CHAPTER 2

IMPROVING NITROGEN AND IRRIGATION WATER USE EFFICIENCY OF ANNUAL RYEGRASS THROUGH ADAPTIVE MANAGEMENT

2.1 INTRODUCTION

Global use of nitrogen (N) fertiliser has increased more than seven-fold since the 1960s (Smil, 1999; Tilman *et al.,* 2002). Only half of this N is recovered in harvested crops, with the remainder entering aquatic and atmospheric systems, contributing to one of the main human-induced perturbations to the earth's environment (Smil, 1999; Steffen *et al.,* 2007). Despite decades of research on matching fertiliser applications to crop requirements, agriculture remains a major source of environmental contamination (Isermann, 1990; Tamminga, 1992; Matson *et al.,* 1997; Stirzaker, 1999; Goulding, 2000).

Irrigated pasture for milk production is an example of a high N-use agricultural system. Growth and quality are very responsive to applications of N fertiliser and since N is seen as a low cost input for the dairy industry (Tas *et al.,* 2006), excessive applications are common (Eckard *et al.,* 1995). However, high levels of N can reduce pasture quality through toxic levels of nitrate, excessive protein content, increased non-protein N and reduced metabolisable energy (Peyraud and Astigarraga, 1998).

Past research has provided a fairly robust management guideline for famers, such as applying 50 kg N ha^{-1} per growth cycle (Eckard *et al*., 1995). Such rigid guidelines could be improved by 1) soil N testing to estimate N mineralisation and N carry-over between harvests (Andraski and Bundy, 2002; Collins and Allinson, 2004; Miles, 2007) 2) mass balance accounting to match inputs and outputs (Hatfield and Prueger, 2004) and 3) improving irrigation practices (Sumanasena *et al.,* 2004). However, taking the appropriate measurements, for example by soil coring, would be expensive and time consuming for each harvest (Collins and Allinson, 2004), particularly as nitrate levels can change rapidly during the growing season after rain or irrigation.

Adaptive management (Walters, 1986) is an approach that sits between a guideline, on the one hand, and trying to measure or estimate all components of the system, on the other (like using an N mass balance approach where components such as leaching, volatilisation and denitrification are difficult to measure or estimate). Adaptive management is generally considered to be the best approach for managing systems with high uncertainty, or where it is impossible or impractical to collect all the necessary information (Holling, 1978; Walters, 1986; Lee, 1993). Although usually used for addressing complex socio-ecological problems, adaptive management may also be a sensible strategy for the seemingly relatively straight forward problem of optimising N nutrition and crop water supply.

Successful adaptive management hinges on our ability to identify a threshold which is easy to measure and that can be linked to action and on-going learning (Stirzaker *et al*., 2010). Since monitoring is expensive, we seek a measurement that can integrate many of the processes involved in the soil water balance and N cycle, in this case the use of a wetting front detector (WFD) which is a passive lysimeter that approximately estimates the water and nitrate levels moving past a certain depth in the soil profile (Stirzaker, 2003; van der Laan *et al.,* 2010). The objectives of this paper are to test the hypotheses that adaptive N and water management approaches can 1) reduce the recommended N application without compromising yield, 2) maintain or improve forage quality, 3) improve water use efficiency, and 4) minimise potential for nitrate leaching.

2.2 MATERIALS AND METHODS

2.2.1 Site description and crop management

The experiment was conducted at the Cedara Department of Agriculture Experimental Farm located in the midlands of KwaZulu-Natal, one of the main milk producing areas of South Africa (altitude 1076 m above sea level, 29°32’S; 30°17’E). The site has a summer dominated mean annual rainfall of 876 mm and reference evapotranspiration of 1511 mm. Monthly mean minimum and maximum temperatures, and monthly total precipitation recorded from a weather station during the study period are shown in Table 2.1.

Table 2.1 Monthly mean minimum and maximum temperature, and total precipitation recorded during the 2007 and 2008 growing seasons, Cedara, South Africa

Year	Parameter	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.
2007	T_{min} (℃)	13.7	10.9	4.3	1.8	1.3	3.7	10.4	11.2	12.3
	T_{max} (℃)	25.1	23.6	23.3	19.6	20.5	22.0	23.8	21.3	23.1
	Rain (mm)	68.2	34.7	10.0	32.6	0	14.2	17.5	155.5	77.4
2008	T_{min} (℃)	13.2	9.0	7.4	4.2	2.9	5.9	5.9	12.9	13.3
	T_{max} (℃)	24.7	22.2	23.2	19.4	21.1	22.9	22.8	22.3	23.7
	Rain (mm)	3.0	71.3	8.2	21.9	13.0	5.4	42.6	37.5	82.2

T_{min} is mean monthly minimum temperature; T_{max} is mean monthly maximum temperature.

Prior to the commencement of the trial in 2007, replicate undisturbed soil core samples were collected to a depth of 1 m for determination of basic soil physical properties (Table 2.2). The site has a deep, red, kaolinitic Hutton soil (Soil Classification Working Group, 1991) with a clay loam texture to a depth of 0.4 m, with a heavier clay soil from 0.4 to 1.0 m. In both years, soil fertility status was determined prior to planting. Ammonium acetate was used for K, Ca and Mg extraction. Organic carbon and N were estimated by mid-infrared spectroscopy (Ben-Dor and Banin). P measured with Bray I. Nitrate and ammonium N were analysed using 1 M KCl extraction. The soil test results of both years were similar and are presented in Table 2.2. 20 kg P ha^{-1} (super phosphate) was incorporated at planting. Both N (limestone ammonium nitrate) and K (potassium chloride) top dressings were applied within two days of each cutting. The seasonal recommended K (200 kg K ha^{-1}) was divided by the expected number of growth cycles, while the N regime was determined by the treatment. Italian ryegrass (*Lolium multiflorum*) cultivar ‘Agriton’ was planted on the 6th March in 2007 and 25th March 2008 at a seeding rate of 30 kg ha^{-1} and a Cambridge Roller was used to facilitate good contact between the seed and soil.

