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Increased stocking rate and associated strategic dry-off decision rules reduced the amount of nitrate-N leached under grazing

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ABSTRACT

The effect of intensive agricultural systems on the environment is of increasing global concern, and recent review articles have highlighted the need for sustainable intensification of food production. In grazing dairy systems, the leaching of nitrate-N (NO_3-N) to groundwater is a primary environmental concern. A herd-level factor considered by many to be a key contributor to the amount of NO_3-N leached from dairy pastures is stocking rate (SR), and some countries have imposed limits to reduce the risk of NO_3-N loss to groundwater. The objective of the current experiment was to determine the effect of dairy cow SR on NO_3-N leached in a grazing system that did not import feed from off-farm and had the same N fertilizer input. Five SR were evaluated (2.2, 2.7, 3.1, 3.7, and 4.3 cows/ha) in a completely randomized design (i.e., 2 replicates of each SR as independent farmlets) over 2 y. Pasture utilization, milk production/hectare, and days in milk/hectare increased with SR, but days in milk/cow and milk production/cow declined. The concentration of NO_3-N in drainage water and the quantity of NO_3-N leached/ha per year declined linearly with increasing SR, and the operating profit/kg NO_3-N leached per ha increased. Higher SR was associated with fewer days in milk/cow, resulting in a reduction in estimated urine N excretion/cow (the main source of N leaching) during the climatically sensitive period for NO_3-N leaching (i.e., late summer to winter). We hypothesized that the reduction in estimated urine N excretion per cow led to an increase in urinary N spread and reduced losses from urine patches. The results presented indicate that lowering SR may not reduce nitrate leaching and highlight the need for a full farm system-level analysis of any management change to determine its effect on productivity and environmental outcomes.

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INTRODUCTION

The efficiency with which resources are used in animal production has improved over the last half century; for example, Capper et al. (2009) have estimated that 21% of the animals, 23% of the feedstuffs, 35% of the water, and only 10% of the land would be required to produce 1 billion kilograms of milk in the United States today compared with dairy systems in 1944. Nevertheless, there is concern in most developed countries about how this intensification of agriculture has contributed to the degradation of water and air quality (FAO, 2006; Huebsch et al., 2013; Place and Mitloehner, 2013) and, more importantly, what will happen to these measures of environmental sustainability in the drive to provide nourishment for the global population of more than 9 billion people projected for 2050.

Although the requirement for food production is set to increase by 70 to 100% over the next 35 yr (FAO, 2009; Godfray et al., 2010), interest in pasture-based dairy production systems has been rejuvenated because of the potential for reduced production costs (Macdonald et al., 2011; Ramsbottom et al., 2015) and perceived animal welfare advantages. However, N-use efficiency has traditionally been low in grazing systems (Ledgard et al., 2009; Huebsch et al., 2013), because intensively managed temperate pastures contain substantially more RDP than is required for the milk production levels achieved (Kolver and Muller, 1998; Roche et al., 2009b); the excess N is excreted in high concentrations in urine and can contribute to increased soil solution and groundwater nitrate-N (**NO_3-N**) concentrations (Di and Cameron, 2007; Shepherd et al., 2010; Huebsch et al., 2013).

A key farm-level factor in successful grazing systems is stocking rate (**SR**), which affects pasture utilization, per-cow and per-hectare milk production, and farm profitability (Macdonald et al., 2008, 2011; McCarthy et al., 2011, 2012). Because pasture utilization and, therefore, the consumption of N/ha increases with SR, it is plausible to assume that the loss of N through leaching will also increase. However, in a recent longitudinal study of groundwater quality as a result of farm management changes on an intensive-grazing dairy farm (Huebsch et al., 2013), the concentration of N in groundwater declined over 11 yr, despite a 20% increase in SR. These results were confounded by changes in several management practices at the study site, including reduced inorganic fertilizer usage, improvements in timing of effluent application, the movement of a dairy soiled water irrigator to areas deemed less vulnerable to leaching, and the use of minimum cultivation reseeding. It was not possible, therefore, to determine the effect of SR per se on the loss of N to groundwater.

We had a unique opportunity to investigate the effect of SR on the amount of NO_3-N leached/hectare and the efficiency with which available N is converted to product. We investigated the effects of 5 SR treatments on pasture growth and utilization, milk production (Macdonald et al., 2008, 2010), and profitability (Macdonald et al., 2011) in a multi-year farm systems experiment. The installation of ceramic cup samplers at 1 m depth in paddocks of all treatments enabled us to determine the effect of SR on NO_3-N leaching under pastoral systems. The objective of this experiment was to investigate the effect of increasing SR on the amount of NO_3-N leached/hectare below the root zone of grazed temperate pastures.

