

Fate of applied biosolids nitrogen in a cut and remove forage system on an alluvial clay loam soil

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Abstract. The fate of nitrogen (N) applied in biosolids was investigated in a forage production system on an alluvial clay loam soil in south-eastern Queensland, Australia. Biosolids were applied in October 2002 at rates of 6, 12, 36, and 54 dry t/ha for aerobically digested biosolids (AE) and 8, 16, 48, and 72 dry t/ha for anaerobically digested biosolids (AN). Rates were based on multiples of the Nitrogen Limited Biosolids Application rate (0.5, 1, 3, and 4.5NLBAR) for each type of biosolid. The experiment included an unfertilised control and a fertilised control that received multiple applications of synthetic fertiliser. Forage sorghum was planted 1 week after biosolids application and harvested 4 times between December 2002 and May 2003. Dry matter production was significantly greater from the biosolids-treated plots (21–27 t/ha) than from the unfertilised (16 t/ha) and fertilised (18 t/ha) controls. The harvested plant material removed an extra 148–488 kg N from the biosolids-treated plots. Partial N budgets were calculated for the 1NLBAR and 4.5NLBAR treatments for each biosolids type at the end of the crop season. Crop removal only accounted for 25–33% of the applied N in the 1NLBAR treatments and as low as 8–15% with 4.5NLBAR. Residual biosolids N was predominantly in the form of organic N (38–51% of applied biosolids N), although there was also a significant proportion (10–23%) as NO₃-N, predominantly in the top 0.90 m of the soil profile. From 12 to 29% of applied N was unaccounted for, and presumed to be lost as gaseous nitrogen and/or ammonia, as a consequence of volatilisation or denitrification, respectively. In-season mineralisation of organic N in biosolids was 43–59% of the applied organic N, which was much greater than the 15% (AN)–25% (AE) expected, based on current NLBAR calculation methods. Excessive biosolids application produced little additional biomass but led to high soil mineral N concentrations that were vulnerable to multiple loss pathways. Queensland Guidelines need to account for higher rates of mineralisation and losses via denitrification and volatilisation and should therefore encourage lower application rates to achieve optimal plant growth and minimise the potential for detrimental impacts on the environment.

Additional keywords: mineralisation, denitrification, ammonia volatilisation, leaching.

Introduction

Intensive agriculture can lead to declining soil fertility, especially reductions in soil organic matter and nitrogen (N) stores (Dalal *et al.* 2003; Haynes *et al.* 2003). It has been reported that the land application of biosolids (the nutrient-rich organic matter derived from wastewater treatment processes) could help to replenish soil organic matter, supply nutrients such as N, P, S, and K to plants, improve soil texture and water-holding capacity, and have beneficial effects on microbial biomass and activity (Eriksen *et al.* 1999; Leifeld *et al.* 2002; Bergkvist *et al.* 2003; Barry *et al.* 2004; Bell *et al.* 2004; Crecchio *et al.* 2004; Meyer *et al.* 2004). The area of agricultural land to which biosolids are applied and the quantity of biosolids used in crop production have been increasing significantly in the last 2 decades, due both to the nutrient value of the biosolids and environmental concerns associated with traditional disposal methods such as landfills and ocean outfalls. The land application of biosolids, however, may have detrimental effects if not managed properly, and reported

problems include possible soil contamination from heavy metals, organic chemicals, and pathogens, the leaching and runoff of added nutrients (mainly N and P), and the risks to food safety posed by some trace metals (Elliott *et al.* 2002; Epstein 2003).

The added mineral and organic N in biosolids can benefit plant growth but is also subject to a series of transformations in the soil-plant ecosystem. Ideally, biosolids application rates should result in the provision of sufficient N to support plant growth, with mineralisation of organic N matched to removal in plant biomass. This would reduce the likelihood of N loss through leaching and runoff, which could have adverse effects on the environment. Forage sorghum (*Sorghum bicolor* (L.) Moench) grown in a cut-and-remove system requires a large amount of N and could be one of the crops suitable for growing on biosolids-amended soils.

