SEÇÃO IX - POLUIÇÃO DO SOLO E QUALIDADE AMBIENTAL

MODELLING THE RISK OF NITRATE LEACHING FROM TWO SOILS AMENDED WITH FIVE DIFFERENT BIOSOLIDS[1]

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SUMMARY

High N concentrations in biosolids are one of the strongest reasons for their agricultural use. However, it is essential to understand the fate of N in soils treated with biosolids for both plant nutrition and managing the environmental risk of NO_3^--N leaching. This work aimed at evaluating the risk of NO_3^--N leaching from a Spodosol and an Oxisol, each one treated with 0.5–8.0 dry Mg ha^{-1} of fresh tertiary sewage sludge, composted biosolids, limed biosolids, heat-dried biosolids and solar-irradiated biosolids. Results indicated that under similar application rates NO_3^--N accumulated up to three times more in the 20 cm topsoil of the Oxisol than the Spodosol. However, a higher water content held at field capacity in the Oxisol compensated for the greater nitrate concentrations. A 20 % NO_3^--N loss from the root zone in the amended Oxisol could be expected. Depending on the biosolids type, 42 to 76 % of the NO_3^--N accumulated in the Spodosol could be expected to leach down from the amended 20 cm topsoil. NO_3^--N expected to leach from the Spodosol ranged from 0.8 (composted sludge) to 3.5 times (limed sludge) the amounts leaching from the Oxisol treated alike. Nevertheless, the risk of NO_3^--N groundwater contamination as a result of a single biosolids land application at 0.5–8.0 dry Mg ha^{-1} could be considered low.

Index terms: biosolids, sewage sludge, nitrogen leaching.

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RESUMO: *MODELAGEM DO RISCO DE LIXIVIAÇÃO DE NITRATO EM DOIS SOLOS TRATADOS COM CINCO DIFERENTES BIOSSÓLIDOS*

Concentrações altas de nitrogênio (N) em biossólidos são uma das maiores razões para a utilização agronômica deles. Entretanto, é essencial entender o destino do N em solos tratados com biossólidos, tanto por motivos de nutrição vegetal quanto para manejar o risco ambiental representado pela lixiviação de nitrato. Este trabalho teve como objetivo avaliar o risco de lixiviação de nitrato em um Espodossolo e em um Latossolo, cada um tratado com doses de 0,5 a 8,0 Mg ha^{-1} de biossólido fresco, biossólido compostado, biossólido caleado, biossólido seco a calor e biossólido irradiado por sol. Os resultados mostraram que, para doses iguais de aplicação, o nitrato acumulou-se até três vezes mais na camada superficial de 20 cm do Latossolo do que do Espodossolo. Entretanto, a maior capacidade de campo do Latossolo compensou as maiores concentrações de nitrato e espera-se a lixiviação de 20 % do nitrato acumulado na camada superficial desse solo. Dependendo do tipo de biossólido, entre 42 e 76 % do nitrato acumulado no Espodossolo serão lixiviados. A expectativa de lixiviação de nitrato no Espodossolo variou de 0,8 (biossólido compostado) a 3,5 vezes (biossólido caleado) em relação ao Latossolo tratado de maneira similar. Entretanto, o risco de contaminação de aqüíferos por lixiviação de nitrato nos solos tratados com uma dose única de biossólidos entre 0,5 e 8,0 Mg ha^{-1} foi considerado baixo.

Termos de indexação: biossólidos, lodo de esgoto, lixiviação de nitrato.

INTRODUCTION

The constantly growing quantities of sewage sludge (biosolids) have led to their use as a source of organic matter for soils (Pascual et al., 1997). The idea of feeding valuable organic matter, containing primarily nitrogen (N) and phosphorus (P), back into the natural cycle forms the basis of using biosolids on land (Frank, 1998). High concentrations of N and P compared to manures and other organic matter sources are one of the strongest reasons for applying biosolids to soils.

Heavy metals, diseases, and environmental hazards related to the high N and P contents in biosolids stand out among the problems arising with the application of sewage materials to land. Therefore, health safety standards, maximum rates and frequency of application have been set according to the concentrations of pathogens, N, and heavy metals in biosolids. The USEPA Part 503 rule (USEPA, 1995) alludes to the need for the application of biosolids at agronomic rates based on biosolids' N content and the crop's N need.