MATERIALS AND METHODS

The component of the experiment evaluating N-use efficiency took place over 2 yr at No. 2 Dairy Farm, DairyNZ, Hamilton, New Zealand (37°47′S, 175°19′E, 40 m above sea level); methods detailing the production measures collected over 3 yr have been reported in detail by Macdonald et al. (2008, 2010). All procedures were approved by the AgResearch Animal Ethics Committee in accordance with the New Zealand Animal Welfare Act. Briefly, 188 Holstein-Friesian cows were randomly allocated to 1 of 2 replicates of 5 SR farmlets (2.2, 2.7, 3.1, 3.7, and 4.3 cows/ha) in a completely randomized design (i.e., 2 replicates of each SR as independent farmlets). The comparative SR (kg of BW/t of total feed DM; Macdonald et al., 2008) equivalent to the SR imposed were expected to be 62, 76, 90, 103, and 120 kg of BW/t of total feed DM available per year, respectively, assuming pasture production/ha was the same on all treatments (18.0 t of DM pasture was grown/ha per year; McGrath et al., 1998) and no feeds were acquired externally to the grazing platform. This would have been equivalent to an annual feed allowance of 8.1, 6.8, 5.8, 4.9, and 4.2 t of feed DM/cow per year for the 2.2, 2.7, 3.1, 3.7, and 4.3 cows/ha SR treatments, respectively. As outlined by Macdonald et al. (2008), however, pasture grown tended to increase ($P = 0.11$), pasture consumed increased linearly ($P < 0.01$), and cow BW decreased with SR, and a small amount of pasture silage was purchased for the highest 2 SR treatments (136 and 189 kg of DM/cow, for the 3.7 and 4.3 cows/ha farmlets, respectively) as required by the Animal Ethics Committee. Therefore, actual comparative SR were 60, 70, 76, 89, and 91 kg of BW/t of total feed DM available for the 2.2, 2.7, 3.1, 3.7, and 4.3 cows/ha SR treatments, respectively, using the BW of the cows in mo 6 of lactation. This is equivalent to an annual allowance of 8.2, 6.7, 6.3, 5.1, and 4.9 t of feed DM/cow, respectively.

Farmlet Management

The farms were managed as seasonal calving systems, with cows calving over 8 wk in spring. Approximately 20% of cows from each farmlet were culled during each lactation, based on reproductive failure, health, age, and genetic merit, and were replaced with primiparous cows 1 mo before the planned start of calving. Age structure did not differ across treatments. Grazing management decision rules were the same across treatments, with the exception of intergrazing interval (rotation length), which was managed to optimize each individual treatment (Macdonald et al., 2008, 2010). Defined grazing areas (paddocks) were grazed in a rotational order, with cows returning to the same area only when more than 2 leaves had appeared on more than two-thirds of perennial ryegrass tillers. All farmlets received 200 kg of N/ha per year as urea, which was applied in split dressings of about 40 kg of N/ha between July and April of each year; the timing of application was the same for all SR treatments.

Nitrogen Consumption and Production

Pasture Measurements. Pasture harvested/ha (i.e., an estimate of DMI/ha) was estimated by calibrated visual appraisal of each paddock during a weekly farm walk (Macdonald et al., 2008). The net pasture accumulation was calculated weekly based on the increase in pasture mass on ungrazed paddocks. Representative samples of pasture were hand-clipped to grazing height from paddocks due to be grazed on each farmlet on one day each month. Representative samples of pasture silage were taken just before feeding and bulked annually. Duplicate samples of all feeds were dried at either 100°C for DM analysis or 60°C for analysis of nutrient composition. All samples dried at 60°C for 72 h were ground to pass through a 1.0-mm sieve (Christy Lab Mill, Suffolk, UK) and analyzed for CP, NDF, ADF, NSC, lipid, and ash using near infrared spectroscopy.

Animal Measurements and Calculations. Individual cow milk yields (kg/d) were recorded on 1 d each week (Tru-Test milk meter system, Palmerston North, New Zealand). Milk fat, CP, and lactose concentrations were determined on composite afternoon and morning aliquot samples using the Fossomatic FT120 (Foss Electric, Hillerød, Denmark). Body weight and BCS were determined every second week following the morning milking or at approximately 0900 h during the nonlactating period. Annual milk yield and milk component yield were calculated for each treatment.

Intake of N was calculated as the product of total pasture and silage consumed per hectare and per cow, multiplied by the average concentration of N/kg DM of each feed; milk N output per cow and per hectare were calculated by multiplying milk yield and CP concentrations and dividing by 6.38. Meat N exported per hectare was calculated using the weight of calves sold/ha and the difference in BW between cull cows sold and replacement heifers entering the herd. Cull cow lean carcass weight was assumed to be 60% of cold carcass weight (Schnell et al., 1997), and calf lean carcass weight was 53% of cold carcass weight (Brown et al., 2005). Protein was estimated to be 20% of lean carcass weight, with protein containing 16% N (Williams, 2007).

Excreted N/d was calculated as the difference between N intake/d and milk N yield/d, ignoring small changes in meat N. Fecal N yield/cow was estimated using the following equation (Castillo et al., 2000):

$$\text{Fecal N, kg/cow per day} = (0.21 \times \text{N intake/cow per day} + 52.3)/1{,}000.$$

Urinary N yield (kg/d) was calculated as excreted N − fecal N. Monthly N in feces and urine was calculated from the daily fecal and urine N estimates, multiplied by the number of days in the month.

