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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.

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.