeling studies addressing the issue of diffuse nitrate pollution in agricultural areas. The expected benefit of involving local experts in describing the system and discussing the results was to produce modeling outcomes that help them answer their questions about assessment of nitrate losses. Two research questions are addressed in this paper: i) how to combine local knowledge and an agricultural database to build a relevant typology of agricultural landscape units in a WPA and ii) how to assess nitrate losses from such landscape units in a way that may help local experts improve environmental management. The assessment framework proposed includes an expert elicitation process aiming to co-design a typology of landscape units (i.e. cropping systems × soil) to be used as quantitative input data into a biophysical model. The biophysical model used, called Syst'N (Parnaudeau et al., 2012), was specifically designed to facilitate discussion with non-scientist users, with several options for post-processing output data and user-friendly visualization interfaces. We tested the assessment framework in a meso-scale WPA prone to nitrate pollution in the Burgundy region, France. The local experts involved were professionals from extension services concerned with the development and implementation of agricultural action plans to alleviate nitrate pollution in the WPA.

2. Materials and methods

2.1. Study area

The study site was Plaine du Saulce, an 86 km^2 WPA located in Burgundy, France. The WPA supplies one third of the 6 million cubic meters of water provided annually to the 60,000 inhabitants of Greater Auxerre. Mean annual rainfall during the study period (2000–2010) was 694 mm, ranging from 552 mm in 2003 to 922 mm in 2001. Mean annual temperature was 12 °C (4 °C in January, 20 °C in July). Geology was dominated by hard calcareous rocks of various permeability. According to CFC and SF_6 dating, the mean travel time of water in the hydrological system was 25 years, but rapid circulation in karsts transferred 20–40% of the water in less than 5 years (Anglade et al., 2012). The predominant soils were Rendzic Leptosol (i.e. shallow and stony calcareous soil) and Calcosol (i.e. deeper, non-stony calcareous soils). These soils are highly permeable; hence, nitrate transfer consists of vertical leaching towards groundwater before reaching the intake point. Soils deeper than one meter represented only 13% of the surface area. The WPA was entirely rural, with agriculture dedicated mostly to cereals and industrial crops (64% of land cover), forests (28% of the area), and other land uses (8% in pastures, semi-natural areas, vineyards, orchards, and urban areas). Point-source emissions were negligible (Association pour la Qualité de l'eau de la Plaine du Saulce, 2012). Nitrate concentration increased during the 1980s until the first peaks over 50 mg NO_3^- l^{-1} were recorded in 1993. Authorities then decided to take measures, and the Association for Drinking Water Quality in Plaine du Saulce (APS) was created in 1998. The association staff consisted of two employees, and one technical advisor of the Chamber of Agriculture was assigned to this territory. Both organizations have collaborated since 1998 on a number of actions, including demonstration plots, technical advice and financial support to promote fertilization plans, catch crops, soil tests and conservation tillage. One significant contribution of the association was to record agricultural practices in more than 700 fields from 2003 to 2009. The agricultural database includes 8–20 farms among the 45 having fields in the WPA, representing 30–81% of the surface area, depending on the year (Table 1).

2.2. The biophysical crop model Syst'N

Syst'N is a Decision Support System (DSS) software developed by the National Institute of Agronomic Research (INRA) and French technical institutes to help assess nitrate losses and improve management in agricultural systems (http://www.rmt-fertilisationetenvironnement.org/). This software, beyond a mere soil–crop model, was developed to meet the requirements and constraints of non-scientist users such as professionals involved in local water quality actions. Since 2005, Syst'N has been co-designed with a panel of potential users, in an iterative process of interviews, computer development and testing (Cerf et al., 2012; Parnaudeau et al., 2012). The biophysical model included in Syst'N is a 1D soil–crop model. It simulates soil nitrogen (N) transformations, crop growth, N uptake, water balance and N losses to water (as NO_3^-) and air (as NH_3, N_2 and N_2O) on a daily time step (Fig. 1). Input data include description of a crop sequence, agricultural management practices, soil and climate. The biophysical model was evaluated for a range of crops (wheat, barley, corn, pea, rape seed, and sunflower) and catch crops (white mustard, ryegrass) (Parnaudeau et al., 2012). Syst'N's equations combine existing submodels: STICS (Brisson et al., 2003) for water and nitrate budgets in soils, AZOFERT (Machet et al., 2004) for mineralization of soils and crop residues, AZODYN (Jeuffroy and Recous, 1999) for crop N uptake, NOE (Henault et al., 2005) for N_2 and N_2O emissions and VOLT'AIR (Genermont and Cellier, 1997) for NH_3 emissions (see Cannavo et al. (2008) for a description of the equations used). These models were selected to function with input data that are generally available for identified end-users. Syst'N also includes post-processing routines of simulation results, a graphical interface for input and output visualization to facilitate use by non-scientist users, and a database of observed and simulated N losses in various conditions to help users interpret simulation results.

Table 1
Summary of information contained in the agricultural database for the Plaine du Saulce water protection area by year.

Characteristic	2003	2004	2005	2006	2007	2008	2009
Number of farms surveyed	8	14	14	16	16	20	20
Number of fields surveyed	223[a]	494[b]	478[a]	741[b]	472[b]	791[b]	722[a]
Surface (ha)	1427	2515	2494	3415	2791	3787	3787
Percentage of total agricultural area surveyed	30	54	53	73	60	81	81

[a] Only crops recorded.
[b] Management practices recorded: sowing and harvesting dates, fertilization type/dates/level, pesticide type/dates/dose.

