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Research article

Simulating the environmental performance of post-harvest management measures to comply with the EU Nitrates Directive

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ABSTRACT

Nitrate (NO_3^-) leaching from farmland remains the predominant source of nitrogen (N) loads to European ground- and surface water. As soil mineral N content at harvest is often high and may increase by mineralisation from crop residues and soil organic matter, it is critical to understand which post-harvest management measures can be taken to restrict the average NO_3^- concentration in ground- and surface waters below the norm of 50 mg l^{-1}. Nitrate leaching was simulated with the EU-rotate_N model on a silty and a sandy soil following the five main arable crops cultivated in Flanders: cut grassland, silage maize, potatoes, sugar beets and winter wheat, in scenarios of optimum fertilisation with and without post-harvest measures. We compared the average NO_3^- concentration in the leaching water at a depth of 90 cm in these scenarios after dividing it by a factor of 2.1 to include natural attenuation processes occurring during transport towards ground- and surface water. For cut grassland, the average attenuated NO_3^- concentration remained below the norm on both soils. In order to comply with the Nitrates Directive, post-harvest measures seemed to be necessary on sandy soils for the four other crops and on silty soils for silage maize and for potatoes. Successful measures appeared to be the early sowing of winter crops after harvesting winter wheat, the undersowing of grass in silage maize and the removal of sugar beet leaves. Potatoes remained a problematic crop as N uptake by winter crops was insufficient to prevent excessive NO_3^- leaching. For each crop, maximum levels of soil mineral N content at harvest were proposed, both with and without additional measures, which could be used in future nutrient legislation. The approach taken here could be upscaled from the field level to the subcatchment level to see how different crops could be arranged within a subcatchment to permit the cultivation of problem crops without adversely affecting the water quality in such a subcatchment.

1. Introduction

In the European Union, agriculture is the predominant source of nitrogen (N) loads to ground- and surface waters (Anonymous, 2013). In Western Europe, nitrate (NO_3^-) leaching is most likely to occur during autumn and winter, and therefore soil mineral N (N_{min}) before the onset of winter can be used as a simple indicator of NO_3^- leaching risks (e.g. De Jong et al., 2009; Haberle et al., 2009). In the range from low to optimum fertilisation rates, most crops leave relatively low and constant residual soil mineral N at harvest (RSMN). Under optimum fertilisation practices, RSMN is considered to be the minimum soil N_{min} buffer necessary to guarantee optimal crop growth and yield. When N fertiliser rates are increased to rates above this optimum, RSMN steeply increases for most crops (Hofman et al., 1981; Neeteson and Whitmore, 1997) and this can lead to significant NO_3^- losses to ground- and surface waters.

In regions with a precipitation surplus during winter, the effect of post-harvest management options on NO_3^- leaching is an important research focus. Post-harvest management options may include sowing winter crops (catch or cash crops), applying N immobilising materials or removing crop residues. In temperate climates, winter crops take up mineral N from the soil after harvest of the main crop and reduce NO_3^- leaching, but the efficiency depends on the N uptake rate of the winter crop in autumn and is determined by the species, the sowing date and the weather conditions (Vos and van der Putten, 1997; Nett et al., 2011).

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Undersowing a catch crop in the main crop may lead to a better development of the catch crop when harvest of the main crop is late (Agneessens et al., 2014). Frost resistant crops might be more efficient than non-frost resistant crops as they do not release mineral N during winter. Ideally, the mineralisation rate of winter crops after incorporation coincides with the N demand of the following crop (Vos and van der Putten, 2001). Incorporation of materials with a high C:N ratio, a high lignin content and a high polyphenol content promotes immobilisation of N_{min} or reduces N mineralisation from crop residues (Chaves et al., 2007). However, the immobilising effect is only observed after a thorough mixing of the immobilising materials with the soil. Removal of N rich crop residues after harvest has a high potential to reduce NO_3^- leaching (Agneessens et al., 2014). Nevertheless, this option is often very difficult to implement in practice.

The measurement of N transformation and N loss processes in the field is difficult and only possible at point scale. Direct measurement of NO_3^- leaching can only be done in isolated soil columns such as with weighing lysimeters, whereas all other methods necessarily rely on calculating NO_3^- leaching rates from measured concentrations and modelled water fluxes. Therefore, NO_3^- leaching at field scale is commonly assessed with dynamic simulation models. Previous simulation studies considering NO_3^- leaching covered topics such as the effect of timing and the rate of fertilisation (e.g. Jégo et al., 2008; Rahn et al., 2010), the influences of the type of N fertilisation and soil amelioration products like compost (e.g. Gerke et al., 1999) and the effect of using catch crops (e.g. Singer et al., 2011; Sapkota et al., 2012). These models are also increasingly used to support decision-making at different scales, which can range from a field scale for farmers, a catchment scale for water suppliers, to a landscape or regional scale for strategic policy decision support (Kersebaum et al., 2007).

