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Virtual nitrogen as a tool for assessment of nitrogen management at the field scale: A crop rotation approach

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ABSTRACT

The efficient management of nitrogen (N) requires accurate quantification of the critical components of the N balance. N budgeting was conducted on a production farm at Górzno, Poland during the 2004–2007 growing seasons for 17 crop sequences: ten oil-seed rape and winter wheat, six maize grown for grain or silage, and one onion monoculture. The measured N components were: i) soil N mineral content measured at 0.0–0.3, 0.3–0.6, and 0.6–0.9 m depths in the soil profile prior to spring growth and immediately after harvest, ii) applied N from fertilizer and farmyard manure, and iii) N content in the harvested crop products and crop residues. Two budgeting procedures, soil surface balance (SSuB), and soil system balance (SSyB), were used to evaluate the impact of cropping sequences on N management. The total N input ranged from 223 to 313 kg N ha^{-1}, primarily derived (40–50%) from the soil mineral N (N_{min}). The N output depended on the N content in the harvestable crop component (R^2 = 0.93).

The average unit productivity of external N in the soil-crop system was calculated to be 35.4 kg cereal units (CU) kg^{-1} N. The critical level, defined as that level at which N resources were fully utilized by the crop, were 51.7 kg CUs kg^{-1} N. Concomitantly, the average productivity of the total pool of plant available N was 19.9 kg CUs kg^{-1} N, with a critical level of 29.8 kg CUs kg^{-1} N. The difference between the average and critical values, a measure of N inefficiency in the soil-crop system, was used to quantify the un-workable pool of N herein defined as virtual N (N_V). Cropping sequences with oilseed rape and winter wheat were less efficient in utilizing externally applied N compared to maize, which greatly increased the amount of N in the harvested product. The efficiency of N present in the soil-crop system can be improved by implementing two key strategies. The first strategy reduces N fertilizer input based on the total N content in the soil-crop system at the beginning of the growing season. The second strategy targets increasing the content of N in the primary yield component, which depends on N uptake and utilization efficiency from soil pools.

The concept of virtual N, based on quantification of the un-worked N_{min} pool, is a basis for sound management of N in a particular cropping sequence. The accuracy of N_V determination based on SSyB characteristics was much more reliable than the SSuB procedure. The results offer holistic tools to develop N fertilizer management practices that reduce the application of excess N, in turn improving both N use efficiency and economic return to farmers while reducing the impact of the production system.

1. Introduction

In intensive agriculture systems, N recovery, or the percentage of N taken up by the crop within one season from the applied fertilizer, is relatively low, ranging from 30 to 50% on production farms (Cassman et al., 2002; Roberts, 2008). As a result, the majority of the applied fertilizer N is not taken up by crop plants and transferred to the harvested components. Moreover, this poor efficiency of fertilizer use

Abbreviations: CUs, cereal units; Cropping systems, ON, onion; OSR, oil seed rape; SMA, silage/grain maize; SB, spring barley; WW, winter wheat; WR, winter rye; N_{os}, N in external sources (precipitation, seeds, farmyard manure); N_{fym}, N in farmyard manure; N_f, N fertilizer applied; N_I, N input to the system from external sources (N_f, N_{os}); N_{min}, soil mineral N; $N_{min\text{-}a}$, residual soil mineral N after harvest; $N_{min\text{-}s}$, soil mineral N at the start of the season in the spring; N_O, N output from the system; N_{res}, N content in crop byproduct and crop residues; N_{rel}, N released from soil resources during the growing season; N_{TI}, total N input; N_{TO}, total N output; N_Y, N output in the main yield; NNB, net N balance; NNE, net N efficiency; NTNB, net total N balance; GTNB, gross total N balance, Nrel = − GNTB; $N_{V\text{-}NI}$, virtual N based on external N input, N_I; $N_{V\text{-}NTI}$, virtual N based on total N input, N_{TI}; UNP, unit N productivity; UNP_{NI}, unit N productivity of external N, N_I; UNP_{NTI}, unit N productivity of total N input, N_{TI}; $Y_{M\text{-}NI}$, maximum attainable yield based on external N input, N_I; $Y_{M\text{-}NTI}$, maximum attainable yield based on total N input, N_{TI}; Y_R, real yield; YG_{NI}, yield gap based on external N input, N_I; YG_{NTI}, yield gap based on total N input, N_{TI}; N_V, virtual nitrogen

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creates a potential threat to the environment, both at the local and global levels (Beaudin et al., 2005; Erisman et al., 2007; Tomer and Liebman, 2014). The key challenge for farm managers and environmentalists is to develop a management strategy oriented towards decreasing the inefficient application of N. However, improving N use efficiency (NUE) cannot be achieved by decreasing the amount of applied N, as this strategy commonly leads to a decline in yield (Dibb, 2000). The holistic approach to improving NUE should primarily be oriented towards synchronizing the N supply with the N requirements of the currently grown crop during its critical yield formation stages. This knowledge is needed to establish the right rate and form of applied N fertilizer (Roberts, 2008; Stark and Richards, 2008; Grzebisz and Diatta, 2012).

Increasing the diversity of crops and crop rotations is one approach to overcome the negative aspects of short cropping sequences and monocultures, currently the predominant practices in intensive cropping systems (Bennett et al., 2011). To some extent, the production efficiency of the cropping sequence relies on the internal cycling of nutrients within the system, including N. Therefore, the system of crops chosen and their rotation is the key for addressing both the production and environmental components of soil functions (Poudel et al., 2001; Struik and Bonciarelli, 1997; Wrzaszcz and Prandecki, 2015).