2.3. A framework for co-designing a typology of cropping systems and soils

2.3.1. Theoretical considerations

Nitrate losses from agricultural fields result from dynamic interactions between pluri-annual crop sequences, agricultural management practices, soils and climate (Lilburne et al., 2003; Beaudoin et al., 2005; Constantin et al., 2010). Assessing diffuse nitrate losses in a WPA implies describing all four of these elements, their variability and their interactions in an agricultural landscape. While we assumed the climate to be homogenous, the agricultural landscape of a meso-scale WPA comprises numerous heterogeneously distributed agricultural fields (Lazrak et al., 2010), each with distinct physical (e.g. soil) and agricultural characteristics (e.g. crop grown) (Faivre et al., 2004). The expert elicitation framework described here aimed to co-design a relevant typology of landscape units based on the concept of the cropping system. Sebillotte (1974) defined a cropping system as “crops, their succession order and the crop management plans associated with each crop for a set of fields managed similarly”. The concepts of landscape agronomy aim to extend this vision of an agricultural field to larger spatial scales, by analyzing the relationships between “farming systems”, “landscape patterns”, and “natural resources” in a territory (Benoit et al., 2012). This implies that landscape patterns result from the combination of a cropping system (i.e. part of “farming systems”) and a soil type (i.e. part of “natural resources”), but also that soil characteristics influence cropping systems. Therefore, we placed special emphasis on interactions when describing our system of interest: i) interactions between crop sequence and crop management plans and ii) interactions between these two components of cropping systems and soils. Accounting for interactions was crucial because a crop management plan depends on the crop rotation in which it is included, and both crop rotations and management plans depend on the soil type. Additionally, assessing nitrate losses from cropping systems involves considering the pluri-annual time scale of the crop sequence, thus accounting for effects of the preceding crop and the intercrop period (Beaudoin et al., 2008). Hence, landscape units in the typology consisted of a description of homogenous units of cropping system × soil.

2.3.2. Combination of expert knowledge and an agricultural database

Expert elicitation was used to co-design a typology of landscape units that make sense to them, without losing sight of the complexity of interactions. Quantitative description of each landscape unit relied on the agricultural database (Table 1) and a soil database. The rationale for involving local experts in a co-design process is that they would understand and agree with the system description (Ravier et al., 2015). Therefore, modeling results would help increase their knowledge about nitrate losses from cropping systems in the area where they are working as technical advisors, which should in turn improve environmental management in the Plaine du Saulce WPA. Expert elicitation was performed prior database analysis, to ensure that the assessment methodology would be guided by the questions formulated by the participants rather than by preexisting databases or models. We elicited information from local experts for all subjective choices in the construction of this quantified typology. The first subjective choice concerned selection of the criteria used to define classes (e.g. “the amount of N fertilizer applied will be a criterion”). Selection of criteria depended on a priori knowledge about the characteristics of cropping systems that control nitrate losses. Subjectivity and expert judgment also played a role when determining i) decision rules about how to relate the databases to the typology and thus determine the percentage of each landscape unit (e.g. “all fields where fertilizer application < reference fertilization level belong to class 1”) and ii) how to quantitatively describe each landscape unit in the model (e.g. “fertilizer application in class 1 is the mean of all fields belonging to this class”). We chose to work with a limited number of local experts who did not have an economic interest related to agriculture in the Plaine du Saulce WPA. Thus, we could implement a ‘co-design’ process (Barreteau et al., 2010) in which discussion and decision are made in a collegial way during workshops. All local experts (see section 2.3.3) were considered as belonging to a homogenous group with the same values, willing to share information and develop knowledge. The result of the elicitation process was a typology of landscape units to be used as modeling situations with the Syst'N software.

2.3.3. Meeting structure

The expert elicitation process involved three local experts: two staff members of APS and one technical adviser of the Chamber of Agriculture. A soil scientist from the Chamber of Agriculture was elicited occasionally for questions related to the soil database. The organizing team comprised three scientists in the field of agronomy. The entire process lasted 10 months, during which three formal meetings were organized at the office shared by the Chamber of Agriculture and APS.

The goal of the first meeting was to agree on common goals for the study. The local participants asked questions about assessment of nitrate losses from cropping systems (e.g. comparison of crop rotation, effect of soil characteristics, effect of soil tillage) and presented their agricultural and soil databases. The organizing team presented Syst'N and the proposed theoretical framework (section 2.3.1.). We agreed on a triple assessment: i) assessment and comparison of nitrate losses at a pluri-annual rotation time scale from existing and/or emerging cropping systems; ii) diagnosis of nitrate losses at an infra-annual time scale, to identify critical periods for nitrate leaching for each cropping system; and iii) prediction of nitrate losses at the scale of the entire WPA, to predict changes in water quality at the intake point in simple scenarios (Fig. 2). We also agreed to co-design a typology of landscape units, in line with our theoretical framework, that would be used as quantified input data to Syst'N.

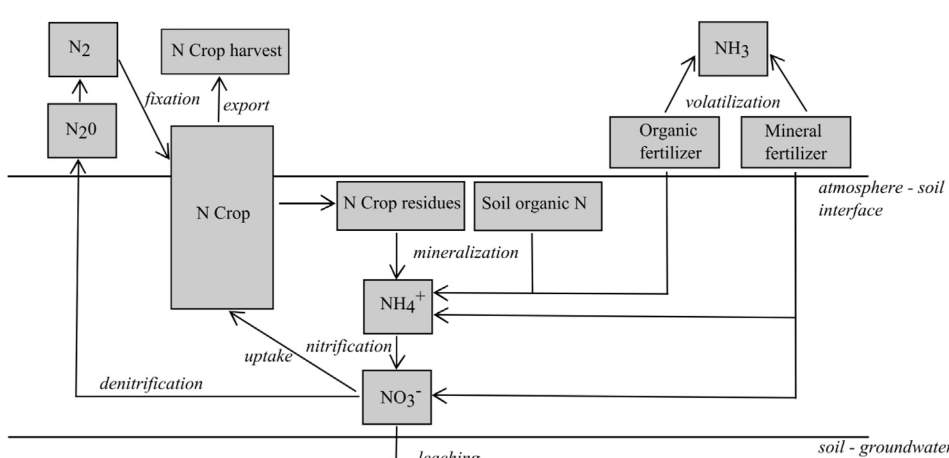

Fig. 1. N fluxes and transformations as simulated by the modeling software Syst'N.

