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Modelling nitrogen leaching from sewage sludge application to arable land in the Lombardy region (northern Italy)

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HIGHLIGHTS

- We model N leaching (22 to 154kgha−1) from sludge application on maize and rice.
- We test 4 sludge types, 6 application times at 5 locations in Lombardy (Italy).
- Sludge distribution in fall involves higher losses compared to winter application.
- No differences in N leaching resulted at different times within fall and winter.
- If good practices are adopted sludge can be spread when application is banned.

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ABSTRACT

Sewage sludge can be used as fertiliser, offering the possibility of safely recycling this waste product as a resource in agricultural applications. As the environmental concerns related to waste recycling in agricultural applications are well-known, restrictions on the use of sewage sludge have been implemented by the EU and local authorities. This work aimed to evaluate the nitrogen leaching associated with the application of sludge and the effectiveness of the temporal restrictions on its application implemented to safeguard the environment in the Lombardy region of northern Italy (120 days in Nitrate Vulnerable Zones and 90 days elsewhere) using the CropSyst model which was first validated. The effects of fertilisation using four different sludge types on N leaching were simulated at five sites under cultivation with maize and rice crops; six different timing schemes for sludge application were tested, three of which involved dates that were in agreement (AT) with the regulation, while the other three were not in agreement (NAT). We detected a significant effect of the sludge type and application timing, whereas the effect of their interaction was never significant. The mean annual leaching was 22 to 154 kg N ha^{-1}. The higher the ammonium N content in the sludge was, the greater the potential for N leaching was found to be. For the maize crop, the distribution of sludge in the late fall period resulted in significantly greater N leaching (61 kg N ha^{-1}) and led to lower yields (9 t DM ha^{-1}) compared to late winter fertilisation (49 kg N ha^{-1}; 10 t DM ha^{-1}), whereas no differences in N leaching or yield were detected between AT and NAT, which was also observed for the rice crop. Therefore, the applied temporal constraints did not always appear to be advantageous for protecting the environment from leaching.

1. Introduction

The European Union aims to encourage the application of sewage sludge for agricultural purposes and to regulate the use of this sludge through Directives 86/278/EEC and 91/271/EEC. As recommended, sewage sludge should be applied with caution in accordance with plant nutrient needs and without impairing the quality of the soil, surface or ground water. Sewage sludge intended for arable land use must be evaluated prior to use in terms of the contents of heavy metals, persistent organic pollutants and pathogenic microorganisms as well as soil characteristics (e.g., the cation exchange capacity and pH). Despite these environmental restrictions, sewage sludge has valuable agronomic properties: its ability to improve physical, chemical and biological properties of soils due to its high organic matter content and nutrient availability is well known (Binder et al., 2002; Cuevas et al., 2003; Singh and Agrawal, 2008; Hussein, 2009). For these reasons, the application of sewage sludge to agricultural soils represents an alternative to the common use of livestock manure for crop production. Moreover, the agricultural use of sewage sludge as a means of waste recycling and disposal results in a lower cost for municipalities

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compared with other handling options (Lundin et al., 2004), such as landfills and incineration.

Several studies have been carried out to understand the effects of the application of sludge to agricultural land. With regard to the environmental impact, both contaminants [e.g., heavy metals, organic compounds (Harrison et al., 2006; Roig et al., 2012) and pathogens (Arthurson, 2008)] and nutrient losses [e.g., of nitrogen (N) and phosphorus] have been examined. In the last two decades, particular attention has been paid to the leaching of N from sludge-amended soils, as shown in several field experiments (Shepherd, 1996; Luo et al., 2003; Samaras et al., 2008; Knowles et al., 2011). Few studies have adopted a modelling approach for evaluating N leaching associated with the application of sewage sludge (Vogeler et al., 2006), whereas such methodology has been used in several studies on nitrate leaching associated with N fertiliser application (Acutis et al., 2000; Confalonieri et al., 2006; Jégo et al., 2012).

In the Lombardy region (northern Italy), sewage sludge obtained from industrial and civil waste treatment and stabilisation processes can be used as organic fertiliser, as defined by Italian regulations (D.Lgs. n. 99/92). Its use is regulated by regional laws (Regione Lombardia, 2004, 2007), which provide a number of specific restrictions. In particular, sewage sludge cannot be distributed on arable land from November 1st to February 28th (120 days) in areas designated as Nitrate Vulnerable Zones (NVZs) and from December 1st to February 28th (90 days) elsewhere [non-Nitrate Vulnerable Zones (nNVZs)]. The spreading of sewage sludge is regulated by the same temporal restrictions applied to liquid and solid manure. Although regional regulations impose a limit on the amount of sewage sludge that can be applied, no threshold for the organic N content is defined. The agronomic use of sludge only requires the adoption of a nutrient management plan (NMP) for supplying nitrogen according to the needs of crops.

The objective of this work was to assess the potential risk regarding nitrogen leaching from arable land in the Lombardy region under sewage sludge fertilisation and to evaluate the effectiveness of the temporal restrictions applied to sludge use to safeguard the environment from nitrate pollution. The effects of the sludge type used and application timing on N leaching were investigated using the CropSyst (Stöckle et al., 2003) simulation model with various pedo-climatic conditions and under flooded rice (*Oryza sativa* L.) and maize (*Zea mays* L.) crops. As reviewed by Cherry et al. (2008), this modelling approach is largely used due to being more comprehensive than other methods for testing different nitrogen management options over a mid-long-term period and because it takes into account different pedo-climatic conditions.

