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Nitrate–nitrogen reduction by established tree and pasture buffer strips associated with a cattle feedlot effluent disposal area near Armidale, NSW Australia

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ABSTRACT

Vegetated buffer strips have been recognized as an important element in overall agro-ecosystem management to reduce the delivery of non-point source pollutants from agricultural land to inland water systems. A buffer strip experiment consisting of two tree species (*Eucalyptus camaldulensis* and *Casuarina cunninghamiana*) with two planting densities and a pasture treatment was conducted to determine the effectiveness of NO_3–N removal from a cattle feedlot effluent disposal area at Tullimba near Armidale, NSW Australia. Different management methods were applied for the buffers where grass and weeds were mowed 2–3 times during the second and third years and were not managed during the rest experimental years for the tree buffer, while grass was harvested 1–3 times per year for the pasture buffer. The differences between tree species and planting density significantly affected tree growth, but the growth difference did not significantly affect their capacities to reduce NO_3–N in soil surface runoff and groundwater. On average for all the tree and pasture treatments, the buffer strips reduced NO_3–N concentration by 8.5%, 14.7% and 14.4% for the surface runoff, shallow and deep groundwater respectively. The tree and pasture buffer strips were not significantly different in NO_3–N reduction for both shallow and deep groundwater while the pasture buffer strips reduced significantly more NO_3–N concentration in surface runoff than the tree buffer strips. Both buffer strips reduced more than 50% of surface runoff volume indicating that both the tree and pasture buffer strips were efficient at removing water and nutrients, mostly through a significant reduction in soil surface runoff volume.

1. Introduction

In the last few decades, pollution associated with both point and non-point sources has been identified as a serious threat to water quality around the world (Dosskey, 2002; Abu-Zreig et al., 2003; Brian et al., 2004; Lee et al., 2004; Liu et al., 2008). Excessive loads of nutrients such as N and P entering groundwater and waterways have been implicated in water pollution and human and animal health risks (Hill, 1996; Di and Cameron, 2002). Increasing concern has been raised about non-point sources pollution because of the difficulty in identifying its origin and then its control (Carpenter et al., 1998). Nitrate leaching and associated water contamination are a worldwide issue, mainly due to the intensification of agricultural activities through the application of more N fertilizers and organic wastes over the past 50 years (Spruill, 2004). Nitrate leaching into ground or surface water bodies may cause eutrophication, algal bloom, and fish poisoning (Cullen, 1991; Bennett, 1993; Lawrence, 1993).

The growing concern of non-point source pollution from certain agricultural and forestry practices has resulted in the development of best management practices (BMPs) that are designed to reduce the impact of these activities. Using vegetative buffer strips to reduce the delivery of non-point sources of pollutants from agricultural land to inland water systems has been recognized as a best management practice in the management of agro-ecosystems (e.g. Jacobs and Gilliam, 1985; Lowrance, 1992; Schade et al., 2002; Abu-Zreig et al., 2003; Hickey and Doran, 2004; Lowrance and Sheridan, 2005). Vegetated buffer strips function to reduce nutrients from surface and subsurface water by plant assimilation, sedimentation, removal and dissipation, and temporary storage (e.g. Schoonover and Williard, 2003; Anderson et al., 2004; Blanco-Canqui et al., 2004; Bedard-Haughn et al., 2005) or by providing certain environmental conditions that could be beneficial to some chemical transformations such as denitrification (e.g. Haycock and Pinary, 1993). These biogeochemical and hydrological processes in riparian vegetated buffer

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strips have been conceptualized by some authors (e.g. McClain et al., 2003; Vidon et al., 2010) as "hot spots and moments" of retention and degradation of pollutants.

Many studies on the function, mechanism and effectiveness of vegetated buffer strips have focused on NO_3–N removal for water quality protection (Vidon et al., 2010). Both forested and herbaceous buffer strips can be effective (Mayer et al., 2007) although obvious contradictions exist in results and conclusions of many studies concerning whether herbaceous or forested buffers are more effective in removing nitrate. For instance, Haycock and Pinary (1993) found that forested buffers were more effective in promoting NO_3–N removal in winter months compared to grass buffers, while Groffman et al. (1991) found higher nitrate rates of removal in grass buffers by comparison with forested buffers. Other studies showed that nitrate removal rates were similar for herbaceous and forested sites (e.g. Sabater et al., 2003). It is also well known that regular cutting of herbaceous vegetation during the growing season can significantly improve N attenuation from both surface and subsurface water (Bedard-Haughn et al., 2005). Therefore, further research is needed to compare nitrate removal efficiency between tree and grass buffer strips at different locations, under different environmental conditions and with different management strategies.

Cattle feedlots are potentially a significant source of non-point sources of pollutants from their liquid and solid effluent disposal areas. Consequently in many countries their operation is regulated by environmental protection authorities that now require best management practices to be implemented to meet environmental requirements and pollution control regulations. Part of best management practice generally includes the installation of vegetated buffer strips to reduce pollutants entering waterways and groundwater systems from effluent disposal areas. We established an experiment to test the effectiveness of trees and pasture buffer strips at reducing nutrient and water movement from a liquid effluent disposal area on a cattle feedlot research facility in New South Wales, Australia. At that time pastures were considered best management practice. The aim of the experiment was to compare the efficiency of trees with pasture buffer strips at reducing nitrate–nitrogen from surface and groundwater flow emanating from the disposal area under suggested best management practices that could be expected to be adopted by industry.

The experimental design included two tree species planted at two densities as well as an accepted pasture buffer strip for that location. The tree species chosen were *Eucalyptus camaldulensis* Dehnh. (river red gum) and *Casuarina cunninghamiana* Miq. (river she-oak). These two species are widespread riparian and floodplain trees over mainland Australia but with many different morphological and physiological traits. *E. camaldulensis* has broad leaves and a strong tap root system with sinker roots from major lateral roots (Bell et al., 1993) while *C. cunninghamiana* has needle like leaves and a more fibrous root system with a weaker tap root (Wang and Duggin, 2008), which suggests that *E. camaldulensis* could more efficiently use deeper subsurface soil water and *C. cunninghamiana* could use surface and shallow subsurface soil moisture more efficiently and hence they could have different effects on nutrient reduction. *E. camaldulensis* grows faster than C. *cunninghamiana* under satisfactory conditions (e.g. Thorburn, 1995). *E. camaldulensis* is also economically more important than *C. cunninghamiana* in terms of their wood products and other by-products such as honey. Two densities for each tree species were also designed in this experiment on the assumption that higher tree density tends to result in higher growth of height, basal area and canopy cover at earlier developing stage, and hence result in higher removal of water and nutrients. The following specific questions will be addressed by this experiment: (1) is there a difference between the two tree species in reducing nitrate movement in soil surface runoff and groundwater? (2) will the use of a higher tree density result in a higher nitrate removal? (3) is the tree or pasture buffer strip more efficient in reducing nitrate from surface runoff and groundwater?

