

Article

Effects of Corn Silage and Alfalfa Hay on Production and Nitrogen Excretion in Lactating Dairy Cows

Daniel Scoresby, Isabelle A. M. A. Teixeira *  and Mireille Chahine *

Twin Falls Research and Extension Center, University of Idaho, 315 Falls Avenue, Evergreen Bldg, Twin Falls, ID 83844, USA

* Correspondence: izabelle@uidaho.edu (I.A.M.A.T.); mchahine@uidaho.edu (M.C.)

Abstract: A meta-regression was conducted on studies published from 2018 to 2023 to explore the effects of nutrient intakes from alfalfa (ALF) and corn silage (CS) on milk yield (MY), energy-corrected milk yield (ECM), N efficiency (N_{EFF}), milk urea nitrogen (MUN), and manure nitrogen excretion (N_{MANURE}) in Holstein lactating cows. The analysis included 193 studies with 698 individual treatment means. Multiple models were developed for each response variable using a backward stepwise approach and cross-evaluated against the database. Nutrient intake from both CS and ALF influenced MY and ECM, with ALF generally having a positive effect. The N_{EFF} was also affected by nutrient intakes from both forages. Generally, greater protein intake reduced N_{EFF} , whereas greater MY was associated with improved N_{EFF} . An increase in the rumen-degradable protein intake (RDPI), especially from ALF, increased MUN. However, no significant effect of protein intake from CS on MUN was observed. Additionally, an increase in crude protein intake and RDPI, regardless of source (CS or ALF), led to an increase in g/d of N_{MANURE} . Our results indicate that nutrient intakes from ALF and CS have different effects on production, excretion, and nitrogen efficiency, supporting their use in targeted nutrient and waste management strategies.

Keywords: energy corrected milk; haylage; manure nitrogen; meta-analysis; meta-regression; milk urea nitrogen; milk yield; nitrogen efficiency



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1. Introduction

Alfalfa (ALF), provided as hay or haylage, and corn silage (CS) are the two most common forage sources in the diets of dairy cows in the Western United States. These forages are good sources of neutral detergent fiber (NDF) but they differ markedly in protein, starch, and mineral content [1,2]. On average, mid-maturity ALF hay contains 20.7% (± 2.37) crude protein (CP), 1.5% (± 0.85) starch, and 41.1% (± 4.84) NDF, while typical CS contains 7.7% (± 0.94) CP, 32.9% (± 6.42) starch, and 40.9% (± 4.75) NDF [1]. The nutritional differences (nutrient content, digestibility, and inclusion rate in the diet) can influence dry matter intake (DMI) and nutrient supply, and thus lactation performance and efficiencies [3,4]. Because CS is more energy-dense than alfalfa, it supplies readily fermentable carbohydrates that can increase DMI and milk yield (MY); however, its higher starch level can predispose cows to rumen acidosis [5–7]. Conversely, the protein and NDF content in alfalfa influence rumen fill, ammonia recycling, microbial protein synthesis, and nitrogen efficiency (N_{EFF}) [8–10].

Over the past 15–20 years, a shift has occurred in the ratio of CS to ALF in the diets of lactating dairy cows in the United States. Corn silage inclusion in the diets of lactating dairy

cows has increased, while ALF use has decreased [11]. This trend parallels an about 40% decrease in U.S. alfalfa acreage and approximately 70% increase in corn silage production in the last 5 decades [12]. This shift has been driven primarily by agronomic and economic factors, such as lower nitrogen-fertilizer costs, easier harvest and storage of corn silage, and favorable farm-gate prices, rather than by differences in nutritive value alone [13,14].

Studies investigating the effects of altering dietary CS and ALF inclusion rates have reported inconsistent results regarding DMI, milk components, and manure nitrogen excretion (N_{MANURE}). For instance, Weiss et al. [13] and Wattiaux and Karg [14] disagreed on crude protein intake (CPI) effects on MY, energy-corrected milk yield (ECM), and N_{MANURE} . Given the changes in dietary forage inclusion rates, there is a need to quantify the impacts of CS and ALF on production, N excretion, and efficiencies, as no comprehensive review of these effects has been performed to date.