Table 2.2 Selected soil physical and chemical properties of the experimental site

Soil property	0 - 0.2 m	0.2 - 0.4 m	0.4 - 1.0 m
Saturation (m^3 m^{-3})	0.498	0.481	0.498
Field capacity (m^3 m^{-3})	0.337	0.331	0.329
Wilting point (m^3 m^{-3})	0.206	0.212	0.192
Bulk density (kg m^{-3})	1220	1280	1170
Clay (%)	30.6-38.1	31.0-42.6	40.1-51.9
Sand (%)	31.9-33.4	23.4-34.7	22.8-34.8
Total N (%)	0.19-0.22	0.19-0.21	0.10-0.15
Organic C (%)	2.7-3.2	2.4-2.8	0.90-1.5
pH (KCl)	4.16-4.40	4.25-4.37	4.61-4.75
P (mg kg^{-1})	23-24	15-24	3-7
K (mg kg^{-1})	173-208	94-138	26-44
Ca (mg kg^{-1})	712-820	711-743	471-653
Mg (mg kg^{-1})	156-202	162-195	167-222
Exchangeable acidity (cmol kg^{-1})	0.27-1.17	0.23-1.07	0.11-0.46
Total cations (cmol kg^{-1})	6.45-6.56	5.90-6.19	4.22-6.11
Acid saturation (%)	9-18	7-17	3-9
NO3-N (mg kg^{-1})	34.8-41.4	20.5-48.4	10.4-22.4
NH4-N (mg kg^{-1})	4.9-6.7	6.9-7.9	5.8-9.0

Soil physical properties were determined in 2007 prior to planting. Soil chemical analysis was conducted in both years prior to planting and the ranges are presented.

A dragline sprinkler irrigation system with a delivery rate of 4.0 mm h^{-1} and a sprinkler spacing of 12 m was used. Plots were 12 m wide and 36 m long with a border spacing between plots of 12 m. Each plot had its own sprinkler lines and was irrigated independently by determining the deficit to field capacity using the Diviner-2000 capacitance probe to a depth of 0.6 m (Sentek®, Australia). Plots were irrigated once a week during autumn, spring and summer; and once every two weeks in winter. Treatments were refilled to field capacity except in summer (where about 15 mm soil deficit was left for rain) and on occasion for the adaptive water management treatment included in this study in 2008 (where irrigation was based on nitrate levels).

A wetting front detector (WFD) is a funnel-shaped, passive lysimeter, used for managing irrigation, salinity and nutrition (Stirzaker and Hutchinson, 2005; Tesfamariam *et al.,* 2009; Van der Laan *et al*., 2010). When the soil around the WFD approaches 3 kPa suction during or shortly after irrigation or rainfall, free water is produced at the base of the funnel (Stirzaker, 2008). The water passes through a filter, is collected in a reservoir, and activates a magnetically latched float. A water sample can later be retrieved for analysis using a syringe. The root zone was determined through soil core sampling to a depth of 1 m, with the majority of roots found in the top 0.6 m (Appendix A1). Therefore, WFDs were installed by augering a hole to depths of 0.15, 0.30, 0.45 and 0.60 m in each plot for monitoring depth of wetting and soil solution N concentration.

2.2.2 Treatments

Three treatments in 2007 and seven treatments in 2008 were set up in a randomised block design with three replications. In 2007, the experiment included three fixed N rate applications over eight harvests; representing high (N_{60}: 60 kg N ha^{-1}), and medium (N_{30}: 30 kg N ha^{-1}) forage target yields and a control with zero N (N_0). To avoid differential carry-over effects from 2007 affecting the treatments in 2008, the second year trial was carried out on different plots. In 2008 the experiment was changed because forage yields between N treatments were similar in the first two to three growth cycles. In addition there was also high soil solution nitrate concentrations in the high N application rate treatment (N_{60}), which could be a source of potential leaching. Therefore, in 2008, treatments were improved by estimating/measuring components of the N balance (such as soil N, mineralisation and crop N uptake) or by using a simpler method (adaptive management). The data collected in 2007 were used to derive the management thresholds for the adaptive N and water treatments for 2008. In 2008, treatments included four fixed N rates and one treatment based on N mass balance calculations. In 2008, there were also two adaptive treatments, the first reducing N input and the second reducing irrigation input, both based on nitrate measurements from WFDs. A detailed description of the 2008 treatments follows:

2.2.2.1 Fixed N application rates

No N was applied at planting to take advantage of high levels of residual N, but N rates of 0, 20, 40 and 60 kg N ha^{-1} (N_0, N_{20}, N_{40} and N_{60}) were applied after each harvest. The aim of this series of treatments was to provide the response curve for N.

2.2.2.2 N mass balance (N_{MB})

This treatment represents the strategy of measuring components of the N cycle to get N applications as accurate as possible. N application was estimated from target crop N uptake and adjusted downwards to account for initial soil nitrate and estimated mineralisable N, hence simplifying the N mass balance (Asadi *et al.*, 2002) equation to:

$$N_{fer} = N_{up} - N_{init} - N_{min} \qquad (2.1)$$

Where: N_{fer} is N input from fertiliser; N_{up} is above ground crop N uptake; N_{init} is initial soil inorganic N and N_{min} is predicted mineralisable N. The mass balance approach used here assumes atmospheric N inputs and gaseous N losses through denitrification and volatilisation to be negligible. Although there could be substantial N leaching at the beginning (due to rainfall and a shallow root system) and towards the end of the season (rainfall and a low canopy cover due to fewer tillers), in this study, for the purpose of calculating N application in this treatment, N leaching was assumed to be negligible, as the pasture was irrigated to field capacity in winter and in summer a soil deficit of about 15 mm was left after irrigation to provide a buffer for storing rainfall and minimising leaching.

N_{up} was estimated as the product of target forage yield and N content based on the N dilution curve of annual ryegrass as reported by Marino *et al.* (2004). Marino *et al.* (2004) established the critical plant N concentration (N_c) for annual ryegrass as:

$$N_c = 4.08\ DM^{-0.38} \qquad (2.2)$$

Where, N_c is the critical total N concentration (%) in forage that produces the maximum amount of biomass, dry matter (DM) forage yield is expressed in t ha^{-1}; 4.08 is an empirical coefficient that represents the N_c at 1 t ha^{-1}; and -0.38 characterises the rate of reduction in N_c during growth. This N dilution curve was tested using the data collected in this study and the values were in the ranges previously reported (Marino *et al.,* 2004) (Appendix A2). The relationship is apparently independent of environmental conditions (Lemaire *et al.,* 2008). An uptake of 62 kg N ha^{-1} was estimated for a yield of 2.0 t ha^{-1}, with critical N concentration of 3.1% using the N dilution curve (Marino *et al*., 2004).