Leachate and Drainage Measurements. To measure leaching of mineral N, 180 porous ceramic cup samplers (Webster et al., 1993) were installed in each farmlet at 1 m depth and at an angle of 45° (to avoid soil disturbance above the sampler for soil solution collection) using the method described by Lord and Shepherd (1993). Samplers were randomly placed and buried in paddocks (4–8 per 0.4-ha paddock) with free-draining silt loam soils (typic impeded allophanic and mottled orthic brown). Samples of leachate were collected at approximately two-weekly intervals during the drainage periods of July to September 1999 and June to September 2000 (i.e., 5–6 times/drainage season), when precipitation exceeded evapotranspiration (Table 1). The samples were analyzed for NO_3-N using high-pressure ion chromatography. Drainage volume was measured from lysimeters (ungrazed) containing undisturbed soil cores (1 m depth). Nitrate leached/ha was calculated as the product of drainage volume at each sampling time and the concentration of NO_3-N in leachate. Weather data during the 2 yr are presented in Table 1. Potential evapotranspiration was calculated from data collected as the maximum evapotranspiration rate that can occur when water availability is not limiting; it is a function of the latent heat of vaporization and heat flux in a water body and includes factors relating to the air saturation level and observed net radiation (Priestly-Taylor evapotranspiration; Winter et al., 1995; Roche et al., 2009a).

Statistical Analysis

Animal and pasture parameters were calculated for each year, averaged across years to provide one value per farmlet and analyzed by ANOVA using the statistical procedures of Genstat (VSN International, Hempstead, UK), with SR as the fixed effect. Linear and quadratic contrasts of SR were included in the model.

For nitrate leachate concentration, measured NO_3-N concentrations in drainage water ≤ 0 mg/kg were changed to 0.05 mg/kg (i.e., equivalent to the lowest non-zero concentration measured). Weighted average values for drainage volume, NO_3-N concentrations in leachate, and NO_3-N leached/ha were calculated for each paddock, collection date, and year. Drainage volume and NO_3-N leached/ha were then calculated for each paddock across collection dates and year. The weighted average NO_3-N concentration in leachate for each paddock was calculated as

$$NO_3\text{-N concentration, mg/kg} = (NO_3\text{-N leached/ha} \div \text{drainage volume}) \times 100.$$

Average annual drainage volume, NO_3-N concentration, and NO_3-N leached/ha were averaged across years and calculated for each SR. Data transformation was not required, because weighted averages conformed with homogeneity of variance. Data were analyzed using linear regression analysis (PROC GLM, SAS software, version 12.1; SAS Institute Inc., Cary, NC), with SR as the fixed effect. Operating profit (Macdonald et al., 2011) per kilogram of nitrate leached was calculated for each SR treatment and analyzed by linear regression, with SR as the fixed effect.

Table 1. Summary weather data during the 2 yr of nitrate leaching measurements

Variable	July	August	September	October	November	December	January	February	March	April	May	June
1998–1999												
Screen maximum temperature, °C	15.7	15.2	17.1	18.9	21.3	22.7	26.8	25.6	24.7	21.0	18.2	14.9
Screen minimum temperature, °C	7.3	5.2	7.0	10.3	10.4	12.5	15.4	13.2	13.4	9.8	7.3	4.3
Minimum grass temperature, °C	4.5	2.0	3.2	7.5	7.1	9.2	13.3	10.8	10.4	5.7	4.1	0.7
10-cm soil temperature, °C	10.4	9.3	11.8	14.8	17.6	20.0	22.8	21.3	19.5	14.5	11.9	8.9
Total precipitation, mm	271	107	43	112	49	62	100	12	38	88	59	90
Total potential evapotranspiration,[1] mm	27	50	77	103	140	165	170	137	112	67	41	25
Drainage,[2] mm	88	96	35	31	—	—	—	—	—	—	—	—
1999–2000												
Screen maximum temperature, °C	14.6	14.8	17.1	19.2	20.8	20.7	22.5	23.1	23.1	19.5	16.6	13.6
Screen minimum temperature, °C	3.4	3.5	5.6	8.4	10.9	10.5	11.6	11.4	9.2	9.4	7.5	4.5
Minimum grass temperature, °C	−0.2	−0.9	1.7	4.2	8.0	8.2	9.0	8.6	4.7	3.1	4.3	1.0
10-cm soil temperature, °C	7.8	8.0	11.4	14.4	17.0	18.5	19.8	20.3	17.6	15.3	12.8	9.5
Total precipitation, mm	137.6	116.6	101.4	29.6	169.6	59.6	67.8	6.2	31.8	109.4	79.4	88.4
Total potential evapotranspiration,[1] mm	30.9	50.3	79.3	106.8	118.9	163.2	150.8	150.7	127.3	71.6	47.9	32.9
Drainage,[2] mm	110	36	64	48	65	—	—	—	—	—	—	—

[1]Total potential evapotranspiration was calculated as a function of latent heat of vaporization and heat flux in a water body; it included factors relating to the air saturation level and observed net radiation: Priestly-Taylor evapotranspiration (Winter et al., 1995; i.e., the maximum evapotranspiration rate that can occur when water availability is not limiting).

[2]Drainage volume was measured from lysimeters (ungrazed) containing undisturbed soil cores (1 m depth). Drainage for the months of June and July were combined (4 and 84 mm, respectively, in 1998–1999, and 45 and 65 mm, respectively, in 1999–2000).