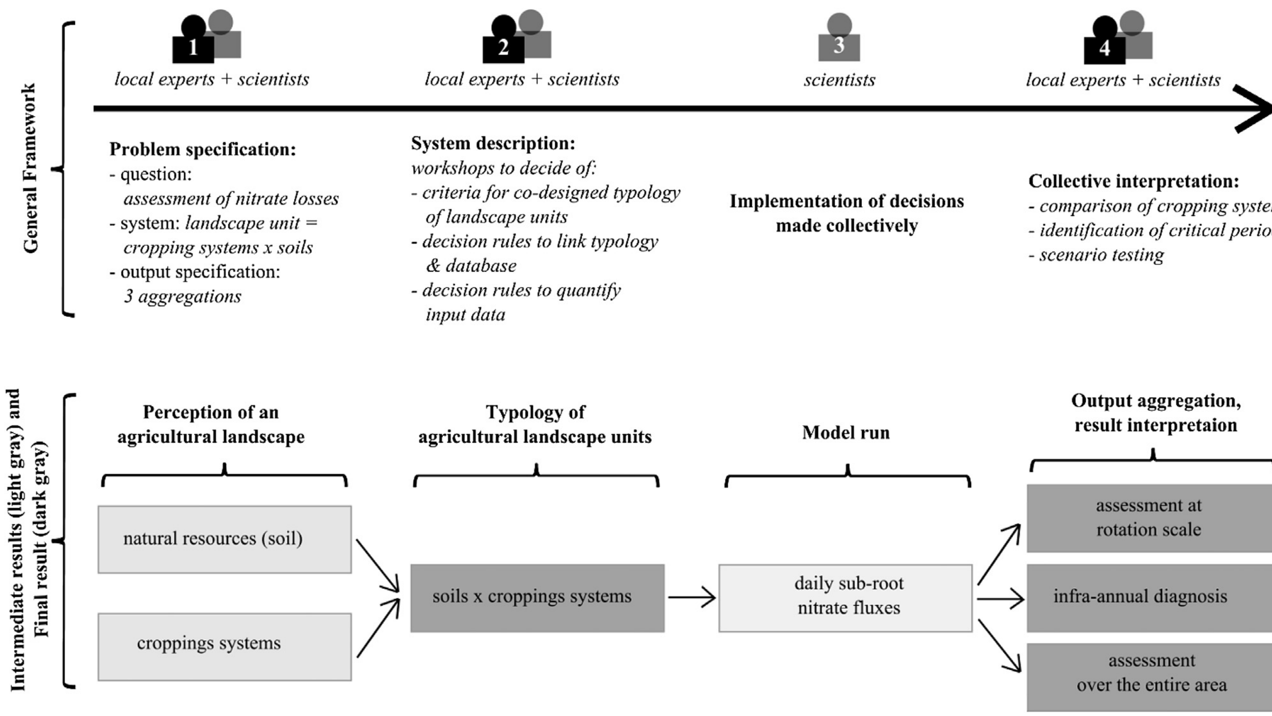

Fig. 2. Framework for participatory assessment of nitrate losses from cropping systems.

The goal of the second meeting was to co-design this typology and agree on decision rules to relate it to the agricultural database. During this meeting, we also evaluated model predictions using local nitrate data at the outlet of Fontaine Creuzy, a small spring draining three intensively monitored fields near the WPA (22 ha). This evaluation involved the use of a simple two-store hydrological model (Ruiz et al., 2002) calibrated to match observed water discharge. Simulated N-nitrate fluxes were then compared with observed data over a period of three years. For the co-designed typology, the elicitation process consisted of a 2-day workshop. According to the framework, the workshop aimed to decide i) which criteria to use to define classes in the typology of landscape units, ii) which decision rules to relate the agricultural and soil database to the typology, and iii) how to quantitatively describe each landscape unit in input files for the biophysical model. Local experts were given total freedom in the definition of landscape units, the scientists' only prerequisite being to select criteria that could be represented by the biophysical soil–crop model. We chose to limit the number of situations modeled to allow for discussion of each via Syst'N' visual output interfaces. All landscape units identified were modeled and discussed, regardless of the surface area they covered in the WPA, because participants were interested in evaluating both dominant and emerging cropping systems. Prior to this study, Syst'N already had post-processing routines and visual interfaces for pluri-annual comparison of cropping systems and infra-annual diagnosis of nitrate losses; thus, the only additional computer development required concerned aggregation of modeling outputs at the scale of the entire WPA. For this, we assumed that the percentage of each crop rotation in the agricultural database was unbiased for a given soil type and that the percentage of each fertilization level in the agricultural database was unbiased for a given soil type × crop rotation. We modeled nitrate losses from non-arable land uses using constant sub-root nitrate concentrations from the literature (Benoit and Fizaine, 1999; Billen and Garnier, 1999; Tournebize et al., 2012). We considered the climate of the 2000–2010 period in model runs. Because nitrate leaching was essentially vertical in the WPA, it was not necessary to consider the spatial distribution of the landscape. Moreover, participants agreed not to produce maps in which individual fields were visible, to avoid risks of conflict with farmers resulting from identification of specific farms when the final report would be made available to the public. Therefore, the spatial description of the agricultural landscape was not fully distributed but semi-distributed, the most important aspect being to allocate the right cropping systems to the right soils (Dupas et al., 2013b).

