ARTICLE IN PRESS

Field Crops Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Residual N effect of long-term applications of cattle slurry using winter wheat as test crop

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A R T I C L E I N F O

Keywords:
N response
Animal manure
Mineral fertilizer
NUE
Askov-LTE

A B S T R A C T

Prediction of optimum fertilizer N requirements depends on reliable estimates of the residual value of N accumulated in soil from historical inputs of mineral fertilizers and animal manures. Using plots embedded in the Askov long-term experiments and treated since 1973 with different rates of N in cattle slurry (50, 100 and 150 kg total-N ha^{-1} termed ½, 1 and 1½ SLU), we estimated the residual N value over two consecutive growth periods (2014/2015 and 2015/2016). We used winter wheat as test crop and soils with a history of mineral fertilizers only (1 PK (no N)) and 1 NPK (100 kg N ha^{-1}) as reference treatments. In the test years, the customary nutrient treatments were withheld and each plot divided into six subplots randomly allocated increasing rates of mineral fertilizer N (0–250 kg N ha^{-1}). The winter wheat yielded more in the first test year due to crop rotational effects and more benign climatic conditions, substantiating that more test years are needed when estimating residual N effects. The residual value of N added previously with NPK was negligible. In the first year, grain yields at N optimum were similar for NPK and SLU, but the amount of fertilizer N needed to reach optimum yield was 36 kg N ha^{-1} smaller for SLU than for NPK. In the second year, wheat grown on 1 NPK and 1 SLU soils showed similar yield optimum and N optimum. The same N optimum was found for 1½ SLU, but this treatment provided a higher grain yield. For unfertilized wheat, grain yields differed little between previous treatments (except for ½ SLU in the second test year). The average N-offtake in grain and straw did not differ between 1 PK and 1 NPK whereas wheat previously supported by 1 SLU removed 6.7 kg N ha^{-1} more. For unfertilized wheat, N offtakes in the first wheat crop were similar for PK and NPK; wheat grown on previous SLU plots removed more N. In the second test year differences were not significant. Excluding ½ SLU, the N use efficiency ranged from 0.60 to 0.74 kg N kg^{-1} N with little difference between previous treatments and years. Interactions between added N and historical N inputs illustrate that residual N effects are of little predictive value for productive cropping systems when based solely on unfertilized test crops.

1. Introduction

Mineralisation of organic nitrogen (N) accumulated in soil from previous inputs of mineral fertilizers, crop residues, and animal manure plays an important role in crop N supply, even for crops receiving generous rates of N in mineral fertilizers. However, the residual effect of N from individual additions is most often small and difficult to quantify under field conditions unless studies involve ^{15}N-labelled materials. Field experiments show that crop recovery of ^{15}N-labelled mineral fertilizer added to cereals shortly before the growth period averages 50% (Pilbeam, 1996; Ladha et al., 2005) while recoveries of ^{15}N added with crop residues or animal manure are smaller and more variable (Christensen, 2004). In the second and third year after addition, uptakes of residual ^{15}N are < 5% and < 2%, respectively, of that originally added and appear unrelated to the source by which the ^{15}N was added (Christensen, 2004; Jensen et al., 1999; Macdonald et al., 2002; Webb et al., 2013). In temperate maritime climates as in NW Europe, part of the added N not recovered by the crop can be subject to leaching and gaseous losses during the subsequent autumn/winter periods, but most of the residual N is retained in the soil organic N pool.

