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Full Length Research Paper

Modelling nitrogen excretion, elephant grass growth and animal production in a stall-feeding dairy system

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This study reports on a simulation model of livestock-forage with excreted nitrogen (N) as a source of N for elephant grass (*Pennisetum purpureum*) growth. It is shown that nitrogen partitioning between urine and feces can be estimated using feed characteristics when elephant grass is the sole feed in stall-fed dairy heifers. The percentage N excreted in feces decreased with increasing dietary N, while N excreted in urine increased with increasing N intake. The simulation results indicate that at stocking level of 5 heifers ha^{-1}, the application of excreted N supported the animals for up to 700 days but an additional heifer led to the depletion of forage within 90 days. It was observed that one hectare without N fertilization would support only 3 heifers for the same duration as 5 heifers on a fertilized hectare. It is concluded that N excretion can be predicted in stall-feeding dairy system, and it is possible for farmers to improve the forage biomass yield and thus animal performance by not only applying manure, but also by using the most appropriate method to minimize excreted N losses.

Key words: Dairy heifers, digestibility, nitrogen excretion, elephant grass, forage growth, manure.

INTRODUCTION

Stall-feeding dairy system in Uganda is based on cultivated elephant grass (*Pennisetum purpureum*) as major forage (Muwanga, 1994; Tumutegyereize et al., 1999), partly because of its high biomass yield compared to other grasses (Kabi and Bareeba, 2007). In this dairy system animal manure can be a very good source of nitrogen for forage growth (Rotz et al., 1999). However, the overall farm efficiency of conversion of nitrogen inputs into products is determined by the efficiency of nitrogen cycling through the soil-plant-animal system (Ledgard, 2001). In stall-feeding systems, almost all excreted N could be collected but a proportion of manure N is lost immediately through volatilization after excretion (Rufino et al., 2006). In addition, manure can lose up to 40% of the N before compositing (Lekasi et al., 2001), and up to 46% of its total N after three months of storage (Thomsen, 2000). On the assumption that the entire urinary N is lost, Rufino et al. (2006) estimate a 10% partial cycling efficiency. Therefore, efficient use of manure depends on handling, storage, and method of application (Rufino et al., 2006). For example, the subsurface and surface application of manure gave 77.8 and 26% more dry matter (DM) yield respectively, compared to no manure application (Kabi and Bareeba, 2007).

A number of studies have been carried out on N excretion. They include Zanton and Heinrichs (2008), Nennich et al. (2006), Nennich et al. (2005) Marini and Van Amburgh (2005), Kebreab et al. (2002), and Wilkerson et al. (1997). Models of whole farm N cycling have also been developed (Kohn et al., 1997; Dou et al., 1996). However, these models are not appropriate for stall-feeding systems that depend solely on cultivated *P. purpureum* where livestock excreta are the only significant N input (Sheldrick et al., 2003). The aim of this study was to predict N excretion and then simulate the effect of excreted N on the forage growth and animal stocking level, by extending the simulation model of heifer growth developed in Tibayungwa et al. (2009).

MATERIALS AND METHODS

This section summarises the procedures, assumptions and equations

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Table 1. The definition of symbols and terminology.

Symbol	Definition	Unit
a	Proportion of water soluble nitrogen in the total nitrogen of a feed	Unit-less
ADIN	Acid detergent insoluble nitrogen in a feed	g/kgDM
b	Proportion of potentially degradable N other than water soluble N of a feed	Unit-less
c	Fractional rumen degradation rate per hour of the *b* fraction of feed N	Unit-less
CP	Crude protein of a diet or in a feed	g/kgDM, g/d
DMTP	Digestible microbial true protein (= metabolizable protein from microbes)	g/d, g/kgDM
DUP	Digestible undegraded protein (N x 6.25)	g/kgDM, g/d
FME	Fermentable metabolizable energy of a diet	MJ/d, MJ/kgDM
MCP	Microbial crude protein supply	g/d, g/kg
MP	Metabolizable protein	g/d, g/kgDM
MTP	Microbial true protein	g/d, g/kg
QDP	Quickly degradable protein (N x 6.25) of a diet or in a feed	g/d, g/kgDM)
r	Rumen digesta fractional outflow rate per hour	Unit-less
SDP	Slowly degradable protein (N x 6.25) of a diet or in a feed	g/d, g/kgDM
UDP	Undegradable dietary protein (N x 6.25) of a diet or in a feed	g/kgDM

tions used to develop a simulation model of dairy heifers from weaning to mating weight, fed on elephant grass in a cut-and-curry dairying system. The AFRC (1993) metabolizable protein system was used to estimate weight gain and nitrogen output.