2. Materials and methods

The Cooperative Research Centre for Meat Quality developed a beef cattle research facility at Tullimba, located 50 km west of Armidale, NSW Australia. The facility comprises a feedlot and infrastructure capable of holding up to 1000 head of cattle. To meet the environmental requirements established by the Environmental Protection Authority, a 20 ha liquid waste disposal area was established where liquid effluent from the feedlot was spray-irrigated. In 1996, we used part of this facility to establish this experimental tree and pasture buffer strips. The experiment site is 740 m above sea level. Temperature ranges from a mean maximum temperature of 28 °C in January and a mean minimum temperature of 0 °C in July. Mean annual rainfall is around 760 mm, with the maximum occurring in January and minimum in either April or June. The non-frost period is about 6 months with an average monthly maximum of 15 frosts occurring in July and August.

The buffer strip (300 m × 20 m) was established below the liquid effluent disposal area with an average slope of 3%. The land was previously used as grassland for cattle and sheep grazing. Soils are yellow sodosols (McKenzie et al., 2004), where the A-horizon is light-sandy clay loam that shows a tendency for dispersion in the A_2 layer. The B-horizon material is orange clay with traces of gravel and sands. Clay content increases slightly with depth. Soil depth to rock exceeds 2 m over the area. The surface soil (0–15 cm) is acidic (pH 5.0–6.0) with moderate to low N and P levels. Average exchangeable sodium percentage (ESP) is 5.2% ranging from 3 to 7% with the Ca/Mg ratio being greater than 2. Soil pH and ESP increase in the underlying A_2 horizon, but the overall level of plant nutrients is lower than at the surface. Soil pH rises in the clay subsoil with sodicity increasing to an average ESP of over 10%. Electrical conductivity (EC) decreases from the surface soil to subsoil. The dense clay subsoil is much less permeable (saturated hydraulic conductivity Ks = 0.0035 cm h^{-1}) than the surface soil (Ks = 6.9 cm h^{-1}). The marked reduction in permeability at the bottom of the A_2 horizon promotes lateral shallow groundwater movement.

This experiment was established as a randomized block design with 5 treatments (4 tree plantations and a pasture) in 3 blocks (replications), giving a total of 15 plots each being 20 m × 18 m. Tree treatment includes two tree species (*E. camaldulensis* and *C. cunninghamiana*) and two planting densities (1250 and 750 trees/ha, i.e. 45 and 27 trees/plot) in 4 rows 4 m apart and a tree spacing in rows of 2 and 3.5 m respectively. The soil was ploughed and deep-ripped in January 1996 before planting trees which were 1-year-old seedlings around 35 cm high on average. Grasses and weeds were controlled by mowing between the rows and manually hoeing around each tree. During the second and third year, grasses between rows were mowed two to three times each growing season by using a tractor-drawn slasher/mulcher, with the mulch being left on the surface. From fourth year on, the grass vegetation under the trees was not managed as the trees grew taller and grass layer became weaker. Tree survival was assessed at 3 months and 12 months of planting respectively. The small number of dead trees was replaced to restore the experiment to full stocking. Tree height, basal area and canopy cover were measured once a year from year 3 to year 6 since establishment.

The pasture was established in March of 1996 with a pasture composite mix that included *Festuca arundinacae* Schreber, *Phalaris aquatica* L., *Lolium* × *hybridum* Hausskn, *Trifolium hirtum* All., *Trifolium pratense* L., *Trifolium repens* L. and *Trifolium subterraneum* L.. The pasture was cut one to three times each year depending on growth and the grass removed from each plot to represent the removal as hay.

The experimental plots were periodically spray-irrigated with a traveling irrigator in the first year following establishment. The main purpose of the irrigation was to promote growth of young trees and the pasture by relieving drought stress on some occasions and to encourage root system development by increasing water deficit on other occasions. To avoid runoff, irrigation rates were less than 5 mm per hour in accordance with soil permeability (Burton, 1993). After the first year, effluent was applied only to the disposal area immediately above the vegetated buffer strips.

The amount of effluent disposed on the crop-pasture area depended on the rainfall received, so that between 1300 and 1400 mm water was added to the area each year. Consequently, effluent irrigation varied from 450 to 700 mm yr^{-1} (Table 1) over the period from 1996 to 2001 respectively. Nitrogen fertilizer was also applied to the irrigated disposal area for the purpose of both promoting crop production and conducting this experiment, with the amount being 33.4, 33.4, 33.4 and 100.2 kg N ha^{-1} for the year from 1998 to 2001 respectively (Table 1).

Surface runoff was collected from November 1998 (year 3) through November 2001 (year 6) from small surface runoff collectors. A collector was made from a 50-cm-long and 15-cm-diameter PVC pipe with a 5-cm-wide slit along the pipe. The collector was installed at the soil surface with the slit facing upslope and perpendicular to the land surface. One end of the pipe was sealed and the other end connected to a 30-L plastic storage container located in a pit. Two runoff collectors were installed for each plot, one being immediately above the plot and the other one below the plot. Surface runoff samples were collected, volumes measured following each rainfall event which was large enough to produce soil surface runoff, and subsamples were taken to the laboratory and frozen until NO_3–N analysis. Runoff samples were collected 9 times in years 3 and 4, 7 times in year 5 and 6 times in year 6. The difference in volumes and NO_3–N concentrations between the runoff samples collected above and below the buffer reflects the net change resulting from runoff moving across the vegetated buffer strip.

To collect groundwater samples three lines of observation wells were installed above, within (10 m from the disposal area) and below each experiment plot. At each sampling site, 3 wells were installed to collect groundwater at 3 different depths. The deep, intermediate and shallow wells were about 2 m, 1 m and at the interface between the A and B soil horizons respectively. In total, 135 wells were installed.