Within the European Union, the use of N in crop production is regulated in order to reduce the environmental load from agricultural activity. The regulatory framework adopted in Denmark is tight and includes restrictions on use of N fertilizer (application times and maximum rates for individual crops) and prescribed use efficiencies for N applied with animal manure (Dalgaard et al., 2014). These depend on

Abbreviations: AM, animal manure; DM, dry matter; LTE, long-term experiment; NPK, mineral fertilizer with N, P and K; NUE, N use efficiency; N_{new}, N added to the test crop; N_{prev}, previous N application; PK, mineral fertilizer with P and K; SLU, cattle slurry

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http://dx.doi.org/10.1016/j.fcr.2017.10.013
Received 16 June 2017; Received in revised form 2 October 2017; Accepted 13 October 2017
0378-4290/

Please cite this article as: Suarez-Tapia, A., Field Crops Research (2017), http://dx.doi.org/10.1016/j.fcr.2017.10.013

animal category and the type of manure (solid or slurry) and imply that ammoniacal N in animal manure is as efficient as N applied with mineral fertilizers. Ammoniacal N in animal manures may account for 20–70% of the total N content (Webb et al., 2013). Replacing mineral N fertilizers with animal manures therefore leads to a larger total N input to the soil. The surplus manure N is in organic form at the time of application, but will later be exposed to mineralization giving rise to a larger residual effect than that created by use of mineral N fertilizers. This has to be accounted for when predicting needs for N fertilization.

Several biological and chemical laboratory tests have been developed for predicting soil N mineralisation potential during a growing season (Ros et al., 2011; Schomberg et al., 2009). Although these tests provide some guidance, their predictive power is generally limited when assessed against N uptake in field grown crops. Alternatively, residual N values can be determined in field experiments where known N inputs have been maintained for long periods by measuring the N uptake in a test crop grown on plots where the usual N application is withheld (Grant et al., 2016; Petersen et al., 2010; Riley, 2016; Sieling et al., 2014; Thomsen et al., 2003). However, leaving the test crop unfertilized may restrict its development. A test plant with poor root development may not be able to fully recover the N mineralized from the soil organic N pool, providing inferior estimates of the real residual N effect. Further, the use of unfertilized test crops ignores potential interactions between residual N effects derived from previous N applications and the effects of N added directly to the test crop.

An alternative approach is to establish the yield response of a test crop exposed to incremental rates of fertilizer N (Petersen et al., 2012). By establishing the N response of test crops grown on plots with different fertilization histories, the residual effect of past N applications can be estimated with greater confidence and with greater relevance to productive cereal cropping systems. This approach was tested in the present study using the Askov Long-Term Experiments on Animal Manure and Mineral Fertilizers (Askov-LTE) as research platform. The residual N effect of manure was determined over two consecutive growth periods employing plots that have had different rates of cattle slurry since 1973. The test crop was winter wheat and soils with a history of mineral fertilizer only (PK and NPK) served as reference treatments. In the two test years, the previous treatments were all withheld and each plot was divided into six subplots randomly allocated increasing rates of mineral N fertilizer. The residual effect of past N applications was then estimated by comparing the N response curve of test crops grown on plots with different fertilization histories.

2. Materials and methods

2.1. Site characteristics and experimental layout of the Askov-LTE

The Askov-LTE was initiated in 1894 and is located on the Lermarken site at Askov Experimental Station, South Jutland (55° 28′ N, 09° 07′ E). The soil is a light sandy loam with 10% clay (< 2 μm), 12% silt (2–20 μm), 43% fine sand (20–200 μm) and 35% coarse sand (200–2000 μm), and classifies as Ultic Hapludalf (USDA Soil Taxonomy) and Aric Haplic Luvisol (WRB classification). Magnesium-enriched lime is added every four years to maintain soil pH in the range 5.5–6.5, and sulfur is added annually at a rate of 12.5 kg S ha^{-1}. The annual mean temperature, precipitation, and evapotranspiration are 7.7 °C, 862 mm, and 543 mm respectively (averaged over the period 1961–1990). Precipitation and mean temperature for the test periods August 2014–July 2015 and August 2015–July 2016 were higher (1060 and 1078 mm, and 8.9 and 9.3 °C, respectively; Fig. 1).

The Askov-LTE includes four separate fields (termed B2, B3, B4 and B5) and is grown with a four course rotation of winter wheat (*Triticum aestivum* L.), silage maize (*Zea mays* L.), spring barley (*Hordeum vulgare* L.) undersown with a grass-clover mixture, and grass-clover that is cut twice in the production year. The B2-field is divided into a west (B2w) and an east (B2e) section. The four crops are rotated across the four fields in a fixed sequence whereby all treatments in a given field grows the same crop a given year. Aboveground biomasses are removed from all plots at harvest. Chemical crop protection measures are applied when needed.