Nutrient enrichment may lead to eutrophication of surface water and contamination of groundwater, which is strongly linked to N and P pollution originating from agriculture and waste sources (Sharpley et al., 1999). P in water is not considered directly toxic to humans and animals and therefore drinking water standards for P have not been established so far. On the other hand, NO_3^- is reduced to NO_2 in human intestine and can cause methemoglobinemia in human infants if NO_3^- is present in sufficient quantity in drinking water. As a result, water is considered inappropriate for human consumption when NO_3^--N concentrations reach values of 10 mg L^{-1} or higher (Haering et al., 2000). According to Polgase & Robison (1996), NO_3^- leaching and subsequent groundwater contamination is potentially one of the most important factors limiting the long-term viability of biosolids application to land.

Two broad considerations in modelling NO_3^- leaching are generally taken into account: the net input of NO_3^- into soil and the transport of NO_3^- with water through the soil (White et al., 1998). NO_3^--N leaching can be simulated by several models at various levels of detail and complexity in respect of temporal and spatial scales. One of the simplest simulations is the screening analysis that provides a rapid means of identifying potential NO_3^- leaching problems (Shaffer et al., 1991). The screening approach uses a simplified water balance and the amount of NO_3^--N available for leaching. Shaffer et al. (1991) encourage the use of a screening analysis first, and then the use of more detailed approaches if significant amounts of NO_3^--N are expected to leach.

Our study aimed at evaluating the environmental risk associated with the agronomic use of biosolids. This risk was evaluated through the potential leaching of N as NO_3^--N from two contrasting soils incubated with the five most common stabilized biosolids: biologically activated sewage sludge, composted biosolids, limed biosolids, heat-dried biosolids and solar-irradiated biosolids.

MATERIAL AND METHODS

Sludge stabilization

A 500 kg sample of fresh tertiary treated biological domestic sewage sludge was taken at Coliban Water Treatment Works in Victoria (Australia) as raw material for stabilized biosolids (composted, limed, heat dried, and solar irradiated biosolids). The fresh sample was analysed in triplicate for gravimetric water content (105 ºC for 48 h), total-N (dry combustion method), and mineral-N (Kjeldahl steam distillation - NH_4^+-N + NO_3^--N) method as described in Rayment & Higginson (1992).

Then, fresh sewage sludge (878 g kg^{-1} moisture, bulk density = 1.2 Mg m^{-3}, C/N ratio = 6.2) were mixed with enough hardwood sawdust and woodchips (bulk agents) to achieve a C/N ratio = 25:1. Three 450 L composting piles were pitched on a sheltered cement pavement, run at 35–65 ºC for 34 days, let to mature for another 60 days and sieved at 2 mm. Lime stabilization used CaO at a 30 % rate to fresh biosolids' dry solids (weight/weight). Heat drying was performed in a furnace at 250 ºC until constant weight. The heat-dried biosolids were ground and passed through a 2 mm sieve. For the solar irradiation process, three 10 kg fresh sludge samples were stored in freely drained plastic bowls under transparent plastic-covers under sunny conditions for 14 days during Melbourne's summer (Australia), with daily temperatures ranging from 12.8–26.5 ºC. The stabilization criteria established in USEPA (1995) were achieved in all the employed processes. All biosolids were analysed in triplicate for gravimetric water, total-N, mineral-N, using the same analytical methods for the fresh sludge (Table 1).

Soils

Two contrasting soils (Table 2) were selected to be amended with the five biosolids: a sandy "Espodossolo Cárbico Órtico" (Spodosol) and a clayey "Latossolo Vermelho Perférrico" (Oxisol) (Embrapa, 1999). Both soils had their 10 cm top layer removed before being collected from native areas. The aim was to simulate barren land situations, namely low organic matter and nutrient contents. Such conditions can better isolate the effects of biosolids from any other organic matter previously present in the soils. A 200 kg sample of the Spodosol was collected from 10–30 cm depth. Another 200 kg sample of the Oxisol was collected from 10–50 cm depth. Both soils were air-dried for 2 weeks and then passed through a 4 mm sieve.