The equations for estimating protein value of feed

Estimation of the metabolizable protein (MP) from crude protein (CP) involves the following calculations. Definitions of symbols used are in Table 1.

$$UDP = CP - \{QDP + SDP\} \tag{1}$$

$$SDP = \{(b \times c)/(c + r)\} \times CP \tag{2}$$

$$QDP = a \times CP \tag{3}$$

Where r is calculated as

$$r = -0.024 + 0.179\{1^{(-0.278L)}\} \tag{4}$$

Where L is level of feeding as a multiple of MJ of ME for maintenance.

$$MCP = FME \times y \tag{5}$$

Where y is microbial protein yield in the rumen (gMCP/MJ of FME), and is calculated as

$$y = 7.0 + 6.0\{1 - e^{(-0.35L)}\} \tag{6}$$

$$DUP = 0.9\{UDP - 6.25 \times ADIN\} \tag{7}$$

$$DMTP = 0.6375 \times MCP \tag{8}$$

$$MP(g/d) = 0.6375 \times MCP + DUP \tag{9}$$

$$ERDP = 0.8 \times QDP + SDP \tag{10}$$

If ERDP supply is less than (or equal to) ERDP required, then

$$MCP(g/d) = ERDP(g/d) \tag{11}$$

Else

$$MCP(g/d) = FME(MJ/d) \times y(gMCP/MJFME) \tag{12}$$

$$FME(MJ/kgDM) = ME \times \begin{pmatrix} 0.467 + 0.00136 \times ODM \\ -0.00000115 \times ODM^2 \end{pmatrix} \tag{13}$$

where ODM is oven dry matter content (g/kg).

The equations for estimating protein requirements

Metabolizable protein requirement for maintenance (kg/d) is estimated as

$$MP_m = 2.30 \times W^{0.75} \tag{14}$$

Metabolizable protein requirement for growth (kg/d) is estimated as

$$\begin{aligned} MP_f &= C6\{168.07 - 0.16869W + 0.0001633W^2\} \times \\ &\quad \{1.12 - 0.1223\Delta W\} \times 1.695\Delta W \end{aligned} \tag{15}$$

Where MP_f is metabolizable protein requirement for liveweight gain (g/d), C6 is a correction factor ranging from 0.8 - 1.0, *W* is liveweight of the animal (kg).

The equations for estimating energy value of feed

The energy value of feed was estimated using the following equations:

$$ME(MJ/kgDM) = 0.0157 \times DOMD(g/kgDM) \tag{16}$$

Where ME is metabolizable energy; DOMD is digestible organic matter in a feed, and is estimated as

$$DOMD = OMD \times (1000 - total\,ash)/1000 \tag{17}$$

Where OMD is organic matter digestibility (g/kg)

$$FME = ME \times \begin{pmatrix} 0.467 + 0.00136 \times ODM \\ -0.00000115 \times ODM^2 \end{pmatrix} \tag{18}$$

Where FME (MJ/kgDM) is fermentable metabolizable energy; ODM is oven dry matter content (g/kg)

The equations for estimating energy requirements

The energy requirement is calculated as follows:

$$M_{mp}(MJ/d) = (E_m/k) \times \ln\left\{B/\left(B - R - 1\right)\right\} \tag{19}$$

Where M_{mp} is ME requirement for both maintenance and production, E_m (MJ/d) is the sum of animal's fasting metabolism (F) and activity allowance (A = 0.0071W) for zero-grazed heifers, R is the scaled energy retention. The fasting metabolism, MJ/(kg fasted weight) $^{0.67}$, is defined as

$$F = 0.53\left(W/1.08\right)^{0.67} \tag{20}$$

The factors B and k are calculated from the efficiencies of utilization of ME as follows:

$$B = \frac{k_m}{\left(k_m - k_f\right)} \tag{21}$$

$$k = k_m \times \ln\left(k_m / k_f\right) \tag{22}$$

Where k is the efficiency of utilization of ME for a given metabolic process, B is a derived parameter to predict energy retention, k_m is the efficiency of utilization of ME for maintenance, k_f is the efficiency of utilization of ME for weight gain. k_m and k_f are calculated as

$$k_m = 0.35q_m + 0.503 \tag{23}$$

$$k_f = 0.78q_m + 0.006 \tag{24}$$

Where q_m is the metabolizability of (GE) at maintenance, (ME)/(GE), where GE is the gross energy of a diet (MJ/d or MJ/kgDM).