For the purpose of analysis, results from the deep and intermediate wells were grouped into a "deep well" category and compared against the "shallow well" category because NO_3–N concentrations of the water samples from the "deep" and "intermediate" wells at the same sampling station were relatively similar.

Water samples from the deep and intermediate wells were collected in a two-step process. Firstly, the old water in the wells was pumped out, allowing a fresh groundwater inflow. After 24 h, water samples were then taken from the fresh inflow. Water samples from the shallow wells were collected immediately once water appeared, because of the ephemeral nature of the flows. Nine sets of samples were collected in year 3 and 4, seven sets in year 5 and six sets in year 6. Water samples were taken to the laboratory and frozen until analysis. Nitrate–nitrogen concentration was analyzed for water samples from surface runoff, shallow and deep wells by using automated methods with a Technicon Auto Analyzer II (Technicon Industrial Systems, Tarrytown, NY).

STATISTICA (Version 4.0, production of StatSoft Inc., 1993) was used for all statistical analyses. The data were subjected to the standard ANOVA test for a randomized block design after testing for normality. STATISTICA (Version 4.0, production of StatSoft Inc., 1993) was used for all statistical analyses. The data were subjected to the standard ANOVA test for a randomized block design after testing for normality. Contrasts and standard errors were calculated and the F-test was used to test the null hypothesis that there was no significant difference between the contrast pairs (2 tree species, 2 tree planting densities and the tree and pasture buffer strips). Data were analyzed to determine if there were differences between the two tree species with the two planting densities in their effects on tree growth, reduction in soil surface runoff volume, reduction in runoff NO_3–N concentration and in groundwater NO_3–N concentration during different years. Data were also analyzed to determine if there were differences between the tree and pasture buffer strips. Data were presented both for the different contrast pairs and for the entire buffer strip on average to provide an understanding of the entire vegetated buffer strip at reduction of NO_3–N concentration in surface runoff, shallow and deep groundwater.

Data on the reduction of soil surface runoff volume and NO_3–N concentration and on the reduction in groundwater NO_3–N concentration in the shallow and deep wells by the vegetated buffer strips were analyzed as percentages. The variance in these data was shown to be homogeneous (equal variance) by Levene's test, so these data were not transformed prior to each ANOVA test.

Table 1
Water (mm) and actual N (kg ha^{-1}) input for the crop-pasture land above the vegetated buffer strip.

Year since plantation establishment in 1996	First year	Second year	Third year	Fourth year	Fifth year	Sixth year
Rainfall	919	742	750	818	676	675
Irrigation	450	630	630	560	700	700
N input via rainfall	8.2	7.4	7.5	7.7	6.2	6.9
N from liquid and solid effluent	27.6	38.7	38.7	34.4	43.0	43.0
N from fertilizer application	0	0	33.4	33.4	33.4	100.2
Total N input	35.8	46.1	79.6	75.5	82.6	150.1

3. Results

3.1. Growth of the trees and pasture

The survival rates of young trees were higher than 95% for both *E. camaldulensis* and *C. cunninghamiana* plots after 12 months. Their growth was measured periodically but only the data from years 3 to 6 are presented when the young trees grew to a reasonable size. The effect of different tree species and planting density on tree height, basal area and canopy cover are presented in Table 2. During the 4-year period, *C. cunninghamiana* individuals were significantly taller than *E. camaldulensis* while density did not significantly affect height growth of the two tree species. The average height of *E. camaldulensis* grew from 2.52 m in year three to 4.39 m in year six, whilst the height of *C. cunninghamiana* grew from 3.12 m to 5.66 m (Table 2). The higher density treatment had a significantly greater basal area for both species over the 4 years (Table 2), while species difference, on average, did not show significant effectiveness on their basal area development. Both tree density and species differences significantly affected tree canopy cover in years three and four following establishment, with *E. camaldulensis* having a lager canopy cover than *C. cunninghamiana* and the higher density plantations having a larger canopy cover than lower density ones (Table 2). Although the trend continued in years five and six, the effect of density and species differences on tree canopy cover gradually reduced to be not significant ($P > 0.080$) (Table 2).

The surface of each pasture plot was entirely covered with improved pasture 3 months after sowing in the first year. The pasture was green but stopped growing during the following winter. The period of growth for the pasture was some 2 months longer than

Table 2
Effect of planting treatments on tree growth for the last 4 years of the experiment.

[a]Year	[b]Treatment	Height (m)	Basal area (m^2 ha^{-1})	Canopy cover (%)
Third	S1D1	2.47a (0.17)	4.17a (0.40)	33.23a (4.24)
	S1D2	2.57a (0.19)	3.46b (0.25)	20.91b (3.21)
	S2D1	3.14b (0.22)	3.86a (0.29)	25.91c (3.05)
	S2D2	3.09b (0.24)	2.04c (0.18)	15.65d (2.17)
Fourth	S1D1	3.18a (0.23)	6.53a (0.37)	45.06a (4.87)
	S1D2	3.24a (0.19)	5.05b (0.37)	37.54b (4.09)
	S2D1	4.09b (0.27)	6.44a (0.55)	40.29c (4.82)
	S2D2	3.88b (0.31)	4.06c (0.36)	34.83b (3.99)
Fifth	S1D1	3.79a (0.18)	9.68a (0.67)	53.56a (5.67)
	S1D2	3.82a (0.22)	7.38b (0.69)	51.85a (4.69)
	S2D1	4.64b (0.37)	10.22a (0.77)	55.73a (6.32)
	S2D2	4.77b (0.31)	7.85b (0.68)	53.27a (4.80)
Sixth	S1D1	4.32a (0.22)	12.61a (1.02)	64.05a (5.88)
	S1D2	4.46a (0.29)	10.46b (0.88)	63.73a (6.72)
	S2D1	5.59b (0.40)	13.75a (1.21)	66.45a (6.66)
	S2D2	5.72b (0.39)	11.03bc (0.98)	64.88a (5.39)

The means with different letters in a column of a year indicate significant differences at $P < 0.05$. Values in parentheses are standard errors of the means.
[a] Year = the year since the plantation was established in 1996.
[b] Treatment: S1 = *E. camaldulensis*; S2 = *C. cunninghamiana*; D1 = planting density as 4 × 2 m; D2 = planting density as 4 × 3.5 m.

that of the trees, starting to grow about 1 month earlier and stopping about 1 month later.

