Soil Biology & Biochemistry 43 (2011) 1362–1371

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

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

Effects of repeated fertilizer and cattle slurry applications over 38 years on N dynamics in a temperate grassland soil

Christoph Müller [a,b,*], Ronald J. Laughlin [c], Peter Christie [c], Catherine J. Watson [c]

[a] School of Biology and Environmental Science, University College Dublin, Belfield, Dublin 4, Ireland
[b] Department of Plant Ecology, Justus-Liebig-University Giessen, Heinrich-Buff-Ring 26, 35392 Giessen, Germany
[c] Agriculture, Food and Environmental Science Division, Agri-Food and Biosciences Institute, Newforge Lane, Belfast BT9 5PX, Ireland

A R T I C L E I N F O

Article history:
Received 3 February 2011
Received in revised form
25 February 2011
Accepted 11 March 2011
Available online 7 April 2011

Keywords:
Cattle slurry
^{15}N tracing
Gross N transformation
Temperate grassland

A B S T R A C T

The effects of repeated synthetic fertilizer or cattle slurry applications at annual rates of 50, 100 or 200 $m^3\ ha^{-1}\ yr^{-1}$ over a 38 year period were investigated with respect to herbage yield, N uptake and gross soil N dynamics at a permanent grassland site. While synthetic fertilizer had a sustained and constant effect on herbage yield and N uptake, increasing cattle slurry application rates increased the herbage yield and N uptake linearly over the entire observation period. Cattle slurry applications, two and four times the recommended rate (50 $m^3\ ha^{-1}\ yr^{-1}$, 170 kg N ha^{-1}), increased N uptake by 46 and 78%, respectively after 38 years. To explain the long-term effect, a ^{15}N tracing study was carried out to identify the potential change in N dynamics under the various treatments. The analysis model evaluated process-specific rates, such as mineralization, from two organic-N pools, as well as nitrification from NH_4^+ and organic-N oxidation. Total mineralization was similar in all treatments. However, while in an unfertilized control treatment more than 90% of NH_4^+ production was related to mineralization of recalcitrant organic-N, a shift occurred toward a predominance of mineralization from labile organic-N in the cattle slurry treatments and this proportion increased with the increase in slurry application rate. Furthermore, the oxidation of recalcitrant organic-N shifted from a predominant NH_4^+ production in the control treatment, toward a predominant NO_3^- production (heterotrophic nitrification) in the cattle slurry treatments. The concomitant increase in heterotrophic nitrification and NH_4^+ oxidation with increasing cattle slurry application rate was mainly responsible for the increase in net NO_3^- production rate. Thus the increase in N uptake and herbage yield on the cattle slurry treatments could be related to NO_3^- rather than NH_4^+ production. The ^{15}N tracing study was successful in revealing process-specific changes in the N cycle in relationship to long-term repeated amendments.

1. Introduction

Repeated application of cattle slurry to grassland is a common farming practice in many areas of the world. Grasslands cover approximately 40% of the Earth's landmass (White et al., 2000). In Europe, approximately half of the agricultural area is grassland and slurry is regularly applied to a large proportion of it. Application of mineral N and/or organic-N in the form of manure has a positive effect on plant growth and N uptake (Shimizu et al., 2009). Organic-N has the advantage that it will increase the residual organic-N, thereby increasing the long-term fertilizer N value (Reijs et al., 2005).