Scaled energy retention (R) is calculated from

$$E_f = C4\left(EV_g \times \Delta W\right) \tag{25}$$

Where $C4$ is the correction factor for ME for heifers (= 1.1) and then:

$$R = \frac{E_f}{E_m} \tag{26}$$

Where E_f is net energy retained in the growing animal (MJ/d), E_m is net energy for maintenance (MJ/d).

Predicting live weight gain

Predicting live weight gain involves the following steps:

Step 1: *Energy value of weight gain*

This is given by the expression

$$EV_g = \frac{C2\left(4.1 + 0.0332W - 0.000009W^2\right)}{\left(1 - C3 \times 0.1475\Delta W\right)} \tag{27}$$

Where EV_g is energy value of tissue gained (MJ/kg), ΔW is live-weight change (kg/d), $C2$ is a correction factor (range 1.00 -- 1.30) for mature body size and sex of animal; $C3$ is a correction factor for plane of nutrition (L), 1 when $L >$ 1 and 0 when $L <$ 1. These correction factors are given in AFRC (1993).

Step 2: *Energy retention*

This is caled energy retention (R) and is as defined in Equation 26.

Step 3: *Metabolisable protein requirement for growth*

Equation 15 is rearranged to estimate weight gain based on MP.

Step 4: *Weight gain*

Equation 25 is rearranged to give

$$\Delta W = \frac{E_f}{\left(C4 \times EV_g\right)} \tag{28}$$

By combining the two equations 27 and 28 that contain the term ΔW, we get

$$\Delta W = \frac{E_f}{\left(C4X + 0.1475E_f\right)} \tag{29}$$

Table 2. Variables, Parameters and coefficients used in the simulation model.

Variable/parameter/ coefficient	Description	Value used[a]
r_g	Rate of forage increase or decrease	0.02
DMI	Dry matter intake (forage harvested)	Calculated
N_n	Accumulated N excreted less losses, initialized at 0	Calculated
g	Forage growth (kg/d)	Calculated
F_0	Initial forage biomass pool, initialized at 1000 kg	Calculated
F_a	Available forage biomass (kg/d)	Calculated
k	Nitrogen loss coefficient	0.3
U	Maximum ungrazed forage biomass	18000
n	Stocking density (number of heifers)	1 - 6
N_l	Nitrogen losses in storage (kg/d), initialized at 0	Calculated
W	Weight of the animal, initialized at 70 kg	Calculated
k_n	Efficiency of MP use for animal growth	0.59
N_u	Urine nitrogen	Calculated
N_f	Fecal nitrogen	Calculated
N_t	Total excreted nitrogen (Urine + Fecal)	Calculated

[a] In this column, calculated values are values computed by the model.

where $X = C2\left(4.1 + 0.0332W - 0.000009W^2\right)$ is taken from equation 27.

Forage growth potential and fertilizer value of excreted nitrogen

Without N fertilizer application, Napier grass yielded 32,400 kg DM ha^{-1} yr^{-1} (Moore and Bushman, 1978), 22,500 kg DM ha^{-1} yr^{-1} (Kabi and Bareeba, 2007), and 18,000 kg DM ha^{-1} yr^{-1} (Binh and Nung, 1995). Based on these findings, the upper limit of elephant grass biomass per hectare was set between 18,000 and 22,000 kg DM ha^{-1} yr^{-1}. Growth potential of elephant grass as a result of applying excreted N was based on the findings by Binh and Nung (1995) that applying 1 kg N ha^{-1} can yield 34.66 kg DM of elephant grass. Then simulated forage growth potential was established by interfacing the nutrient availability with the forage submodel.

Dry matter intake and weight gain

Table 2 shows variables, parameters and coefficients used. According to AFRC (1993), the dry matter intake (DMI) is estimated as

$$DMI(kg/d) = MER/(M/D) \tag{30}$$

where MER is Metabolizable energy requirement (MJ/d), M/D is metabolizable energy (MJ/kgDM). This estimation of DMI is appropriate where daily gain is predetermined and forage is available in adequate amount. In a case where the DMI depends on forage availability and daily gain is not known forehand, the intake can be estimated based on experimental observations. We used an estimate of 2.7% of body weight based on Kariuki et al. (1998) value of 2.94%, Diaz-Solis et al. (2006) value of 2.54% and Blomquist (2005) value of 2.5 - 3.0% of the body weight.