N_{init} was the average of nitrate measurements from the WFDs (installed to a depth of 0.6 m) which responded after irrigation or rainfall. The last irrigation of the previous growth cycle was used as initial soil N for the following growth cycle. The solution concentration in mg L^{-1} was converted to kg N ha^{-1} using the volumetric soil water content (θ) of the active rooting depth of annual ryegrass (z) with equation (2.3). This assumes that the resident nitrate concentration in the soil solution was well mixed and therefore equal to nitrate concentration in the mobile soil solution sampled by the detectors. This assumption may, however, not be completely accurate, but this provides a logical means to estimate available nitrate in soil when expensive and time consuming soil analyses are not available. Nitrate N is the dominant form of inorganic N in agricultural soils and NH_4-N forms are usually excluded in soil testing (Vazquez *et al*., 2006), hence NH_4 was assumed to be low and similar in all treatments.

$$N_{init} = (0.226\ WFD_{NO3}\ \rho_w\ \theta\ z)/100 \qquad (2.3)$$

Where: N_{init} is estimated initial N in kg ha^{-1}; WFD_{NO3} (mg L^{-1}) is average nitrate concentration measured from WFDs that recorded fronts just prior to harvest; z is the rooting depth (0.6 m); θ is water content at 3 kPa suction (0.41 m^3 m^{-3}) when the sample is collected; ρ_w is the density of water (1000 kg m^{-3}) and 0.226 is the factor for converting nitrate to nitrate-N and 100 is a conversion factor to kg ha^{-1}.

N_{min} was predicted from initial organic carbon from the soil samples collected at the beginning of the season (Figure 2.1). Miles (2007) developed approximate N release curves for this study region based on soil organic carbon and long term weather data for soils with non-limiting C:N ratios.

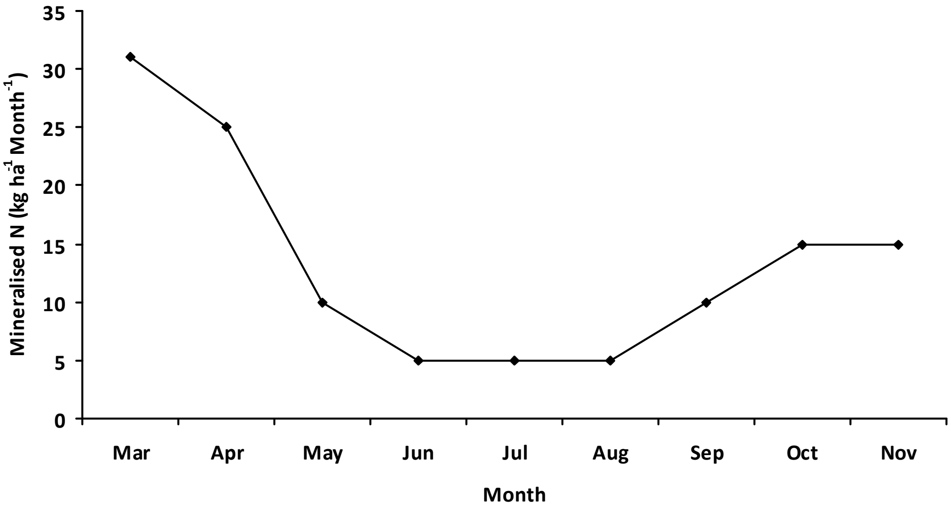

Figure 2.1 Monthly N mineralisation estimates based on organic carbon collected at the beginning of the season

2.2.2.3 Adaptive N (N_{soil})

In this treatment, mean soil solution nitrate concentration of 50 mg L^{-1} was selected as the optimum level by considering both yield and forage quality (Figure 2.2). This value was between the nitrate concentration levels which were detected by WFDs in the soil solution of the N_{30} and N_{60} treatments in 2007. This was a compromise between attaining maximum yield (N_{60} treatment) and optimum quality (N_{30}). As a result, in 2008, N applied for the re-growth after harvest was based on average soil solution nitrate concentrations from all WFDs that responded to the last irrigation/rainfall event of the previous growth cycle. When average soil solution nitrate concentrations exceeded 50 mg L^{-1}, no N was applied. When concentrations were below 25 mg L^{-1}, the recommended 50 kg N ha^{-1} was applied. In between these levels (25 - 50 mg L^{-1}), half of the recommended rate (25 kg N ha^{-1}) was applied (Table 2.3).

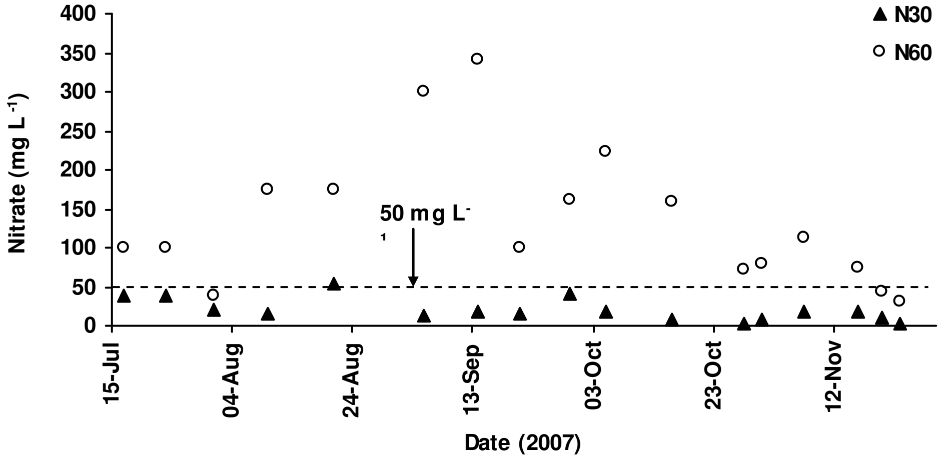

Figure 2.2 Mean nitrate concentrations of wetting front detectors installed at all depths in treatments which received 30 kg N ha^{-1} cycle $^{-1}$ (N_{30}) and 60 kg N ha^{-1} cycle $^{-1}$ (N_{60}) in 2007 (dotted horizontal line represents nitrate threshold level)

2.2.2.4 Adaptive water (N_{water})

Results from 2007 showed that soil solution nitrate increased with higher inputs of fertiliser (Figures 2.3a and b). We hypothesise that high N concentrations at 0.30 and 0.45 m depths increase the probability of N leaching. This adaptive water treatment involved reducing irrigation in response to the depth that irrigation or rainfall penetrated, and to the nitrate concentration of the water sample (Table 2.3). Soil solution nitrate concentration of 25 mg L^{-1} (5.6 mg NO_3-N L^{-1}) was taken as threshold. If concentrations collected from the 0.30 m deep WFD exceeded 25 mg L^{-1}, the irrigation amount was reduced by watering only until the magnetically latched float of the 0.15 m WFD was activated (Figure 2.3a). If the concentrations from the 0.45 m WFD exceeded 25 mg L^{-1}, the scheduled irrigation event was cancelled (Figure 2.3b).