The third meeting consisted of presentation and discussion of modeling results. Model outputs were post-processed by Syst'N, and its visual interfaces were used to analyze the results at the pluri-annual rotation time-scale (sub-section 3.2.2) and at a tri-monthly scale (sub-section 3.2.3). Aggregation of outputs at the scale of the entire WPA (weighted by surface area) tested the ability of the approach to predict nitrate concentration at the intake point and open up prospects of testing simple scenarios (3.2.4).

3. Results

3.1. Description of cropping systems and soils

Four criteria were chosen to aggregate the diversity of landscape patterns in the WPA into homogenous landscape units: soil type, crop rotation, amount of N fertilizer applied, and catch crop strategy. We accounted for interdependences between these four components of landscape units both in the definition of the classes (e.g. fertilization level 1 has different meanings depending on the crop rotation, the crop considered and the soil type) and in the linkage between cropping systems and soil types (i.e. the percentage of surface area occupied by each cropping system varies among soils) (Fig. 3). During the workshop, local experts mentioned the possibility of including soil tillage practices as an additional criterion in the typology, but we had to discard this idea because the biophysical model Syst'N contained little consideration of tillage. The components of crop management plans not used to define landscape units (e.g. sowing and harvesting dates, tillage practices) were entered in the model as mean observed values or the most frequently observed practices.

The following sub-sections present the decision rules used to determine the percentage of each landscape unit in the WPA and to quantitatively describe each landscape unit for the modeling, based on the agricultural database.

3.1.1. Characterization of soil types

The French IGCS ("Inventaire, Gestion et Conservation des Sols") soil survey described 14 soils in the Plaine du Saulce WPA. Expert elicitation resulted in grouping these soils into three main types based on characteristics known to influence nitrate losses. Soil depth was taken as the main characteristic in the typology because other factors varied little (e.g. soil organic matter) or correlated with soil depth (e.g. plant-extractable water, $CaCO_3$ content). Then, the dominant soil in each of the three classes was considered for the modeling:

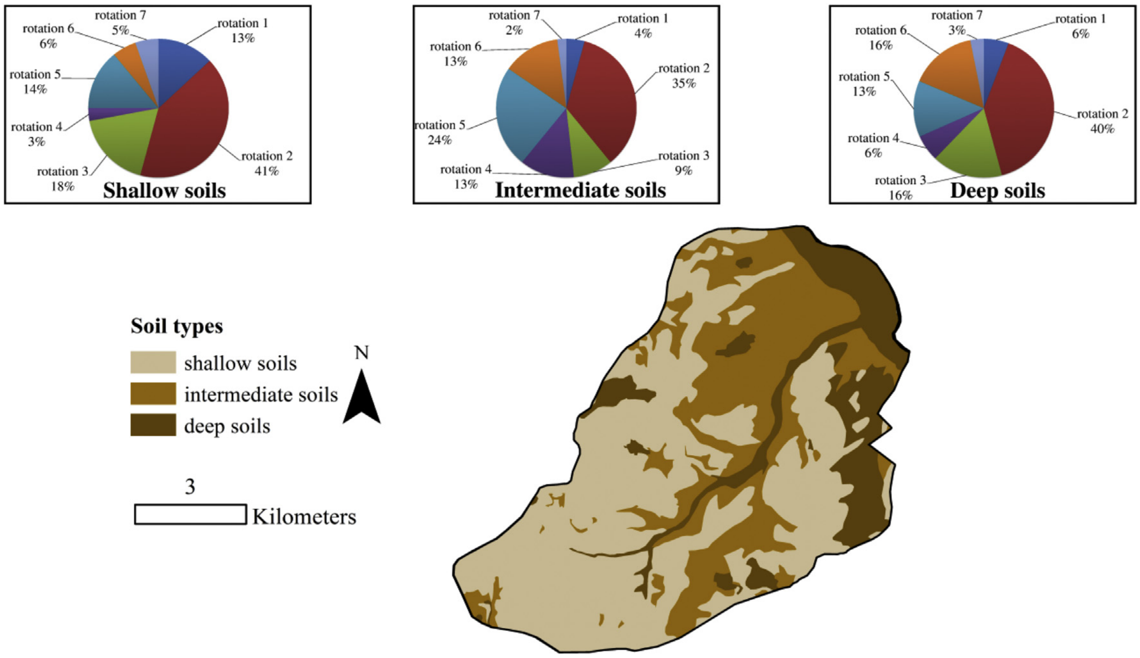

Fig. 3. Map of soil types and frequency of crop rotations per soil type in the Plaine du Saulce water protection area, based on 7 years data.

- 1: shallow soils (58% of arable land in the WPA): modeled as Rendzic Leptosol (World Reference Base for Soil Resources, 2006)
- 2: intermediate soils (29% of arable land): modeled as Calcosol
- 3: deep soils (13% of arable land): modeled as Calcosol decarbonated in the surface layer

Soil parameters input into the model corresponded to IGCS description of the soil considered (Table 2).