Transformations of applied biosolids N are complicated and site-specific, and largely depend on the biosolids composition, climatic conditions, soil types and properties, as well as the

agricultural production system. A quantitative understanding of the transformations of the applied biosolids N is crucial for maximising N use in crop growth and minimising the off-site impacts on the environment. For example, provision of biosolids N to plants relies on the mineralisation of the organic N in the biosolids, and research results have indicated that mineralisation rates range from 12 to 90% of the applied biosolids organic N in the year of application (Adegbidi and Briggs 2003; Vieira *et al.* 2005; Mendoza *et al.* 2006).

There is little information on the N transformations in biosolids applied to cropping land in the subtropical areas in Australia, as most of the research has been conducted in areas of temperate climate and in the northern hemisphere. The objectives of this study were to (1) evaluate plant response to applied biosolids and (2) estimate the fate of the applied biosolids N in a cut and remove forage system at a site where N was the sole limiting nutrient, and (3) use this information to make better informed regulations/guidelines for the land application of biosolids in Queensland.

Materials and methods

Site details

The experimental site was located on a private property at Lowood (27°27'S, 152°34'E) in south-eastern Queensland and had been managed as a grazed grass pasture for a number of years. Abundant grass pasture residues were found on the soil surface when the study started. The area has a history of long, hot summers and mild winters with an average annual rainfall about 800 mm falling mainly in summer (November–February). Average maximum and minimum temperatures during the experiment from October 2002 to May 2003 were 29.3 and 15.7°C. Rainfall was well below average and supplementary irrigation was used to establish and maintain the crop during dry periods. Continued dry seasonal conditions coupled with a shortage of irrigation water limited the study to 1 summer growing season.

Experimental details

The experiment was established on a heavy alluvial clay loam soil (Vertosol; 55% clay, 23% silt, 21% sand; Table 1) (Isbell 1996), using a randomised complete block design with 10 treatments replicated three times. Each of the experimental plots had an area of 75.6 m² (14 by 5.4 m), with a 2-m gap between the experimental plots.

Treatments included an unfertilised control (UC, no fertiliser applied) and a fertilised control (FC) that received commercial fertiliser equivalent to 60 kg N, 15 kg P, 37 kg K, and 2 kg S/ha applied before planting and incorporated with tillage, and then

re-applied by top-dressing shortly after the second biomass harvest (approx. 80 days after planting). The remaining 8 treatments consisted of varying rates of aerobically (AE) or anaerobically (AN) digested biosolids (dewatered cake) from 2 south-east Queensland wastewater treatment plants. The AN biosolids was produced by a plant with an urban catchment area, while the AE biosolids was produced by a plant with a semi-rural catchment area. Most of ammonium-N will be lost due to ammonia volatilisation during the process of digesting biosolids aerobically (Epstein 2003), and it is generally believed that aerobically digested biosolids have a higher mineralisation rate than anaerobically digested biosolids (Henry *et al.* 1999; Hseu and Huang 2005).

The Nitrogen Limited Biosolids Application Rate (NLBAR) was calculated for each biosolid using the method recommended by the former New South Wales Environment Protection Authority (NSW EPA 1997), with treatments representing 0.5, 1, 3, and 4.5 times this rate for each biosolid. The target crop N requirement to be met from mineralisation of organic N in biosolids was 180 kg N/ha, with the assumption that net mineralisation rates were 25% for the AE and 15% for the AN biosolids. The corresponding rates of product applied were 6, 12, 36, and 54 dry t/ha for the AE biosolids and 8, 16, 48, and 72 dry t/ha for the AN biosolids, respectively. The total N applied in a 1NLBAR application of each biosolid was 732 (AE) and 997 (AN) kg N/ha, respectively.

The 2 biosolids were applied in mid-October 2002 and incorporated into the top 0.15 m of soil using rotary hoe on the day of application. Forage sorghum was planted 1 week later, with an overhead irrigation of 25 mm to ensure good plant establishment. Plant biomass was harvested 4 times (42, 76, 139, and 214 days after planting) by cutting all plants from 1 m length from each of the 2 middle rows in each plot. The experimental site received irrigation (25 mm) after the second harvest to ensure ratoon crop establishment. The plants were frosted in early May 2003, just prior to the last (fourth) harvest.