Organic manures contain both a range of easily degradable organic C and N and mineral N compounds (Beauchamp et al., 1989). Studies have shown that repeated long-term applications of organic manures will enhance soil organic C and N contents, particularly the more labile soil organic matter, as well as soil microbial biomass and enzyme activity (Hao et al., 2003; Kirchmann et al., 2004; Mallory and Griffin, 2007; Zaman et al., 2004). At low rates of organic amendments it has been reported that the bacterial (and not the fungal) biomass is stimulated (Bittman et al., 2005; Marschner et al., 2003). The concentrations of soil organic C and N are often linearly related to the amount of manure applied, thus both the number of repeated amendments and the rate of application can affect the potentially available N in soil after slurry applications (Hao et al., 2003; Mallory and Griffin, 2007; Zaman et al., 2004). Furthermore, repeated slurry applications will have a long-term effect on soil characteristics such as the pore size distribution, water status or pH, which can indirectly

* Corresponding author. Department of Plant Ecology, Justus-Liebig-University Giessen, Heinrich-Buff-Ring 26, 35392 Giessen, Germany. Tel.: +49 0641 9935301; fax: +49 0641 9935309.
E-mail address: Christoph.Mueller@bot2.bio.uni-giessen.de (C. Müller).

0038-0717/$ – see front matter
doi:10.1016/j.soilbio.2011.03.014

influence soil C and N dynamics (Curtin and Wen, 1999; Thomsen et al., 1999). Since changes in organic C and N occur slowly (e.g. results from the Rothamsted Broadbalk study show that it may take a 100 years to reach a new equilibrium) (Kirchmann et al., 2004), observations from long-term amendment studies are extremely valuable.

Readily available C and N in organic manure increase the microbial biomass and its subsequent activity which in turn affects the mineralization rates (net release of NH_4^+ and NO_3^-) (Mallory and Griffin, 2007). A typical observation made after repeated long-term applications is that net NO_3^- production (net nitrification) is stimulated but not net NH_4^+ production (net ammonification) (Habteselassie et al., 2006). This leads to enhanced NO_3^- concentrations in the soil which can enhance NO_3^- leaching, potential denitrification activity and gaseous N emissions (Dambreville et al., 2006; Hao et al., 2003; Rochette et al., 2000; Zaman et al., 2004). One laboratory study showed that the rate of gross NO_3^- production after slurry application in a temperate grassland soil was enhanced more than 20-fold, possibly as a result of heterotrophic activity being stimulated (Müller et al., 2003). Another study showed that the availability of recently added N to soil was strongly affected by the N amendment history and whether organic or mineral N fertilizer had been applied (Mallory and Griffin, 2007). Organic manures tend to increase the more labile soil organic matter (SOM) which is characterized by an enhanced decomposability (Kirchmann et al., 2004; Sleutel et al., 2006). Thus, SOM mineralization is related to at least two conceptual SOM pools, decomposition of a passive/slow SOM pool and an active/labile SOM pool. Mallory and Griffin (2007) showed that such an approach was successful when predicting SOM mineralization (NO_3^- production) in soil after slurry application. They also showed that historic amendments reduced the availability of recently applied N, due to immobilization of N into the active SOM pool. High N immobilization is likely related to an increase in microbial biomass and may also explain the reduced leaching observed after slurry amendment in another grassland study (Bittman et al., 2005). Thus, there is evidence to suggest that N transformations after slurry application are affected by N amendment history.

Mallory and Griffin (2007) concluded that net rates are difficult to interpret because of the various production and consumption processes that occur simultaneously. While net N transformation studies will show how the availability of mineral N (NH_4^+ and NO_3^-) is affected, these studies fail to provide a mechanistic explanation of how the N amendment history affects specific N transformation pathways in soil. For instance, amendment with organic-N may enhance the gross NH_4^+ production in soil, but at the same time increasing organic C may also stimulate N immobilization into microbial biomass. Thus net NH_4^+ production rates may remain unaffected while the overall turnover of NH_4^+ may increase, leading to a more active and dynamic system.