To address this gap, we conducted a meta-regression [15,16] to evaluate how varying nutrient intakes from ALF and CS affect MY, ECM, milk urea nitrogen (MUN), N_{MANURE} , and N_{EFF} in lactating Holstein cows. By synthesizing nutrient intake and response data across a broad range of CS and ALF inclusion levels, this analysis aims to improve our understanding of how shifts in forage inclusion influence milk production and N excretion, thereby providing insights into optimizing forage strategies for enhanced productivity and environmental sustainability.

2. Materials and Methods

2.1. Data Collection

Data used for the meta-regression were collected from studies published from 2018 to 2023. Publications were retrieved from index databases, such as PubMed, Web of Science, SCIELO, and Scopus. The 2018–2023 timeframe was chosen to reflect both the most current genetic potential of the Holstein cows and the varieties of corn and alfalfa currently used worldwide, ensuring the relevance of the results.

An initial search yielded 1569 studies using the search terms “milk urea nitrogen”, “MUN”, and “cow”. Publications categorized as reviews, meta-analyses, abstracts, or other non-primary research types were excluded (Figure 1). After downloading the studies, further selection criteria were applied: (1) studies must include information on milk production and components (milk fat, milk protein) and MUN; (2) must provide dietary ingredients; (3) must include ALF as either hay or haylage and/or CS in the diet; (4) must involve lactating Holstein dairy cows; (5) exclude diets with grazed pasture; and (6) must include data on dry matter intake (DMI). Studies that failed to meet these criteria were excluded.

A summary of the study selection process is shown in a PRISMA flow chart (Figure 1) [17]. If a study included multiple treatments, only those meeting the criteria were retained. Studies involving heat stress or challenges to DMI were also excluded to avoid confounding factors that could bias the analysis. Ultimately, 193 studies comprising 698 treatment means were included in the final database. The descriptive statistics of the database are shown in Table 1.

2.2. Calculations

For studies lacking reported values for energy-corrected milk (ECM), milk fat (M_{FAT})% or kg/d, or milk crude protein (M_{PROTEIN})% or kg/d, the variables were calculated. If both percent and yield were missing, the study was discarded. Missing M_{FAT} and M_{PROTEIN} variables, whether in kg or percentage, were calculated. Missing M_{FAT} and M_{PROTEIN} production (in kg) were calculated by multiplying the MY by the respective percentage divided by 100. The M_{FAT} and M_{PROTEIN} percentages were calculated by dividing the

yield in kg by MY. The ECM values, when not reported, were calculated using an equation proposed by Sjaunja et al. [18] and evaluated by Hall [19]:

$$\text{ECM (kg/d)} = 0.25 \times \text{MY (kg)} + 12.2 \times \text{M}_{\text{FAT}} \text{ (kg)} + 7.7 \times \text{M}_{\text{PROTEIN}} \text{ (kg)}$$

Milk true protein (MTP) values were converted to $\text{M}_{\text{PROTEIN}}$ when the latter was not reported. The $\text{M}_{\text{PROTEIN}}$ was calculated by adding 0.19% to MTP [20–24], representing the mean non-protein nitrogen (NPN) content in milk. The equation is as follows:

$$\text{M}_{\text{PROTEIN}} (\%) = \text{MTP} (\%) + 0.19\%$$

The DMI of CS and ALF was calculated by multiplying their inclusion rates in the diet (on a DM basis) by the DMI. Nutrient intakes (CP, rumen-undegradable protein (RUP), rumen-degradable protein (RDP), and NDF) from ALF and CS were calculated in a similar manner, based on ALF and CS nutrient compositions reported in the publications. When the specific nutrient content of ALF or CS was not reported in the study, the NASEM feed library values [1] were used. Remaining DMI and nutrient intakes were calculated by subtracting the CS and ALF contributions from the total diet values. These intakes were categorized as “OTHER” (referring to other ingredients).

The N_{EFF} , when not reported, was calculated as follows:

$$\text{N}_{\text{EFF}} = \text{Milk Nitrogen (kg/d)} / \text{Nitrogen Intake (kg/d)}$$