The harvested biomass was oven-dried at 60°C and the dry weight was recorded. The dried plant material was mulched and a subsample was ground to pass a 1-mm sieve for chemical analysis. After the last biomass harvest in May 2003, soil samples were collected from the UC and FC treatments and the 1NLBAR and 4.5NLBAR treatments for each biosolid. Soil samples were not collected from the 0.5NLBAR and 3NLBAR treatments, to reduce the operational and analytical cost. Soil cores were collected from 4 randomly selected sites in each plot, separated into depth increments of 0–0.10, 0.10–0.20, 0.20–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20, 1.20–1.50, and 1.50–1.80 m and then combined to provide a bulked sample from each depth increment in each plot. Soil samples for soil

Table 1. Selected soil (0–0.10 m) and biosolids properties

Results are means of 3 replicates. Biosolids values were based on dry matter. n.d., not detected

	pH	EC (mS/cm)	C	N	P (%)	K	S	NH ₄	NO ₃	Cd (mg/kg)	Cu	Mn	Zn
Soil	6.8	0.22	4.4	0.4	0.15	0.34	0.05	n.d.	<2	0.1	34	990	88
Aerobic biosolids	6.5	199	33.5	6.23	4.25	1	0.81	0.28	2	2	292	121	454
Anaerobic biosolids	7.6	681	33	6.11	3.51	0.32	1.43	1.2	2	3.9	708	207	1874

characterising were also collected from the UC treatment before biosolids application in depth increments of 0–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.50 m. The soils were air-dried (40°C) and ground to pass a 2-mm sieve before chemical analysis.

Chemical analysis

Standard soil fertility analyses were conducted using methodology outlined in Rayment and Higginson (1992). The pH and EC of both soil and biosolids were determined using a 1:5 soil/biosolids to water ratio. Soil and biosolids total K, P, S, Cd, Cu, Mg, Mn, and Zn were determined by either graphite furnace atomic absorption spectroscopy (Cd) or inductively coupled plasma-atomic emission spectroscopy (for all other elements) following digestion using a concentrated acid mixture of 3:1 HNO₃:HCl (volume).

Biosolids and soil profile mineral N (NH₄ and NO₃) was extracted using a 1:10 ratio of biosolids/soil: 2 M KCl solution, and then determined by an automated colorimetric method (Method 7C2, Rayment and Higginson 1992). The quantity of NO₃-N determined by this method included both nitrite-N and nitrate-N. Biosolids and soil total N (0–0.30 m) was determined by a semi-micro Kjeldahl digestion method (Bremner 1996). Total C of both biosolids and soil and plant N were determined by a dry-combustion method using a LECO CNS-2000 analyser (LECO Corporation, MI, USA).

Statistical analysis

Total forage sorghum dry matter production, nutrient concentrations, and nutrient uptakes were compared between the biosolids treatments and the 2 controls (UC and FC) using standard analysis of variance techniques. The differences between the treatment means were tested for statistical significance using the least significant difference (l.s.d.) procedure in GENSTAT[®] (6th Edn). Profile total N and mineral N concentrations and N contents (kg/ha) were also analysed for each profile depth increment and also on the basis of summed profile totals to a depth of 0.30 m (in terms of total N) and 1.80 m (for profile NO₃-N).

Results and discussion

There was 471 mm of rain during the October 2002–May 2003 experimental period, with about one-third (151 mm) recorded in February (Fig. 1). Supplementary irrigations of 25 mm were applied in October 2002 (after planting) and again during early establishment of the third ratoon crop. The total incident rainfall plus irrigation was 117 mm between planting and the first harvest, 80 mm between the first and second harvests, 176 mm between the second and third harvests, and 148 mm between the third and fourth harvests.

Characterisation of the soil and biosolids

The soil analysis (Table 1) suggested that the main nutritional constraint was likely to be an increasing N deficit as biomass was removed in a cut-and-remove forage sorghum system. Most soil N was in the organic form and there was little mineral N in the topsoil when the study started, although the high organic C concentration (4.4%) and the relatively low C:N ratio (11:1)

suggested significant reserves of potentially mineralisable N to maintain productivity in the UC treatment.

The biosolids represented a rich source of N (6.1–6.2%) and P (3.5–4.3%), in addition to supplying significant quantities of other macro- and micronutrients (Table 1). About 20% of the total N was NH₄-N in the AN biosolids, but was only 5% of the total N in the AE biosolids. The higher pH of the AN biosolids, combined with the high NH₄-N concentration, represented a potential risk for gaseous N losses due to NH₃ volatilisation, although the NLBAR calculations already assume that 80% of NH₄-N in biosolids is lost to the atmosphere (NSW EPA 1997). Incorporation of biosolids immediately after application can reduce N loss through ammonia volatilisation, especially for the AN biosolids.