3.1.2. Crop rotations

Seven crop rotations were chosen by the participants, either because they were frequent in the WPA or because the participants considered them as innovative and wanted to test them:

- rotation 1: rape seed–winter wheat–winter wheat–winter barley
- rotation 2: rape seed –winter wheat–winter barley
- rotation 3: rape seed–winter wheat–spring barley–winter barley
- rotation 4: rape seed–winter wheat–spring barley
- rotation 5: rape seed–winter wheat–sunflower–winter wheat–winter barley
- rotation 6: rape seed–winter wheat–spring pea–winter wheat–winter barley
- rotation 7: rape seed–winter wheat–spring pea–winter wheat–sunflower–winter barley

We used the agricultural database to determine the percentage of each crop rotation in each soil type of the WPA. Due to the large amount of missing data in the seven years represented by the database (each field was surveyed 1–7 times) and because recorded crop sequences did not exactly match the rotations chosen, we established expert rules to attribute each recorded crop sequence to one of the seven crop rotations. The expert rules consisted of "if-then" allocation rules that were first proposed by the scientists, discussed with the local experts and then modified in an iterative process. The final rules were:

- if "sunflower" present and "spring pea" absent → rotation 5
- if "spring pea" present and "sunflower" absent → rotation 6
- if "spring pea" present and "sunflower" present → rotation 7
- if "spring pea" absent and "sunflower" absent and "spring barley" present
  - if only one "rape seed" present in recorded sequence → rotation 4
  - if at least two "rape seed" present in recorded sequence → rotation 3
- if "spring pea" absent and "sunflower" absent and "spring barley" absent

Table 2
Description of soil types in the Plaine du Saulce water protection area.

Soil type	Layer depth (cm)	% Clay	% Silt	% Sand	Soil texture	Density	% Stones	% Organic matter	C:N ratio	% $CaCO_3$	pH
1: shallow	0–30	38	52	10	loam	1.45	25	4.5	8.7	20	7.5
	30–50	38	52	10	silty clay	1.45	75	NA	NA	NA	NA
2: intermediate	0–25	35	58	7	silty clay	1.45	5	3.4	8.7	45	7.2
	25–60	42	50	8	clay	1.45	10	NA	NA	NA	NA
	60–80	30	60	10	silty clay	1.45	75	NA	NA	NA	NA
3: deep	0–20	38	56	6	silty clay	1.40	0	3.1	8.7	0	7.2
	20–90	55	42	3	clay	1.30	0	NA	NA	NA	NA
	90–110	55	42	3	clay	1.30	95	NA	NA	NA	NA

- if two "winter wheat" present in a row → rotation 1
- else → rotation 2

The percentage of each crop rotation differed among soil types (Fig. 3), e.g. crop rotation 6, which includes spring peas, was less often present in shallow stony soils than in the two other soil types. This confirmed our hypothesis than characteristics of cropping systems, such as crop rotation, are indeed dependent on soil characteristics.

3.1.3. Fertilizer application

Three classes of fertilizer application levels were determined in comparison to a reference level. The reference levels used were the legal fertilization levels set by a prefectural decree for each crop and soil (DDT de l'Yonne, 2011). We could integrate, to some extent, the fact that fertilization of a given crop depends on the crop rotation in which it is included, because the legal levels included (for wheat only) the effect of the preceding crop. The agricultural database served to assign a fertilization level to each recorded field, as follows:

- fertilization 1: low level, i.e. fields in which fertilizer application was <100% of the reference
- fertilization 2: intermediate level, i.e. fields in which fertilizer application was 100–110% of the reference
- fertilization 3: high level, i.e. fields in which fertilizer application was >110% of the reference

Thresholds were chosen to obtain a comparable number of fields in each class. In the model, we set fertilization level 1 at 82% of the reference, i.e. the mean of recorded fields in class "fertilization 1". Fertilization level 2 was set at 106% of the reference, i.e. the mean of recorded fields in class "fertilization 2". Fertilization level 3 was set at 125% of the reference, i.e. the mean of recorded fields in class "fertilization 3".

3.1.4. Catch crop strategy

Two catch crop strategies were distinguished:

- catch crop 1: presence of a catch crop before each spring crop and volunteer rape seed (self-established rape seed plant from the previous year's crop) kept after each rape seed crop
- catch crop 0: no catch crop and no volunteer rape seed

Due to a lack of data about the plant species grown, the catch crop was modeled as white mustard (*Sinapsis alba* L.), considered the most frequent catch crop according to the local experts. In the "catch crop 1" strategy, the sowing date was August 31st, and the destruction date was December 1st (mean of observed dates). The sowing date after spring pea was the day of pea harvest, and the destruction date was September 20th; after a rape seed crop, volunteers were kept until September 20th (requirements of the decree).

The agricultural database did not contain information about the actual extent of catch crops during the simulation period (2000–2010), but, according to the local experts, their use increased during this period until becoming mandatory in 2011. Thus, scientists and local experts agreed to test two extreme scenarios: i) absence of a catch crop in the WPA, to describe past agricultural practices; and ii) generalization of catch crops in the WPA, to explore effects of the legal requirement to introduce catch crops, assuming that all other factors would remain unchanged.

3.2. Summary of simulation results

3.2.1. Model evaluation

Simulated N-nitrate losses at the outlet of the Fontaine Creuzy spring fitted observed loads well. Syst'N loss prediction from 2008 to 2011 was 18.1 kg N ha^{-1} yr^{-1}, i.e. 3% higher than observations (Fig. 4). Year-to-year error ranged from −6% to +14%.

This evaluation served to confirm that the model performed well in the local context, increasing participants' trust in its predictions.

3.2.2. Pluri-annual comparison of cropping systems and soils

Predicted nitrate losses to water from the landscape units modeled confirmed that interactions between factors played an important role: individually, the factors soil type/rotation/fertilization level/catch crop strategy explained only 10%/5%/2%/10% of the variance of pluri-annual nitrate losses, respectively (one-factor ANOVA). On the other hand, soil type, catch crop strategy and their interactions explained 92% of the variance (two-factor ANOVA with interactions).

For a given cropping system, the three soil types had different vulnerabilities to nitrate losses, with the highest nitrate losses in the shallow soil (Fig. 5). The crop rotations with the lowest nitrate losses were those with a high frequency of rape seed and catch crop–spring crop sequence. Fertilization level was the factor with the smallest effect, given our definition of fertilization classes: even though the lowest fertilization levels generated the lowest nitrate losses to water for a given soil type × crop rotation, balanced fertilization (i.e. fertilization levels 1 and 2) did not appear to be sufficient to reduce losses greatly. Introduction of a catch crop proved effective in reducing nitrate losses, especially in rotations with a catch crop–spring crop sequence instead of a winter cereal (winter wheat or winter barley).