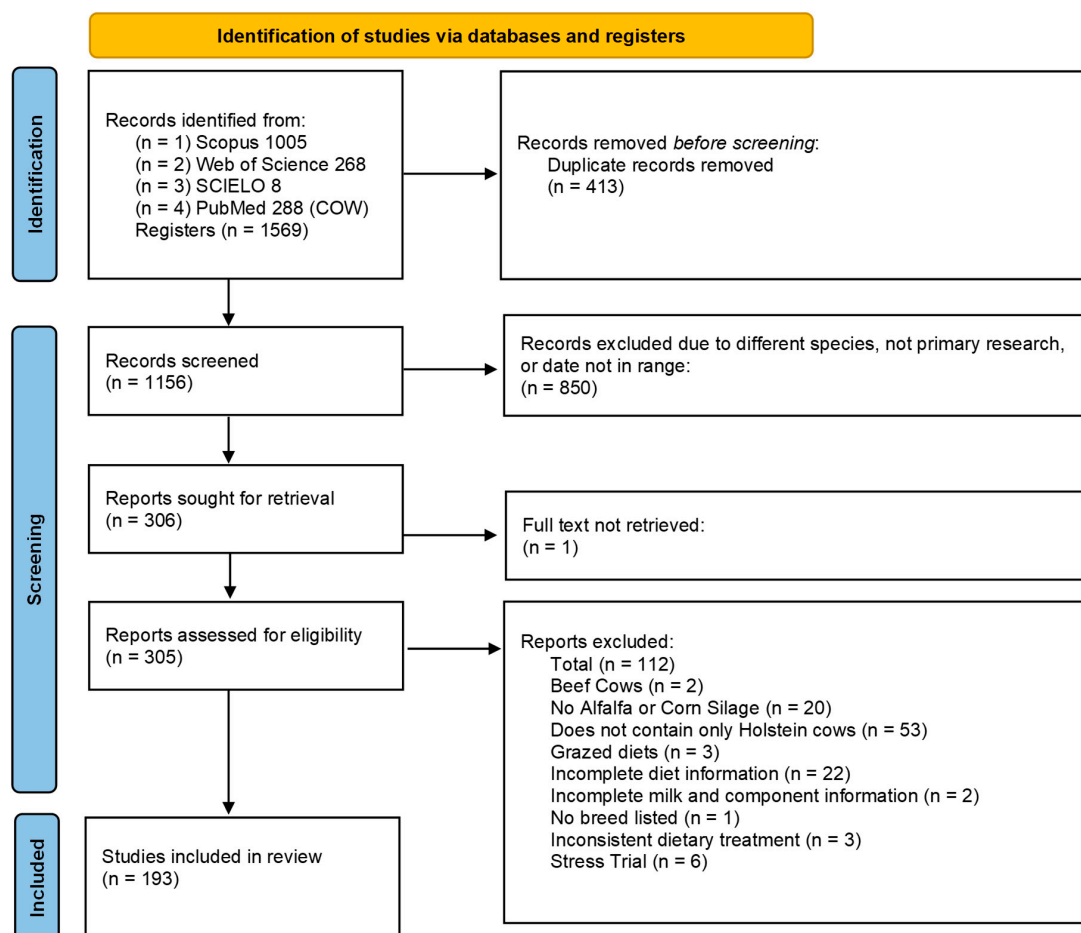


Figure 1. PRISMA flowchart showing the process of identifying and screening eligible studies for inclusion into the primary database. Date range used: 2018–2023. Keywords used: milk urea nitrogen + cow, MUN + cow.

Table 1. Descriptive statistics of the database production and intake variables.