Forage sorghum production

Biosolids application led to an increase in cumulative forage sorghum biomass production, with yields from both AE and AN biosolids (21–27 t/ha) being greater than that either the UC (16 t/ha) or the FC (18 t/ha) treatments (Fig. 2). This positive

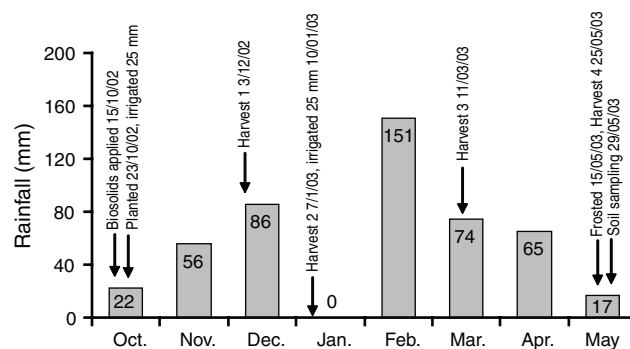


Fig. 1. Rainfall distribution during the experimental period and the dates of important experimental events.

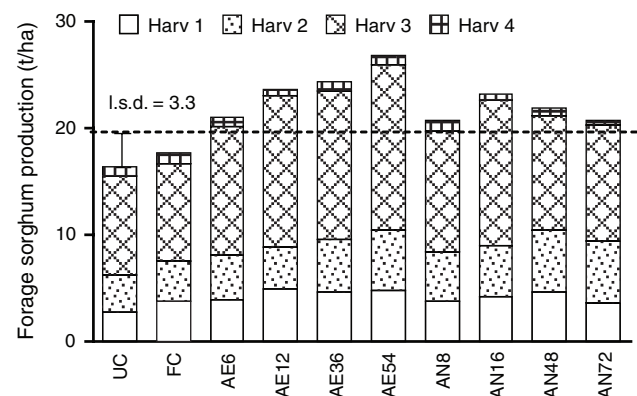


Fig. 2. Forage sorghum production as affected by the application of 2 biosolids at different rates to an alluvial clay loam soil in subtropical Australia. The l.s.d. value was based on the cumulative forage sorghum production of the 4 harvests. UC, Unfertilised control; AE6, AE12, AE36, and AE54, aerobically digested biosolids applied at 6, 12, 36, and 54 dry t/ha; AN8, AN16, AN48, and AN72, anaerobically digested biosolids applied at 8, 16, 48, and 72 dry t/ha.

response to biosolids application was consistent with the findings of other researchers (e.g. Cogger *et al.* 2001; Binder *et al.* 2002; Barry *et al.* 2004) who reported that the land application of biosolids led to higher biomass production and higher yields of many crops, including forage grasses, maize, sorghum, wheat, and cotton.

There were significant interactions between the biosolids application rate and the type of biosolids product. In plots receiving the AE biosolids, increasing the application rate from 6 to 54 t/ha (i.e. 0.5 to 4.5NLBAR) consistently increased the overall production from 21 to 27 t/ha. However, the response was less consistent in the AN biosolids, where a net increase of 2 t biomass/ha was observed when the biosolids application rate was increased from 8 to 16 t/ha (i.e. 0.5 to 1NLBAR), but there was either no change or a slight decrease in biomass production at application rates >1NLBAR. The reason for this apparent negative impact of high rates of AN biosolids is unclear. Speculation that this effect may have been due to the high NH₄-N concentrations, as suggested by Britto and Kronzucker (2002), was unlikely as the bulk of the effect was recorded in Harvest 3. This effect could not be attributed to nitrite toxicity even through there was large NO₃-N content in the high (4.5NLBAR) biosolids treatment (Fig. 3) (the reported NO₃-N was actually the sum of soil nitrate- and nitrite-N). Nitrite accumulation was likely in the neutral and poorly aerated soil used in our study, as these conditions inhibit the conversion of nitrite to nitrate more than the conversion of ammonia to nitrite (Oke 1966; Lee 1979). However, the similarity in NO₃-N contents between the AN and AE biosolids (Fig. 3) suggests