Soil physical characteristics

Blank and biosolids-amended soil samples were analysed in triplicate for texture, bulk density-ρ_b, total porosity-PSR and field capacity-FC (Cassel & Nielsen, 1986) before incubation for the simulation of NO_3^--N leaching (Table 2).

Mineralisation experiment

Triplicate 1.5 kg soil samples were amended with 0.5, 1.0, 2.0, 4.0, 6.0, and 8.0 dry Mg biosolids ha^{-1} and filled in 1.7 L free-draining pots. The amended-soils were wetted with deionised water to their pot capacity, as described by Cassel & Nielsen (1986), and covered with plastic lids punched with three 4 mm holes.

Table 2. Some characteristics of the two selected soils (means ± standard deviations, n = 3)

Characteristic	Spodosol	Oxisol
	(10–30 cm)	(10–50 cm)
Total-N (g kg^{-1})	0.38 ± 0.03	1.6 ± 0.11
Mineral-N (mg kg^{-1})	0.1 ± 0.01	5.0 ± 0.08
pH [1:5 water (w/v)]	4.9 ± 0.1	5.0 ± 0.1
Clay (g kg^{-1})	48 ± 3	499 ± 38
Silt (g kg^{-1})	37 ± 1	145 ± 9
Sand (g kg^{-1})	915 ± 21	356 ± 19
θ_b (Mg m^{-3})	1.6 ± 0.1	0.9 ± 0.1
PSR (m^3 m^{-3})	0.41 ± 0.01	0.67 ± 0.08
FC (m^3 m^{-3})	0.07 ± 0.02	0.31 ± 0.02

Table 1. Moisture (θg), total-N, and mineral-N of biosolids (means ± standard deviations, n = 3)

Material	θ g	Total-N	Mineral-N
	g kg^{-1}		mg kg^{-1}
Fresh sludge	878 ± 2	65.1 ± 0.20	624 ± 54
Composted biosolids	551 ± 12	15.9 ± 0.71	277 ± 5
30 %-CaO biosolids	763 ± 0.2	40.1 ± 1.71	93.8 ± 4.6
250 °C-dried biosolids	34 ± 1	64.8 ± 0.31	356 ± 15
Solar-irradiated biosolids	801 ± 2	65.3 ± 0.63	803 ± 13

Pots containing amended soils were incubated at 25 ºC (± 1 ºC) in a high humidity chamber (95 % air moisture) for 12 hours light/day during 23 weeks for a non-leaching experiment. Three pots containing 1.5 kg blank-Spodosol and three with blank-Oxisol were placed together with the others as control. Blank control soils and amended soils were mixed prior to each sampling, which occurred on day 0 and after 1, 3, 7, 15, and 23 weeks. Pots were randomised weekly and deionised water was sprayed over the surface every second week to replace moisture losses.

Nitrate recovery from incubated soils

Incubated soil samples were extracted in triplicate from each pot with a 2 mol L^{-1} KCl solution at 1:10 material/solution ratio and shaken for 1 hour. Extracts were immediately filtered through Whatman 42 paper filters and analysed on the same day for NO_3^--N by the Kjeldahl steam distillation method as described by Rayment & Higginson (1992). Means from each pot were grouped per treatment (three pots each) to calculate treatment means.

Data for modelling

The modelling of NO_3^--leaching was based on the data collected from soil samples analysed on day 0 and in the 1st, 3rd, 7th, 15th and 23rd weeks of incubation (six months of trial). Monthly rainfall and pan-evaporation data (long-term means for Melbourne, latitude 37.81 South and longitude 144.97 East) were provided by the Bureau of Meteorology. Pan-evaporation values were converted to effective evapotranspiration by multiplying by the crop factor - 0.8 (Table 3).

Table 3. Some long-term climate data for Melbourne

Month	Rainfall	Effective evapotranspiration	Surplus water for leaching
	mm		
January	48.7	148.8	-100.1
February	47.5	127.7	-82.2
March	51.0	101.7	-50.7
April	57.8	62.4	-4.6
May	57.3	48.1	9.2
June	50.0	29.6	20.4
July	48.2	38.7	9.5
August	50.5	44.6	5.9
September	59.0	62.4	-3.4
October	67.3	91.8	-24.5
November	59.9	112.8	-59.9
December	59.6	136.3	-76.7

Source: BOM (1999).