The main nutrient treatments are plots dressed with different rates (0, ½, 1 and 1½ times the standard rate for a given crop; grass-clover remains without nutrient additions) of total-N, P and K in animal manure (AM) or mineral fertilizers (NPK). Also included are plots receiving only P and K in mineral fertilizers (1 PK). From 1894 to 1972, AM was farmyard manure supplemented with liquid manure (urine). Since 1973, AM has been cattle slurry (SLU) with approximately 5% dry matter (DM) and 60–70% of its total-N content in ammoniacal N. Averaged across the rotation, 1 SLU and 1 NPK represent an annual input of 100 kg N, 20 kg P and 80 kg K ha^{-1}. The treatment 1 SLU corresponds to 25 t slurry ha^{-1} (w/w). Further details are given by Christensen et al. (2006).

2.2. Experiment testing the residual N value of slurry

This study was embedded in the B2-field using four replicate plots of the treatments ½ SLU, 1 SLU and 1½ SLU in the B2w section. The residual N value of cattle slurry was determined over two consecutive growing periods (2014/15 and 2015/16) using winter wheat (cv. Hereford) as test crop and plots with a history of mineral fertilizer (1 PK and 1 NPK) as reference treatments. Table 1 shows the N inputs in the customary nutrient treatments and selected soil chemical characteristics. Following harvest of the preceding crop of spring barley (29 July 2014), the grass-clover undersown in the barley was terminated by glyphosate and the field was then ploughed one week later. The first test crop of winter wheat was sown on 17 September 2014 while the second test crop was sown on 30 September 2015. In the two test years, the previous (customary) nutrient treatments (termed N_{prev}) were withheld. Within each N_{prev} plot, six subplots (each 5.7 m^{-2}) were randomly allocated rates of N in calcium-ammonium-nitrate corresponding to 0, 50, 100, 150, 200 or 250 kg N ha^{-1} (termed N_{new}). Following application of N_{new} in the spring, the central part of the subplot (1.30 m^{-2} in 2015; 1.15 m^{-2} in 2016) was marked up and used for harvest yield determination (Fig. 2). The wheat was harvested by hand at physiological maturity (leaving 4 cm of stubble) and divided into grain and straw. Table 2 show dates for main field operations.

Grain and straw fractions were dried at 80 °C in a ventilated oven for 18 h. Grain yields are based on 85% DM; straw yields are reported as 100% DM. The N concentration in grain and straw was determined on dry subsamples (milled to < 0.5 mm) using a Flash 2000 Organic Elemental Analyser (Thermo Fisher Scientific, USA).

2.3. Calculations and statistical analyses

The experimental design was a split-plot with 5 levels of N_{prev}, 6 levels of N_{new}, and 4 replicates. Grain yields of cereals exposed to increasing N rates usually follows a curvilinear trend and the agronomic optimum rate of N_{new} was calculated using the quadratic model: $Y = ax^2 + bx + c$, where Y is grain yield, x is added N_{new}: the quadratic (a) and linear coefficients (b), and the intercept (c) are constants obtained by fitting the model to yield data. The agronomic optimum (maximum yield per kg N_{new} applied) was found by equating the first derivative of the production function to zero and estimating the N rate that maximizes yield.

The N uptake in cereals subject to increasing rates of N application usually follows a linear trend and calculation of the N use efficiency (NUE) of N_{new} was based on the regression equation: $Y_N = a_N + b_N (x)$ where Y_N is the N uptake, x is added N_{new}, and a_N and b_N are calculated by model fitting. The coefficient a_N represents N uptake with no N addition, and b_N is the NUE of added N.

The variables reported in this study (Y) are: Grain yield, straw yield, and total N offtake (grain + straw N). The linear model applied for