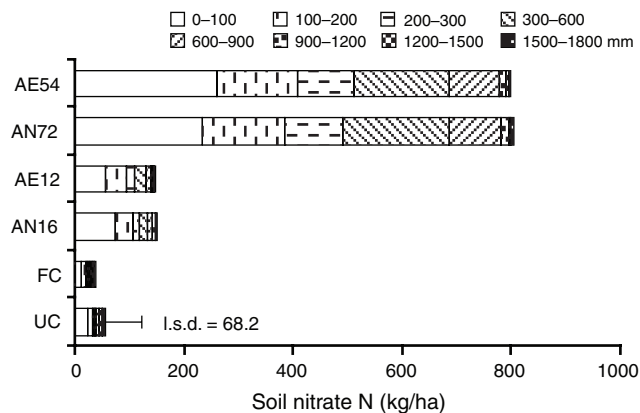


Fig. 3. Distribution of NO₃-N in the top 1.80 m soil profile at the end of the summer growing season. The l.s.d. value was calculated using the sum of the nitrate recovered in the 0–1.80 m soil profile. UC, Unfertilised control; FC, fertilised control; AE12 and AE54, aerobically digested biosolids applied at 12 and 54 dry t/ha; AN16 and AN72, anaerobically digested biosolids applied at 16 and 72 dry t/ha.

that nitrite accumulation is also unlikely, as the effect should have occurred at the high rates of both biosolids.

The effect of biosolids application on the concentrations of N, P, K, and S in the harvested plant material is shown in Table 2. Biomass harvested from the biosolids-treated plots generally had higher nutrient concentrations than those produced from the UC or the FC plots. The weighted average N and S concentrations over the whole growing season were

Table 2. Concentrations of N, P, K, and S in the harvested plant material as affected by the type and rate of the applied biosolids
Values are means of 3 replicates

Treatment	Harvest					Harvest				
	1	2	3	4	Mean	1	2	3	4	Mean
	N (%)					P (%)				
UC	2.14	1.78	0.95	3.25	1.36	0.40	0.43	0.42	0.51	0.41
FC	2.67	2.10	0.95	3.25	1.68	0.38	0.36	0.42	0.54	0.40
AE6	3.00	2.57	1.37	3.63	2.15	0.40	0.39	0.32	0.46	0.38
AE12	2.97	2.47	1.36	3.72	2.04	0.41	0.37	0.35	0.49	0.39
AE36	3.61	3.05	2.15	3.79	2.60	0.51	0.40	0.38	0.57	0.41
AE54	3.61	3.05	2.15	3.79	2.66	0.58	0.45	0.40	0.62	0.45
AN8	2.91	2.09	1.11	3.56	1.77	0.40	0.38	0.32	0.47	0.36
AN16	3.31	2.73	1.52	3.71	2.07	0.40	0.36	0.33	0.46	0.35
AN48	3.85	3.09	2.25	3.77	2.64	0.54	0.39	0.43	0.59	0.42
AN72	3.85	3.09	2.25	3.77	2.69	0.55	0.47	0.45	0.61	0.45
l.s.d. (P=0.05)	0.21	0.46	0.43	0.34	0.35	0.09	0.07	0.09	0.09	0.05
	K (%)					S (%)				
UC	4.64	3.99	3.00	2.77	3.59	0.14	0.13	0.11	0.20	0.12
FC	4.70	4.08	3.00	2.73	3.56	0.16	0.14	0.11	0.19	0.13
AE6	4.85	4.24	3.22	2.44	3.69	0.17	0.17	0.12	0.22	0.15
AE12	5.03	4.18	3.07	2.66	3.61	0.17	0.16	0.11	0.22	0.14
AE36	4.65	4.05	3.08	2.63	3.56	0.18	0.16	0.12	0.22	0.14
AE54	4.73	4.07	3.33	2.54	3.72	0.18	0.17	0.12	0.22	0.14
AN8	5.06	4.20	3.07	2.41	3.65	0.17	0.15	0.12	0.22	0.14
AN16	4.82	4.21	3.01	2.35	3.56	0.17	0.16	0.12	0.22	0.14
AN48	4.70	4.14	3.25	2.58	3.76	0.20	0.17	0.14	0.22	0.16
AN72	4.70	4.41	3.41	2.48	4.03	0.20	0.17	0.13	0.22	0.15
l.s.d. (P=0.05)	0.53	0.49	0.64	0.46	0.35	0.03	0.02	0.03	0.02	0.01