Variable ¹	n ²	Mean	StDev ³	Min ⁴	Max ⁵
BW, kg	267	666.12	57.88	533.00	800.00
MY, kg/d	698	35.40	7.36	19.00	58.70
ECM, kg/d	689	35.16	7.34	17.22	57.60
Milk Fat%	689	3.75	0.47	2.34	5.26
Milk Fat, kg/d	689	1.32	0.30	0.57	2.28
Milk Protein%	689	3.19	0.24	1.91	3.85
Milk Protein, kg/d	689	1.13	0.22	0.60	1.77
Milk Lactose%	628	4.75	0.21	3.02	5.27
Milk Lactose, kg/d	628	1.71	0.53	0.85	11.67
MUN, mg/dl	698	12.76	2.80	5.30	25.40
Nitrogen Efficiency	683	0.31	0.06	0.16	0.58
Urine Nitrogen, g/d	220	197.11	52.46	85.00	348.00
Fecal Nitrogen, g/d	364	231.24	97.75	45.52	508.00
Manure Nitrogen, g/d	206	407.79	94.86	224.00	738.00
Diet					
DMI, kg/d	698	23.24	3.41	14.14	33.65
CPI, kg/d	694	3.65	0.48	2.14	5.51
RDPI, kg/d	209	2.47	1.34	1.55	13.48
RUPI, kg/d	196	1.51	1.18	0.62	9.15
NDFI, kg/d	592	7.58	1.14	4.20	14.4
StarchI, kg/d	399	5.71	1.24	1.83	12.02
Corn silage					
DMI CS, kg/d	666	7.54	2.94	1.13	14.67
CPI CS, kg/d	666	0.58	0.23	0.08	1.16
RDPI CS, kg/d	666	0.39	0.15	0.05	0.78
RUPI CS, kg/d	666	0.19	0.07	0.03	0.38
NDFI CS, kg/d	666	3.13	1.25	0.48	6.58
StarchI CS, kg/d	666	2.47	1.01	0.25	5.39
Alfalfa					
DMI ALF, kg/d	443	3.97	2.21	0.11	13.26
CPI ALF, kg/d	443	0.80	0.48	0.01	3.31
RDPI ALF, kg/d	443	0.61	0.35	0.01	2.42
RUPI ALF, kg/d	443	0.19	0.13	0.00	0.89
NDFI ALF, kg/d	443	1.61	0.90	0.06	5.73
StarchI ALF, kg/d	443	0.07	0.05	0.00	0.27
Other ingredients					
DMI OTHER, kg/d	698	13.53	3.55	4.71	27.79
CPI OTHER, kg/d	694	2.61	0.61	0.35	4.47
RDPI OTHER, kg/d	209	1.63	1.38	0.47	12.67
RUPI OTHER, kg/d	196	1.16	1.21	0.07	8.75
NDFI OTHER, kg/d	592	3.68	1.76	0.02	14.04
StarchI OTHER, kg/d	399	3.15	1.38	0.00	8.49

¹ BW = body weight; MY = milk yield; ECM = energy-corrected milk; MUN = milk urea nitrogen; nitrogen efficiency = milk nitrogen/nitrogen intake; DMI = dry matter intake; CPI = crude protein intake; RDPI = rumen-degradable protein intake; RUPI = rumen-undegradable protein intake; NDFI = neutral detergent fiber intake; StarchI = starch intake; ___ CS = intake from corn silage; ___ ALF = intake from alfalfa; ___ OTHER = intake from other ingredients; ² n = number of observations; ³ StDev = standard deviation; ⁴ Min = minimum; ⁵ Max = maximum.

2.3. Statistical Analysis

All statistical analyses were performed using the R programming language (version 2023.12.1+402) [25,26]. Descriptive statistics were calculated using the psych package (version 2.4.6.26), and preliminary plots were generated with the ggplot2 (version 3.5.1) and Gally (version 2.2.1) packages. Model development was performed using the lme4 and lmerTest (version 3.1-3) packages [27,28]. Mixed models were fitted to the data using

maximum likelihood estimation, considering study as a random effect. Data were weighted by the square root of the number of observations in each treatment mean.

A stepwise approach with backward elimination was employed, sequentially removing variables from the global model until all remaining variables had p -values ≤ 0.05 . Collinearity was assessed using variance inflation factors (VIFs). All variables in the final models had VIFs of less than 4, indicating minimal collinearity. The models were cross-evaluated against the database. The evaluation metrics included the concordance correlation coefficient (CCC) and root mean squared error (RMSE). These were calculated from residuals unadjusted for random study effects (as obtained using the predict function in lme4), following the methods described by Lin [29] and Bibby and Toutenburg [30].

3. Results

The three predictive models for estimating MY are presented in Table 2. Model MY1 included BW and dietary CPI as significant variables (RMSE = 4.81% mean and CCC = 0.97). Model MY2 incorporated DMI from ALF, CS, and OTHER (RMSE = 3.94% mean and CCC = 0.98). Finally, model MY3 used the specific nutrient intakes from these ingredients (RMSE = 4.88% mean and CCC = 0.96).

Table 2. Predictive models for milk yield (kg/d) in lactating Holstein cows fed corn silage (CS) and/or alfalfa hay or haylage (ALF).