3.2. Reduction of surface runoff volume and NO_3–N concentration by buffer strips

Soil surface runoff was reduced by the different tree plantation and pasture buffer strips by 49.9%–57.7% (Table 3) with an average of 52.3%, consequently resulting in NO_3–N load reduction by 53.0%–60.9% with an average of 56.4%. Runoff volume reductions were not significantly different either between the tree treatments or between the tree and pasture buffer strips (Table 3 and Fig. 1a). Similarly, runoff volume reduction rates did not indicate significant difference over the years of 3–6 for both the tree and pasture buffer strips (Fig. 2a).

In general, NO_3–N concentrations in surface runoff below the buffer strips were lower than that above the buffer strips for all the tree plantation and pasture treatments (Table 3) with an average concentration reduction rate of 8.5%, ranging from 6.1% to 13.3%. The reduction rates were not significantly different between the tree buffer strip treatments (Fig. 1b) while the reduction rate for the pasture treatment was significantly higher ($P = 0.011$) than that for any of the tree treatments (Fig. 1b). The reduction of runoff NO_3–N concentration was significantly greater ($P < 0.05$) in year 6 than that of the 3 previous years for both plantations and pasture (Fig. 2b).

3.3. Reduction of groundwater NO_3–N concentration by buffer strips

Nitrate–nitrogen concentrations in groundwater samples collected from the observation wells below the buffer strips were generally lower than that from the wells within and above the buffer both for shallow (Table 4) and deep wells (Table 5). Nitrate–nitrogen concentration in "deep groundwater" was 40–60% higher than that in "shallow groundwater" for all samples collected from sampling wells above, within and below vegetated buffer strips (Tables 4 and 5; Fig. 3). NO_3–N concentrations, when averaged across all treatments and years, were significantly different for groundwater above and below the buffer strips for both shallow wells ($P = 0.030$) and deep wells ($P = 0.004$) (Fig. 3). Mean NO_3–N concentration reduction rates were between 13.8% and 16.0% (Fig. 4) with average values of 14.7% and 14.3% for the shallow and deep groundwater respectively.

There were no significant differences ($P > 0.05$) in NO_3–N reduction rates among the tree and pasture buffer strip treatments for the shallow (Fig. 4a) and deep groundwater (Fig. 4b). Reduction in NO_3–N concentration for both tree plantations and pasture buffer strips was not significantly different ($P > 0.05$) among years 3, 4 and 5 either for the shallow (Fig. 5a) or deep (Fig. 5b) groundwater. However, the reduction rates in year 6 were significantly higher ($P < 0.05$) than any of the previous 3 years (Fig. 5).

Table 3
Reduction in soil surface runoff volume and NO_3–N concentration by vegetated buffer strips.

[a]Year	[b]Treatment	Runoff volume (L m^{-1})		Runoff volume reduction (%)	Runoff NO_3–N concentration (mg L^{-1})		Runoff NO_3–N concentration reduction (%)	NO_3–N load (g m^{-1})		NO_3–N load reduction (%)
		Above buffer	Below buffer		Above buffer	Below buffer		Above buffer	Below buffer	
Third	S1D1	18,580	8776	52.8a	0.77 (0.12)	0.72 (0.09)	6.5a	14.4	6.3	56.3a
	S1D2	18,683	9047	51.6a	0.82 (0.10)	0.77 (0.09)	6.1a	15.3	7.0	54.3a
	S2D1	19,056	8833	53.7a	1.01 (0.09)	0.93 (0.12)	7.9a	19.2	8.2	57.3a
	S2D2	18,457	9254	49.9a	0.90 (0.16)	0.84 (0.13)	6.7a	16.6	7.8	53.0a
	Pasture	18,810	8755	53.5a	0.88 (0.15)	0.79 (0.08)	10.2b	16.6	6.9	58.4a
Fourth	S1D1	16,345	7671	53.1a	0.85 (0.08)	0.79 (0.10)	7.1a	13.9	6.1	56.1a
	S1D2	15,991	7756	51.5a	1.18 (0.11)	1.10 (0.11)	6.8a	18.9	8.5	55.0a
	S2D1	16,721	7079	57.7a	1.15 (0.13)	1.06 (0.12)	7.8a	19.2	7.5	60.9a
	S2D2	16,695	8152	51.2a	1.11 (0.17)	1.04 (0.08)	6.3a	18.5	8.5	54.1a
	Pasture	16,084	7623	52.6a	1.09 (0.10)	0.98 (0.09)	10.1b	17.5	7.5	57.1a
Fifth	S1D1	15,954	7766	51.3a	1.10 (0.15)	1.02 (0.14)	7.3a	17.6	7.9	55.1a
	S1D2	16,098	7909	50.9a	1.21 (0.14)	1.13 (0.13)	6.6a	19.5	8.9	54.4a
	S2D1	15,863	7598	52.1a	0.89 (0.09)	0.82 (0.10)	7.9a	14.1	6.2	56.0a
	S2D2	15,792	7902	50.0a	1.02 (0.09)	0.94 (0.11)	7.8a	16.1	7.4	54.0a
	Pasture	16,103	7859	51.2a	1.19 (0.14)	1.05 (0.13)	11.8b	19.2	8.5	55.7a
Sixth	S1D1	17,450	8077	53.7a	1.42 (0.15)	1.25 (0.12)	12.0a	24.8	10.1	59.3a
	S1D2	17,309	8345	51.8a	1.70 (0.16)	1.53 (0.14)	10.0b	29.4	12.8	56.5a
	S2D1	17,018	7655	55.0a	1.58 (0.18)	1.41 (0.17)	10.8b	26.9	10.8	59.9a
	S2D2	17,635	8399	52.4a	1.54 (0.11)	1.39 (0.12)	9.7b	27.2	11.7	57.0a
	Pasture	17,366	8631	50.3a	1.65 (0.18)	1.43 (0.13)	13.3a	28.7	12.3	57.1a

The means with different letters in a column of a year indicate significant differences at $P < 0.05$. Values in parentheses are standard errors of the means.
[a] Year = the year since the plantation was established in 1996.
[b] Treatment: S1 = *E. camaldulensis*; S2 = *C. cunninghamiana*; D1 = planting density as 4 × 2 m; D2 = planting density as 4 × 3.5 m.

