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Performance assessment of nitrate leaching models for highly vulnerable soils used in low-input farming based on lysimeter data

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HIGHLIGHTS

- We compared the performance of six detailed nitrate leaching models.
- The models were applied to a lysimeter with a soil highly vulnerable to leaching.
- The low-input farming system contained nitrogen catch crops, difficult to parameterize.
- Performance assessment should not be based solely on nitrate concentrations.
- An accurate calibration does not guarantee a good predictive power of the model.

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ABSTRACT

The agricultural sector faces the challenge of ensuring food security without an excessive burden on the environment. Simulation models provide excellent instruments for researchers to gain more insight into relevant processes and best agricultural practices and provide tools for planners for decision making support. The extent to which models are capable of reliable extrapolation and prediction is important for exploring new farming systems or assessing the impacts of future land and climate changes.

A performance assessment was conducted by testing six detailed state-of-the-art models for simulation of nitrate leaching (**ARMOSA**, **COUPMODEL**, **DAISY**, **EPIC**, **SIMWASER/STOTRASIM**, **SWAP/ANIMO**) for lysimeter data of the Wagna experimental field station in Eastern Austria, where the soil is highly vulnerable to nitrate leaching.

Three consecutive phases were distinguished to gain insight in the predictive power of the models: 1) a blind test for 2005–2008 in which only soil hydraulic characteristics, meteorological data and information about the agricultural management were accessible; 2) a calibration for the same period in which essential information on field observations was additionally available to the modellers; and 3) a validation for 2009–2011 with the corresponding type of data available as for the blind test. A set of statistical metrics (mean absolute error, root mean squared error, index of agreement, model efficiency, root relative squared error, Pearson's linear correlation coefficient) was applied for testing the results and comparing the models.

None of the models performed good for all of the statistical metrics. Models designed for nitrate leaching in high-input farming systems had difficulties in accurately predicting leaching in low-input farming systems that are strongly influenced by the retention of nitrogen in catch crops and nitrogen fixation by legumes. An accurate calibration does not guarantee a good predictive power of the model. Nevertheless all models were able to identify years and crops with high- and low-leaching rates.

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1. Introduction

Agriculture is the major land use in Europe (ca. 50% of overall land area) and has strongly increased its use of external inputs (fertilizer, pesticides and water) over the last 50 years. The environmental effects of intensive agriculture include a decline in biodiversity, eutrophication of ecosystems and surface waters, acidification, global warming, air pollution and diffuse nitrate pollution of groundwater. A global challenge is to produce enough food for the ever-growing population and at the same time minimizing the loss of reactive nitrogen (N) to the environment. Since the 1980s, agriculture in Western Europe has managed to reduce its N surpluses, owing to stringent national and European community policies (Vitousek et al., 2009; Grizzetti et al., 2011).

The main aim of the Nitrates Directive (EU, 1991: Directive 91/676/EEC) is to reduce water pollution caused or induced by nitrates and phosphorus from agricultural sources. The Nitrates Directive legally restricts farm application of manure to 170 kg ha^{-1} of nitrogen, or in case of derogation to inputs up to 250 kg ha^{-1} (Oenema, 2004). An implementation measure of the Nitrates Directive is the establishment of codes of Good Agricultural Practice. Recommended measures include, among others, the application of crop rotations, the cultivation of a soil winter cover and catch crops to prevent nitrate leaching and run-off during wet seasons. Catch crops create a new challenge in the assessment of environmental effects of crop rotations. In theory, catch crops take up N that would otherwise be lost, and, after incorporation of the crop residues into the soil, make this N available to the succeeding crop via mineralization. However, the influence of a catch crop on the nitrogen supply to the succeeding crop can vary greatly and range from a positive to a negative effect (Nett et al., 2011). The effect is determined by the N uptake capacity, the rooting depth of a catch crop, the weather and soil conditions as well as the rooting depth of the succeeding crop (Thorup-Kristensen, 2006).

Models are an important tool for assessment of environmental impacts of a certain agricultural practice and are also an instrument for increasing the understanding of the biological, pedological and hydrological factors that affect productivity and the risk of nitrate leaching. For this reason, for more than 30 years simulation models have been developed and applied in the research on nitrate leaching. The different model descriptions are a reflection of the intended purpose, the physical conditions and the available data for model application and the knowledge and skill of the model developer. Technical implementations have evolved from stand-alone model codes to modelling platforms comprising modular models able to include and compare different process descriptions.