We evaluated the dry-matter production and N uptake pattern from various field plots at a grassland site in Northern Ireland over the last 38 years. To explain changing biomass production and N uptake rates over this period, in particular under slurry application, it was hypothesized that slurry must have had an effect on the internal nitrogen Mineralization-Immobilization-Turnover (MIT) in the soil. Thus, a ^{15}N tracing study was carried out to identify potential impacts of antecedent slurry application on gross soil N transformations in the different treatments to help explain the observed long-term N uptake trends. To obtain a process-based understanding of the N dynamics under repeated slurry amendments, it is important to evaluate the individual gross N transformation rates (Mallory and Griffin, 2007). Therefore, in this study we used a ^{15}N tracing technique with a grassland soil to which one rate of synthetic fertilizer or slurry at three different rates had been applied each year since 1970 (Christie, 1987). The ^{15}N tracing model considered pool size specific N transformation rates. Furthermore, in line with previous studies we used a model that considered two soil organic matter pools, an active (labile) and a slow (recalcitrant) soil organic matter pool (Mallory and Griffin, 2007; Thomsen and Olesen, 2000). The division into two conceptual SOM pools is supported by studies showing that the soil C:N ratio in long-term studies shifts toward labile SOM and higher enzyme activity with slurry applications (Kirchmann et al., 2004). Thus, the main aim of the current study was to show how repeated long-term applications of synthetic fertilizer and various rates of slurry applications influence the internal N dynamics, and in particular the individual gross N transformation rates, in a grassland soil. The potential N release (particularly in the form of NO_3^-) under various long-term slurry application rates has implications for N fertilizer recommendations and fertilizer and slurry management strategies.

2. Materials and methods

2.1. Site description and experimental setup

The field experiment from which the soil samples were taken was described in detail by Christie (1987). Briefly, the soil (a clay loam with 42% sand, 24% silt and 34% clay) has developed on glacial till overlying Silurian shales and greywackes, has an organic matter content of 4.25%, and its hydrogeological class number within HOST (Hydrology of Soil Types) is 18 *sensu* Boorman et al. (1995). The site is considered typical of a substantial area of grassland in Northern Ireland. Forty-eight rectangular plots, each 29.75 m^2 in area, were established in 1970 on a re-seeded perennial ryegrass sward at Hillsborough, Co. Down (O.S. Grid Reference J 244577) at an elevation of about 120 m above sea level. There are eight treatments: (1) unamended control (received fertilizer as in (2) for 3 years (1970–1972) and then no further nutrient applications); (2) fertilizer control receiving 200 kg N (as ammonium nitrate until June 1974 and subsequently as urea), 32 kg P and 160 kg K $ha^{-1}\,yr^{-1}$ to maintain a balance of NPK inputs and outputs; (3)–(5) cow slurry applied at 50, 100 or 200 $m^3\,ha^{-1}\,yr^{-1}$; (6)–(8) pig slurry applied at the same three rates. There were six replicates giving a total of 48 plots in a randomized block design with two replicates of each treatment fully randomized within each of three blocks. The sward was cut three times each year at the silage stage, approximately at the end of May, July and September. The fertilizer and slurries were applied by hand and by watering can respectively in three equal dressings, first in spring after annual soil sampling and again immediately after the first two herbage cuts.

2.2. Determination of herbage dry-matter and % N in herbage

Herbage was dried at 60 °C and subsequently ground with a ball mill (Retsch, Germany). Total N in the herbage was determined by Kjeldahl digestion in the years from 1970 to 1988 and thereafter by using a Carlo Erba NA1500 elemental analyzer (Carlo Erba, Milan, Italy).

2.3. Experimental treatments used in laboratory study

For determination of gross N dynamics (see Section 2.4), soil samples were collected from treatments (1)–(5) in February 2007 to compare three application rates of cow slurry with both types of control. The treatments are referred to as control (CT), fertilizer control (CF), slurry-low, 50 $m^3\,ha^{-1}\,yr^{-1}$ (SL), slurry-medium, 100 $m^3\,ha^{-1}\,yr^{-1}$ (SM) and slurry-high, 200 $m^3\,ha^{-1}\,yr^{-1}$ (SH). Ten soil cores were randomly taken per plot to a depth of 10 cm, sieved (<6 mm) and stored at 4 °C for one week before use. Within each