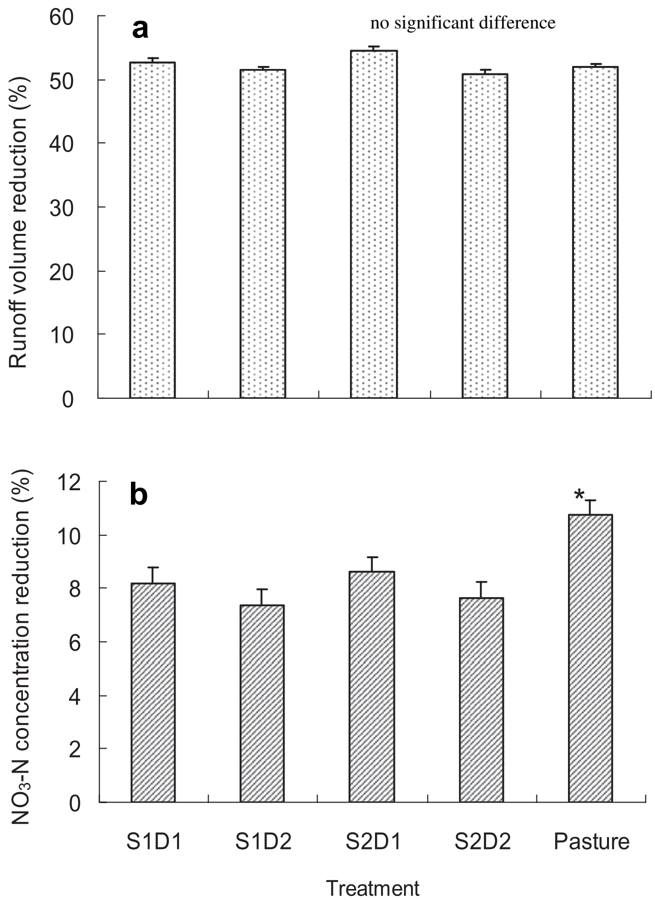

Fig. 1. Comparison in reduction of soil surface runoff volume (a) and NO_3–N concentration (b) by the tree and pasture buffer strip treatments averaged across years 3–6. Treatment: S1 = *E. camaldulensis*; S2 = *C. cunninghamiana*; D1 = planting density as 4 × 2 m; D2 = planting density as 4 × 3.5 m. *Indicates significant difference ($P = 0.011$) in NO_3–N concentration reduction by the pasture than any of the tree buffer strips.

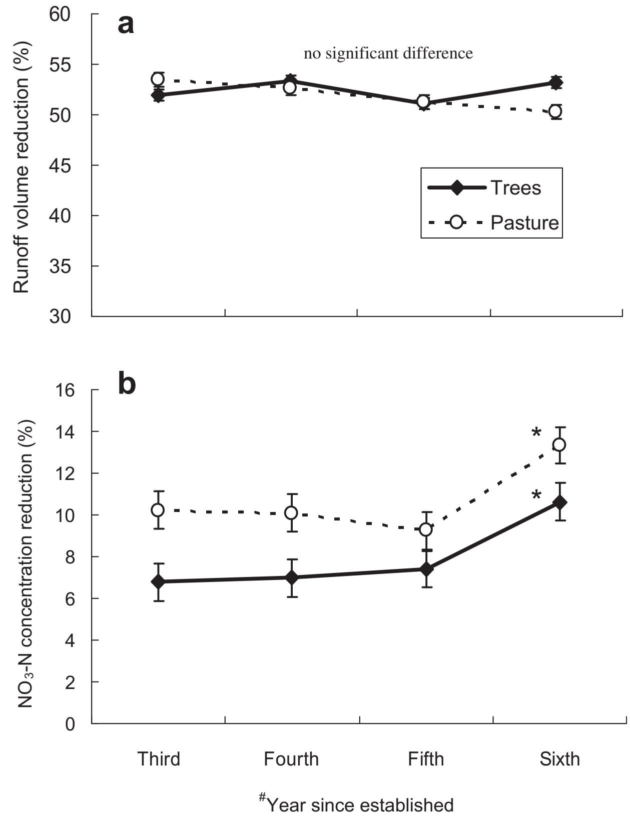

Fig. 2. Average reduction of soil surface runoff volume (a) and NO_3–N concentration (b) by the vegetated buffer strips over the different years. [#]The year since the buffer strips were established in 1996. *Indicates significant difference ($P < 0.05$) in reduction of NO_3–N concentration between year 6 and any of previous years.

4. Discussion

Growth rates of *E. camaldulensis* and *C. cunninghamiana* in this study (Table 2) were better or comparable with that reported from the same area (e.g. Reid et al., 1996; Wall, 1997). However, these two species generally grow much faster under better climatic and soil conditions in Australia. For example, Stewart (1991) reported that the mean height of 4-year-old *E. camaldulensis* irrigated with wastewater at four sites in Victoria were 8.9 m. Normally, *E. camaldulensis* grows faster than *C. cunninghamiana* (e.g. Thorburn, 1995), however, *C. cunninghamiana* was always significantly taller than *E. camaldulensis* in this experiment. This suggests that *C. cunninghamiana* may be better adaptive to the natural environment of this area compared with *E. camaldulensis*. Alternately, may be *E. camaldulensis* is more sensitive to weed competition that was ineffectively repressed by the mowing treatment. Therefore, the adaption and growth of the two tree species still need longer observation and investigation.

E. camaldulensis has broad leaves and a strong tap root system with sinker roots from major lateral roots (Bell et al., 1993) while *C. cunninghamiana* has needle like leaves and a more fibrous root system with a weaker tap root (Wang and Duggin, 2008). Such architectural differences suggest that *E. camaldulensis* may be more efficient at using deeper subsurface soil water while *C. cunninghamiana* may use surface and shallow subsurface soil moisture more efficiently and

Table 4
Changes in soil water NO_3–N concentration (mg L^{-1}) in shallow wells by vegetated buffer strips.