significantly higher in the biosolids-treated plots (1.8–2.7% N and 0.14–0.16% S) than the UC plots (1.4% N and 0.12% S). However, the weighted average K concentrations from the biosolids-treated plots (3.6–4.0%) were similar to, or only slightly higher than, that of the UC plots (3.6%), while there was little difference in P concentrations between the UC (0.41%) and the biosolids-treated (0.35–0.45%) plots. These latter effects were not surprising as the soil was already rich in P and K before the biosolids application. Significant differences in N, K, P, and S concentrations were generally not found between the plant material harvested from the AE and the AN biosolids treated plots when the 2 biosolids were applied at comparable total N rates.

Fate of the applied biosolids N

The application of biosolids at 1NLBAR application rates (i.e. 12 tAE/ha and 16 tAN/ha) led to a net increase of total soil N by 375 (AE) and 514 (AN) kg N/ha at the end of the study (Table 3), while the 4.5NLBAR application rates increased total soil N by 2432 and 2828 kg N/ha, respectively. This residual soil N accounted for 51% and 74% (AE) and 52% and 55% (AN) of the total applied biosolids N in the 1NLBAR and 4.5NLBAR application rates, respectively. About 70–80% of the residual total soil N was in the organic N form and ranged from 282 (1NLBAR AE) to 2078 (4.5NLBAR AN) kg/ha in the top 0.30 m soil profile. Little difference in the amount of residual total N was found between the 2 biosolids types, even though the applied N in the AN biosolids treatments was 260 kg N/ha (1NLBAR) and 1180 kg N/ha (4.5NLBAR) greater than in the AE biosolids plots.

The amount of N remaining in mineral N form varied from 93 kg/ha (1NLBAR AE) to 750 kg/ha (4.5NLBAR AN), with almost all the residual mineral N located in the top 0.60–0.90 m of the soil profile (Fig. 3). The lack of significant difference in the amount of the residual mineral N between the biosolids-treated plots and UC plots in the 1.50–1.80 m soil depth indicated negligible N leaching below the monitored 0–1.80 m soil profile. This observation was consistent with the relatively dry seasonal conditions and the high plant available water content on these soils (15–20 mm/0.10 m).

The harvested plant biomass removed an additional 244 (1NLBAR AE) to 488 kg N/ha (4.5NLBAR AE) from the biosolids-treated plots, compared with that from UC. The N removed in plant biomass accounted for 25% (AN 1NLBAR), 33% (AE 1NLBAR), 7% (AN 4.5NLBAR) and 15% (AE 4.5NLBAR) of the total N applied. Cogger *et al.* (1999) reported that forage grasses removed 28–40% of the applied biosolids N, while similar or lesser proportional N removal has been recorded in other crops such as maize and sorghum (Binder *et al.* 2002). In this study the biomass produced in the first harvest was reduced by drought. Continued wet weather delayed the third harvest, resulting in cooler temperatures and, eventually, killing frosts that limited biomass produced at the fourth harvest at the end of the season. Under more favourable weather conditions, or with better reserves of stored soil water or irrigation water, forage sorghum production would have been expected to be greater, as would the amount of removed N.

The increased plant N removal in the biosolids treatments was due to both the increased overall forage sorghum production (Fig. 2) and the increased N concentrations in harvested plant materials (Table 2). The contribution of the fourth harvest to the total N removal was minimal, even though the N concentration in the plant materials was, in general, higher from the biosolids-treated plots than the UC plots.