NO_3^--N leaching model

NO_3^--N expected to leach from the amended 20 cm topsoils was modelled based on the studies of Shaffer et al. (1991) and White et al. (1998). Shaffer et al. (1991) introduced the Nitrate Leaching and Economic Analysis Package - NLEAP as a rapid and site-specific model for the estimation of NO_3^--N leaching potential. NLEAP uses an exponential probability density function (pdf) for predicting N leached for periods of time or cumulative drainage, which can be calculated as precipitation in excess of evaporation from meteorological data (White et al., 1998). Because the input variables are easily measured, White et al. (1998) point out the great potential of exponential pdf as a management tool. Edis (1998) explains that indigenous solutes such as NO_3^--N formed in soil are generally distributed throughout the water-filled porosity, which means that pdf-based models could describe changes in drainage flux of NO_3^--N concentrations advantageously (White et al., 1998). Using such a pdf approach, NO_3^--N expected to leach (N_L) from the incubated soils' 20 cm layer was calculated by the formula:

$$N_L = N_O\left[1-\exp\left(\frac{-R}{FC}\right)\right] \quad \text{(Equation 1)}$$

where N_0 is the amount of NO_3^--N available in a given soil layer (kg ha^{-1}), R is surplus water for leaching (mm), and FC the field capacity of the soil layer (mm). Values of N_0 (kg ha^{-1}) were derived from the NO_3^--N concentrations (mg kg^{-1} soil) measured in weeks 0, 1, 3, 7, 15 and 23 of soil incubation.

The distance the leachate was transported through the soil profile in time was calculated according to White (1997):

$$z(t) = \frac{R}{FC} \quad \text{(Equation 2)}$$

where Z is the distance (mm), t is a given time, R is surplus water for leaching (mm), and FC is the field capacity of the soil layer (m^3 m^{-3}).

Data transformation from mg kg^{-1} to kg ha^{-1} and mg L^{-1} considered a 20 cm soil layer, soil FC and bulk density. Analysis of variance and Tukey test were performed with Minitab® 12.1 for Windows.

RESULTS AND DISCUSSION

NO_3^--N available for leaching (N_0)

From the environmental point of view, NO_3^--N accumulation in soils should be avoided. However, mineralization of biosolids' organic N and nitrification occurred in all amended soil samples

thereafter. Nitrification increased N_0 according to both application rate and time and as a result accumulated a maximum of 36 kg ha^{-1} of NO_3^--N in the Spodosol and 86 kg ha^{-1} of NO_3^--N in the Oxisol after 23 weeks of biosolids-soil incubation (Table 4). Based on the concept that N loss is related to the amount of potentially leachable N present in soil, the risk of NO_3^--N leaching from soils treated with biosolids would be greater with increased application rates and time.

For the same biosolids and application rate, amounts of nitrified and accumulated N varied in the two contrasting soils. Nitrification in the Spodosol was highest for solar-irradiated biosolids, then fresh = 30 %-CaO > composted = 250 ºC-dried biosolids. NO_3^--N accumulated three times as much in the Spodosol treated with solar-irradiated biosolids as with 250 ºC-dried biosolids (Table 4). Amounts of NO_3^--N produced in incubated Oxisol could be ranked as fresh = solar-irradiated > 250 ºC-dried = composted, which is equivalent to 30 %-CaO biosolids. There was also an approximately three-fold difference between the highest and the lowest NO_3^--N contents accumulated in the Oxisol (Table 4). Finally, the Spodosol and Oxisol treated with fresh and solar-irradiated biosolids ended up with the highest NO_3^--N concentrations. These two biosolids manifested the highest potential for nitrate leaching, whereas the application of composted or 250 ºC-dried biosolids to the soils would pose the least risk under the given experimental conditions.

The 250 ºC-dried biosolids incubated in the Spodosol remained under 4 mg NO_3^--N kg^{-1} soil throughout the entire trial, which poses no threat to groundwater. Low nitrification rates are frequently reported when heat-dried biosolids are incorporated into soils (Smith et al., 1998). Considering that soil pH, temperature and moisture were not unfavourable for the occurrence of nitrification during the experiment, the heat treatment, which sterilises sewage sludge for all kinds of organisms, must have caused a shortage of nitrifying organisms in the 250 ºC-dried biosolids.