[a]Year	[b]Treatment	Above buffer zone	Within buffer zone	Below buffer zone
Third	S1D1	2.29a (0.15)	2.11a (0.15)	2.04a (0.18)
	S1D2	1.97a (0.12)	1.88a (0.13)	1.79a (0.11)
	S2D1	2.30a (0.19)	2.08a (0.13)	2.15a (0.13)
	S2D2	1.99a (0.09)	1.99a (0.05)	1.86a (0.08)
	Pasture	1.92a (0.07)	1.87a (0.06)	1.78a (0.12)
Fourth	S1D1	2.15a (0.13)	2.08ab (0.09)	1.83b (0.10)
	S1D2	2.07a (0.11)	1.85a (0.14)	1.83a (0.09)
	S2D1	2.23a (0.15)	2.15ab (0.13)	1.90b (0.10)
	S2D2	2.19a (0.08)	1.97ab (0.02)	1.79b (0.08)
	Pasture	2.25a (0.07)	2.06b (0.09)	1.94b (0.02)
Fifth	S1D1	2.01a (0.11)	1.93a (0.08)	1.78a (0.14)
	S1D2	1.99a (0.13)	1.80a (0.12)	1.77a (0.11)
	S2D1	2.02a (0.07)	2.00a (0.10)	1.69b (0.09)
	S2D2	1.99a (0.08)	1.85ab (0.04)	1.64b (0.08)
	Pasture	1.97a (0.17)	1.77b (0.08)	1.74b (0.10)
Sixth	S1D1	3.45a (0.16)	3.01b (0.14)	2.68c (0.07)
	S1D2	3.47a (0.13)	2.99b (0.07)	2.65c (0.14)
	S2D1	3.08a (0.09)	2.45b (0.09)	2.39b (0.11)
	S2D2	3.22a (0.14)	2.66b (0.01)	2.52b (0.09)
	Pasture	3.40a (0.09)	2.62b (0.11)	2.65b (0.15)

The means with different letters in a row indicate significant differences at $P < 0.05$. Values in parentheses are standard errors of the means.
[a] Year = the year since the plantation was established in 1996.
[b] Treatment: S1 = *E. camaldulensis*; S2 = *C. cunninghamiana*; D1 = planting density as 4 × 2 m; D2 = planting density as 4 × 3.5 m.

Table 5
Changes in soil water NO_3–N concentration (mg L^{-1}) in the deep wells by vegetated buffer strips.

[a]Year	[b]Treatment	Above buffer zone	Within buffer zone	Below buffer zone
Third year	S1D1	3.26a (0.18)	3.05ab (0.12)	2.87b (0.14)
	S1D2	3.54a (0.21)	3.70a (0.09)	3.14b (0.09)
	S2D1	3.52a (0.11)	3.39a (0.13)	3.27a (0.11)
	S2D2	4.60a (0.15)	4.01b (0.27)	4.06b (0.14)
	Pasture	3.94a (0.22)	3.56b (0.19)	3.42b (0.13)
Fourth year	S1D1	4.17a (0.23)	3.77b (0.20)	3.58b (0.09)
	S1D2	4.22a (0.19)	4.06a (0.15)	3.75b (0.19)
	S2D1	4.71a (0.25)	4.51a (0.23)	4.08b (0.20)
	S2D2	4.85a (0.30)	4.67a (0.27)	4.39b (0.17)
	Pasture	4.40a (0.18)	4.05b (0.14)	3.89b (0.14)
Fifth year	S1D1	3.85a (0.20)	3.45b (0.11)	3.30b (0.13)
	S1D2	3.71a (0.21)	3.34b (0.19)	3.19b (0.16)
	S2D1	4.05a (0.26)	3.73ab (0.21)	3.48b (0.21)
	S2D2	4.00a (0.17)	3.71ab (0.26)	3.45b (0.18)
	Pasture	4.28 (0.18)	3.95 (0.30)	3.76 (0.20)
Sixth year	S1D1	5.25a (0.32)	4.67b (0.31)	4.03c (0.25)
	S1D2	5.20a (0.28)	4.69b (0.22)	4.22c (0.17)
	S2D1	5.78a (0.33)	4.55b (0.25)	4.45b (0.31)
	S2D2	5.27a (0.19)	4.79b (0.36)	4.20c (0.24)
	Pasture	5.49a (0.27)	4.95b (0.28)	4.44c (0.19)

The means with different letters in a row indicate significant differences at $P < 0.05$. Values in parentheses are standard errors of the means.
[a] Year = the year since the plantation was established in 1996.
[b] Treatment: S1 = *E. camaldulensis*; S2 = *C. cunninghamiana*; D1 = planting density as 4 × 2 m; D2 = density as 4 × 3.5 m.

hence nutrient depletion may be different for each species However, the results from this study showed that there was no significant difference between the two species in reducing surface runoff volume and NO_3–N concentration (Table 3; Fig. 1a) and on the NO_3–N reduction in both shallow and deep groundwater flows (Fig. 4) and consequently did not support the assumption at this developmental stage of the plantation. Our glasshouse simulation experiment (Wang and Duggin, 2008) showed the difference in tree root structure and distribution between the two species, whereas the difference did not show significant influence on NO_3–N removal from groundwater. Further study on the relation between root development and nutrient uptake, assimilation and removal from soil-water system is needed for the two species because the trees were quite young in our experiments.

Many studies have been undertaken on tree or forest buffer strips over the past 50 years or so, but rarely consider the influence

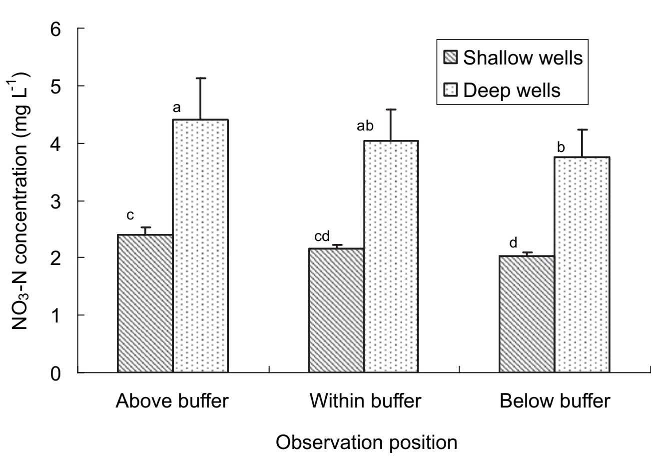

Fig. 3. Comparison of groundwater NO_3–N concentrations between the shallow and deep wells and between the zones above, within and bellow the vegetated buffer strips for all treatments (including the pasture plots) averaged across years 3–6. The bars with different letters indicate a significant difference ($P < 0.05$) in NO_3–N concentrations.