RESULTS AND DISCUSSION

Effect of SR on Pasture and Animal Production

The strengths of the experiment reported are (1) the arrangement of treatments was ordered, with 5 SR under very similar management decision rules evaluated over 2 yr; (2) feed imported from outside the farmlets was limited to less than 5% of the total feed consumed/ha and offered only in the 2 highest stocked farmlets; and (3) N fertilizer use was held constant across farmlets. Therefore, the effect of SR on NO_3-N leached/ha was not confounded by imported inputs or other significant changes to farm management.

Production and reproduction data have been reported by Macdonald et al. (2008) and the economics of altering SR have been reported by Macdonald et al. (2010, 2011). Briefly, pasture utilization increased by 2,073 kg of DM/ha ($P < 0.01$) for each additional cow/ha increase in SR (Table 2). Pasture ME concentration increased with SR (MJ/kg DM; $P < 0.001$), resulting in a linear increase ($P < 0.001$) in energy consumed of 25 GJ/ha for every additional cow/ha. As a result, milk yield and yield of fat, protein, and lactose per hectare increased ($P < 0.01$) linearly with SR, although milk yield and yield of milk components per cow declined ($P < 0.01$) because of the lower feed availability/cow and the shorter ($P < 0.001$) lactation lengths with increased SR (Table 2).

Lactation lengths (DIM/cow) declined linearly ($P < 0.001$) with increasing SR (−34 d for every additional cow/ha increase in SR), because of the need to manage winter and spring feed supply and cow BCS as SR increased. However, the number of DIM/ha (i.e., cows/ha × DIM/cow) increased linearly with SR (143 d/ha for each additional cow; $P < 0.001$). The percent of cows culled and replaced by heifers did not vary with SR; however, because of the greater number of cows/ha, the number of cows culled and heifers reared/ha increased linearly with SR, as did the number of calves sold/ha. Cow BW at culling declined linearly with increasing SR, but calf birth weight was not affected. We observed ($P = 0.10$) a quadratic effect of SR on operating profit/ha, although the variation in operating profit across SR treatments was small (<15%).

Effect of SR on the Amount of NO_3-N Leached per Hectare

The annualized effects of SR on N intake and the amount of N excreted in feces and urine, the N-use efficiency, and the amount of NO_3-N leached/ha are presented in Table 3 and Figure 1. Although we observed only a small increase in N input/ha through

Table 2. Effect of stocking rate in a seasonal spring-calving pasture-based system on pasture and silage consumption, pasture and silage N concentration, milk production/ha, lactation length, and operating profit/ha (adapted from Macdonald et al., 2008, 2011)

	Stocking rate, cows/ha					*P*-value	
Item	2.2	2.7	3.1	3.7	4.3	Linear	Quadratic
Comparative stocking rate[1]	60	70	76	89	91		
Pasture consumed, kg of DM/ha per year	12,098	13,785	14,322	15,609	16,597	<0.01	0.22
Silage consumed, kg of DM/ha per year	354	543	562	812	876	<0.01	<0.05
Pasture N, % of DM	3.6	3.6	3.6	3.5	3.5		
Silage N, % of DM	2.4	2.2	1.4	2.3	2.9		
Annual milk yield, kg/ha	11,071	11,747	12,796	13,380	14,828	<0.01	0.69
Annual fat yield, kg/ha	507	557	595	625	647	<0.01	<0.05
Annual protein yield, kg/ha	388	415	452	467	494	<0.01	0.31
Cow lactation length, d	291	274	258	234	221	<0.001	0.74
Operating profit,[2] NZ$/ha	1,614	1,753	1,857	1,715	1,646	0.97	0.10

[1]Comparative stocking rate accounts for cow size and total feed available and is measured in kg of BW/t of feed DM available per hectare (Macdonald et al., 2008).

[2]Operating profit is gross revenue less operating expenses (see Macdonald et al., 2011).

supplementary feed purchased for the 2 highest SR treatments (11.8 and 23.4 kg of N/ha, respectively), N consumed/ha and N output in milk and meat/ha increased by 94 and 8.5 kg/ha, respectively, for every 1 cow/ha increase in SR. Fecal and urinary N excreted/ha also increased. However, N intake and milk, fecal, and urine N output/cow declined with increasing SR.

Stocking rate did not affect N-use efficiency/ha, as measured by the output of N in milk and meat relative to total N intake (13–14%) or net importation of N (i.e., fertilizer N ± silage imported/exported; 35%). The levels of N-use efficiency reported in this study are similar to those reported by Huebsch et al. (2013) for pasture-based systems in Ireland. Huebsch et al. (2013) did acknowledge a reduction in NO_3-N leaching with increasing pasture harvest, although the cause of the lower NO_3-N leached in their study was multifactorial. In the study reported here, NO_3-N leached/ha declined 8.4 kg and 5.9 kg with each 1 t of DM pasture harvested/ha (i.e., grazed plus conservation) and consumed directly/ha (i.e., grazed only), respectively.