Smith et al. (1998) observed different NO_3^--N concentrations in twelve biosolids incubated in soils. They found that the NO_3^--N accumulation rate in soils was controlled by soil type and stability of the organic N contained in biosolids. Dewatering significantly reduces NO_3^- formation in amended soils through the removal of soluble NH_4^+-N (Smith et al., 1998). Similar results were found by Shepherd (1996) who reported that a lower initial NH_4^+-N content and mineralisation rates result in lower NO_3^--N formation and less leaching from sludge-amended soils.

Modelling NO_3^--N leaching based on incubated amended soils over time and without plant N uptake displays the worst scenario since NO_3^- leaching is higher in fallow soils than those where plants grow (Laverman, 2000). Crop N uptake reduces leaching and NO_3^--N losses from planted fields are likely to occur only when the crop N need is exceeded (Shepherd, 1996).

The Oxisol accumulated up to three times more N_0 in the 20 cm topsoil (kg ha^{-1}) than the Spodosol treated alike (Table 4). But as the Oxisol can hold approximately four times more water at FC than the Spodosol (Table 2), it can compensate higher N_0 values.

Soil water infiltration (R)

Water drainage is the most important factor for nitrate movement downwards into the soil profile (Edis, 1998). Under the present experimental conditions, the water drained in June was twice as much as in May and July and over three times as much as in August (Table 3). Since the highest risk of NO_3^--N leaching from biosolids-amended soils occurred in June, this was the only month considered for modelling.

Field capacity (FC)

Soil incorporation of biosolids is frequently reported to improve the soil structure and a higher amount of water held at FC may be expected (Joshua et al., 1998). Nevertheless, there were no significant changes in the physical characteristics of the Oxisol and the Spodosol caused by biosolids incorporation at 0.5–8.0 dry Mg ha^{-1}, except through the

Table 4. Maximum NO_3^--N concentrations retrieved from blank and amended-soils during 23 weeks of incubation

Treatment	NO_3^-–N	NO_3^-–N (0–20 cm)
	mg kg^{-1}	kg ha^{-1}
	Spodosol	
Blank-soil	0.99 a	2.9 a
Fresh bisolids	10.6 b	30 b
Composted biosolids	4.56 c	13.1 de
30 %-CaO-biosolids	9.44 b	27 b
250 °C-dried biosolids	3.72 c	10.7 d
Solar-irradiated biosolids	12.4 d	36 c
	Oxisol	
Blank-soil	8.96 b	15.2 e
Fresh bisolids	50.4 e	86 f
Composted biosolids	19.2 fg	33 c
30 %-CaO-biosolids	17.2 g	29 b
250 °C dried biosolids	20.5 f	35 c
Solar-irradiated biosolids	50.5 e	86 f

Means with same letter within rows are not statistically different by the Tukey test.

incorporation of composted biosolids in the Spodosol (Figure 1). The application of composted biosolids linearly increased the water content held at FC, which may significantly reduce water percolation from the 20 cm amended topsoil.

Although not significant at p = 0.10, an opposite effect was noticed in the Spodosol treated with 30 %-CaO biosolids where the water content at FC tended to decrease (Figure 1). A reasonable explanation could not be found, but the application of CaO on the Spodosol seems to have a negative effect on the soil structure and needs to be further investigated.

Biosolids rates required to alter the soil's physical characteristics have been reported as very high. Epstein (1997) had to incorporate 100 dry Mg ha^{-1} of fresh sewage sludge to a silt loam soil to observe a shifted soil water retention curve. Magesan et al. (1996) had to apply domestic sewage sludge consecutively for five years to a sandy soil in order to increase PSR and hydraulic conductivity. Such high application rates are not justified to avoid water percolation from soils, since the produced and leached NO_3^--N amounts would probably offset the higher water amounts retained at FC.

NO_3^--N expected to leach (N_L)

Data fitted to Equation 1 have shown that NO_3^--N expected to leach from amended soils (N_L) ranged from 20 % to 76 % of the NO_3^--N available for leaching (N_0), depending on both biosolids and soil types (Figure 2). Higher NO_3^--N concentrations in the Oxisol were in fact counterbalanced by higher amounts of water held at FC. As a result, top NO_3^--N concentrations expected to leach down from Oxisol treated with fresh or solar-irradiated biosolids reached 17 kg ha^{-1} against 21–24 kg ha^{-1} from Spodosol amended with solar-irradiated and 30 %-CaO biosolids (Figure 2).