Given the crucial importance of defining management strategies that allow to abide to the Nitrates Directive in intensive farming, we have simulated the effect of a range of post-harvest management options following cut grassland, silage maize, potatoes, sugar beets and winter wheat, which are the main non-permanent crops in Belgium and Western Europe. Our aim was to evaluate which management practices have potential to reduce NO_3^- leaching to ground- and surface water to below 50 mg l^{-1} in scenarios of optimum fertilisation of the main crop, i.e. in scenarios of relatively low RSMN. We have simulated each scenario on a silt loam soil and a sandy soil to evaluate the effect of texture on the NO_3^- concentration, even though we acknowledge that not every crop is cultivated to the same extent on both soil types.

Our hypotheses were that i) without additional post-harvest measures, the norm of 50 mg NO_3^- l^{-1} in ground- and surface water will be exceeded for the four arable crops even under optimum N fertilisation rates, but not for cut grassland and that ii) efficient post-harvest measures can be implemented which will result in NO_3^- concentrations below 50 mg NO_3^- l^{-1} in ground- and surface water for these five crops.

2. Materials and methods

2.1. Description of EU-rotate_N model

The EU-rotate_N model used in this study (Version 1.8) was developed as a decision support tool to specifically assess effects of crop rotations and fertilisation practices on crop yields and N losses across Europe. A detailed description of the model is outside of the scope of this study, and can be found in Rahn et al. (2010). Here we introduce the main model features only briefly and provide detail on how essential inputs were obtained and used in the model.

The model has inherited considerable parts of other intensively tested models such as DAISY and N_Able. As a whole, the EU-rotate_N model was validated against a number of vegetable rotations in Germany and Norway (Rahn et al., 2010). Crop growth and N uptake patterns were adequately predicted for crop rotations in Italy (Nendel et al., 2013), except the prediction of soil N_{min} in some cases in autumn, which was attributed to a less accurate simulation of soil N mineralisation.

The model simulates crop growth and water and N dynamics using a daily time step. Nitrogen mineralisation is based on three pools (soil organic matter (SOM), soil microbial biomass, and added organic material), each consisting of a fast and slowly decomposable compartiment (Hansen et al., 1990). Water movement in the soil follows a capacity type approach and depends on the storage capacity of each layer and an empirical drainage rule, while two-dimensional capillary flow is accounted for by adopting a soil water normalised diffusion approach (Rose, 1968; Ritchie, 1998). Crop evapotranspiration is calculated using Penman-Monteith algorithms (Allen et al., 1998) and depends on the reference evapotranspiration and a crop coefficient varying with crop development. Daily NO_3^- migration in each soil layer is proportional to the amount of water that moves upward or downward.

Crop development and N uptake is a function of crop N demand (Greenwood et al., 1996; Greenwood, 2001) and potential N uptake by the roots (Pedersen et al., 2010). For cash crops, the user specifies a target yield, which together with temperature, soil moisture content and crop N content, determines the daily growth rate. For catch crops, the user determines a daily growth rate (good, medium or bad) which is controlled by temperature and crop N content and which cannot exceed a set maximum dry weight increment. On a daily basis, a percentage of the catch crop biomass is returned to the soil as litter and then mineralised. Root biomass is calculated as a fraction of aboveground crop biomass while root growth is simulated by a thermal time approach and distributed in a two-dimensional soil grid.

2.2. Model input variables

2.2.1. Locations

The simulations were carried out for five crops on the two most important soil textures (on an area basis) in Flanders, i.e. a silty soil (silt loam according to USDA classification system) in Rukkelingen-Loon (50° 43′ 36.76″ N, 5° 15′ 45.19″ E) and a sandy soil (loamy fine sand according to USDA classification system) in Bottelare (50° 58′ 5.29″ N, 3° 44′ 55.77″ E). These two representative fields were selected from an existing dataset which was used for calibration and validation of the EU-rotate_N model in a previous study (De Waele et al., 2014). Soil texture, SOM content, bulk density (BD) of 0–30, 30–60 and 60–90 cm layer and the pH of the 0–30 cm layer of these two fields were measured and used as input data in the model (Table 1). The soil water contents at saturation, at field capacity and at the permanent wilting point were determined for the 3 layers based on soil texture, SOM content and BD using an average output of 4 pedotransfer functions (Donatelli et al., 1996).

2.2.2. Meteorological data

Flanders has a temperate maritime climate with mild winters and cool summers. The precipitation is evenly distributed over the year but prolonged dry or wet spells are not uncommon. The mean precipitation surplus during the winter period is about 300 mm in Flanders (Batelaan and De Smedt, 2007). Simulations were carried out for 23 intercrop seasons (1992–2015) for which daily air temperature (minimum, mean and maximum) and precipitation were available from a weather station in Melle (KMI, 2015) (Fig. A.1), which is 109 and 4 km away from respectively the silty and the sandy soil site. Other parameters necessary to run the model