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CASIMOD'N: An agro-hydrological distributed model of catchment-scale nitrogen dynamics integrating farming system decisions

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ABSTRACT

This work presents the new integrative model CASIMOD'N (Catchment and Agricultural Systems Integrated MODel for Nitrogen), which assesses effects of farming systems on nitrogen (N) dynamics at the catchment level. Its main innovation is the consideration of the level of the farming system through production strategies, farmer decisions and the expression of decisions as management practices, along with the link between these farming systems, their practices and water pollution. CASIMOD'N integrates farming systems at the farm level and N transfers and transformations at the field, farm and catchment levels. It was built by adapting and combining three models: the catchment-scale biophysical model TNT2 and two farm-scale models, TOURNESOL and FUMIGENE, for the allocation of land use and manure, respectively. The intrinsic logic behind farming system design and function was represented by ensuring agreement between livestock-feeding and manure-management strategies under specific farm constraints (land fragmentation, distance between fields and farmyards) and agronomic rules. The model is able to simulate management practices (crop, manure and mineral fertiliser allocation).

An assessment of the farming system modelling was performed by comparing the management practices simulated with CASIMOD'N with (i) observed data from a livestock-oriented catchment and (ii) a reference dataset of management practices reconstructed with a Markov chain and Knapsack-based algorithm. Then, the spatial distributions of the main N fluxes at the sub-catchment scale simulated with CASIMOD'N and based on the reconstructed management practices are discussed.

Simulations of the two options had few differences in spatial distribution of the main N compartments, organic and mineral fertilisation and N flux at the outlets both at catchment and sub-catchment levels. However, CASIMOD'N was more accurate for simulating farming systems than the reconstructed reference dataset of management practices. This suggests that CASIMOD'N can be used to conceive, implement and assess prospective scenarios involving farming system redesign.

1. Introduction

Increases in nitrogen (N) emissions in ground and surface waters due to intensive agriculture have been widely reported (Billen et al., 2005; Cinnirella et al., 2005) and are often associated with eutrophication (Jarvie et al., 2005) and health issues (Koo and O'Connell, 2006). The European Union (EU) stated that all water bodies shall recover a "good and non-deteriorating" ecological status by 2015 (Water Framework Directive (EC, 2000)), which requires thorough understanding of the causal chain linking farming activities to water pollution.

To encompass the entire chain and find ways to adapt farming systems to new environmental objectives, it is essential to consider both anthropogenic and biophysical systems and their interactions. A farming system is defined as an anthropogenic decision system in interaction with a biotechnical system (Gibon et al., 1999; Gouttenoire et al., 2010). Farmers' decisions are driven by their production objectives, and production strategies aim to satisfy these objectives. The set of farmer decisions is expressed as management practices (Dedieu et al., 2008): crop allocation (crop succession and spatial distribution), manure allocation (waste type, rates, spreading dates and receiving crops) and mineral fertiliser allocations (rates, spreading dates and receiving crops).

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Systemic integration requires paying specific attention to interactions between decisions and biophysical systems (Gouttenoire et al., 2010), making the farming system a "finalised biophysical and managed" system (Dedieu et al., 2008).

When the regional scale is adapted to assess the effects of macro-economic drivers, the catchment, sometimes referred to as a mesoscale (Breuer et al., 2008), is a relevant scale for addressing water-quality-management issues (Gourbesville, 2008). Both the catchment and farm scales include the field scale, where management practices from farmer decisions drive and interact with biophysical and biogeochemical processes. At the catchment scale, it is crucial to consider the spatial distribution of management practices and interactions between farming systems and environmental resources and constraints (Sorel et al., 2010).

Models are powerful tools for understanding the effect of management practices at the catchment scale by simulating scenarios (Cugier et al., 2005; Servais et al., 2007) and are used to support decision (Horn et al., 2004; Gascuel-Odoux et al., 2009), to assess options of mitigations (Wilkinson and Eidinow, 2008; Salmon-Monviola et al., 2011) and/or to share common understanding (Sterk et al., 2011).