Table 2.3 Treatments in 2007 and 2008: fixed N application rates (N_0, N_{20}, N_{30}, N_{40}, N_{60}), N application based on mass balance calculation (N_{MB}), adaptive N management (N_{soil}) and adaptive water management (N_{water})

Fixed rates				N_{MB} (2008)		N_{soil} (2008)		N_{water} (2008)	
2007	N rate[§]	2008	N rate	Soil NO_3[β]	N rate	Soil NO_3	N rate	Soil NO_3	Next irrigation
N_0	0	N_0	0	As initial N in mass balance calculation	equation 1	>50	0	WFD_{30}>25	Reduced
N_{30}	30	N_{20}	20			25-50	25	WFD_{45} >25	Cancelled
N_{60}	60	N_{40}	40			<25	50		
		N_{60}	60						

[§] N rates in kg ha^{-1} $cycle^{-1}$.

[β] Soil solution nitrate in mg L^{-1}.

Adaptive management is about designing and carrying out management actions as experiments from which one can learn. Therefore, the thresholds for the adaptive management treatments were somewhat arbitrarily selected in the knowledge that they would be improved with experience.

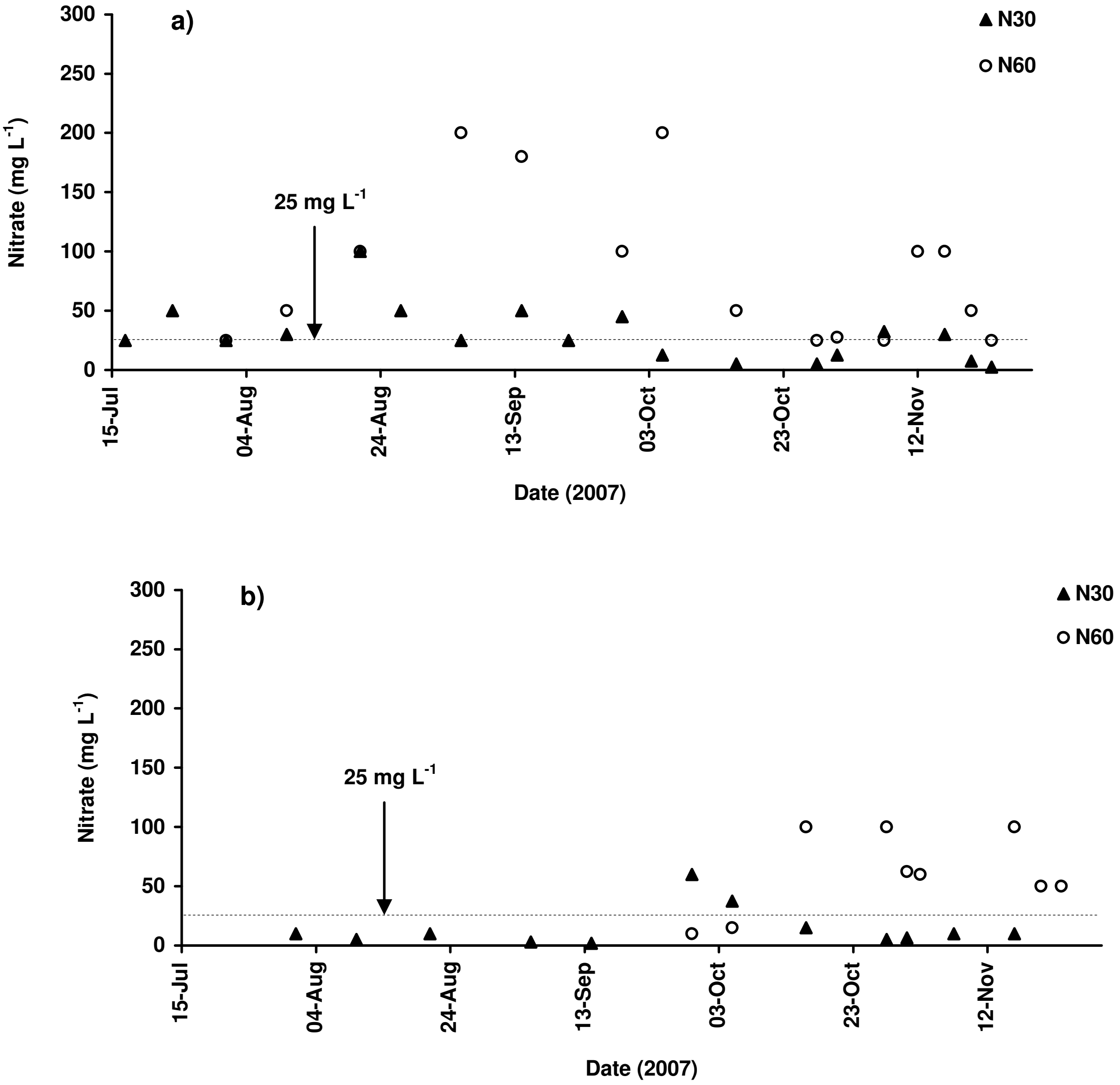

Figure 2.3 Nitrate concentrations of wetting front detectors installed at a) 0.30 m and b) 0.45 m in treatments which received 30 kg N ha^{-1} cycle $^{-1}$ (N_{30}) and 60 kg N ha^{-1} cycle $^{-1}$ (N_{60}) in 2007 (dotted horizontal line represents nitrate threshold level)

2.2.3 Data collection and calculations

The pasture was harvested to 50 mm stubble height at the two to three leaf stage from 1 m^2 quadrants using a manual grass mower. A total of nine samples per treatment (three from each plot) were collected for yield and quality determinations. After taking samples, the whole field was harvested to a height of 50 mm with a tractor drawn mower. Forage dry matter was determined by oven drying samples at 70 °C to constant mass. Samples were milled to pass through a 0.1 mm sieve and were kept in bottles until quality could be determined. Total N was determined by Kjeldahl analysis (AOAC, 2000) and crude protein content (CP) was calculated by multiplying total N concentration by 6.25.

