Improving nitrogen and irrigation water use efficiency through adaptive management: A case study using annual ryegrass

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ABSTRACT

Nitrogen is often poorly managed in irrigated agro-ecosystems. Accumulation and leaching of N can occur due to excessive fertiliser N, high soil inorganic N carryover between seasons, rapid mineralisation in spring and poor irrigation scheduling. This can reduce forage yield, quality and N-use efficiency, and lead to pollution of soil and water resources. Experiments were conducted to test whether adaptive nitrogen and irrigation management approaches using ryegrass as a case study could (1) reduce N application without compromising yield, (2) maintain or improve forage quality, (3) improve water use efficiency, and (4) minimise potential for nitrate leaching, using the current local recommended fertiliser rates as a baseline. Adaptive management strategies based on the concentration of nitrate measured in a wetting front detector at different depths reduced fertiliser N application by 28–32% compared to the baseline recommendation, reduced residual soil N that is potentially leachable, and improved forage quality without reduction in forage yield. The essence of the adaptive approach is to set thresholds for action that are relatively easy to monitor, based on a simple conceptualisation of the system. The thresholds were defined for the depth that a strong wetting front could be passively detected under field conditions, and for the concentration of nitrate in the percolating water. These thresholds were chosen as simple integral measures of the water and N cycles. Results suggest that a good adaptive manager would improve the thresholds for action as more experience is gained.

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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 nitrogen 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 nitrogen 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 nitrogen and reduced metabolisable energy (Peyraud and Astigarraga, 1998).

Past research has provided a fairly robust management guideline for farmers, 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 (Samanasena 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 straightforward 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 approximates the water and nitrate 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 hypothesis 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. Materials and methods

2.1. Site description and general crop management

The experiment was conducted at the Cedara Agricultural Research Council experimental site 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 1.

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). 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, the fertility status of the soil was determined (Table 2) prior to planting. Ammonium acetate was used for K, Ca and Mg extraction. Organic carbon and nitrogen were estimated by mid-infrared spectroscopy. P was measured with Bray I.

Table 1

<table>
<thead>
<tr>
<th>Year</th>
<th>Parameter</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>$T_{min}$ (°C)</td>
<td>25.1</td>
<td>23.6</td>
<td>23.3</td>
<td>19.6</td>
<td>20.5</td>
<td>22.0</td>
<td>23.8</td>
<td>21.3</td>
<td>23.1</td>
</tr>
<tr>
<td>2008</td>
<td>$T_{min}$ (°C)</td>
<td>13.7</td>
<td>10.9</td>
<td>4.3</td>
<td>1.8</td>
<td>1.3</td>
<td>3.7</td>
<td>10.4</td>
<td>11.2</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Physical*</th>
<th>0.0–0.2 m</th>
<th>0.2–0.4 m</th>
<th>0.4–1.0 m</th>
<th>Chemical*</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay (%)</td>
<td>34.3 (2.9)b</td>
<td>37.4 (5.8)</td>
<td>45.0 (3.5)</td>
<td>Total N (%)</td>
<td>0.32 (0.02)</td>
<td>0.29 (0.03)</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>33.9 (3.0)</td>
<td>33.5 (2.5)</td>
<td>25.8 (1.2)</td>
<td>Organic C (%)</td>
<td>2.8 (0.21)</td>
<td>3.2 (0.16)</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>31.8 (1.6)</td>
<td>29.1 (6.4)</td>
<td>29.2 (2.8)</td>
<td>pH (KCl)</td>
<td>4.6 (0.11)</td>
<td>4.4 (0.17)</td>
</tr>
<tr>
<td>Saturation (m³ m⁻³)</td>
<td>0.488 (0.009)</td>
<td>0.481 (0.032)</td>
<td>0.498 (0.019)</td>
<td>P (mg kg⁻¹)</td>
<td>28 (8)</td>
<td>24 (5)</td>
</tr>
<tr>
<td>Field capacity (m³ m⁻³)</td>
<td>0.337 (0.014)</td>
<td>0.331 (0.005)</td>
<td>0.329 (0.046)</td>
<td>K (mg kg⁻¹)</td>
<td>173 (21)</td>
<td>208 (23)</td>
</tr>
<tr>
<td>Wilting point (m³ m⁻³)</td>
<td>0.206 (0.012)</td>
<td>0.212 (0.016)</td>
<td>0.192 (0.018)</td>
<td>Ca (mg kg⁻¹)</td>
<td>712 (29)</td>
<td>820 (17)</td>
</tr>
<tr>
<td>Bulk density (kg m⁻³)</td>
<td>1220 (27)</td>
<td>1280 (24)</td>
<td>1170 (46)</td>
<td>Mg (mg kg⁻¹)</td>
<td>156 (12)</td>
<td>202 (14)</td>
</tr>
</tbody>
</table>

* Soil physical properties were determined in 2007 prior to planting.
\[b\] Standard deviations.
\[c\] Soil chemical analysis was conducted in both years prior to planting. Ammonium acetate was used for K, Ca and Mg extraction. Organic carbon and nitrogen were estimated by mid-infrared spectroscopy. P was measured with Bray I.
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 (N60: 60 kg N ha$^{-1}$), and medium (N30: 30 kg N ha$^{-1}$) forage target yields and a control with zero N (N0). To avoid differential carry-over effects from 2007 affecting the treatments in 2008, the second year trial was carried out on different plots. The experiment was changed in 2008 because in the first two to three growth cycles of 2007, forage yields between N treatments were similar. In addition there were also high soil solution nitrate levels in the high N application rate treatment (N60), 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. Treatments

#### 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$^{-1}$ (N0, N20, N40 and N60) were applied after each harvest. The aim of this series of treatments was to provide the response curve for N.