Predictors ¹	Eq. MY1			Eq. MY2			Eq. MY3		
	Estimates	CI	p	Estimates	CI	p	Estimates	CI	p
Intercept	−15.13579	−27.43–−2.84	0.016	7.45623	4.05–10.86	<0.001	25.801	19.90–31.70	<0.001
BW, kg/d	0.06875	0.05–0.09	<0.001						
CPI, kg/d	1.75266	0.30–3.21	0.018						
DMI CS, kg/d				1.27056	1.07–1.47	<0.001			
DMI ALF, kg/d				0.93381	0.72–1.15	<0.001			
DMI OTHER, kg/d				1.30989	1.15–1.47	<0.001			
CPI OTHER, kg/d							2.3086	1.01–3.61	0.001
RUPI ALF, kg							10.5055	3.25–17.77	0.005
NDFI CS, kg							1.8115	1.02–2.61	<0.001
NDFI OTHER, kg							−0.7386	−1.40–−0.07	0.030
Random Effects									
σ^2	19.71			10.09			15.97		
τ_{00}	40.58 PubID			31.35 PubID			41.33 PubID		
N_{study}	72 PubID			118 PubID			102 PubID		
$N_{\text{observations}}$	263			411			357		
RMSE, % mean	4.81			3.94			4.88		
CCC	0.97			0.98			0.96		
AICc	1450.07			2071.04			1936.20		

¹ BW = body weight; CPI = crude protein intake; DMI CS = dry matter intake from corn silage; DMI ALF = dry matter intake from alfalfa; DMI OTHER = dry matter intake from other ingredients; CPI OTHER = CPI from other ingredients; RUPI ALF = rumen-undegradable protein intake from alfalfa; NDFI CS = neutral detergent fiber intake from corn silage; NDFI OTHER = neutral detergent fiber intake from other ingredients. σ^2 = mean random effect variance; τ_{00} = between study variance; N_{study} = number of publications; $N_{\text{observations}}$ = number of treatment means used; RMSE = root mean squared error (% of observed mean); CCC = concordance correlation coefficient; AICc = corrected Akaike information criterion; PubID = publications.

Body weight and crude protein intake (CPI) have a positive effect on MY. Corn silage and ALF both have mixed effects on MY, depending on the nutrient used for calculation. The positive coefficients of DMI from CS, ALF, and OTHER indicate that within the intake ranges in the database, higher DMI from these dietary ingredients is associated with greater MY. However, when evaluated by specific nutrient intakes, the effects varied. Rumen-undegradable protein intake (RUPI) from ALF, neutral detergent fiber intake (NDFI) from CS, and CPI from OTHER have a positive effect on MY, while NDFI from OTHER had a negative effect.

Three predictive models for ECM were generated, similar to those for MY (Table 3). Three significant models were identified. Model ECM1 included BW and dietary CPI and NDFI with both BW and CPI positively affected ECM but dietary NDFI had a negative impact (RMSE = 4.05% and CCC = 0.98). Model ECM2, similar to MY2, showed that DMI from CS, ALF, and OTHER positively affected ECM (RMSE = 3.63% and CCC = 0.98). In model ECM3 we observed that starch intake (StarchI) from OTHER, RDP intake (RDPI) from ALF, and RUPi from OTHER all had a positive effect on ECM, while NDFI from ALF and OTHER had a negative effect (RMSE = 3.43% and CCC = 0.98).

Table 3. Predictive models for energy-corrected milk (kg/d) in lactating Holstein cows fed corn silage (CS) and/or alfalfa hay or haylage (ALF).

Predictors ¹	Eq. ECM1			Eq. ECM2			Eq. ECM3		
	Estimates	CI	p	Estimates	CI	p	Estimates	CI	p
Intercept	−19.467169	−31.13–−7.81	0.001	9.76469	6.65–12.88	<0.001	38.10539	28.48–47.73	<0.001
BW, kg	0.078344	0.06–0.09	<0.001				0.05170	0.04–0.07	<0.001
Parity									
Multiparous							−11.37229	−14.91–−7.83	<0.001
Primiparous							−13.35990	−16.79–−9.93	<0.001
CPI, kg	3.043271	1.40–4.69	<0.001						
NDFI, kg	−0.970384	−1.72–−0.22	0.012						
DMI CS, kg				1.17165	0.98–1.36	<0.001			
DMI ALF, kg				0.82427	0.63–1.02	<0.001			
DMI OTHER, kg				1.16999	1.02–1.32	<0.001			
RDPI ALF, kg							107.41111	79.87–134.95	<0.001
RUPi OTHER, kg							1.94412	1.30–2.58	<0.001
NDFI ALF, kg							−58.48674	−70.24–−46.73	<0.001
NDFI OTHER, kg							−2.57496	−3.37–−1.78	<0.001
StarchI ALF, kg							122.54377	87.42–157.67	<0.001
Random Effects									
σ^2	11.82			8.28			6.57		
τ_{00}	46.02 PubID			26.51 PubID			0.48 PubID		
N _{study}	56 PubID			116 PubID			15 PubID		
N _{observations}	200			404			43		
RMSE, % mean	4.05			3.63			3.43		
CCC	0.98			0.98			0.98		
AICc	1042.53			1961.14			177.53		