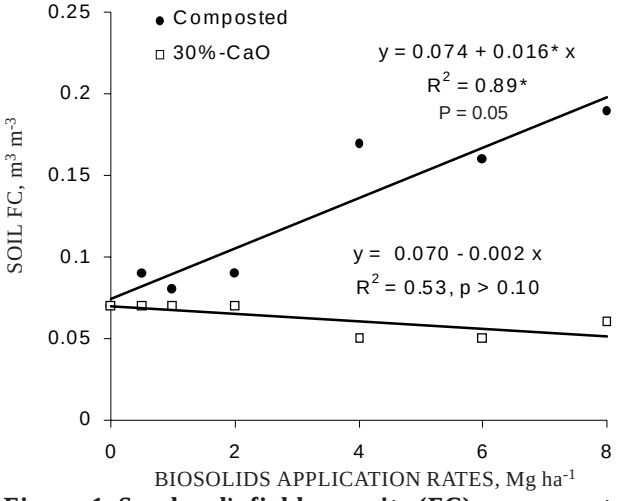

Figure 1. Spodosol's field capacity (FC) responses to the application of composted and 30 %-CaO biosolids.

Figure 2 depicts the combined effect of N_0 and FC on N_L. As biosolids applied at 0.5–8.0 dry Mg ha^{-1} did not change the Oxisols's water content at FC, N_L depended on the amounts of mineralised and nitrified N in this soil over the trial period. A fixed 20 % loss of the nitrate stocked in the 20 cm amended-Oxisol topsoil (N_0) was expected to leach regardless of the biosolids type (Figure 2). Composted and 30 %-CaO biosolids altered water content at FC in the Spodosol and different N_0 proportions were due to leach (N_L) from this soil: N_L was 42 % of N_0 from Spodosol treated with composted biosolids, 66 % for soil samples treated with fresh, 250 ºC-dried and solar-irradiated biosolids, and 76 % of N_0 from the Spodosol treated with 30 %-CaO biosolids (Figure 2). As long as NO_3^--N contamination of groundwater is a concern, solar-irradiated and 30 %-CaO biosolids should not be applied to Spodosols. Composted and 250 ºC-dried biosolids would be more appropriate to be used in such soils.

At a similar NO_3^--N concentration in both soils, nitrate would leach between 3–4 times more from the Spodosol's topsoil than from the Oxisol's (Figure 2). However, mineralization and nitrification rates of biosolids were different in the two soils. As a result, at the same biosolids and application rate the amounts of NO_3^--N expected to leach from the Spodosol's 20 cm topsoil (kg ha^{-1}) ranged from 0.8 (composted biosolids) to 3.5 the amounts due to leaching from the topsoil of the Oxisol (Table 4 versus Figure 2). Nevertheless, leachate from the Spodosol was from 0.6 (composted biosolids) to 4.5 times (30 %-CaO biosolids) the nitrate concentrations leached from the Oxisol (Table 5).

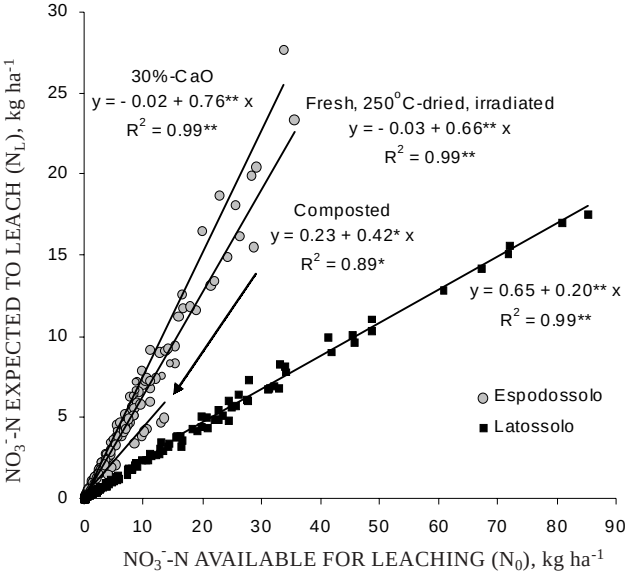

Figure 2. Regression of NO_3^--N expected to leach (N_L) on NO_3^--N available for leaching (N_O) for amended Spodosol and Oxisol considering 20 cm topsoil.