#### 2.2.2. N mass balance (NMB)

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:

$$N_{\text{fer}} = N_{\text{up}} - N_{\text{init}} - N_{\text{min}} \tag{1}$$

where $N_{\text{fer}}$ is N input from fertiliser; $N_{\text{up}}$ is above ground crop N uptake; $N_{\text{init}}$ is initial soil inorganic N and $N_{\text{min}}$ is predicted mineralisable N. The mass balance approach used here assumes atmospheric N inputs and gaseous N losses through denitrification.
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 N0, N20, N40, N60), N mass balance (N\(_{MB}\)), and adaptive N (N\(_{soil}\)) and water (N\(_{water}\)) treatments in 2008.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Yield (t ha(^{-1}))</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 May</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>01 July</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>07 August</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>05 September</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>01 October</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>24 October</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>16 November</td>
<td>0.38</td>
<td></td>
</tr>
</tbody>
</table>

Source of variation
d\(^{d}\) Mean squares

<table>
<thead>
<tr>
<th>Treatment</th>
<th>df</th>
<th>d(^{d})</th>
<th>Mean squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error</td>
<td>12</td>
<td>0.012</td>
<td>0.021</td>
</tr>
<tr>
<td>Significance</td>
<td>ns</td>
<td>ns</td>
<td>** ns**</td>
</tr>
</tbody>
</table>

\(^{a}\) Number of growth cycles.

\(^{b}\) Values followed by the same letter within a column are not significantly different.

\(^{c}\) Values in brackets are fertilizer N application rates (kg N ha\(^{-1}\) cycle\(^{-1}\)).

\(^{d}\) Degrees of freedom.

ns non-significant.

** Significant at the 0.01 probability level.

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 rainfall. The last irrigation of the previous growth cycle was used as a logical means to estimate available nitrate in soil solution.

N\(_{soil}\) 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 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 the 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 (\(\theta\)) of the active rooting depth of ryegrass (\(D\)) with Eq. (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. Nitrates 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.

\[ N_{init} = \frac{0.226 \times WFD_{NO3} \times \rho_{w} \times D}{100} \] (3)

Table 6

<table>
<thead>
<tr>
<th>Treatment</th>
<th>N rate</th>
<th>NUE</th>
<th>I</th>
<th>ET</th>
<th>IUE</th>
<th>WUE</th>
<th>Nitrate(^{b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>N0</td>
<td>0</td>
<td>–</td>
<td>343c</td>
<td>493d</td>
<td>17.5d</td>
<td>12.2c</td>
<td>13.1c</td>
</tr>
<tr>
<td>N20</td>
<td>120</td>
<td>33.4a</td>
<td>382ab</td>
<td>547bc</td>
<td>26.2c</td>
<td>18.3b</td>
<td>21.7b</td>
</tr>
<tr>
<td>N40</td>
<td>240</td>
<td>29.1ab</td>
<td>384ab</td>
<td>564ab</td>
<td>33.9ab</td>
<td>23.0a</td>
<td>64.5b</td>
</tr>
<tr>
<td>N60</td>
<td>360</td>
<td>21.7b</td>
<td>408a</td>
<td>571a</td>
<td>33.9ab</td>
<td>23.0a</td>
<td>101.6a</td>
</tr>
<tr>
<td>N80</td>
<td>216</td>
<td>30.9a</td>
<td>411a</td>
<td>563ab</td>
<td>30.9b</td>
<td>22.5a</td>
<td>21.8c</td>
</tr>
<tr>
<td>Nsoil</td>
<td>220</td>
<td>32.4a</td>
<td>396ab</td>
<td>561ab</td>
<td>33.1ab</td>
<td>23.4a</td>
<td>23.8c</td>
</tr>
<tr>
<td>Nwater</td>
<td>205</td>
<td>34.1a</td>
<td>367bc</td>
<td>529c</td>
<td>35.5a</td>
<td>24.5a</td>
<td>27.4c</td>
</tr>
</tbody>
</table>

Source of variation
d\(^{d}\) Mean squares

<table>
<thead>
<tr>
<th>Treatment</th>
<th>df</th>
<th>d(^{d})</th>
<th>Mean squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error</td>
<td>12</td>
<td>7.41</td>
<td>133.06</td>
</tr>
<tr>
<td>Significance</td>
<td>ns</td>
<td>ns</td>
<td>** ns**</td>
</tr>
</tbody>
</table>

\(^{a}\) Values followed by the same letter within a column are not significantly different.