Partial N budgets for the biosolids treatments indicated significant amounts of biosolids N that could not be accounted for. This ranged from 114 (1NLBAR) to 379 (4.5NLBAR) kg N/ha for the AE biosolids and 234 (1NLBAR) to 1292 (4.5NLBAR) for the AN biosolids treatments (Table 3), with the unaccounted N likely to have been lost to the environment through ammonia volatilisation and emission of N₂O and/or N₂ gases. The lost N represented 12% (4.5NLBAR AE) to 29% (4.5NLBAR AN) of the total applied N and no significant difference in the percentage N loss was found between the 2 application rates for either the AE or AN biosolids. However, the N loss was significantly higher from the AN biosolids-treated plots (24–29% of the applied N) than the AE biosolids-treated plots (12–16%). The N loss reported here is moderate compared with the N loss from the applied inorganic N, due to the relatively slower process of the mineral N release from the organic N pool. Constable and Rochester (1988)

Table 3. Fate of the applied biosolids N following 4 harvests of forage sorghum during an 8-month period after biosolids application

Values are means of 3 replicates; within columns, means followed by the same letter are not significantly different at $P=0.05$

Treatment	Biosolids N applied			Net N removed by plant ^A (kg N/ha)	Residue biosolids org. N in soil ^B (0–0.30 m)	Net NO ₃ -N in soil ^C (0–1.80 m)	Estimated biosolids N		
	Org.	NH ₄ -N	NO ₃ -N				Mineralised ^D (% applied org. N)	Loss ^E (% applied tot. N)	
Aerobic 12 t/ha	685.6	47.9	<0.1	733.5	243.9a	282a	93.3a	58.9bc	15.5a
Aerobic 54 t/ha	3085.2	215.5	0.1	3300.8	487.9b	1688b	743.8b	45.3a	11.5a
Anaerobic 16 t/ha	804.8	191.9	<0.1	996.7	248.4a	418a	95.7a	48.1ab	23.5b
Anaerobic 72 t/ha	3622.5	863.6	0.1	4486.2	365.3b	2078b	749.5b	42.6a	28.8b

^AAmounts of plant N removed from biosolids treatments – those from unfertilised control treatment.

^BAmounts of organic N recovered from biosolids treatments – those from unfertilised control treatment.

^CDifference in the amounts of NO₃-N found between biosolids treatments and unfertilised control treatment.

^D100 × (N of biosolids origin removed by plant + net soil profile NO₃-N of biosolids origin + N lost – NH₄-N applied in biosolids – NO₃-N applied in biosolids)/biosolids organic N applied, assuming that all the N lost and removed by plant was in the mineral N form.

^ETotal applied biosolids N – net mineral N of biosolids origin removed by plant – residual biosolids organic N in the top 0.30 m soil – net NO₃-N of biosolids origin in the 0–1.80 m soil profile.

found that losses of inorganic nitrogen fertiliser from Vertosols in irrigated cotton were 80–90% under the similar climate conditions.

There was no runoff during the growing season and no evidence of leaching below the monitored soil profile (Fig. 3), so the N unaccounted for was probably lost in gaseous form, either as NH_3 gas through volatilisation or N_2O and/or N_2 gases through denitrification. The higher N loss from the AN compared with the AE biosolids-treated plots could theoretically be attributed, at least in part, to higher NH_3 volatilisation, as the NH_4 concentration in the AN biosolids was about 4 times as high as in the AE biosolids (Table 1). The propensity for N loss through NH_3 volatilisation depends on many factors, but 2 of the key factors favouring NH_3 volatilisation are high NH_4 concentration and high pH. The AN biosolids had a pH of 7.6 and 1200 mg $\text{NH}_4\text{-N/kg}$, while the AE biosolids had a pH of 6.5 and only 280 mg $\text{NH}_4\text{-N/kg}$, and it was therefore expected that the AN biosolids would lose more N through NH_3 volatilisation. Robinson and Röper (2003) indicated that 44–55% of the applied biosolids $\text{NH}_4\text{-N}$ was lost within 14 days and believed that this N loss was an underestimation as their experiment was conducted under unfavourable weather conditions for volatilisation (low temperature, high humidity, and little wind). He *et al.* (2003) reported that in an incubation experiment the N loss through NH_3 volatilisation over 180 days accounted for 18% of the applied mineral N when biosolids were applied on the soil surface but <4% when biosolids were incorporated into the soil. This phenomenon is already embedded in the NLBAR calculation (NSW EPA 1997), with the amount of mineral N applied as NH_4 in the biosolids discounted by 75–80% for expected NH_3 volatilisation losses.