We observed a trend for a linear decline ($P = 0.06$) in NO_3-N leached/ha with increasing SR, which coincided with the trend for a decline ($P = 0.06$) in the concentration of NO_3-N in leachate with increasing SR (Figure 1). The estimated NO_3-N leached/ha was based on an assumption of the same level of net drainage across treatments, measured using ungrazed lysimeters (i.e., 250 and 263 mm/yr in yr 1 and 2, respectively). The decline in NO_3-N leached/ha with increasing SR was somewhat surprising; it has been assumed an increase in SR leads to an increase in NO_3-N leaching because of the very low N-use efficiency in grazing animals (European Community, 1991; Vogeler et al., 2013). Previous research from New Zealand (Ledgard et al., 1999) and Ireland (Huebsch et al., 2013; McCarthy et al., 2015)

Table 3. Effect of stocking rate in a seasonal, spring-calving pasture-based system on average annual N intake, productive output of N in milk, and N excreted in feces and urine[1]

	Stocking rate, cows/ha					*P*-value	
Item	2.2	2.7	3.1	3.7	4.3	Linear	Quadratic
N intake, kg/ha	435	476	502	514	539	<0.01	<0.05
N intake, kg/cow	204	181	169	149	133	<0.001	<0.01
N in milk, kg/ha	69	78	86	89	93	<0.01	<0.05
Excreted N/ha, kg	366	398	416	426	446	<0.01	<0.05
N in feces/ha, kg	132	150	162	174	190	<0.001	<0.01
N in urine/ha, kg	233	248	254	252	256	0.08	0.09
N in milk, kg/cow	32	29	29	25	22	<0.001	<0.05
Excreted N/cow, kg	172	152	141	124	111	<0.001	<0.001
N in feces/cow, kg	62	57	55	50	47	<0.001	<0.01
N in urine/cow, kg	110	95	86	73	64	<0.001	<0.001
Milk and meat N/total N consumed, %	14	13	14	13	13	0.20	0.52
Milk and meat N/kg of N leached	1.21	1.99	1.89	2.51	3.55	<0.05	0.08
Operating profit/kg of N leached, NZ$	31	52	48	57	73	<0.05	0.15

[1]Fecal N was estimated from N intake: Fecal N, kg/d = (0.21 × N intake + 52.3)/1,000 (Castillo et al., 2000); Urine N = N intake – (Milk N + Fecal N).

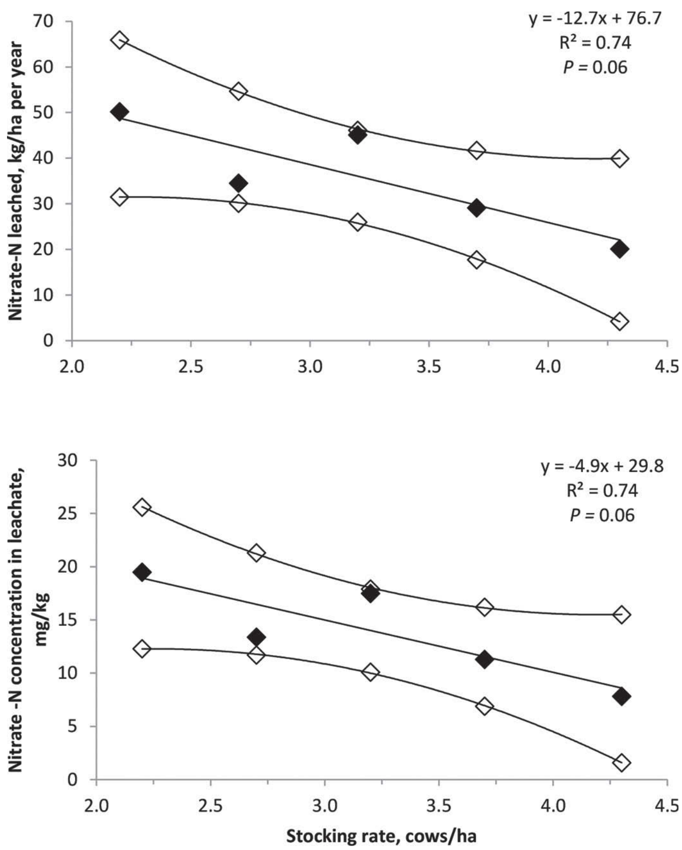

Figure 1. Effect of stocking rate (mean and 95% confidence interval) in a seasonal, spring-calving, pasture-based system on average concentration of nitrate-N in leachate under rotational grazing and the total amount of nitrate-N leached per hectare. Dairy cows were stocked at 2.2, 2.7, 3.1, 3.7, or 4.3 cows/ha over a 3-yr period.

also refutes the suggestion of a positive relationship between SR and NO_3-N leached, but does not point to a negative association. Nevertheless, those studies were not designed to elucidate a response curve to SR.

We observed relatively high variability in measured NO_3-N leaching (Figure 1). This is a well-recognized finding when using ceramic cup samplers to estimate leaching from urine N patches in grazed pastures (e.g., Lilburne et al., 2012) and makes an accurate prediction of NO_3-N leached from SR difficult. However, this variability did not detract from the response curve presented, which indicated, on average, that NO_3-N leached/ha declined with increasing SR in a grazed dairy system that imported very little feed from off-farm. A further point to consider is that these leaching results referred to the dairy farm, and replacement animals were grazed off-farm. In practice, a higher SR will increase the requirements for feeding replacements and associated N leaching, although this represents the equivalent of only about an additional 1.75 kg of NO_3-N/ha for every 1-cow increase in SR.