3.2.3. Infra-annual diagnosis of nitrate losses

We discussed infra-annual dynamics of nitrate leaching with the local experts to identify critical periods in each crop rotation. Syst'N's graphical interface (specifically, tri-monthly) served as a support for the discussion. During the final meeting, in which model predictions were presented, participants could zoom in on specific periods to examine nitrate losses in more detail in each situation. Autumn and winter were identified as critical periods for nitrate leaching: when rape seed, catch crops or volunteers were present at this time of the year, they could take up N from the soil and thus decrease losses. In contrast, winter cereals did

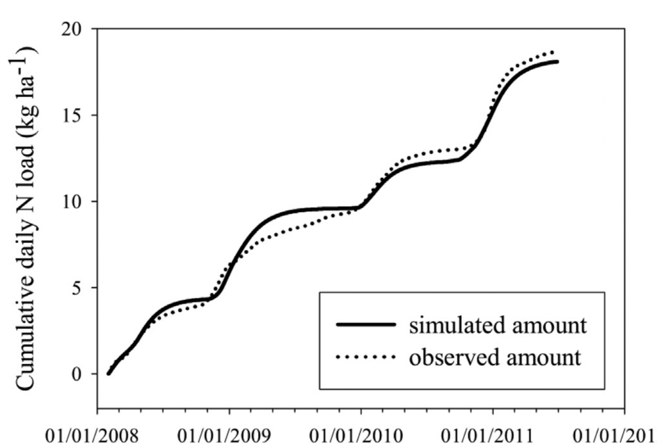

Fig. 4. Cumulative daily N loads observed and simulated at the outlet of Fontaine Creuzy during the 2008–2011 period.

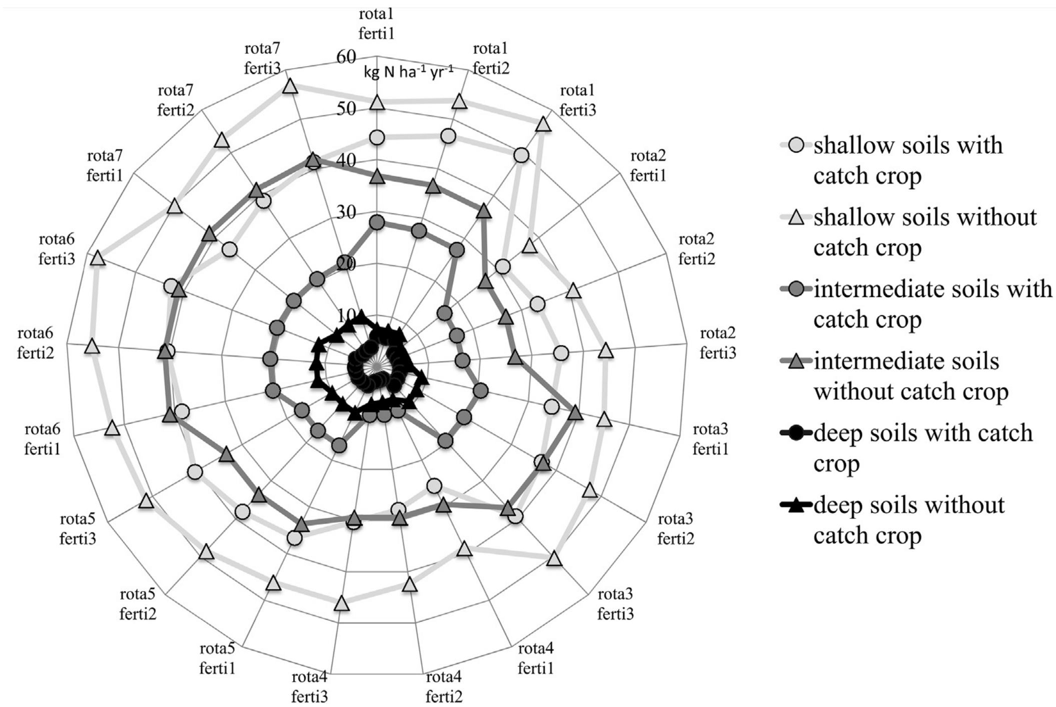

Fig. 5. Annual nitrate losses to water in the Plaine du Saulce water protection area predicted by Syst'N for soil type × crop rotation combinations. All nitrate losses are normalized to kg N ha^{-1} yr^{-1} regardless of the length of each crop rotation (see section 3.1. for description of soil types, crop rotation and fertilization levels).

not appear to take up N efficiently during the winter period. Interdependency among crops in a rotation was identified. For example, when volunteer rape was kept (Fig. 6a), nitrate leaching was lower at the beginning of the following winter wheat than if soils were kept bare during the intercrop period (Fig. 6b). This example demonstrates the need to consider pluri-annual crop rotations when assessing nitrate losses, rather than individual crops.