Soil solution samples were collected from WFDs the day following an irrigation/rainfall event, in order to standardise the sampling time and to allow for some soil water redistribution within the profile. For each sample, nitrate concentration was analysed using an RQ Easy Nitrate Reflectometer (Merck KGaA, Germany). Soil cores were also sampled to a depth of 2 m in September and November 2008 from each plot using an auger. Nitrate was determined with an auto-analyzer after extraction using 1M KCl. Potential nitrate leaching (free draining) was determined as the difference of nitrate measurements below the root zone between two successive core sampling dates (September and November).

Crop water use or evapotranspiration of varying treatments was estimated using the soil water balance equation according to Jovanovic and Annandale (1999):

$$ET = P + I - R - Dr - \Delta Q \qquad (2.4)$$

Where: P is precipitation, I is irrigation, R is runoff, Dr is deep drainage below the rooting depth (0.6 m), and ΔQ represents soil water storage. All terms are expressed in mm. R was assumed to be negligible because of a dense pasture cover and relatively level field. Precipitation that exceeded soil water deficit to field capacity in the 0.6 m profile was considered to be lost as drainage. A positive ΔQ indicates a gain in soil water storage. ΔQ was estimated from soil water content measurements with a Diviner probe between two irrigation intervals to a depth of 0.6 m.

Irrigation (IUE), water (WUE) and fertiliser N (NUE) use efficiencies were calculated using:

$$\text{IUE} = \text{Forage yield}/\text{I} \tag{2.5}$$

$$\text{WUE} = \text{Forage yield}/\text{ET} \tag{2.6}$$

$$\text{NUE} = (\text{Forage yield from fertilised treatment} - \text{Forage yield from } N_0)/\text{Applied N} \tag{2.7}$$

2.2.4 Statistical analysis

Analyses of variance (ANOVA) for forage yield, crude protein, nitrogen use, irrigation applied, water use, irrigation and water use efficiencies, and soil solution nitrate concentrations were conducted using SAS (SAS, 2002). Multiple comparisons of means were performed using LSD_{Tukey} at a significance level of $P < 0.05$.

2.3 RESULTS and DISCUSSION

2.3.1 Forage yield and quality

In 2007, maximum forage yields were obtained with N_{60} while the optimum quality was for the N_{30} treatment (Table 2.4). In 2008, in all growth cycles, there were no significant forage yield differences between fixed N rates (N_{40} and N_{60}) and N_{MB}, N_{soil} and N_{water}, except N_{water} in the third cycle (Table 2.5). In both years, there were no significant differences in forage yield between treatments in the first two growth cycles (Tables 2.4 and 2.5). As the seasons progressed, however, significantly different forage yields were exhibited showing the effect of N fertiliser, probably as a result of profile N depletion and reduced N mineralisation (Figure 2.1). The significantly lower forage yield of N_{water} in the third cycle of 2008 could be due to water stress as one irrigation event was cancelled. This did not occur in the fifth cycle when irrigation was skipped because of high rainfall (Table 2.1).

Table 2.4 Forage yield (t ha^{-1}), crude protein (CP: g kg^{-1} DM), total N application rates (kg ha^{-1}), fertiliser N use efficiency (NUE: kg DM kg^{-1} N), irrigation (I: mm), evapotranspiration (ET: mm), irrigation use efficiency (IUE: kg DM ha^{-1} mm^{-1}) and water use efficiency (WUE: kg DM ha^{-1} mm^{-1}) of annual ryegrass under a range of fixed N rate (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) treatments in 2007

Treatment		Forage yield									CP	N rate	NUE	I	ET	IUE	WUE
		07 May 1[§]	11 June 2	11 July 3	08 Aug 4	04 Sep 5	27 Sep 6	24 Oct 7	20 Nov 8	Total							
N_0		2.06a[β]	1.71a	1.16b	0.90c	0.61c	0.65b	0.53c	0.61c	8.23c	172c	0	-	435b	701b	18.8b	12.5b
N_{30}		2.06a	1.72a	1.46a	1.23b	1.76b	1.77a	1.87b	1.35b	13.21b	224b	280	20.8	529a	779a	26.9a	18.3a
N_{60}		2.09a	1.79a	1.58a	1.66a	2.35a	1.98a	2.35a	1.81a	15.61a	265a	460	15.4	565a	816a	29.2a	20.6a
Source of variation	df[φ]	Mean squares															
Treatment	2	0.001	0.006	0.140	0.005	2.324	1.542	2.664	1.095	42.54	6332	-	-	7686	10920	98.20	52.39
Error	4	0.006	0.013	0.004	0.443	0.016	0.007	0.006	0.003	0.048	39.33	-	-	342.1	1016	2.602	0.795
Significance		ns	ns	**	**	**	**	**	**	**	**	-	-	**	**	**	**

[§] Number of growth cycles. [β] Values followed by the same letter within a column are not significantly different.

[φ] Degrees of freedom. ns non-significant and ** significant at the 0.01 probability level.

Table 2.5 Forage yield (t ha^{-1}) and crude protein (CP: g kg^{-1} DM) of annual ryegrass under a range of fixed N rates (0, 20, 40, 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60}), N mass balance (N_{MB}), and adaptive N (N_{soil}) and water (N_{water}) treatments in 2008

Treatment	Yield (t ha^{-1})								CP
	28 May 1[§]	01 July 2	07 Aug 3	05 Sep 4	01 Oct 5	24 Oct 6	16 Nov 7	Total	
N_0	1.10a[β]	1.91a	0.95d	0.76c	0.41c	0.46c	0.41c	5.9c	143d
N_{20}	1.08a	1.96a	1.54c	1.44b	1.34b	1.54b	1.10b	10.0b	175c
N_{40}	1.04a	2.02a	2.10a	2.08a	1.95a	1.97a	1.82a	13.0a	221b
N_{60}	1.09a	2.03a	2.14a	2.16a	2.28a	2.06a	2.05a	13.8a	272a
N_{MB}	1.12a	1.97a (0)[‡]	1.97ab (38)	1.96a (46)	2.05a (47)	1.81ab (43)	1.80a (41)	12.7a	217b
N_{soil}	1.05a	2.07a (0)	1.91ab (20)	2.02a (50)	2.20a (50)	1.92a (50)	1.95a (50)	13.1a	228b
N_{water}	1.16a	1.98a (0)	1.84b (40)	2.01a (47)	2.17a (40)	1.94a (39)	1.92a (39)	13.0a	219b

Source of variation	df[φ]	Mean squares								
Treatment	6	0.005	0.007	0.520	0.770	1.376	0.935	1.093	23.00	5038.10
Error	12	0.004	0.017	0.008	0.029	0.014	0.012	0.021	0.182	24.81
Significance		ns	ns	**	**	**	**	**	**	**

[§] Number of growth cycles.