Many biophysical models, such as SWAT (Arnold et al., 1998), SHETRAN (Birkinshaw and Ewen, 2000), TNT2 (Beaujouan et al., 2001, 2002; Oehler et al., 2009), and DNMT (Liu et al., 2005) operate at the catchment scale and aim to simulating the effect of management practices, considered as input variables of the models on N transfers and transformations. In these models, farming systems and in particular farmer decisions are not explicitly represented. Several models simulate farming systems, such as IFSM (Corson et al., 2007; Rotz et al., 2011), WFM (Wastney et al., 2002), FASSET (Jacobsen et al., 1998; Hutchings et al., 2007), LSM and WFM (Matthews et al., 2006a,b), but they generally predict N losses at the field scale (1-D model) and do not consider the effect of spatial characteristics in an agricultural region, such as field location and distribution of soil properties. Ignoring interactions between the farmer decision system and biotechnical systems may oversimplify descriptions of farming systems. In areas with high livestock production density generating high nutrient fluxes, many farmer decisions concern livestock-feeding and manure management (Chardon, 2008); therefore, the influence of farm spatial structure on farmer decisions is important. Consequently, it is essential to integrate explicitly farming system functioning and N transfers and transformations at the catchment scale. Few attempts to develop models in this direction have been performed. One model, LANAS (Theobald et al., 2004), integrates farm modelling into an agro-hydrological model at the catchment scale (INCA, Whitehead et al., 1998) but remains semi-distributed. The NITROSCAPE project (Duretz et al., 2011) also aims to combine farm and catchment systems, but farming practices are defined at the field scale and only a virtual catchment has been assessed so far. Most recently, the CSAM (Cropping Systems Allocation Model) was developed to construct data base of management practices at field scale for producing environmental results at catchment scale (Salmon-Monviola et al., 2012). This database constitutes a reference set of management practices reconstructed with a Markov chain and Knapsack-based algorithm.

The objective of this paper is to present a new integrative model, CASIMOD'N (Catchment and Agricultural Systems Integrated MODel for Nitrogen) that aims to quantify ex ante the effect of agricultural policy on N fluxes, while explicitly considering the faming-system level. CASIMOD'N combines farming system modelling (via production strategies, farmer decisions and their expression as management practices) and N fluxes at the catchment scale. To evaluate the accuracy of CASIMOD'N, we compared its predictions of management practices with either (i) management practices observed from surveys or (ii) management practices statistical reconstructed with CSAM. The spatial distribution of the main N fluxes obtained with management practices issued from CSAM and CASIMOD'N in several sub-catchments was then assessed.

2. Material and methods

2.1. Description of CASIMOD'N

CASIMOD'N simulates N transfers and transformations at the catchment scale while ensuring farming system consistency by integrating farmers' production strategies and their subsequent management practices. CASIMOD'N results from adapting and combining three models: the agro-hydrological model TNT2, which simulates all N fluxes at the catchment scale (Beaujouan et al., 2002), and two decision-making models that simulate farming system management at the farm scale, TOURNESOL (Garcia et al., 2005) and FUMIGENE (Chardon et al., 2008).

TNT2 is process-based and spatially distributed to account for potential spatial interactions such as nitrate leached upslope and its effect on lowland uptake or bottomland denitrification (Oehler et al., 2009). It represents crop growth and nitrogen transformation based on the plant-soil model STICS (Brisson et al., 1998). In TNT2, field management practices are input data.

TOURNESOL and FUMIGENE introduce the farming system level into CASIMOD'N. They have already been applied independently with detailed datasets to two farms (Chardon et al., 2008) and to one experimental farm (Garcia et al., 2005), respectively. Both models are planning models by optimisation and determine, once a year, the management practices to apply to each field in the coming year. TOURNESOL produces a crop allocation plan and FUMIGENE a manure allocation plan to fulfil the objectives of each farming system, given farmer constraints. These plans ensure consistency between expected livestock-feed requirements and manure and crop production under a set of agronomic rules (effect of crop successions, minimum and maximum durations for perennial crops, and prioritisation of crop-manure pairs) and a set of constraints. The constraints concern farmland structure (land fragmentation, field distance from the farmstead and for each field, the possibility of being grazed by dairy cows or of receiving manure), machinery (minimum and maximum application rates), fields (soil agronomic potential) and regulations (prohibitions on locations or periods of manure spreading).

TOURNESOL inputs include expected livestock-feed requirements as a function of dairy or suckler production and livestock-feeding strategy. Livestock-feed requirements (e.g. silage or grazed grass, maize and straw) are determined (*t* of dry matter) for different animal types (milking cows, sucklers and heifers) (Table 1). Next, positive fictive prices are given to surpluses, and negative ones to deficits, of each livestock feed. The fictive prices prevent optimisation only on an economic basis and are used to represent farmer priorities. For instance, if a farmer aims for forage self-sufficiency, fictive prices exceed the market price for forage deficits, whereas if forage self-sufficiency is not a priority, fictive prices equal observed market prices (Chardon et al., 2007). The crop-allocation plan integrates livestock-feed requirements and farmers' priorities. The objective function considers the sum of the values of all livestock feeds' surpluses or deficits and is maximised during the optimisation procedure. The optimisation procedure is based on a genetic algorithm: an initial population of several crop-allocation plans is randomly generated, and characteristics of plans with the highest scores of the objective function are selected to generate the next set of crop-allocation plans, until the algorithm converges to an optimal crop-allocation plan. Thus, a crop-allocation plan is selected that satisfies expected livestock-feed requirements and farmers' priorities and ensures that potential crop requirements