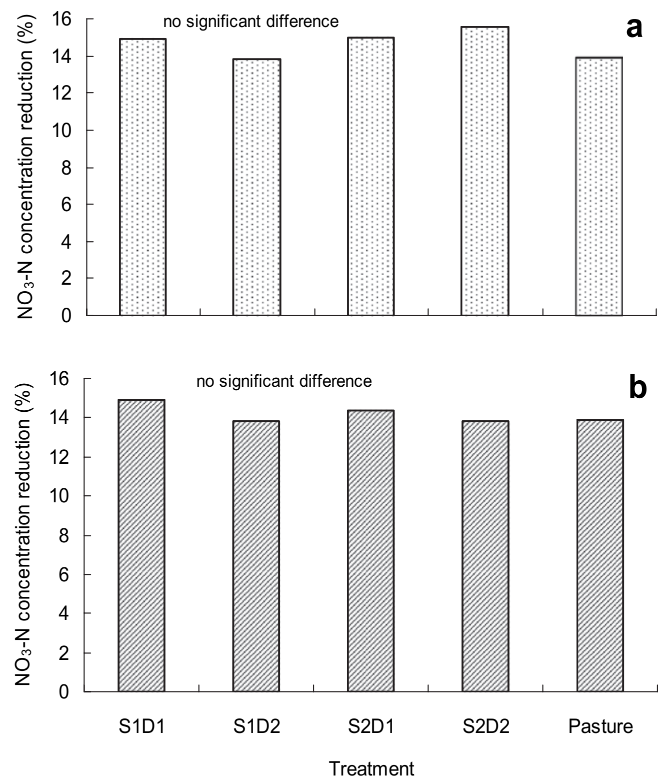

Fig. 4. Comparison in reduction of groundwater NO_3–N concentrations in the shallow wells (a) and deep wells (b) by the vegetated buffer strip treatments averaged across years 3–6. Treatment: S1 = *E. camaldulensis*; S2 = *C. cunninghamiana*; D1 = planting density as 4 × 2 m; D2 = planting density as 4 × 3.5 m.

of tree physiological traits such as nutrient assimilation on the effectiveness of nutrient reduction. Some studies (e.g. Warren, 2006; Paulding et al., 2010) showed that eucalypts such as *Eucalyptus obliqua*, *Eucalyptus radiata* and *Eucalyptus rubida*, preferred ammonium source of nitrogen with a 30–50 times faster uptake rate than nitrate. The preference of *E. camaldulensis* is uncertain and as far as we can tell untested. On the other hand, *C. cunninghamiana* is a nitrogen-fixing tree (Boland et al., 2006) that hardly need N by definition. Therefore, the use of these two species may not be an ideal choice in a vegetated buffer that is designed to remove N although they are local species and naturally occur in riparian zones.

Most researchers have suggested that one of the major processes for vegetated buffer strips in reducing nitrogen pollution is plant uptake (e.g. Lowrance, 1992; Paterson and Schnoor, 1993; Dosskey, 2001, 2002), which implies that faster plant growth rates may result in higher nitrogen reduction rates. In this study, the difference between tree species and density significantly affected tree growth of height, basal area and canopy cover to some extent in different years of growth (Table 2). However, the growth differences did not significantly affect their ability to reduce NO_3–N in soil surface runoff and shallow and deep groundwater. These results reflected the complexity in estimating the capacity of real-world buffer strips (Lowrance and Sheridan, 2005; Dosskey et al., 2010) in reducing non-point sources of nutrient pollution. This was likely controlled, not only by the uptake and assimilation ability of the vegetation but also by complex soil-water interactions, particularly denitrification (Nelson et al., 1995; Dhondt et al., 2002; Bedard-Haughn et al., 2004). These aspects of vegetated buffer strips need to be studied further.

Nitrate–nitrogen concentration reductions for both the tree plantation and pasture buffer strips were not significantly different

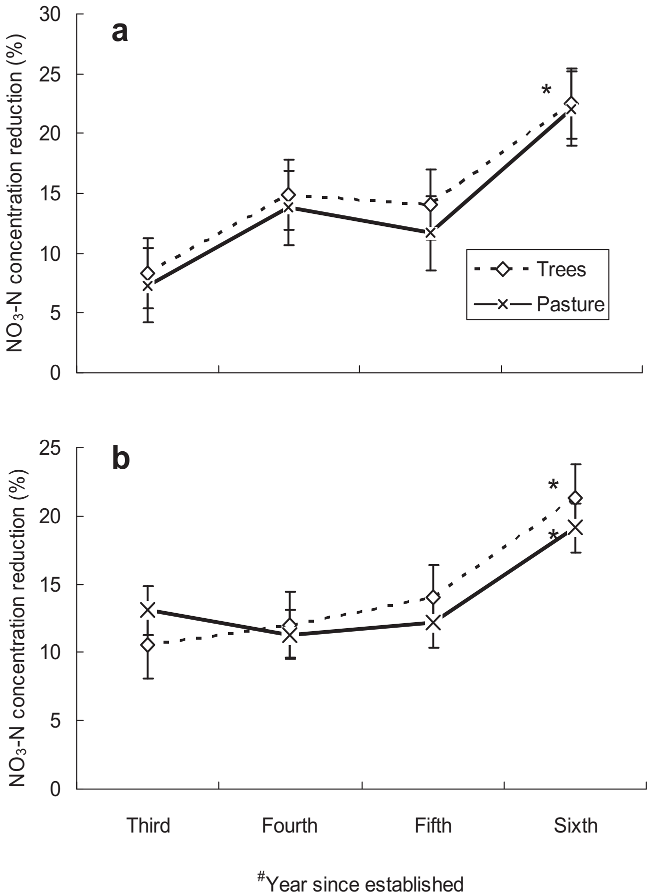

Fig. 5. Average reduction in groundwater NO_3–N concentration in the shallow wells (a) and deep wells (b) by the buffer strips over the different years. #The year since the buffer strips were established in 1996. *Indicates significant difference ($P < 0.05$) in NO_3–N concentration reduction between year 6 and any of previous years.

for the third, fourth and fifth years after establishment either for shallow (Fig. 5a) and deep (Fig. 5b) groundwater or surface runoff (Fig. 2b). However NO_3–N reduction rates in year six were significantly higher than that of all previous years (Fig. 5a and b). This may be explained by an increase in fertilizer nitrogen input (from 79.6, 75.5 and 82.6 kg N ha^{-1} to 150.2 kg N ha^{-1}) (Table 1) to the disposal area rather than an increase in tree growth in that year. These results were comparable to our reported glasshouse experiment (Wang and Duggin, 2008). Borin and Bigon (2002) reported similar results that higher abatement of NO_3–N in correspondence to higher loads of nitrogen. The response or mechanism may be due to a higher plant uptake when more NO_3–N was made available in the soil solution (Lowrance, 1992; O'Neil and Gordon, 1994). However, Sabater et al. (2003) reported that, although NO_3–N removal by biological mechanisms in riparian zones is related closely to the load, an exponential negative decay for NO_3–N removal efficiency is likely to occur when inputs increased above 5 mg N L^{-1}.