After part of ME and MP have been used for maintenance, daily gain (DG) is dependent on the balance between Metabolizable energy for growth (MEg) and Metabolizable protein for growth (MPg); if potential growth due to metabolizable protein (Gp) is greater than the potential growth due to metabolizable energy (Ge), then MEg is considered limiting and the growth is determined by Ge. Else if potential growth due to metabolizable protein (Gp) is less than potential growth due to metabolizable energy (Ge), then MPg is considered limiting and the growth is determined by Gp. The simulated DG is then added to the weight to get a new weight (W), and the process is repeated for the desired number of days.

Excreted nitrogen and forage subcomponents

Table 2 shows variables, parameters and coefficients used. The nitrogen subcomponent is based on the following calculations:

$$BEN = 0.35 * (W^{0.75}) \tag{31}$$

where BEN is basal endogenous nitrogen. According to Orskov (1982) BEN is partitioned as 64% fecal and 36% urine, therefore

$$N_u = MP * ((1 - k_n)/6.25) + 0.36 * BEN \tag{32}$$

$$\begin{aligned} N_f = {} & (0.25 * MCP/6.25) + (0.15 * MTP/6.25) + \\ & ((0.512 * UDP/6.25) + ADIN) + 0.64 * BEN \end{aligned} \tag{33}$$

$$N_t = N_u + N_f \tag{34}$$

$$N_l = k * N_t \tag{35}$$

$$N_n = N_t - N_l \tag{36}$$

Dynamic equilibrium was assumed for pasture growth and senescence. Forage growth follows the logistic growth function and is estimated as

$$F_a = F_0 * r_g (1 - F_0/U) - DMI + g \tag{37}$$

$$\begin{aligned} & IF \quad F_a \geq 0.027 * W, \\ & THEN \quad DMI = 0.027 * W * n, \quad ELSE \quad DMI = F_a \end{aligned} \tag{38}$$

$$\begin{aligned} & IF \quad F_a \geq 0.027 * W, \\ & THEN \quad DMI = 0.027 * W * n, \quad ELSE \quad DMI = F_a \end{aligned} \tag{39}$$

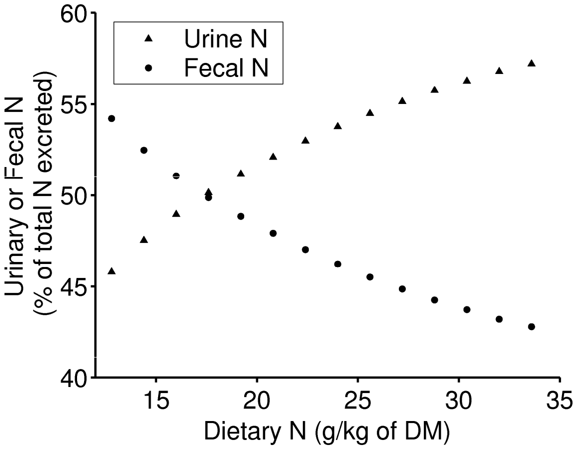

Figure 1. Route of excreted N in dairy heifers as a function of dietary N.

The simulation model is coded in VENSIM 5.5 (The Ventana Simulation Environment, Ventana Systems, Inc.), based on differential equations with $\Delta t = 1$ day.

RESULTS AND DISCUSSION

Nitrogen excretion

Figure 1 shows the the partition of excreted N between urine and feces. The percentage N excreted in feces decreased with increasing dietary N, while N excreted in urine increased with increasing N intake. The decrease in fecal N with increasing N intake is due to an increasing dilution of the metabolic fecal N, leading to increased apparent digestibility for N (Marini and Van Amburgh, 2005). The increase in urinary N as N intake increases is due to reduced efficiency of dietary N for growth as requirements are met and the excess N excreted mainly in urine (Nennich et al., 2005). Therefore knowing the optimal level of N intake is important to avoid the unnecessary excess.

Forage growth and animal production

At a stocking level of 3 heifers ha^{-1}, without N fertilizer application the forage biomass accumulates up to 12,000kg DM ha^{-1} and declines progressively till depletion within two years, whereas with N application the forage biomass accumulates to 17,000 kg DM ha^{-1} and slightly declines to 15,000 kg DM ha^{-1} in the same period (Figure 2). With application of excreted N the stocking level can be increased from 3 to 5 heifers ha^{-1} and the system takes the same time to collapse as 3 heifers ha^{-1} with no N application (Figure 3), but one more heifer collapses the system within 3 months (Figure 4).