Table 5. Leachate's maximum NO_3^--N concentrations expected to leave the 20 cm amended-topsoils with 20.4 mm of drainage

Treatment	Spodosol	Oxisol
	mg L^{-1}	
Fresh sludge	75.5a	85.8f
Composted biosolids	28.4b	44.1g
30 %-CaO biosolids	135.8c	29.9b
250 °C-dried biosolids	35.3d	40.2g
Solar-irradiated biosolids	114.2e	83.3f

Means with same letter are not statistically different by the Tukey test.

NO_3^--N leaching-distance into soil profile [z(t)]

As NO_3^--N moves downward into the soil profile, the risk of groundwater contamination is reduced by dilution, since more water is needed for percolation and also because part of the NO_3^--N is retained in a given soil layer. This effect was well demonstrated by Mitchell et al. (2000) who applied approximately 20 dry Mg ha^{-1} of digested sewage sludge to a forested Spodosol in Scotland to recover 10 kg ha^{-1} NO_3^--N from the O_1 horizon, but only 4 kg ha^{-1} from approximately 50 cm deeper.

Maximum surplus water under Melbourne conditions over a year (Table 3) would leach NO_3^--N 64 cm deeper into the Spodosol's 20 cm toplayer, and 15 cm deeper into the Oxisol profile according to Equation 2. Such short distances travelled in a year do not threaten deep groundwater on a short-term basis. Lysimeter studies also indicated that the amount of NO_3^--N leaching from an Argissolo (Ultisol) amended with sewage sludge at 30 dry Mg ha^{-1} would not significantly affect groundwater (Barry et al., 1998).

Joshua et al. (1998) applied sewage sludge at 30–120 dry Mg ha^{-1} to Australian pastures and measured significant NO_3^--N movement in soils as deep as 70 cm after one year. But, as concentrations remained under 10 mg NO_3^--N kg^{-1} at such depth, they concluded that a single application of sewage sludge to pastures did not pose risks of groundwater contamination.

For a different rainfall regime the contribution from each factor (N_0, R, FC) may change. Accordingly, some countries manage NO_3^- leaching risk from biosolids through rainfall. For instance, some European countries ban application of digested sludge between late summer and early winter to reduce water pollution by NO_3^--N (Smith et al., 1998). Shepherd (1996) stated that sludges applied early in the United Kingdom autumn presented a greater potential for N leaching because of the greater winter rainfall and drainage.

NO_3^- leaching is also sensitive to land management practices, with the largest losses usually occurring under bare fallow conditions. The presence of a cover crop may drastically reduce NO_3^- leachate since much of the mineralised N is taken up by plants (Edis, 1998; Shepherd, 1996). Values of NO_3^--N expected to leach from 20 cm topsoils (Figure 2 and Table 5) would surely be lower for biosolids-treated soils under a cover crop. However, the relative leaching risks from the two selected soils amended with the five biosolids could be well illustrated here. The adopted approach could figure out the highest risk posed to groundwater by a single biosolids application. Such a risk can be considered low for the application rates used.

CONCLUSIONS

1. NO_3^--N expected to leach from biosolids incubated in the clayey Oxisol depended exclusively on the amounts of nitrified N. Changes in the sandy Spodosol's field capacity by some biosolids strongly influenced amounts of NO_3^--N expected to leach from this latter soil.

2. The application of solar-irradiated and fresh biosolids at least doubled the risk posed by NO_3^--N to groundwater compared to the application of composted, 250 °C-dried and 30 %-CaO biosolids to the Oxisol.

3. Composting and heat-drying could reduce the NO_3^--N leaching risk of fresh sludge applications to Spodosol to a third.

4. For similar amounts of NO_3^--N present in soils, the risk of NO_3^--N leaching from Spodosol was between 3 and 4 times higher than from the Oxisol.

5. Leaching was limited to 64 cm soil depth below root zone and the risk of NO_3^--N groundwater contamination caused by a single application of biosolids at rates up to 8.0 dry Mg ha^{-1} can be considered low for both soils.

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