[β] Values followed by the same letter within a column are not significantly different.

[‡] Values in brackets are fertiliser N application rates (kg N ha^{-1} cycle^{-1}).

[φ] Degrees of freedom.

ns non-significant and ** significant at the 0.01 probability level.

Forage crude protein (CP) concentrations above 220 g kg^{-1} DM may drastically increase nitrate levels, leading to nitrate toxicity (Marais *et al.,* 2003) and increases the risk of N losses from cows through urinary excretion (Tas *et al.,* 2006). Crude protein concentrations exceeded this threshold in the N_{60} treatment (272 g kg^{-1} DM), while it was close to 220 g kg^{-1} DM in the N_{soil}, N_{water}, N_{40}, and N_{MB} treatments (Table 2.5).

2.3.2 Nitrogen rates and nitrogen use efficiency

Seasonal N fertiliser recommendation for annual ryegrass by the South African Department of Agriculture (SADA) is 350 kg N ha^{-1} per year (usually 50 kg N ha^{-1} per cycle) for a target forage yield of 12 t ha^{-1} year^{-1}. As there were no yield differences between N_{40} and N_{60}, it was assumed that the recommended 50 kg N ha^{-1} per cycle would have produced a similar yield. Therefore, the recommended N rate of 50 kg N ha^{-1} per cycle was used as the benchmark against which certain N treatments are compared. When all the parameters required in the N_{MB} approach were measured or calculated, N application was reduced by 28%, from a recommended 300 kg N ha^{-1} per year (50 kg N ha^{-1} per cycle for six cycles) to only 216 kg N ha^{-1} per year. However, the much simpler approaches of adjusting N or irrigation according to threshold values from a WFD reduced applications by 27% (220 kg N ha^{-1}) and 32% (205 kg N ha^{-1}) respectively, compared with the annual recommendation, with no significant impact on yield (Table 2.6). The most marked N fertiliser input reductions using adaptive management strategies were in the second growth cycle when reductions of 100% were observed for both adaptive N treatments with respect to SADA recommendations. In the 3rd cycle, reductions of 60% in N_{soil} and 23% in N_{water} were observed with respect to SADA recommendations (Table 2.6).

Generally, fertiliser use efficiencies (NUE) were higher in 2008 than 2007 (Tables 2.4 and 2.6), probably because no N was applied in the first growth cycle of 2008. An additional growth cycle and higher forage yields obtained from the N_0 treatment could also possibly explain reduced fertiliser NUE in 2007. In 2008, adaptive N and water managements showed significantly higher NUE compared to the fixed rate of $N_{60.}$

Table 2.6 Total N application rates (kg ha^{-1}), fertiliser N use efficiency (NUE: kg DM kg^{-1} N), irrigation (I: mm), evapotranspiration (ET: mm), irrigation use efficiency (IUE: kg DM ha^{-1} mm^{-1}) and water use efficiency (WUE: kg DM ha^{-1} mm^{-1}) of annual ryegrass and soil solution nitrate concentrations (mg L^{-1}) under a range of fixed N rates (0, 20, 40, 60 kg ha^{-1} cycle^{-1} for N_{0}, N_{20}, N_{40}, N_{60}), N mass balance (N_{MB}), and adaptive N (N_{soil}) and water (N_{water}) treatments in 2008

Treatment		N rate	NUE	I	ET	IUE	WUE	Nitrate$^{\beta}$
N_{0}		0	-	343c	493d	17.5d	12.2c	13.1c
N_{20}		120	33.4a§	382ab	547bc	26.2c	18.3b	13.3c
N_{40}		240	29.1ab	384ab	564ab	33.9ab	23.0a	64.5b
N_{60}		360	21.7b	408a	571a	33.9ab	24.2a	101.6a
N_{MB}		216	30.9a	411a	563ab	30.9b	22.5a	21.8c
N_{soil}		220	32.4a	396ab	561ab	33.1ab	23.4a	23.8c
N_{water}		205	34.1a	367bc	529c	35.5a	24.6a	27.4c
Source of variation	df$^{\varphi}$	Mean squares						
Treatment	6	-	62.38	1721.19	2304.43	120.34	60.25	3279.2
Error	12	-	7.41	133.06	69.78	1.180	0.728	72.1
Significance		-	**	**	**	**	**	**

§Values followed by the same letter within a column are not significantly different.

$^{\beta}$Mean nitrates collected from WFDs installed at 0.45 m soil depth.

$^{\varphi}$Degrees of freedom. ns non-significant and ** significant at the 0.01 probability level.

2.3.3 Water use efficiency

In the N_{water} treatment in 2008, irrigations were cancelled on the 23rd of July in growth cycle three and the 27th of September in growth cycle five (Figure 2.4). On both occasions, WFDs at 0.45 m had responded to rainfall. At the beginning of the fourth (August 10) and fifth (September 7) growth cycles, irrigations were reduced according to the N threshold trigger and the pasture was irrigated only until the 0.15 m deep WFDs responded.