In this experiment, NO_3–N concentration in deep groundwater was 40–60% higher than that of shallow groundwater for all samples collected in sampling wells above, within and below the vegetated buffer strips (Tables 4 and 5; Fig. 3). This difference may be due to the differences in root distribution with soil depth but also to NO_3–N movement within the soil profile. Nitrate–nitrogen is relatively mobile and may be easily leached from the soil. Groundwater moves more slowly in the deep clay soil (saturated hydraulic conductivity Ks = 0.0035 cm h^{-1}) than in the sandy clay-loam soil of the A-horizon (Ks = 6.9 cm h^{-1}). Therefore, NO_3–N may be more readily leached from the surface soil and accumulate in the deep soil-groundwater system, resulting in higher NO_3–N concentration in deeper than in shallower groundwater.

In this study, all the buffer strip treatments reduced soil surface runoff volume by more than 50% (Table 3; Fig. 1a), accordingly resulting in NO_3–N load reduction by more than 53% (Table 3), although the difference in reduction of both runoff volume and NO_3–N concentration among the treatments was not significant (Fig. 1a). This demonstrates that both the tree and pasture buffer strips are efficient at reducing NO_3–N, principally through a significant reduction of soil surface runoff volume. Borin et al. (2005, 2010) also found similar results. Therefore, it can be reasonably concluded that reduction in runoff volumes rather than in nutrient concentration was the key factor in abating nutrient pollution load taking into consideration of surface flow.

Putting the tree and pasture treatments together, the buffer strips reduced NO_3–N concentration from the surface runoff (Fig. 1b), shallow and deep groundwater (Fig. 4a and b) by average reduction rates of 8.5%, 14.7% and 14.4% respectively. This result indicated that the vegetated buffer strips had an efficient function to reduce nitrogen pollution for both surface runoff and groundwater, which has been demonstrated by many previous studies around the world (e.g. Osborne and Kovacic, 1993; Lowrance and Sheridan, 2005; Wigington et al., 2003), though the reduction percentage was at the lower level by comparison with other reported studies (Brian et al., 2004).

The performance of tree and pasture buffer strips in this study was variable in reducing NO_3–N concentration in surface runoff, shallow and deep groundwater. The pasture buffer strips reduced significantly more NO_3–N in surface runoff than the tree buffer strips (Table 3; Fig. 1b) while the tree and pasture buffer strips were not significantly different in NO_3–N removal for both shallow and deep groundwater (Fig. 4). This result may be partially explained by the different management strategies applied to the pasture buffer against the tree buffer. For the pasture buffer, grass was harvested 1–3 times per year, while grass and weeds were mowed 2–3 times during the second and third years and were not managed during the rest experimental years for the tree buffer. The study of Bedard-Haughn et al. (2005) supports this hypothesis that nitrate reduction is greater when grass is harvested. This may be one possible reason why surface runoff nitrate reduction was greater in the pasture buffer than the tree buffer in our experiment. Another possible reason is the difference in ground cover between the pasture and the tree buffers. Fortier et al. (2011) has reported that even in small buffer strips, trees can intercept much light and cause significant reduction in the understory biomass. A reduced ground cover may be related to NO_3–N increase in runoff in the tree buffer. Furthermore, *C. cunninghamiana* is a nitrogen-fixer that may have caused an increase in nitrate concentration in the top soil horizon. *E. camaldulensis* may uptake lower rate of nitrate according to some previous study about other *Eucalyptus* species (Boland et al., 2006). Therefore, the choice of tree species in this experiment may have affected the ability of NO_3–N reduction in the tree buffer.

Previous studies reported different results for tree and grass buffer strips in attenuating non-point sources of nutrient pollution. For instance, Osborne and Kovacic (1993) reported that a forest riparian zone in Illinois was more efficient in removing NO_3–N from shallow groundwater than an adjacent grass riparian area. A poplar vegetated riparian zone in England was found to retain more NO_3–N from groundwater than a grass riparian strip (Haycock and Pinary, 1993). Verchot et al. (1997) reported that nitrate attenuation in a grass-vegetated field edge was lower compared to a forest. Groffman et al. (1991) found higher nitrate removal rates in grass buffers when comparison with forested buffers. Sabater et al. (2003) showed that N removal rates were similar for herbaceous and forested sites. Most of these studies were based on mature forests rather than younger, developing plantations such as in our study. It is well known that mature forests have many different characteristics in comparison with newly established plantations, such as deeper rooting systems that are important for groundwater nitrate abatement (Verchot et al., 1997), and higher soil organic carbon content which is particularly important for soil denitrification (Haycock and Pinary, 1993). The lack of difference between tree and pasture buffer strips may change over time as the plantations develop further.

5. Summary and conclusion

The difference between tree species (*E. camaldulensis* and *C. cunninghamiana*) and planting density significantly affected tree growth (height, basal area and canopy cover) although the growth differences did not significantly affect their capacity to reduce NO_3–N in soil surface runoff and shallow and deep groundwater. Using the average of 4 years of data, the tree and pasture buffer strips reduced NO_3–N concentration by 8.5%, 14.7% and 14.4% for the surface runoff, shallow and deep groundwater respectively. The tree and pasture buffer strips were not significantly different in NO_3–N removal for both shallow and deep groundwater while the pasture buffer reduced significantly more NO_3–N concentration in surface runoff than the tree buffer strips. Although the tree and pasture buffer strips did not show significant differences in reducing surface runoff volume, both buffer strips reduced more than 50% of surface runoff volume. This indicates that both the tree and pasture buffer strips are significantly efficient at reduing NO_3–N, principally through a significant reduction in soil surface runoff volume (50–57%) together with a reduction in NO_3–N concentration (7–13%) to give an average reduction in total NO_3–N load of 53–61%.

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