¹ BW = body weight; CPI = crude protein intake; NDFI = neutral detergent fiber intake; DMI CS = dry matter intake from corn silage; DMI ALF = dry matter intake from alfalfa; DMI OTHER = dry matter intake from other ingredients; RDPI ALF = rumen-degradable intake from alfalfa; RUPi OTHER = rumen-undegradable intake from other ingredients; NDFI ALF = NDFI from alfalfa; NDFI OTHER = NDFI from other ingredients; StarchI ALF = starch intake from alfalfa. σ^2 = mean random effect variance; τ_{00} = between study variance; N_{study} = number of publications; N_{observations} = number of treatment means used; RMSE = root mean squared error (% of observed mean); CCC = concordance correlation coefficient; AICc = corrected Akaike information criterion; PubID = publications.

Nitrogen efficiency yielded five models, as shown in Tables 4 and 5. Model N_{EFF}1 showed both BW and MY having a positive effect on N_{EFF} while CPI and NDFI had negative effects (RMSE = 2.39% and CCC = 0.99). Model N_{EFF}2 also showed CPI with a negative effect with StarchI and ECM having positive effects (RMSE = 2.93% and CCC = 0.99). Model N_{EFF}3 showed ECM had a positive effect and DMI from ALF had a negative effect (RMSE = 5.54% and CCC = 0.95). Model N_{EFF}4 showed that both BW and ECM had positive effects on N_{EFF}, while CPI from CS, ALF, and OTHER had negative effects (RMSE = 2.32% and CCC = 0.99). Model N_{EFF}5 showed ECM had a positive effect and MUN, NDFI from OTHER, and RDPI from ALF and CS had negative effects (RMSE = 4.29% and CCC = 0.97).

Table 4. Predictive models for nitrogen efficiency (N_{EFF}) in lactating Holstein cows fed corn silage (CS) and/or alfalfa hay or haylage (ALF).

Predictors ¹	Estimates	Eq. N_{EFF1}		Estimates	Eq. N_{EFF2}		Estimates	Eq. N_{EFF3}	
		CI	<i>p</i>		CI	<i>p</i>		CI	<i>p</i>
Intercept	0.2429	0.19–0.30	<0.001	0.3388	0.31–0.36	<0.001	0.1076	0.08–0.14	<0.001
BW, kg	0.0002937	0.00–0.00	<0.001						
MY, kg/d	0.004383	0.00–0.00	<0.001						
ECM, kg				0.00722	0.01–0.01	<0.001	0.005903	0.01–0.01	<0.001
CPI, kg	−0.06407	−0.07–−0.06	<0.001	−0.08463	−0.09–−0.08	<0.001			
NDFI, kg	−0.006491	−0.01–−0.00	0.001						
StarchI, kg				0.004169	0.00–0.01	<0.001			
DMI ALF, kg							−0.002897	−0.00–−0.00	0.003
Random Effects									
σ^2	0.00033			0.00041			0.00136		
τ_{00}	0.00069			0.00057			0.00152		
N_{study}	56 PubID			106 PubID			126 PubID		
$N_{observations}$	200			397			430		
RMSE, % mean	2.39			2.93			5.54		
CCC	0.99			0.99			0.95		
AICc	−1030.36			−2087.78			−1747.70		

¹ BW = body weight; MY = milk yield; ECM = energy-corrected milk; CPI = crude protein intake; StarchI = starch intake; NDFI = neutral detergent fiber intake; DMI ALF = dry matter intake from alfalfa. σ^2 = mean random effect variance; τ_{00} = between-study variance; N_{study} = number of publications; $N_{observations}$ = number of treatment means used; RMSE = root mean squared error (% of observed mean); CCC = concordance correlation coefficient; AICc = corrected Akaike information criterion; PubID = publication identification.