This increase in stocking level translates to 66.7%

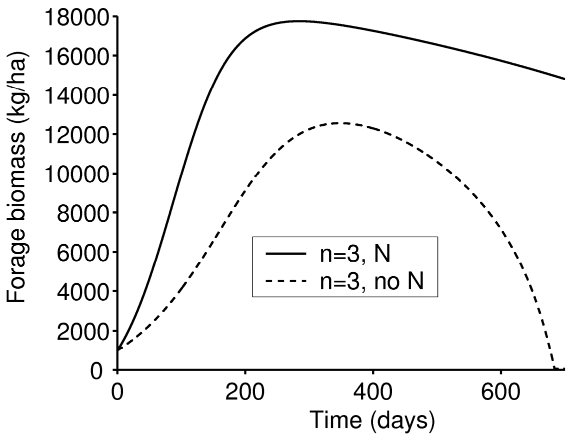

Figure 2. Forage biomass at fixed stocking level with and without N application.

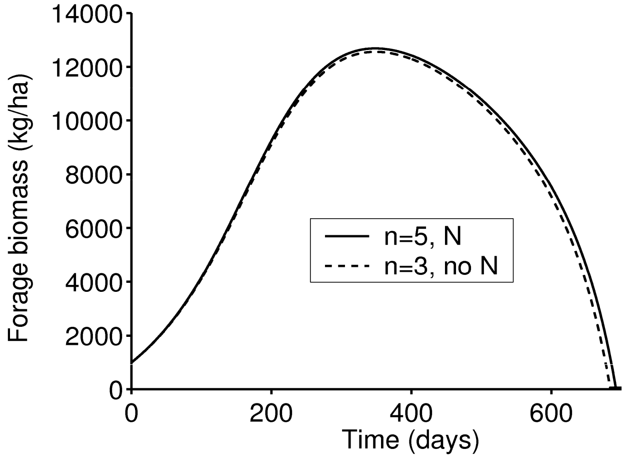

Figure 3. Forage biomass under different stocking levels and different N regimes.

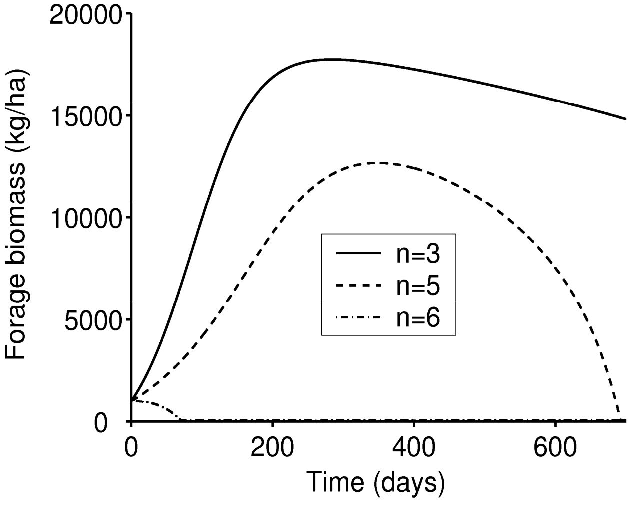

Figure 4. Forage biomass at different stocking levels with N application.

increased forage DM yield, that is comparable to 77.8% reported in Kabi and Bareeba (2007) using the subsurface application method. The difference could be explained by the fact that in this simulation model N was the only input whereas in Kabi and Bareeba (2007) the other nutrients in manure could have partly contributed to the observed DM yield. However, During and Weeda (1973) observes that forage biomass increase is mainly due to N although growth responses to phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) are expected in poor soils. Given that efficient use of manure depends on handling, storage and method of application (Rufino et al., 2006), and the improved DM yield in elephant grass of 77.8 and 26% with subsurface and surface application respectively (Kabi and Bareeba, 2007), it is possible for farmers to improve forage biomass yield and subsequently animal performance by applying manure. Furthermore, nitrogen losses in storage (Lekasi et al., 2001; Thomsen, 2000) and surface application (Sørensen et al., 2003) may be minimized by immediately applying the manure using the subsurface method (Kabi and Bareeba, 2007) and timing the application to synchronise peak mineral N availability and peak plant N demand (Lekasi et al., 2001). These observations were the basis for choosing k = 0.3 (Table 2). In conclusion, it is therefore possible for farmers to improve the forage biomass yield and thus animal performance by not only applying manures, but also by using the most appropriate method to minimize excreted N losses.

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