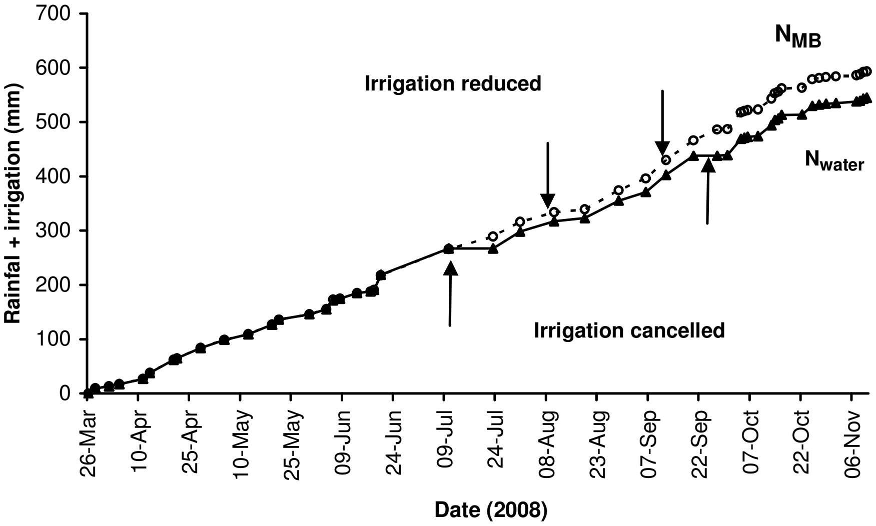

Figure 2.4 Rainfall plus irrigation for N mass balance (N_{MB}) and adaptive water (N_{water}) treatments in 2008 (upward arrows show cancellation of irrigation events and downward arrows reduced irrigation amount)

There were significant differences in irrigation applied and water use between treatments in 2007 (Table 2.4) and 2008 (Table 2.6). In 2008, significantly lower irrigation was applied to N_{water} than N_{MB}. This was due to reduced amount or cancellation of irrigation events as a result of deep WFD response. Seasonal irrigation use efficiency of N_{water} was significantly higher than that of N_{MB}.

2.3.4 Potential leaching

Soil NO_3 concentrations from WFDs (Figure 2.5) and soil coring (Figure 2.6) increased with increase in fertiliser application rate. The N_{MB}, adaptive N (N_{soil}), and water (N_{water}) treatments showed similar soil solution nitrate concentrations, which were mostly lower than the South African (DWAF, 1993) permissible drinking water standard of 44.5 mg NO_3 L^{-1} (10 mg NO_3-N L^{-1}) in all growth cycles except for the first (Figure 2.5), where there was high initial inorganic N and mineralised organic N after tillage (Figure 2.1). The soil solution collected from deep WFDs may not directly be considered to be leaching because the WFDs are not responsive to slow rates of drainage. However, the results do help to identify conditions when nitrate leaching is likely to occur, as shown by deep soil coring (Figure 2.6).

Both adaptive N and water treatments showed relatively lower NO_3 concentrations (soil solution and core samples) than treatment N_{40}, even though the seasonal N application was similar. For example, mean NO_3 concentrations collected from 0.45 m WFDs in the N_{40} treatment were significantly higher than those of the adaptive treatments (Table 2.6). Differences in soil nitrate at 2 m between the September (before the rainy season) and November (end of growing season) soil core sampling dates, were more than 50 mg kg^{-1} for the N_{40} and N_{60} fixed rate treatments (Figure 2.6). The difference in nitrates in the adaptive treatments were, however, less than 25 mg kg^{-1} showing the advantages of adaptive N treatments in reducing the risk of N leaching.

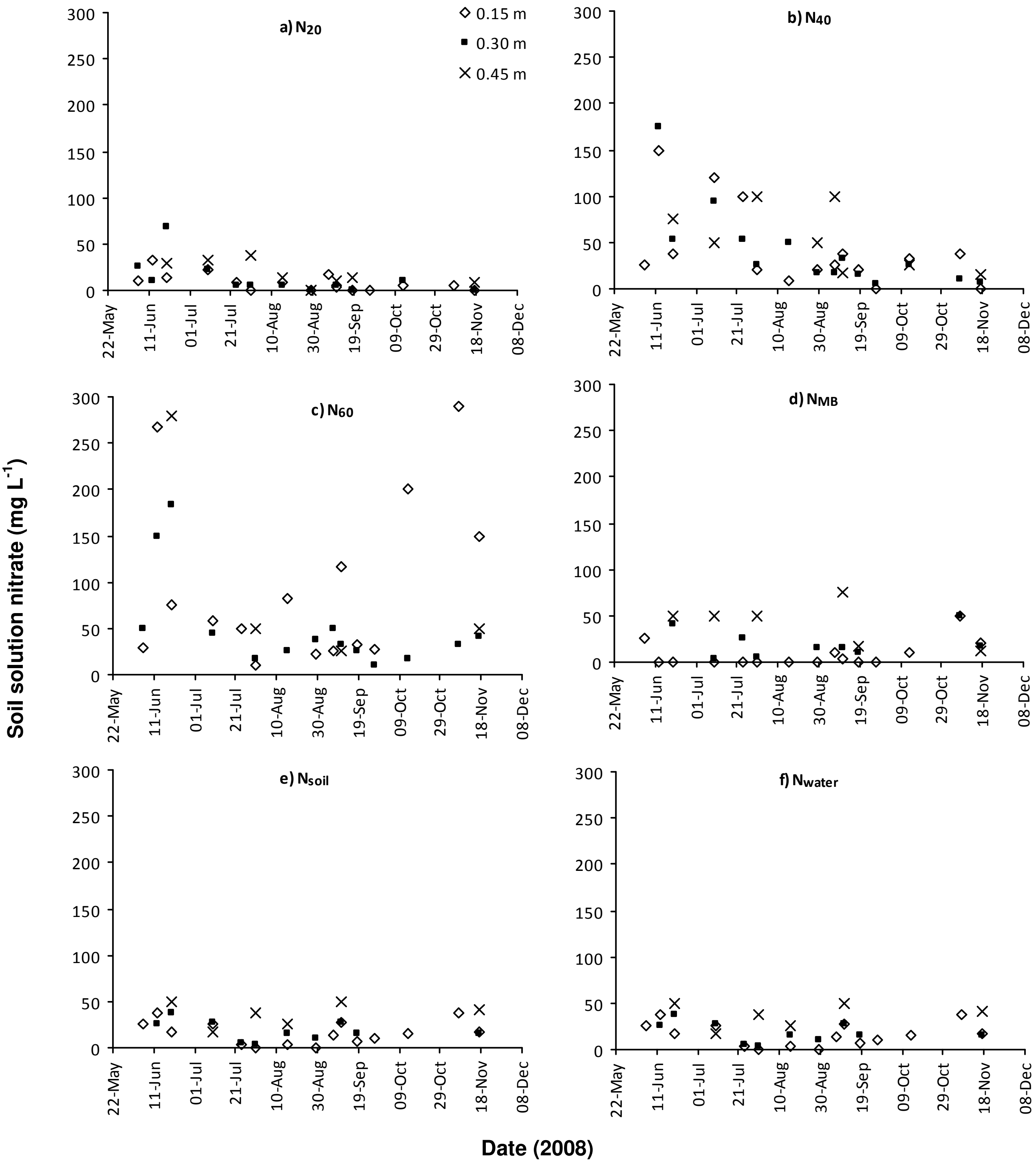

Figure 2.5 Soil solution nitrate concentrations collected from 0.15 (◊), 0.30 (■) and 0.45 (x) m deep wetting front detectors installed in the a) 20 kg ha^{-1} cycle^{-1} (N_{20}), b) 40 kg ha^{-1} cycle^{-1} (N_{40}), c) 60 kg ha^{-1} cycle^{-1} (N_{60}), d) N mass balance (N_{MB}), e) adaptive N (N_{soil}) and f) adaptive water (N_{water}) treatments in 2008

