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Optimising crop production and nitrate leaching in China: Measured and simulated effects of straw incorporation and nitrogen fertilisation☆

Kiril Manevski[a,c,*], Christen D. Børgesen[a], Xiaoxin Li[b], Mathias N. Andersen[a,c], Xiying Zhang[b], Per Abrahamsen[d], Chunsheng Hu[b], Søren Hansen[b,d]

[a] Department of Agroecology, Aarhus University, Blichers Allé 20, 8830 Tjele, Denmark
[b] Institute of Genetics and Developmental Biology, Chinese Academy of Science, Huaizhong Lu 286, 050021 Shijiazhuang, China
[c] Sino-Danish Center for Education and Research, Zhongguancun College, 271 N 4th Ring Road, Haidian, 100080 Beijing, China
[d] Department of Plant and Environmental Sciences, University of Copenhagen, Thorvaldsensvej 40, Frederiksberg, 1871 Copenhagen, Denmark

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ABSTRACT

The sustainability of growing a maize—winter wheat double crop rotation in the North China Plain (NCP) has been questioned due to its high nitrogen (N) fertiliser use and low N use efficiency. This paper presents field data and evaluation and application of the soil–vegetation–atmosphere transfer model *Daisy* for estimating crop production and nitrate leaching from silty loam fields in the NCP. The main objectives were to: *i)* calibrate and validate *Daisy* for the NCP pedo-climate and field management conditions, and *ii)* use the calibrated model and the field data in a multi-response analyses to optimise the N fertiliser rate for maize and winter wheat under different field managements including straw incorporation.

The model sensitivity analysis indicated that a few measurable crop parameters impact the simulated yield, while most of the studied topsoil parameters affect the simulated nitrate leaching. The model evaluation was overall satisfactory, with root mean squared residuals (*RMSR*) for simulated aboveground biomass and nitrogen content at harvest, monthly evapotranspiration, annual drainage and nitrate leaching out of the root zone of, respectively, 0.9 Mg ha^{-1}, 20 kg N ha^{-1}, 30 mm, 10 mm and 10 kg N ha^{-1} for the calibration, and 1.2 Mg ha^{-1}, 26 kg N ha^{-1}, 38 mm, 14 mm and 17 kg N ha^{-1} for the validation. The values of mean absolute deviation, model efficiency and determination coefficient were also overall satisfactory, except for soil water dynamics, where the model was often found erratic. Re-validation run showed that the calibrated *Daisy* model was able to simulate long-term dynamics of crop grain yield and topsoil carbon content in a silty loam field in the NCP well, with respective *RMSR* of 1.7 and 1.6 Mg ha^{-1}. The analyses of the model and the field results showed that quadratic, Mitscherlich and linear-plateau statistical models may estimate different economic optimal N rates, underlining the importance of model choice for response analyses to avoid excess use of N fertiliser. The analyses further showed that an annual fertiliser rate of about 300 kg N ha^{-1} (100 for maize and 200 for wheat) for the double crop rotation with straw incorporation is the most optimal in balancing crop production and nitrate leaching under the studied conditions, given the soil replenishment with N from straw mineralisation, atmospheric deposition and residual fertiliser.

This work provides a sound reference for determining N fertiliser rates that are agro-environmentally optimal for similar and other cropping systems and regions in China and extends the application of the *Daisy* model to the analyses of complex agro-ecosystems and management practices under semi-arid climate.

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Abbreviations: NCP, North China Plain; C, Carbon; N, Nitrogen; C/N, Carbon to nitrogen ratio; SOM, Soil organic matter; ET, Evapotranspiration; DM, Dry matter; DS, Development stage of plant phenology; EONR, Economically optimum nitrogen rate; RMSR, Root mean squared residuals; SVAT, soil–vegetation–atmosphere transfer.

☆ Capsule: Agro-environmental analysis of maize—winter wheat double crop rotation in the North China Plain.

* Corresponding author at: Department of Agroecology, Aarhus University, Blichers Allé 20, 8830 Tjele, Denmark.
E-mail address: kiril.manevski@agro.au.dk (K. Manevski).

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1. Introduction

Food security in China has a high political priority as sufficient food production is needed for a growing population. Since 2004 the Chinese government has been subsidising farmers in order to intensify their crop production, leading to intensive use of fertilisers and pesticides (Sun et al., 2012). The North China Plain (NCP) is the most important region for agricultural production in China, supplying 40% and 60% of the national maize and winter wheat productions, respectively. Both crops are harvested within a year, with maize planted in June and harvested in October, and winter wheat planted few days after and harvested the following June. The continuous overuse of nitrogen (N) fertiliser in the maize—winter wheat double crop rotation, ranging typically between 400 and 600 kg N ha^{-1} and mostly supplied from urea, has resulted in large soil N surpluses and nitrate leaching out of the root zone (Ju et al., 2009) and has increased nitrate concentrations in the upper groundwater and in river and lake waters (Chen, 2010). This is not sustainable in relation to either current and future drinking water requirements or the ecology of the freshwater systems. As China must address the joint challenges of food production and environmental degradation expeditiously, effective methods are required that can balance the use of N fertiliser against the need for both high crop yield (food security) and low nitrate leaching (protection of freshwaters).