It was not possible to determine with certainty the reason for the negative association between SR and NO_3-N leached/ha from this study, but possible mechanisms include (1) a reduction in N intake/cow and, therefore, urinary N excreted/cow, particularly during the most sensitive part of the year for N leaching (Table 4); (2) a greater spread of urinary N with increasing SR, due to more cow × urination events; and (3) an increase in pasture N harvested/ha and the associated increase in milk and meat N exported per ha.

Lower N Leaching Because of Lower N Intake, Greater N Partitioning to BCS Gain, and Urinary N Output/Cow

The timing of N deposition in urine patches is critical to the risk of N loss (Shepherd et al., 2010). When pasture is growing actively, most of the plant-available NH_4 and NO_3-N in the soil are readily taken up by the

Table 4. Effect of stocking rate in a seasonal, spring-calving pasture-based system on N intake, productive output of N in milk, and N excreted in feces and urine[1] between February and June,[2] inclusive

	Stocking rate, cows/ha					*P*-value	
Item	2.2	2.7	3.1	3.7	4.3	Linear	Quadratic
N intake, kg/ha	171	187	182	163	167	0.37	0.56
N intake, kg/cow	84	74	66	53	47	<0.001	<0.01
N in milk, kg/ha	16	17	18	14	10.8	0.10	<0.05
Excreted N/ha, kg	155	170	164	149	156	0.54	0.77
N in feces/ha, kg	52	59	60	58	64	0.08	0.25
N in urine/ha, kg	103	111	104	90	93	0.13	0.37
N in milk, kg/cow	8	7	7	5	3.1	<0.01	<0.01
Excreted N/cow, kg	76	67	59	49	44	<0.01	<0.01
N in feces/cow, kg	25	23	22	19	18	<0.001	<0.01
N in urine/cow, kg	51	44	37	30	26	<0.01	<0.01

[1]Fecal N was estimated from N intake: Fecal N, kg/d = (0.21 × N intake + 52.3)/1,000 (Castillo et al., 2000); Urine N = N intake – (Milk N + Fecal N).

[2]Period regarded as most sensitive period for N in urine to contribute to N leaching during the drainage season (Shepherd et al., 2010).

sward. However, when pasture growth declines during autumn, NO_3-N can accumulate in the topsoil (Whitehead, 1995; Shepherd et al., 2010). In free-draining soils, when the amount of precipitation exceeds evapotranspiration (i.e., drainage season; Table 1), surplus water moves downward through the soil profile and any NO_3-N positioned in the topsoil under these conditions has a high risk of being leached (Shepherd et al., 2010).

In temperate climate zones, the timing of drainage (i.e., winter) generally coincides with the time of lowest pasture growth and, therefore, sward N uptake (Roche et al., 2009a). Therefore, urine N deposition during autumn and early winter, as pasture growth slows and the balance of precipitation and evapotranspiration swings in favor of drainage, should be a greater risk factor for N leaching than urinary N deposited during late winter, spring, and summer, when pasture is at peak growth (Roche et al., 2009b) and evapotranspiration exceeds precipitation (Roche et al., 2009a). Consistent with this premise, Shepherd et al. (2010) reported that N leaching from urine (800 kg of N/ha) was high when deposited between February and May (i.e., equivalent to 210 to 300 DIM in a southern hemisphere seasonal spring-calving dairy system), but significantly less N was leached from urine applied during July and August (i.e., equivalent to 1–60 DIM in a seasonal spring-calving dairy system in the southern hemisphere).

In grazing systems that do not import feed, cow lactation length is used as a management strategy to ensure a match between feed demand and supply. For example, DIM/cow declined with SR due to culling of less productive stock and an early cessation of lactation. This ensured that feed demand was reduced in autumn, enabling the creation of a store of pasture before calving and giving cows adequate time to gain BCS before calving, as high-SR cows were thinner in late lactation (Roche et al., 2007). An estimate of the effect of SR on the amount of N consumed, secreted in milk, and excreted in urine/cow and per ha during the "sensitive" months is presented in Table 4. With increasing SR, N intake/lactating cow declined because of lower DMI; furthermore, a greater proportion of cows were nonlactating through autumn because of the shorter lactation length. They were consuming approximately 50% of the DM and, more importantly, the N of a lactating cow on the same calendar day. Both of these factors result in a decline in N intake/cow with increasing SR. In addition, cow BCS in mid to late lactation declines with SR (Roche et al., 2007); a greater proportion of the N consumption during this period would be partitioned to muscle accretion because of the stock-management strategies employed to ensure optimum BCS at calving.