2. Materials and methods

2.1. Lombardy plain area

The agricultural plain examined in this study is located in the Po Valley and covers an area of approximately 700,000 ha. Across this area, which is characterised by high pedo-climatic variability, as reported by Fumagalli et al. (2011), intensive maize-based cropping systems lead to a high risk of nitrate pollution (Perego et al., 2012), with 62% of the total area being defined as vulnerable to nitrates (Regione Lombardia, 2006). Other crops, such as rice, winter wheat (*Triticum aestivum* L.), alfalfa (*Medicago sativa* L.), soybean [*Glycine max* (L.) Merr.], and Italian ryegrass (*Lolium multiflorum* Lam.) are also widely cultivated. Organic fertilisers, such as solid and liquid dairy manure, pig slurry and sewage sludge, together with mineral fertilisers are generally applied to ensure elevated crop production (Fumagalli et al., 2011, 2012). Water irrigation is generally applied via border and sprinkler methods (Perego et al., 2012). Tillage is mostly carried out by ploughing and harrowing in the region, whereas minimum and no-tillage are rarely adopted.

2.2. Model validation

CropSyst (Stöckle et al., 2003), a deterministic, multi-year multi-crop daily time-step simulation model, was selected for this work because this model had already been parameterised and evaluated for cropping systems typical of northern Italy (Donatelli et al., 1997; Bechini, 1999; Confalonieri and Bechini, 2004; Morari et al., 2004; Confalonieri and Bocchi, 2005; Bechini et al., 2006; Confalonieri et al., 2006, 2009a,b; Bonfante et al., 2010; Bocchiola et al., 2013).

A large representative dataset collected at six monitoring sites on the Lombardy plain (Perego et al., 2012) was first used to validate the model parameters. Experimental datasets were collected over a maximum of five years at the following five sites, most of which were sown with maize: Caviaga (LO, province of Lodi, 45.31°N, 9.50°E, 72 m a.s.l.), Cerese (MN1 and MN2, province of Mantova, 45.12°N, 10.79°E, 20 m a.s.l.), Landriano (PV, province of Pavia, 45.28°N, 9.27°E, 84 m a.s.l.), Ghisalba (BG, province of Bergamo, 45.69°N, 9.75°E, 178 m a.s.l.), and Luignano (CR, province of Cremona, 45.17°N, 9.9°E, 57 m a.s.l.). In particular, data on meteorological variables, crop management practices, soil physical and chemical properties (e.g., texture, pH), crop- and soil-related variables (e.g., crop yield, crop N uptake, soil water content) and the mineral nitrogen concentration in soil water were collected. This validation dataset covered a wide range of conditions: i) the average annual rainfall ranged from 760 to 1070 mm year^{-1}; ii) the soil texture from sandy to clay loam; and iii) the average annual nitrogen application to maize crops using organic and mineral fertilisers from 0 to 609 and from 69 to 314 kg ha^{-1}, respectively; iv) the applied fertilisers included dairy manure, pig slurry, sewage sludge, ammonium nitrate, urea and nitrogen compounds; v) the sowing and harvesting dates for maize (both for silage and for grain) extended from March to April and from August to October, respectively; and vi) sprinkler irrigation was performed with amounts of about 280 mm and border irrigation was carried out with amounts of 240 to 350 mm.

The CropSyst validation was based on comparisons between the observed and simulated mean annual data on the above-ground biomass (AGB), crop yield, crop N uptake and N leaching. The AGB, yield and crop N uptake at harvest time were observed directly, whereas annual N leaching was derived from the NO_3–N concentration determined in soil water solutions. Different statistical indexes were calculated to evaluate the goodness of fit of the model, which included (i) the relative root mean square error (RRMSE, minimum and optimum = 0%), (ii) coefficient of residual mass (CRM, 0–1, optimum = 0, if positive indicates model underestimation); (iii) determination coefficient R^2 ($-\infty$ / $+\infty$, optimum = 1); (iv) modelling efficiency (EF, $-\infty$ / 1, optimum = 1, if positive, indicates that the model is a better predictor than the average of measured values) (Loague and Green, 1991); (v) normalised median absolute error (MdAE); (vi) robust modelling efficiency (REF) (Chung et al., 1999); (vii) P-value of a paired t-test (P(t), 0–1; optimum = 1); and (viii) percentage of error (−100% / +100%, optimum = 0%). In addition, a comparison between the simulated and observed NO_3–N concentrations in soil water solutions was carried out for the LO monitoring site, where two types of sewage sludge were applied. At the LO site, ceramic cups were placed at the bottom depth of the soil profile (1.4 m) to collect the soil solution, in which the NO_3–N concentration was measured approximately every 15 days over a four-year period (2002–2006). In this case just the relative root mean square error (RRMSE) and the modelling efficiency (EF) were used to assess the model performance.

For the rice crop, validation was not performed because we used the crop-related parameters validated under the pedo-climatic conditions of the Lombardy region by Confalonieri and Bocchi (2005). We set the parameters related to soil nitrogen transformation as proposed by Confalonieri et al. (2006), who calibrated and validated them based on observed data on soil mineral nitrogen contents.