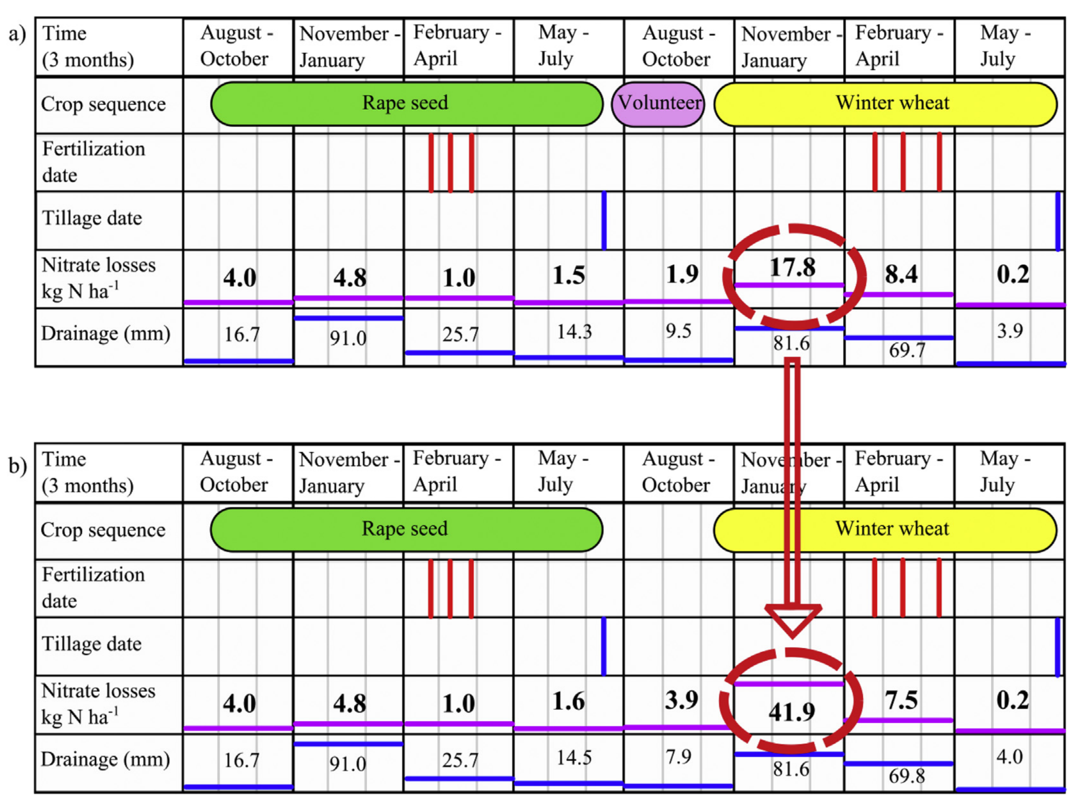

Fig. 6. Syst'N output interface (simplified and translated into English) comparing rape seed–winter wheat intercrop period (a) with volunteers and (b) without volunteers in rotation 1 (rape seed–winter wheat–winter wheat–winter barley). Note that the effect of the presence/absence of volunteers was visible during the next crop.

3.2.4. Predicted nitrate losses from the entire area

Aggregation of predicted nitrate losses from each landscape unit resulted in a predicted mean sub-root nitrate concentration as high as 53.6 mg NO_3^- l^{-1} without catch crops and 41.3 mg NO_3^- l^{-1} with catch crops during the 2000–2010 period. Mean nitrate concentration measured during the same period was 41.4 mg NO_3^- l^{-1} at the intake point. Aggregated predictions showed that shallow soils contributed 80% of WPA nitrate losses, while representing 58% of the arable land. Conversely, deep soils contributed only 2% of WPA nitrate losses, while representing 13% of the arable land. This WPA-wide prediction constituted another validation of the model, further increasing participant's trust in its predictions.

4. Discussion

4.1. Interactions between cropping systems and soils control nitrate losses

Few regional-scale studies on the impact of agriculture on water quality consider variability in soil types (e.g. Dupas et al., 2013a, 2015). This case study demonstrates that considering soil characteristics is crucial from two perspectives: i) the typology of landscape units shows that cropping system characteristics depend on soil types and ii) nitrate losses result from interactions between cropping systems and soils.

The infra-annual diagnosis of nitrate losses illustrates the importance of considering pluri-annual crop rotations, rather than individual crops, in regional-scale studies. Indeed, model predictions show that intercrop periods were critical for nitrate losses, and that high nitrate losses during the growing season of one crop could result from sub-optimal management during the previous crop or previous intercrop period (Fig. 6). The influence of crop rotations and management during intercrop periods has long been identified via agronomic experiments (e.g. Beaudoin et al., 2005; Constantin et al., 2010; Amossé et al., 2014), but it has rarely been included in regional-scale agro-hydrological models. Hence, the influence of soil characteristics and of pluri-annual crop rotations should be considered both when assessing nitrate losses and defining action plans to mitigate nitrate pollution (Schoumans et al., 2011).

4.2. Influence of participants and the software on modeling choices and outcomes

Using a model is often regarded as one way to ensure objectivity (Voinov and Gaddis, 2008); however, selecting a model unavoidably restricts the range of possible outcomes (Sterk et al., 2009). In the present assessment framework, the use of a crop model fosters reflection on cropping systems but precludes reflection on entire farming systems or non-agricultural buffer zones, contrarily to other models (Le Gal et al., 2010; Passy et al., 2012; Moreau et al., 2013; Garnier et al., 2014). It also precludes reflection on socio-economic drivers that influence farming activities by focusing on technical adaptations in the current socio-economic context. Interestingly, a simultaneous study on solutions to alleviate water pollution in the Plaine du Saulce WPA, conducted with different methods and tools, concluded that organic agriculture and the reintroduction of animal production would have a positive effect on N management (Anglade et al., 2012). These kinds of outcomes were beyond the scope of our modeling framework. However, we noted a convergence of views among participants in the Plaine du Saulce project that reasonable changes in agriculture in the mid-term and from a local perspective should involve reflection on cropping systems. Such convergence of views has been observed elsewhere (e.g. Ingram, 2008; Raymond et al., 2010; Hossard et al., 2013) as a consequence of prior exchange of knowledge between scientists and non-scientist participants via formal training or the media. Despite this convergence, it was crucial that the organizing team presented the modeling software and the potential outcomes of its use at the beginning of the study (Reed, 2008).

