Agriculture, Ecosystems and Environment 141 (2011) 350–358

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

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

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ARTICLE INFO

Article history:
Received 26 October 2010
Received in revised form 14 March 2011
Accepted 29 March 2011
Available online 22 April 2011

Keywords:
Forage yield
Soil solution nitrate
Threshold soil nitrate
Wetting front detector

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.

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 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 carryover 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

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doi:10.1016/j.agee.2011.03.018

Table 1
Monthly mean minimum and maximum temperature, and total precipitation recorded during the 2007 and 2008 growing seasons, Cedara, South Africa.

Year	Parameter	March	April	May	June	July	August	September	October	November
2007	T_{min} (°C)	25.1	23.6	23.3	19.6	20.5	22.0	23.8	21.3	23.1
	T_{max} (°C)	13.7	10.9	4.3	1.8	1.3	3.7	10.4	11.2	12.3
	Rain (mm)	68.2	34.7	10.0	32.6	0	14.2	17.5	155.5	77.4
2008	T_{min} (°C)	24.7	22.2	23.2	19.4	21.1	22.9	22.8	22.3	23.7
	T_{max} (°C)	13.2	9.0	7.4	4.2	2.9	5.9	5.9	12.9	13.3
	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.

Table 2
Selected soil physical and chemical properties of the experimental site.

Physical[a]	0–0.2 m	0.2–0.4 m	0.4–1.0 m	Chemical[c]	2007	2008
Clay (%)	34.3 (2.9)[b]	37.4 (5.8)	45.0 (3.5)	Total N (%)	0.32 (0.02)	0.29 (0.03)
Silt (%)	33.9 (3.0)	33.5 (2.5)	25.8 (1.2)	Organic C (%)	2.8 (0.21)	3.2 (0.16)
Sand (%)	31.8 (1.6)	29.1 (6.4)	29.2 (2.8)	pH (KCl)	4.6 (0.11)	4.4 (0.17)
Saturation ($m^3\,m^{-3}$)	0.498 (0.009)	0.481 (0.032)	0.498 (0.019)	P (mg kg^{-1})	28 (8)	24 (5)
Field capacity ($m^3\,m^{-3}$)	0.337 (0.014)	0.331 (0.005)	0.329 (0.046)	K (mg kg^{-1})	173 (21)	208 (23)
Wilting point ($m^3\,m^{-3}$)	0.206 (0.012)	0.212 (0.016)	0.192 (0.018)	Ca (mg kg^{-1})	712 (29)	820 (17)
Bulk density (kg m^{-3})	1220 (27)	1280 (24)	1170 (46)	Mg (mg kg^{-1})	156 (12)	202 (14)

[a] 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 measured with Bray I.

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 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 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. 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. 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. Recommended planting dates for this region is between mid-February and mid-April each year.

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

Table 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[a]	2008	N rate	Soil NO_3[b]	N rate	Soil NO_3	N rate	Soil NO_3	Next irrigation
		N_0	0	As initial N in mass balance calculation	Eq. (1)	>50	0	WFD_{30} > 25	Reduced
N_0	0	N_{20}	20			25–50	25	WFD_{45} > 25	Cancelled
N_{30}	30	N_{40}	40			<25	50		
N_{60}	60	N_{60}	60						

[a] N rates in kg ha^{-1} $cycle^{-1}$.
[b] Soil solution nitrate in mg L^{-1}.