Field experiments are essential in quantifying effects of field management such as N fertiliser application or straw incorporation on crop production and nitrate leaching. Crop yield response to fertiliser rates is often described by statistical models in order to determine the fertiliser requirement of a crop in relation to soil type and its nutrient status, quality of the fertiliser and economic considerations (Fageria and Baligar, 2005; Ju and Christie, 2011; Valkama et al., 2013). The nitrate leaching response to fertiliser rates may also be described with statistical models, though this is often not enough to explain the variation in leaching or to link it with field management. Some studies report large increases in leaching already at low fertiliser rates (Simmelsgaard and Djurhuus, 1998), while others report that leaching starts to increase at or slightly below the economically optimal rate (Delin and Stenberg, 2014; Goulding, 2000). Individual and linked processes affect nitrate leaching, such as mineralisation of soil organic matter (SOM) and nitrification during seasons of limited crop growth with water surpluses leading to percolation that increases leaching, or denitrification due to water logging that decreases leaching. Moreover, optimisation of the fertiliser rate is intrinsically linked with the incorporation of crop residues and straw promoted in the last decades in the NCP, which has steadily increased the soil organic matter (SOM) content (Zhang et al., 2013). Increasing the SOM pool and its potential mineralisation affects the crop N supply. Process-based models of agro-ecosystem dynamics are useful to quantitatively assess the N cycle and better understand the links between N sources, losses and crop N demands in space and time.

Field-scale, process-based models differ primarily in their objective, i.e., some focus on simulating crop growth and yield with comparatively crude descriptions of soil processes, while others include details of the flows of water, heat, carbon (C) and N between the crop and the soil, as well as their interactions; fewer models integrate the soil–vegetation–atmosphere transfer (SVAT) component in their framework, allowing essential mechanisms of crop growth and responses to weather, soil and management to be captured. Several studies have quantified crop production and environmental impacts of the maize—winter wheat double crop rotation in response to N inputs in the NCP with process-based models (e.g., Cui et al., 2014; Hu et al., 2006; Michalczyk et al., 2014). Regardless of their level of complexity and assumptions, the models in these studies have been calibrated using field data from the NCP in order to decrease parameter uncertainty related to the pedo-climatic conditions of application (Palosuo et al., 2011). *Daisy* is a process-based SVAT model primarily designed and parameterised using soil measurements and cropping systems under the sub-humid temperate climate of Northern Europe (e.g., Doltra et al., 2011; Manevski et al., 2015; Salazar et al., 2013; Svendsen et al., 1995). While many other models simulate nitrate leaching rates in relation to soil water content above field capacity, *Daisy* treats leaching as process driven by the integrated effect of the redistribution of soil water and subsequent convection-dispersion of nitrate, which are especially important under semi-arid climates, such as in the NCP, where even small quantities of water below field capacity affect crop growth and soil nutrient status. As such, the model is an attractive tool for studying agro-environmental problems in China, particularly for balancing crop yield with nitrate leaching. However, *Daisy* has not been set up for other pedo-climatic environments such as for the semi-arid NCP and its agronomic practice of an annual double crop rotation.

The objectives of this study were to: *i*) collect field data of crop production and nitrate leaching from a maize—winter wheat double crop rotation grown on the typical silty loam soils in the NCP, *ii*) use the field data to set up the *Daisy* model for the Chinese pedo-climatic environment and cropping system and *iii*) utilise the field data and the calibrated model for a robust response analyses to determine an optimal field management in relation to straw incorporation and N fertiliser rate for the crops that will return high yields and low nitrate leaching.

2. Materials and methods

2.1. Field experiments

Fertilisation experiments with maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) grown in a double crop rotation were established in 1998 at the Luancheng Agro-Ecological Experimental Station (37°53′15″N, 114°40′47″E, elevation 50 m), Chinese Academy of Sciences, located in the Shijiazhuang Prefecture in the NCP. The climate is continental and semi-arid, with cold and dry winters and hot and rainy summers. The mean temperature ranges from −5 °C in January to 28 °C in July, and precipitation is around 500 mm $year^{-1}$, most of which (>70%) occurs in the summer (July to September). The potential evapotranspiration is around 1000 mm $year^{-1}$. The data used in the present study were obtained from two fields: field A during 2007–2013 and field B during 2000–2004. Although both fields have a silty loam soil (Haplic Cambisol according to the FAO classification, about 55% silt content across the 2.0 m soil profile), there are different clay contents of 17% and 4.6% in the topsoil, and 30% and 15% in the subsoil, for field A and field B, respectively. Table 1 summarises the field experiments and the data used in the study, and Table 2 describes the soil characteristics in the fields.

Field A had straw incorporated N response plots measuring 7 × 10 m in a complete block design with three replications. The plots were top-dressed with annual fertiliser rates of 0, 200, 400 and 600 kg N ha^{-1} from urea (46-0-0), hereinafter referred to as N0, N200, N400 and N600 treatments, respectively. Half of the fertiliser amount was applied on maize during flowering in August, while the other half was applied in a split dosage to winter wheat at planting in October and at stem elongation in April. Detailed crop measurements were conducted for one double cropping season, i.e., from June 2012 to June 2013. Crops were sampled from small sampling area at the center of each plot in three replications at juvenile, flowering and harvest. Leaf area index (LAI) was measured by LiCor3100 (Li-Cor Environmental, USA). Dry matter (DM) of leaf, stem and grain was determined after oven-drying; their total N content was determined by Kjeldahl System 2300 (Tecator, Sweden). In addi-

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