Table 5. Predictive models for nitrogen efficiency in lactating Holstein cows fed corn silage (CS) and/or alfalfa hay or haylage (ALF) (continued models N_{EFF4} and N_{EFF5}).

Predictors ¹	Estimates	Eq. N_{EFF4}		Estimates	Eq. N_{EFF5}	
		CI	<i>p</i>		CI	<i>p</i>
Intercept	0.2703	0.22–0.32	<0.001	0.2966	0.25–0.34	<0.001
BW, kg	0.00008072	0.00–0.00	0.033			
MUN, mg/dL				−0.007868	−0.01–−0.01	<0.001
ECM, kg	0.006571	0.01–0.01	<0.001	0.00656	0.01–0.01	<0.001
CPI CS, kg	−0.0553	−0.08–−0.03	<0.001			
CPI ALF, kg	−0.0683	−0.08–−0.06	<0.001			
CPI OTHER, kg	−0.07041	−0.08–−0.06	<0.001			
RDPI ALF, kg				−0.05374	−0.07–−0.04	<0.001
NDFI OTHER, kg				−0.0135	−0.02–−0.01	<0.001
RDPI CS, kg				−0.1305	−0.18–−0.08	<0.001
Random Effects						
σ^2	0.00033			0.00041		
τ_{00}	0.00069 PubID			0.00057 PubID		
N_{study}	56 PubID			106 PubID		
$N_{observations}$	200			397		
RMSE, % mean	2.39			2.93		
CCC	0.99			0.99		
AICc	−1030.36			−2087.78		

¹ BW = body weight; MUN = milk urea nitrogen; ECM = energy-corrected milk; CPI CS = crude protein intake from corn silage; CPI ALF = crude protein intake from alfalfa; CPI OTHER = crude protein intake from other ingredients; RDPI ALF = rumen-degradable protein intake from alfalfa; NDFI OTHER = neutral detergent fiber intake from other ingredients; RDPI CS = rumen-degradable protein intake from corn silage. σ^2 = mean random effect variance; τ_{00} = between-study variance; N_{study} = number of publications; $N_{observations}$ = number of treatment means used; RMSE = root mean squared error (% of observed mean); CCC = concordance correlation coefficient; AICc = corrected Akaike information criterion; PubID = publications.

Three models were developed for predicting MUN (Table 6). Model MUN1 showed total RDPI and RUPI having a positive effect on MUN while NDFI and StarchI both had negative effects on MUN (RMSE = 6.28% and CCC = 0.94). Model MUN2 used DMI from CS and ECM, with both variables having a negative effect (RMSE = 9.63% and CCC = 0.88).

Model MUN3 showed that RDPI from ALF and OTHER had positive effects on MUN, while NDFI from CS and StarchI from OTHER had negative effects (RMSE = 7.77% and CCC = 0.91).

Table 6. Predictive models for milk urea nitrogen (MUN) in lactating Holstein cows fed corn silage (CS) and/or alfalfa hay or haylage (ALF).

Predictors ¹	Eq. MUN1			Eq. MUN2			Eq. MUN3		
	Estimates	CI	p	Estimates	CI	p	Estimates	CI	p
Intercept	8.5515	4.59–12.52	<0.001	15.04963	13.57–16.53	<0.001	9.8962	5.68–14.11	<0.001
ECM, kg/d				−0.04117	−0.08–−0.00	0.041			
RDPI, kg	3.7959	2.53–5.06	<0.001						
RUPI, kg	3.5421	1.50–5.58	0.001						
NDFI, kg	−0.5498	−0.89–−0.21	0.002						
StarchI, kg	−1.0052	−1.34–−0.67	<0.001						
DMI CS, kg				−0.10091	−0.20–−0.01	0.036			
RDPI ALF, kg							2.9104	0.25–5.57	0.033
RDPI OTHER, kg							4.5414	3.20–5.88	<0.001
NDFI CS, kg							−0.8119	−1.60–−0.03	0.043
StarchI OTHER, kg							−0.8071	−1.21–−0.41	<0.001
Random Effects									
σ^2	2.45			6.72			3.47		
τ_{00}	5.44 PubID			5.38 PubID			3.11 PubID		
N _{study}	25 PubID			178 PubID			21 PubID		
N _{observations}	95			657			72		
RMSE, % mean	6.28			9.63			7.77		
CCC	0.94			0.88			0.91		
AICc	341.66			2774.93			272.50		