Interestingly, DIM/ha increased with SR (144 d for each additional cow/ha; $P < 0.01$) and urinary N excreted/ha tended to increase ($P < 0.10$); however, urinary N excreted/cow (Tables 3 and 4) and NO_3^- N leached/ha declined (Figure 1) with SR and DIM/ha. This appears to contradict the assertion of Peyraud and Delaby (2006) that N excretion increases linearly with grazing days per hectare. However, in context, they are compatible. If we accept that the primary reason for the negative association between SR and NO_3-N leaching/ha is a reduction in surplus N intake and urinary N excretion/cow during the "sensitive" months for N accumulation before the drainage season, and that reducing DIM/cow with increasing SR is the management strategy that facilitates this, the negative association between SR and NO_3-N leached will not hold true in autumn-calving scenarios or in spring-calving systems in which supplementary feeds are provided in autumn to extend DIM/cow. In these situations, DIM/cow, N intake/cow or both during the autumn do not decline with SR and, in fact, NO_3-N leached/ha could, very likely, increase (Ledgard et al., 2006; Peyraud and Delaby, 2006); for example, Ledgard et al. (2006) reported that the NO_3-N leached increased by approximately 18 kg/ha per year for every additional cow/ha increase in SR, when imported feed was used to extend DIM/cow in autumn. The results presented here indicate that NO_3-N leached/ha declined with increasing SR in seasonal, spring-calving pasture-based systems, provided that DIM/cow during the autumn declined with SR. It is noteworthy, however, that this reduction in NO_3-N leached occurred despite an increase in annual pasture utilization/ha and milk output/ha.

Lower N Leaching Because of Increased Spread of Urinary N with Increasing SR

The overall amount of NO_3-N leached below the root zone is closely linked to the N surplus in the soil at the end of the growing season (Farrugia et al., 1997; Wachendorf et al., 2004; Shepherd et al., 2010). A potential contributing factor to the decline in NO_3-N leached with increasing SR, therefore, is a greater spread of urinary N with increasing SR. Such an effect, if it occurs, would reduce the N deposition rate in each urine patch and lead to a greater potential plant N recovery (Ledgard et al., 2015). This would be expected if total N excretion occurred across more cows (i.e., at higher SR) and, therefore, more urine patches, assuming the number of urinations/cow per day are relatively constant. The calculated urine-N excreted/cow decreased with SR (Table 4), and this may have caused a reduction in urinary N concentration, assuming that urination frequency and volume per cow did not decline by an equivalent proportion to the decline in DMI. This critical assumption has not been directly studied, and further research is required to evaluate the effects of SR on urination frequency and urine N concentration. If we assume this to be true, however, the lower urinary N output would result in a decrease in the concentration of N in urine patches with increasing SR, reducing the risk of NO_3-N leaching. Di and Cameron (2007) reported that NO_3-N leached/ha declined quadratically as the kg N/ha applied in urine declined. The data set presented here indicate that for every additional kg N excreted in urine/cow between February and June, 0.96 kg of NO_3-N was leached/ha ($P < 0.05$; r = 0.86). Therefore, the reduction in urinary N excretion/cow due to the lower DMI of a high-CP feed by lactating and nonlactating cows during the sensitive months is a plausible reason for the decline in NO_3-N loss with greater SR.

Additionally, an increase in the level of surface soil compaction with increased SR could result in greater horizontal spread of urine after excretion on soil, with an associated decrease in urine patch N rate and a greater likelihood of plant N recovery. This may also increase gaseous losses of N by denitrification (e.g., Menneer et al., 2005), thereby resulting in less excess N in the soil for loss by leaching. However, any increase in soil compaction in this study did not reduce pasture growth (Macdonald et al., 2008, 2010). Further detailed research is required to better understand the possible effects of SR on urination frequency, urine patch size, the horizontal spread of excreted urinary N, and N leaching losses.

Lower N Leaching Because of the Timing of Greater N Harvest and Export

Another possible reason for the reduction in NO_3-N leached with increasing SR could be the timing of the positive association between pasture harvested per hectare and SR, and milk production per hectare. Pasture harvested per hectare increased with SR; this greater harvest of DM and N was between July and February, however, and there was no difference in DM or N harvested/ha during the "sensitive" months of the year for the accumulation of N at risk of leaching (i.e., March to June). Thus, any increase in urinary N per hectare as a result of increased pasture harvest was during the period of the year when evapotranspiration exceeded precipitation (i.e., no drainage) and the likelihood of N leaching below the root zone was low. McCarthy et al. (2016) reported a similar profile of pasture harvest associated with increased SR, with the increase occurring during the peak pasture-growing period in spring but not at other times of the year. The timing of the increase in pasture harvested directly by the cow with increasing SR allows for greater land productivity without increasing the farm's NO_3-N leaching footprint and supports the use of higher SR as a means of increasing milk production/ha while reducing NO_3-N leaching, provided additional feed N is not imported.

Implications for Farm Profitability and Farming in Nitrogen-Sensitive Zones

A nitrogen-sensitive zone or a nitrogen-vulnerable zone is a conservation designation for areas of land that drain into NO_3-N polluted waters or waters that could become polluted by NO_3-N. They have become commonplace where animal population density near waterways has led to an increase in water NO_3-N concentrations (Oenema et al., 2011). In general, regulations around nitrogen-sensitive zones are designed to ensure that no more than a defined amount of N is leached per hectare.