Many participatory modeling studies engage local participants in developing the models they use (Oliver et al., 2012). In the present assessment framework, local experts are fully involved in co-designing a typology of landscape units, i.e. description of the system of interest, but simulation of nitrate losses is performed with a pre-existing biophysical model. This apparent lack of inclusion of local experts in model design is motivated by three arguments: i) developing agronomic DSS software is time-consuming due to the complexity of the equations in soil–crop biophysical models; ii) Syst'N's equations are valid for most agro-pedo-climatic contexts and iii) environmental data such as sub-root nitrate loads measured in the local context are generally not sufficient for robust parameterization of a biophysical model. For these reasons, Syst'N had been developed in collaboration with a panel of potential end-users broader that just those of the Plaine du Saulce extension service (Parnaudeau et al., 2012; Prost et al., 2012). However, confronting the model with a “real-life” use situation in the Plaine du Saulce project identified two shortcomings in Syst'N: i) no representation of the effect of tillage practices on N cycling and ii) no post-processing routine to aggregate model predictions at the scale of a WPA. The first could not be fixed during the project due to a lack of existing scientific knowledge, while the second was overcome by applying an additional post-processing routine. Thus, confronting modeling software with “real-life” use situations contributes to their iterative improvement (Prost et al., 2012). Model validation in the local context is an integral part of the modeling methodology: although local environmental data are generally not sufficient to parameterize a model, they must be confronted with model predictions to ensure the model is valid in the context of use.

4.3. Limits and potential improvements

Crop models such as Syst'N do not consider the decennial response time of hydrological systems. In that respect, spatially aggregating nitrate losses as a weighted mean of surface area is interesting in that it can increase participants' trust in model predictions (Hossard et al., 2013) by showing that the predicted nitrate concentration is of the same order of magnitude as the observed concentration. It does not, however, inform public decision makers about the delay between the implementation of agricultural actions and improvement of water quality, unlike fully-integrated agro-hydrological models (e.g. Ledoux et al., 2007; Moreau et al., 2012, 2013), which include water and nitrate routing functions. In contrast, crop models are more appropriate for assessment at the cropping system level, i.e. the level at which agronomic improvements can be envisioned.

Unlike other assessment approaches, the present framework does not consider the farm-decision level when describing the agricultural landscape because of the low diversity of farming systems in the study area (all were arable farms with similar crops). The homogenous units of agricultural landscapes considered in this framework constitute an intermediate spatial level between the field and the farm level (Boiffin et al., 2014). These units enable working with a small number of agronomically sound modeling situations. Such modeling situations resemble demonstration test plots, which extension services were accustomed to. Another benefit of working with typical situations is to reduce the risk of conflict by not identifying specific farms or fields, while still being able to allocate the correct percentage of each cropping system to each soil, thus ensuring correct representation of the agricultural landscape in the WPA.

Many authors advocate involving participants who represent a broad section of the identified stakeholders and interest groups in participatory projects dealing with natural resource management, especially when 'social learning' is an objective (Reed et al., 2010, 2014; Carr et al., 2012). However, Voinov and Bousquet (2010) and Barreteau et al. (2010) point out that it is difficult to involve many participants in a co-design process. In the Plaine du Saulce project, we decided to restrict participants to local experts we assumed had solid knowledge of the diversity of farmers' agricultural practices in the WPA. Generally, we believe that working with a small number of local experts is sufficient for performing the initial assessment of nitrate losses in a WPA, but if the participatory process aimed to lead to collective decision making, it would have being necessary to involve farmers. Specifically, the present assessment study highlighted that re-allocating current cropping systems with a better consideration of soil characteristics could lead to substantial reduction in nitrate emissions. Adopting and implementing such a management plan would only be possible if farmers are involved from the very first stages of a participatory process (Ravier et al., 2015). The design of Syst'N interfaces for input and output visualization makes it suitable for working with a larger number of non-scientist participants, including farmers. Future work with the Syst'N software, with a larger diversity of participants and agro-pedo-climatic contexts will help improve the assessment methodology, particularly the sociological evaluation.

5. Conclusion

We developed a participatory assessment framework involving local experts at several stages of a modeling study of nitrate losses. The framework includes i) a methodology for co-designing a typology of landscape units (i.e. cropping systems × soils) where expert elicitation is performed prior database analysis and ii) a participatory assessment of nitrate losses with a modeling software adapted for use with non-scientist participants. Results show that it is possible to account for agronomic considerations, such as soil–cropping systems interactions and delayed effect of agricultural practices in a crop rotation, in a regional scale assessment study. Combining local expertise and an agricultural database proved effective for describing modeling units without precluding the complexity of interactions between their components (such as soil–crop interactions). Modeling software that offers different options for post-processing predictions helps to focus on different aspects of a complex system. In the example of regional scale assessment of nitrate losses from cropping systems, aggregation at the rotation and WPA scales helped participants identify the most vulnerable cropping systems and soils, while infra-annual output allowed them to identify critical periods for nitrate leaching for each situation. Finally, testing the software in a "real-life" use situation helped identify new needs of end-users, which will help to improve it for future use. The assessment framework presented in this paper can be applied to other situations and modeling tools: the methodology combining local knowledge, databases and biophysical modeling is applicable in various agro-pedo-climatic contexts. Different criteria for the typology of landscape units from those used in this study could be selected depending on the context, although it is likely that the central role of soils highlighted here will be valid in all situations. Beyond the issue of nitrate losses in rural WPAs, working with local experts to define a research question and criteria for a typology of modeling units prior analysis of the database is applicable to other environmental management problems. We believe this approach helps direct the assessment methodology according to a question formulated by local participants rather than a preexisting database or model.

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