Calibration and validation of models contribute to their reliability. In addition also an analysis of the implemented process descriptions and the mutual comparison of models provides information on the predictive power. Several model comparison studies have been conducted in which nitrate leaching models were compared (De Willigen and Neeteson, 1985; Vereecken et al., 1991; De Willigen, 1991; Diekkrüger et al., 1995; Moreels et al., 2003; Kersebaum et al., 2007; Jabro et al., 2012). Most of them were related to ordinary agricultural conditions with a single crop on a typical agricultural soil. Thus, there is no information (comparison) available for situations in soils that are highly vulnerable to nitrate leaching in combination with low-input conditions and the use of catch crops.

It is widely recognised that despite the deterministic nature of process oriented models they often have a limited validity range for certain climatic, pedological, hydrological and agronomic circumstances characterised by high inputs. It is not clear whether the models are able to produce relatively reliable predictions for low-input conditions. A better insight into the model performance for such uncommon circumstances underpins conclusions about the predictive power.

In this study a number of models were inter-compared for low-input conditions of one of the lysimeters of the Wagna experimental research station, Austria (Klammler and Fank, 2014-this issue) for three typical conditions for which they were not designed: 1) the crop rotation which included an uncommon crop (oil pumpkin), 2) catch crops for which the N-uptake was not measured, and 3) the soil which is consisted of a shallow soil vulnerable to nitrate leaching on top of a highly conductive gravel layer. The objectives of this study were: 1) to assess the performance of state-of-the-art nitrate leaching models as they are used in the scientific research community, for the abovementioned conditions, 2) to inter-compare the models for analysing their predictive power, and 3) to identify strengths and weaknesses of bio-physically based models.

2. Materials and methods

2.1. Description of the lysimeter

Observations of a lysimeter located in the agricultural experimental field station in Wagna in Eastern Austria (46° 46.113′N, 15° 33.140′E; altitude 265 m) were used (Klammler and Fank, 2014-this issue). Since 1987 different cultivation strategies are investigated concerning nitrogen-fertilizer input, nitrate leaching and crop yields. In 2004, the cultivation changed into comparing low-input farming and organic farming, each covering 50% of the test site. Since then, two of the test plots have been equipped with two weighable, monolithic, high-precision lysimeters (2 m depth, 1 m^2 surface). The lysimeter in the conventional tillage test plot (KON-system) is subject for this study. Cultivation practices including crop species, sowing and harvest dates, and fertilizer applications in the test plot are presented in Table 1.

The lysimeters are equipped with soil water samplers, soil moisture probes, matrix sensors/tensiometer and soil temperature probes at four measuring depths (0.35, 0.6, 0.9, 1.8 m). An accompanied measuring profile for soil moisture, matrix potential and soil temperature is also installed outside the lysimeters (same depths as inside the lysimeter) to determine if the conditions inside the lysimeter are representative for the rest of the field. At the bottom of the lysimeter (depth 1.8 m) a suction cup rake was installed which kept the pressure head at this depth equal to that outside the lysimeter. The water sucked off was collected, weighted and sampled for the determination of the nitrate concentration. While quantity of seepage water was recorded automatically in 0.1 mm resolution by a tipping bucket, nitrogen concentration in the accumulated leachate was analysed in an approximately weekly interval. Furthermore, a weather station is installed at agricultural test site in Wagna for the recording of air temperature, relative humidity, shortwave solar radiation, wind speed, wind direction, precipitation, sunshine duration and atmospheric pressure at high temporal resolution (Klammler and Fank, 2014-this issue). Annual precipitation rates and cumulative probabilities of the rates relative to the values of the period 1961–2011 are presented in Table 2.

Annual rainfall amounts during the calibration years can be considered as moderate, the first year of the validation period is characterised by an extremely high rainfall and during the last year of the validation a low precipitation amount was recorded.

2.2. Description of models

This performance assessment study was conducted as part of the EU-FP7 GENESIS project (2009–2014) by six partners. Six well-known detailed models for European research on field-scale crop and soil water and soil nitrogen dynamics were chosen: **ARMOSA**, **CoupModel** (**COUP**), **DAISY**, **EPIC**, **SIMWASER–STOTRASIM** and **SWAP–ANIMO**. It goes beyond the scope of this paper to give full details on the process descriptions of the six models used. Brief descriptions will be given in the text and inter-comparison of processes and various other characteristics can be found in the Supplementary material. All models are one-dimensional.