Modern, high-input agriculture relies on applied fertilizer N (N_f) for optimal productive output. In spite of restrictive administrative regulations, N use efficiency is not satisfactory for the environmental contamination that results (Dalton and Brand-Hardy, 2003; Eickhout et al., 2006). Therefore, sound management of N_f requires reliable diagnostic tools that are available to both scientists and farmers. The reliability of the frequently used N mass balance procedures such as the Farm Gate Balance (FGB) and the Soil Surface Balance (SSuB) for N leaching prediction is questionable (Beek et al., 2003; Sassenrath et al., 2013; Haene et al.,2014). As pointed out recently by Blesh and Drinkwater (2013), the sustainable management of N in the soil-crop system requires data on the flow and fate of N at the field level. It is our contention that the “field” should be considered a single agro-ecosystem unit, similar to the basic hydrographic unit of a river catchment. The N_{min} resources, monitored at the beginning and end of the growing season of a particular crop, can be used in the SSuB budgeting procedure. This assumption should be the core of the Soil System Balance (SSyB), which is still a more theoretical than a practical approach (Cherry et al., 2008).

The objective of our research was to use N balance calculations based on two approaches: i) the soil surface balance, and ii) the soil system balance, to determine the amount of virtual N, which is the N not actually, but potentially used by plants during the growing season. We hypothesize that the N_V is the primary factor determining the yield gap between the actual harvested yield and the threshold maximum attainable yield in a given cropping sequence. The secondary objective was to identify N budget parameters useful in the effective management of the yield gap.

2. Materials and methods

2.1. Study site

This study was performed on a production farm located in central-western Poland (51.74 N, 17.83 E) during the 2004–2007 growing seasons. The farm has 400 ha of agricultural land, primarily arable soils originating from sand or loamy sand. Each field is considered a separate experimental unit; field sizes are listed in Table 1. The fields were managed with production scale equipment using standard crop production practices for the region. The cropping system is composed of two or four crops in rotation. The three predominant crops are winter oilseed rape (OSR), maize for grain (SMA) or silage (SMA^S), and winter wheat (WW). The acronyms of the cropping sequences presented in Table 1 indicate the frequency of oilseed rape or maize in a particular cropping sequence. Winter crops, like oilseed rape and winter wheat, are sown in the third decade of August or September of the preceding year, respectively. Maize is sown in the 3rd decade of April. Oilseed rape is harvested in the second or third decade of July, winter wheat and other cereals in the first decade of August, and maize in the first decade of October. All harvested products, including silage maize, are sold. Straw of cereals and OSR removed from the fields are replaced with farmyard manure, which is applied primarily to maize.

Phosphorus and potassium are commonly applied prior to sowing at rates based on soil test ratings. As reported in Table 1, phosphorus fertilizer was not applied to 11 of the 17 crop fields in 2005. N fertilizers were applied at different rates, depending on the crop. Fungicide and insecticide applications were made according to standard agricultural practices for each particular crop as needed. Yield of cereals and oilseed rape was measured with a combine harvester and maize by silage harvester; yields are reported for each field from machine harvest data and expressed in t ha^{-1}. To facilitate comparison, yields of all crops were converted into Cereal Units (CUs). CUs have been proposed as an allocation method for use in life cycle assessments of agricultural production systems to provide a common basis for comparison of yields across different crops and cropping systems (Brankatschk and Finkbeiner, 2014). CUs are calculated using the aggregated metabolizable energy of barley as a reference (1 kg barley = 12.56 MJ; Brankatschk and Finkbeiner, 2014). For this study, the indices used are: cereal grain = 1.0; maize grain = 1.0; OSR seed = 2.0; silage maize = 0.13; and onion = 0.25 (Harasim, 2006).

2.2. Meteorological conditions

The experimental site is located in the area of Europe dominated by a continental temperate climate (Jongman et al., 2006), where a high year-to-year variability of weather indices is typical. Climatic conditions during the study period and long-term averages are summarized in Table 2. The 50-year average annual precipitation is 578 mm and the mean air temperature is 8.6 °C. The most deleterious condition for yield performance is the frequent shortage of precipitation with a concomitant increase in temperature. These conditions are unfavorable for plant growth and yield when they occur in April for oilseed rape, in May to June for winter wheat, and in July for maize (Grzebisz, 2011, 2012). The most extensive drought, which impacted OSR, occurred in April of the 2006/2007 season, with total rainfall of only 16% of the 50-year average. For wheat, the worst growing conditions were experienced in June of the 2004/2005 and 2005/2006 seasons (Table 2).

2.3. Soil, plant sampling and analysis

During the study, composite soil samples were collected from each field twice a year: at the beginning of each spring season for winter crops and prior to planting the spring crops (acronym: spring); and after harvest of cereals and oilseed rape in July/August or at the beginning of October (acronym: autumn). Soil was sampled in triplicate from each field in a 4 ha grid, with the total number of samples collected from each field adjusted for field size (Stępień et al., 2013). Soil samples were taken at three depths: 0.0–0.3 m, 0.31–0.6 m, and 0.61–0.9 m. The total number of soil samples (observations) for OSR cropping sequences equaled 918 (459 for each sampling date), and for SMA and onion cropping sequences were 864 (432). The mineral forms of N (NH_4^+ and NO_3^-) were determined in “fresh” soil samples. Twenty grams of soil were shaken for 1 h with 100 cm^3 of 0.01 M $CaCl_2$ solution (soil/solution ratio 5:1; m/v; Houba et al., 1986). Concentrations of NH_4^+ and NO_3^- were determined by the colorimetric method using flow injection analyses (FIAstar5000, FOSS) after filtering through Munktell 3 h filter paper. The method of analysis for NO_3^- concentration consists of two basic steps: reduction from nitrate to nitrite using a cadmium column and then colorimetric determination of nitrite, based on the Griess-Ilosvay reaction with N-(1-Naphtyl)ethylene-diamine dichloride as a