In addition to the $\text{NH}_4\text{-N}$ already in the biosolids when applied to the soil, a large amount of NH_4 could also be produced in a short period following the biosolids application, as part of the organic N mineralisation process. Data presented in Bell *et al.* (2004) indicated as much as 40% of the applied organic N could be transformed into $\text{NH}_4\text{-N}$ only 8 weeks after amending a red Ferrosol soil with AN biosolids at 20 dry t/ha. The newly mineralised $\text{NH}_4\text{-N}$ would also be subject to loss through NH_3 volatilisation, especially if subsequent nitrification reactions were inhibited by dry soil or high $\text{NO}_3\text{-N}$ concentrations (Sierra and Marbán 2000; Breuer *et al.* 2002).

Another pathway for N losses would be through denitrification, as all the conditions favouring denitrification activity were met during this study. The heavy soil structure (55% clay), restricted drainage, temporarily and locally saturated soil conditions caused by either rainfall (≥ 40 mm in 1 or 2 days in a wet February) or irrigation, plus abundant organic C (4.4% in the top 0.10 m of soil and >30% in the biosolids; Table 1) and low C:N ratio in both the biosolids (5:1) and the soil (11:1 in the top 0.10 m soil) would have provided favourable conditions for denitrification activity (Pu *et al.* 2001). Mendoza *et al.* (2006) reported that the NH_3 loss from a biosolids-amended soil did not account for all N loss and attributed the unaccounted N losses to denitrification.

The N lost through either NH_3 volatilisation or denitrification must have been in the mineral N form. Similarly, the N removed by the harvested plant materials must also have been in the

mineral N form before the N could be taken up by the plant. The total mineral N that could be accounted for at the end of the growing season (soil mineral N, lost N, and plant N removed) ranged from 450–578 kg N/ha (1NLBAR for AE and AN biosolids) to 1610–2407 kg N/ha (4.5NLBAR for AE and AN biosolids). The N mineralised from organic sources in the applied biosolids (total accountable mineral N – applied biosolids mineral N) was therefore 402, 1396, 386, and 1543 kg N/ha, or 59%, 45%, 48%, and 43% of the applied organic N for the 1NLBAR and 4.5NLBAR rates of the AE and AN biosolids, respectively. Mineralisation rates appeared to be higher for the AE biosolids than the AN biosolids only at the 1NLBAR application rate.

Mineralisation rates calculated in this study were well above the mineralisation rates suggested by the NSW EPA (1997), viz. 15% for the AN biosolids and 25% for the AE biosolids. The very low C:N ratio of both biosolids (5:1), combined with the low C:N ratio in soil (11:1), would have favoured the mineralisation process and reduced any chance of net immobilisation of soil mineral N once biosolids were incorporated into soil (Green and Blackmer 1995). Furthermore, the warmer (and occasionally wetter) climatic conditions in subtropical south-eastern Queensland, compared with those in southern NSW where much of the biosolids research in Australia has been conducted (e.g. Salt *et al.* 1996), would be expected to accelerate the rate of organic matter decomposition and therefore N mineralisation.

Conclusions

Significant proportions of total N from both AE and AN biosolids applied to an alluvial clay loam soil were unaccounted for at the end of a summer growing season. This unrecovered N was probably lost via either ammonia volatilisation and/or denitrification, as there was no runoff during the experimental period and no evidence of leaching losses below the depth of soil sampling. The relative contribution of each of the two pathways to gaseous N loss was not clear.

A large amount of the residual biosolids N remained in the soil profile at the end of the summer growing season, mainly in the top 0.30 m, despite removal of 21–27 t dry matter/ha over 4 biomass harvests. This residual N fertility suggests excellent residual value for future crop production, provided further losses (gaseous or leaching) can be minimised. Under the warmer conditions in this subtropical area, the mineralisation rate was 2–3 times greater than the rates used by the NSW EPA to calculate NLBAR application rates. The biosolids applications at 0.5NLBAR (6 t/ha for AE and 8 t/ha for AN biosolids) could supply enough nutrients (primarily N at this site) to ensure forage sorghum production at least matched, if not exceeded, that recorded with artificial fertiliser. Higher biosolids application rates did not produce large increases in forage sorghum production but resulted in significant increases in soil $\text{NO}_3\text{-N}$, raising the potential risks of losses to the environment through denitrification, leaching, and runoff.

Our results show that the assumptions of mineralisation rates used in the New South Wales Guidelines are not appropriate for Queensland conditions, and lower biosolids rates are

recommended in Queensland to optimise the agronomic benefit and minimise potential environmental impacts.

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