

Sensitivity analysis of spatio-temporal models describing nitrogen transfers, transformations and losses at the landscape scale.

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Abstract

Modelling complex systems such as agroecosystems often requires the quantification of a large number of input factors. Sensitivity analyses are useful to assess the impact of input factors on model outcomes and to determine the appropriate spatial and temporal resolution of models. Comprehensive spatial and dynamic sensitivity analyses were applied to the model Nitroscape, a deterministic spatially distributed model describing nitrogen transfers and transformations in rural landscapes, simulating five years of farm management in an intensive rural area of 3 km². 11 global input factors were explored, characterizing spatial resolution of the simulations, the physical parameters of the landscape and the agricultural practices. Their impact on 29 spatially-distributed model outcomes was assessed through standard analysis of variance. Cluster analyses were applied to summarize the results of the sensitivity analysis on the ensemble of model outcomes. The purpose of this paper is to present the methods and preliminary results that we developed to carry out and to visualize comprehensive spatial and dynamic sensitivity analyses of multiple input factors on multiple outcomes.

Keywords

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Modeling nitrogen transfers, transformations and losses from processes integration at the landscape scale requires using complex models which are spatially and temporally explicit. Model predictions may vary considerably, depending on the initial conditions and input parameters. Therefore, it is important to characterize their robustness and variability through sensitivity analyses.

A variety of techniques have been developed to perform sensitivity analysis in spatially and dynamic models at different stages. Methods for exploring model inputs may range from the simplest one-factor-at-a-time screening techniques proposed by Morris (1991) to the exploration of representative combinations of factors in factorial designs, as described by Chen (2011). Recently, Moreau et al. (2013), proposed a method to take into account the spatial distribution and the granularity of input parameters in sensitivity analyses. Besides, Marrel et al. (2011) proposed a technique to extend variance-based methods well suited to analyse scalar outputs to dynamic and spatially explicit outcomes, rendering spatial maps of the sensitivity of each output to each model input. Finally, Ligmann-Zielinska (2013) showed that spatially explicit sensitivity analyses and analyses that aggregate outputs at different scales of description are complementary, but at the same time can lead to different decisions regarding input factor prioritization.

Here, we present an analysis of sensitivity of the NitroScape model developed by Duret et al. (2011), with the specific aim to compare the impact of spatial granularity of the model to the impact of global parameters describing physical characteristics of the landscape and agricultural practices on spatially-distributed model outcomes. A central concern of the presented work is to provide tools for integrating the results of spatially

explicit sensitivity analyses applied on multiple model outcomes.

Nitroscape is a deterministic, spatially explicit and dynamic model describing the transfers and transformations of reactive forms of nitrogen (Nr) in rural landscapes of a few km² to a few tenth of km². It couples four modules characterizing processes of farm management, biotransformations and transfers of Nr by the atmospheric and hydrological pathways. It simulates Nr flows and losses within and between several landscape compartments: the atmosphere, the hydro-pedosphere (groundwater, water table and streams) and the terrestrial agroecosystems (livestock buildings, croplands, grasslands and semi-natural areas).

In order to evaluate the impact of global model inputs on the model outcomes, 11 parameters were selected. They characterized the spatial resolution of the model (size of the horizontal grid and depth of surface layers), the physical features of the landscape (soil characteristics) and the agricultural management (fertilization). A complete fractional factorial design with 11 categorical factors and 3 levels per factor was generated. The resulting plan comprised 243 units and the design resolution was 5, which allowed estimating main effects and two-factor interactions unconfounded.

The range of explored input values represented both the range of values observed in real settings and the degree of uncertainty in the measured or estimated values. Landscape structure (*e.g.* topography, land use), initial conditions (*e.g.* soil mineral content, agroecosystem characteristics) and forcing inputs (*e.g.* agricultural practices, meteorology) were common for all units in the factorial design. Their values were set from real measurements to represent an intensive rural area with mixed crops, pig farming and unmanaged ecosystems characterized by humid climatic conditions and little temperature contrasts.

Each run of the plan simulated nitrogen transfers, transformations and losses in a virtual landscape representing 300 ha of a catchment area with agricultural and farming activity, during 5 years, with daily outputs at the outlet and monthly outputs on the whole grid after an initialization period of two years. The impact of model inputs was evaluated on 29 model outcomes: 5 variables describing the catchment outflow, 9 spatially-distributed variables describing inter-compartment fluxes and 15 spatially-distributed variables describing the local state of the system.

NitroScape spatially-distributed output variables were aggregated to obtain either time-series describing spatially aggregated outcomes or maps of temporally aggregated outcomes. A principal component analysis (PCA) was applied to time series and spatial distributions to reduce their dimensionality. The influence of factors on each model outcome (expressed as aggregated data or in terms of its principal components) was explored through a standard analysis of variance (ANOVA) considering up to second-order interactions: the variability of each component of each outcome (day in time series, pixel in maps, or principal component), spread over the experimental design, was ascribed to every factor and two-factor interaction by partitioning the sum of squared deviations. The relative importance of factors and interactions was measured with sensitivity indices based on this partitioning. Finally, a cluster analysis and a PCA were applied to summarize the ensemble of results of the sensitivity analysis on the whole set of model outcomes, in order to identify outcomes with similar response to model inputs and to discriminate the effect of each factor and two-factor interaction on the ensemble of outcomes.

The methods here presented may be used to perform dynamic and spatial sensitivity analyses of models with multiple outcomes. The novel contributions of our proposal can be split into three aspects. Firstly, we simultaneously considered the spatial resolution of the model, the physical characteristics of the landscape and the agricultural practices in a single experimental design. This allows evaluating not only the main effect of the spatial resolution, but also its interactions with the other factors. Secondly, we aggregated either spatially or temporally each outcome and we carried out a global sensitivity analysis on the aggregated variables. This allows identifying patterns in the temporal sequences and in the spatial distributions of the sensitivity indexes that may arise from the model structure (seasonality and spatial structure of the landscape, respectively). And thirdly, we analysed the ensemble of results of the sensitivity analyses on multiple outcomes. This allows grouping together model outcomes that are mainly sensitive to the same inputs and identifying the factors that impact the ensemble of outcomes in a similar way.

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