Macdonald et al. (2011) reported a curvilinear response to SR in operating profit/ha and Macdonald et al. (2010) reported that this was irrespective of farm decision rules used to manage the different SR, as long as very little feed was imported. Nevertheless, the actual effect of SR on operating profit/ha was very small (Table 2). Financial success, however, is dictated by the operating profit generated relative to the primary factor limiting output. For example, in a housed system, where bunk space or stall space is defined, operating profit for the business is maximized when profit/cow is maximized, because the number of cows that can be housed is limited. Similarly, in a milk quota environment, such as Canada's, a producer cannot produce more than their quota allows; therefore, profit maximization involves the maximizing the margin per liter of the quota. In most grazing systems, production from pasture is limited by land and, so, as Macdonald et al. (2011) rightly presented, operating profit per hectare is the appropriate metric for defining profit maximization under different SR treatments, assuming the same total asset value.

Using the same philosophy, in a nitrogen-sensitive zone, profit maximization relates not to operating profit/ha, but to the amount of profit that can be generated per kilogram of NO_3-N leached, because this is the limitation to increased output: farms cannot produce more milk if increased production means a greater amount of leachate. By this metric, the results presented here indicate that operating profit in a seasonal, spring-calving, pasture-based dairy farm in a nitrogen-sensitive zone would increase linearly with SR (NZ$16.90/kg of NO_3-N leached for every extra cow/ha increase in SR, provided cows are dried off during autumn, because it is a climatically sensitive period for NO_3-N leaching; Figure 2; $P < 0.05$), although this finding is greatly influenced by the slope of the N leaching function with SR. This is contrary to what legislation in Europe has sought to achieve (European Community, 2000) and to what has been proposed for seasonal-calving dairy farms in New Zealand (Vogeler et al., 2013). Because the effect of SR on NO_3-N leaching in a spring-calving seasonal system is probably due to the effect of low CP intake/cow and low urinary N excretion/cow during a sensitive NO_3-N accumulation period because of a reduction in lactation length, DIM/cow also affects the operating profit/kg of NO_3-N leached (Figure 2); within the range measured here (i.e., ~220–300 d), operating profit/kg NO_3-N leached declined by NZ$0.48 for every extra DIM/cow. In nitrogen-sensitive zones, profitability in seasonal spring-calving grazing systems increases with SR, on average, provided additional feeds or fertilizer N inputs are not purchased and DIM/cow are reduced in autumn to facilitate BCS gain and pasture storage for winter feed.

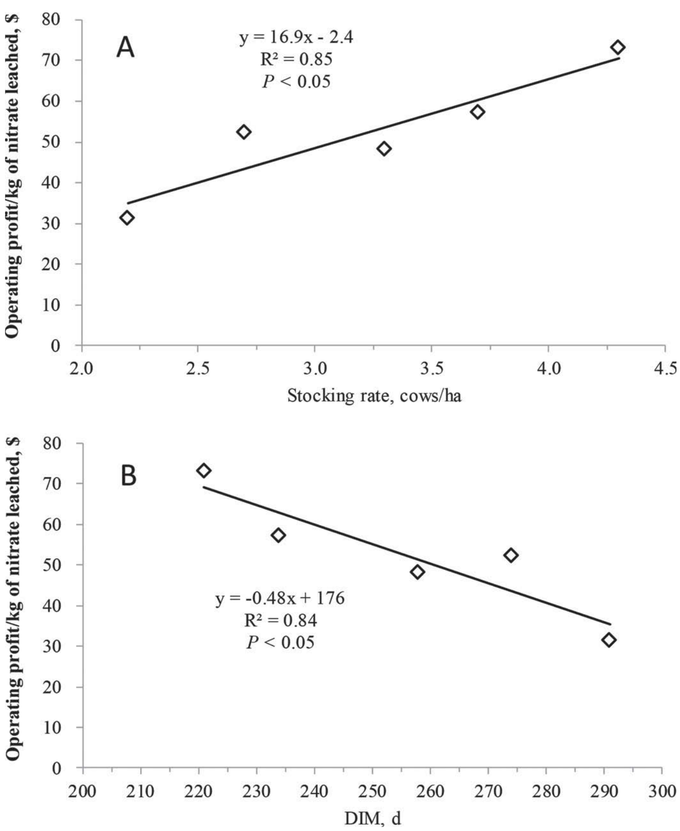

Figure 2. Association between stocking rate (A) and DIM/cow (B) and operating profit/kg of nitrate-N leached per hectare in a seasonal, spring-calving, pasture-based system.

CONCLUSIONS

In a seasonal, spring-calving, pasture-based dairy production system that imports less than 5% of feed from off-farm and that had no change in N fertilizer use, NO_3-N leached/ha tended to decline with increasing SR. This occurred despite a linear increase in pasture harvest and in milk output/ha. This finding was associated with a decrease in average DIM/cow as SR increased. The reduction in DIM/cow resulted in a lower intake of CP during autumn, reducing the urinary excretion of N during the most sensitive period for leaching of urine N. We postulate that this finding was associated with the increased spread of urinary N, greater plant recovery of N, and lower leaching from urine patches. These data do not support the premise that lowering SR in itself is a means of reducing NO_3-N leaching. The results indicate a need to carefully consider any management changes around SR in trying to effect change in NO_3-N leached/ha. A full farm system-level analysis of any change must be undertaken to determine its effect on productivity and environmental outcomes.

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