\(^{b}\) Mean nitrates collected from WFDs installed at 0.45 m soil depth.

\(^{c}\) Degrees of freedom.

ns non-significant.

** Significant at the 0.01 probability level.

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 crop quality (Fig. 2). This value was between the nitrate concentration levels, which were detected by WFDs in the soil solution of the N30 and N60 treatments in 2007. This was a compromise between attaining maximum yield (N60 treatment) and optimum quality (N30). 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 3).

2.2.4. Adaptive water ($N_{water}$) 

Results from 2007 showed that soil solution nitrate increased with higher inputs of fertiliser (Fig. 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 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 (Fig. 3a). If the concentrations from the 0.45 m WFD exceeded 25 mg L$^{-1}$, the scheduled irrigation event was cancelled (Fig. 3b).

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.
2.3. Data collection and calculations

The pasture was harvested to 50 mm stubble height at the two to three leaf stage from 1 m² 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 1 M KCl. Potential nitrate leaching (free draining) was determined as the difference in 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):

\[
ET = P + I - R - Dr - \Delta Q
\]

where \( P \) is precipitation, \( I \) is irrigation, \( R \) is runoff, \( Dr \) is deep drainage below the rooting depth (0.6 m), and \( \Delta Q \) 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 \( \Delta Q \) indicates a gain in soil water storage. \( \Delta Q \) was estimated from soil water content measurements with a Diviner probe between two irrigation intervals to a depth of 0.6 m.
Fig. 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.

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

\[
\text{IUE} = \frac{\text{Forage yield}}{I} 
\]

\[
\text{WUE} = \frac{\text{Forage yield}}{ET} 
\]

\[
\text{NUE} = \frac{\text{Forage yield from fertilised treatment} - \text{Forage yield from N} \_0}{\text{Applied N}} 
\]

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 \(P < 0.05\).

3. Results and discussion

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 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 5). In both years, there were no significant differences in forage yield between treatments in the first two growth cycles (Tables 4 and 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 (Fig. 1). The significantly low 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 1).

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 N60 treatment (272 g kg\(^{-1}\) DM), while it was close to 220 g kg\(^{-1}\) DM in the Nsoil, Nwater, N40, and NMB treatments (Table 5).

### 3.2. N rates and N 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 N40 and N60, 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 NMB 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 of six cycles) to only 216 kg N ha\(^{-1}\) per year. However, the much simpler approaches of reducing 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 5). 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 Nsoil and 23% in Nwater were observed with respect to SADA recommendations (Table 6).

Generally, fertiliser use efficiencies (NUE) were higher in 2008 than 2007 (Tables 4 and 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 N0 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 N60.

### 3.3. Water use efficiency

In the Nwater treatment in 2008, irrigations were cancelled on the 23rd of July in growth cycle three and the 27th of September in growth cycle five (Fig. 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. There were significant differences in irrigation applied and water use between treatments in 2007 (Table 4) and 2008 (Table 6). In 2008, significantly lower irrigation was applied to Nwater than NMB. This was due to reduced amount or cancellation of irrigation events as a result of deep WFD response. Seasonal irrigation use efficiency of Nwater was significantly higher than that of NMB.

### 3.4. Potential leaching

Soil NO\(_3\) concentrations from WFDs (Fig. 5) and soil coring (Fig. 6) increased with increase in fertiliser application rate. The NMB, adaptive N (Nsoil), and water (Nwater) treatments showed similar soil solution nitrate concentrations, which were mostly lower than the South African (DWF, 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 (Fig. 5), where there was high initial inorganic N and mineralised organic N after tillage (Fig. 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 (Fig. 6).

Both adaptive N and water treatments showed relatively lower NO\(_3\) concentrations (soil solution and core samples) than treatment N40, even though the seasonal N application was similar. For example, mean NO\(_3\) concentrations collected from 0.45 m WFDs in the N40 treatment were significantly higher than those of the adaptive treatments (Table 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 kg N ha\(^{-1}\) for the N40 and N60 fixed rate treatments (Fig. 6). The difference in nitrates in the adaptive treatments were, however, less than 25 kg N ha\(^{-1}\) showing the advantages of adaptive N treatments in reducing the risk of N leaching.

### 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 (NMB). 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.

The thresholds used in this study do have weaknesses in their interpretation. For example, the WFD used to collect water samples does not respond to fronts moving at suction drier than 2–3 kPa (Stirzaker, 2008). Furthermore, the nitrate concentration of the leaching water may be different from the resident soil water which would be available to the pasture (Corwin et al., 1991; van der Laan et al., 2010). Moreover, the thresholds were selected from just one season’s data, but they could no doubt be improved.

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 standards organisation (ISO). However, farmers are intuitively 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 (Wilson et al., 2009; Stirzaker et al., 2010). A good adaptive manager is expected to improve these thresholds as more experience is gained. A manager could for example select a lower threshold than 25 mg L\(^{-1}\), or alternatively he could combine the two adaptive treatments to seek alternative strategies.

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