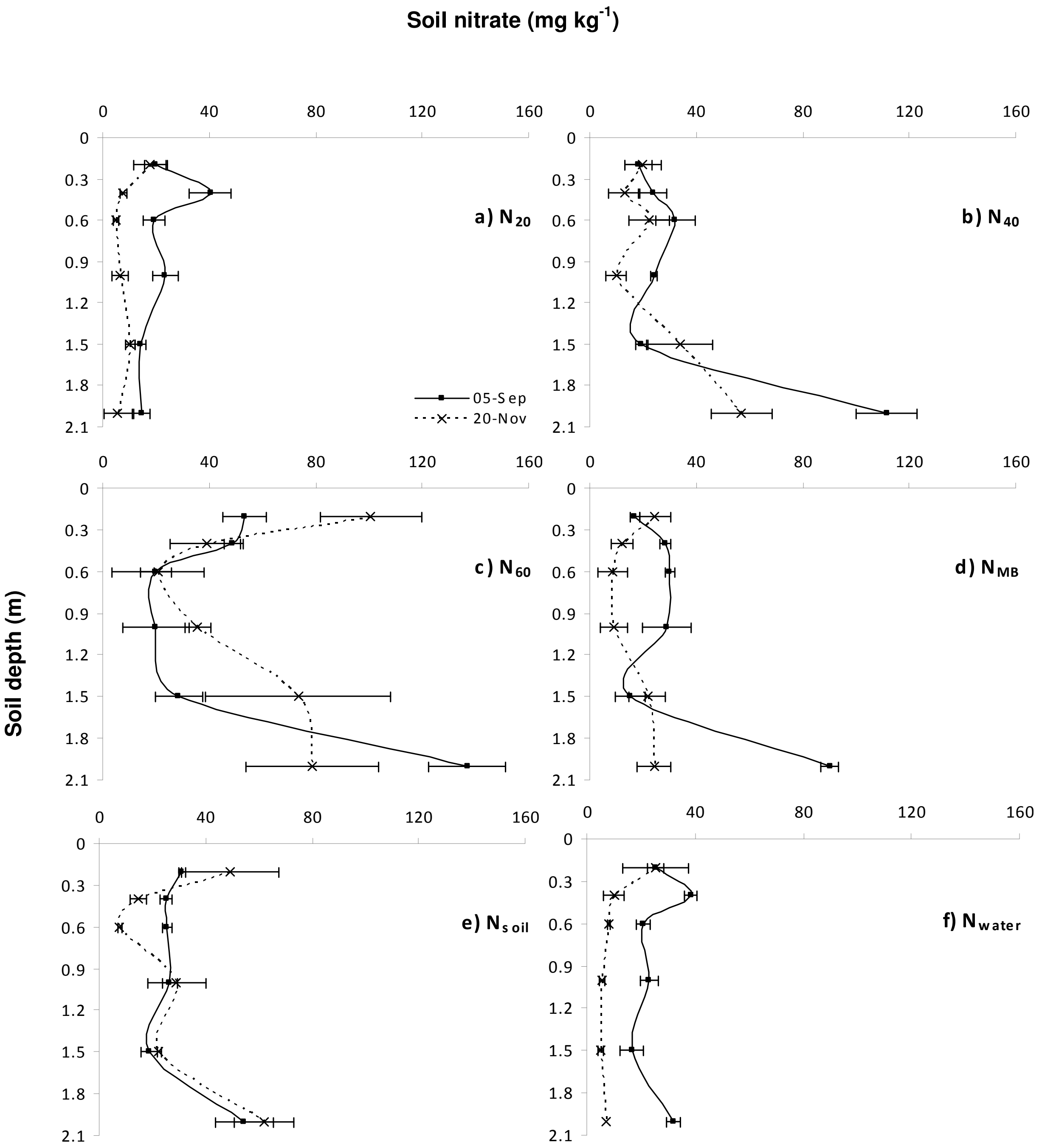

Figure 2.6 Soil nitrate concentrations (mg kg^{-1}) collected from soil cores in September (solid line) and November (dotted line) for the a) 20 kg ha^{-1} cycle^{-1} (N_{20}), b) 40 kg ha^{-1} cycle^{-1} (N_{40}), c) 60 kg ha^{-1} cycle^{-1} (N_{60}), d) N mass balance (N_{MB}), e) adaptive N (N_{soil}) and f) adaptive water (N_{water}) treatments in 2008

2.4 CONCLUSIONS

Results from the first and second seasons showed that the optimum N application per cycle was between 30-60 and 40-60 kg N ha^{-1} respectively, close to the current recommendation of 50 kg N ha^{-1} per cycle. Seasonal N application could be reduced by 28% when many of the components of the N balance were measured at the start of each cutting cycle (N_{MB}). However, the expense of such monitoring may not be justifiable on economic grounds. The trial showed that N savings from intensive monitoring could also be realised through a much simpler adaptive approach based on thresholds for the nitrate concentration in the soil solution. With respect to the baseline recommendations from the South African Department of Agriculture, N application was reduced by 27% and 32% respectively in the two adaptive treatments (reduced N application and reduced water application). Both adaptive treatments resulted in an improvement of forage quality with no yield reduction, and a lower risk of N leaching.

Some may also argue that the use of simple thresholds is little more than an environmental management strategy (EMS), such as those promoted by the international standard organisation (ISO). However, farmers are subjective adaptive managers and the use of simple monitoring and thresholds presents a way to structure their learning, and they represent our simplest conceptualisation of the problem to be managed. A good adaptive manager is expected to improve these thresholds as more experience is gained. For example, lower threshold values than 25 mg L^{-1} could be selected or the two adaptive treatments could be combined to seek alternative strategies.