¹ ECM = energy-corrected milk; RDPI = rumen-degradable protein intake; RUPI = rumen-undegradable protein intake; NDFI = neutral detergent fiber intake; StarchI = starch intake; DMI CS = dry matter intake from corn silage; RDPI ALF = RDPI from alfalfa; RDPI OTHER = RDPI from other ingredients; NDFI OTHER = NDFI from other ingredients; StarchI OTHER = starch intake from other ingredients. σ^2 = mean random effect variance; τ_{00} = between-study variance; N_{study} = number of publications; N_{observations} = number of treatment means used; RMSE = root mean squared error (% of observed mean); CCC = concordance correlation coefficient; AICc = corrected Akaike information criterion; PubID = publications.

Two models were generated for N_{MANURE}, shown in Table 7. Model N_{MANURE}1 showed both ECM and total CPI having a positive effect on N_{MANURE} (RMSE = 13.25% and CCC = 0.94). Model N_{MANURE}2 also showed ECM with a positive effect (RMSE = 1.56% and CCC = 1.00). The RDPI from CS, ALF, and OTHER all had positive effects with NDFI from OTHER and StarchI from ALF had negative effects.

Three models were developed for predicting MUN (Table 6). Model MUN1 showed total RDPI and RUPI having a positive effect on MUN, while NDFI and StarchI both had negative effects on MUN (RMSE = 6.28% and CCC = 0.94). Model MUN2 used DMI from CS and ECM, with both variables having a negative effect (RMSE = 9.63% and CCC = 0.88). Model MUN3 showed RDPI from ALF and OTHER had positive effects on MUN, while NDFI from CS and StarchI from OTHER had negative effects (RMSE = 7.77% and CCC = 0.91).

Two models were generated for N_{MANURE}, shown in Table 7. Model N_{MANURE}1 showed both ECM and total CPI having a positive effect on N_{MANURE} (RMSE = 13.25% and CCC = 0.94). Model N_{MANURE}2 also showed ECM with a positive effect (RMSE = 1.56% and CCC = 1.00). The RDPI from CS, ALF, and OTHER all had positive effects, with NDFI from OTHER and StarchI from ALF having negative effects.

Table 7. Predictive models for manure nitrogen (N_{MANURE}) in lactating Holstein cows fed corn silage (CS) and/or alfalfa hay or haylage (ALF).

Predictors ¹	Eq. $N_{\text{MANURE}}1$			Eq. $N_{\text{MANURE}}2$		
	Estimates	CI	<i>p</i>	Estimates	CI	<i>p</i>
Intercept	−103.887	−203.05—−4.72	0.040	−434.065	−687.47—−180.66	0.003
ECM, kg	5.943	3.24–8.65	<0.001	18.34	13.07–23.61	<0.001
CPI, kg	65.823	40.52–91.12	<0.001			
RDPI CS, kg				855.078	600.70–1109.46	<0.001
RDPI ALF, kg				650.672	255.05–1046.30	0.004
RDPI OTHER, kg				80.184	38.14–122.22	0.001
NDFI OTHER, kg				−41.438	−62.01—−20.87	0.001
StarchI ALF, kg				−7910.577	−10472.73—−5348.42	<0.001
Random Effects						
σ^2	8202.6			243.35		
τ_{00}	9352.96 PubID			2882.05 PubID		
N_{study}	102 PubID			8 PubID		
$N_{\text{observations}}$	375			22		
RMSE, % mean	13.25			1.56		
CCC	0.94			1.00		
AICc	4278.32			157.30		

¹ ECM = energy-corrected milk; CPI = crude protein intake; RDPI CS = rumen-degradable protein intake from corn silage; RDPI ALF = rumen-degradable protein intake from alfalfa; RDPI OTHER = rumen-degradable protein intake from other ingredients; NDFI OTHER = neutral detergent fiber intake from other ingredients; StarchI ALF = starch intake from alfalfa. σ^2 = mean random effect variance; τ_{00} = between-study variance; N_{study} = number of publications; $N_{\text{observations}}$ = number of treatment means used; RMSE = root mean squared error (% of observed mean); CCC = concordance correlation coefficient; AICc = corrected Akaike information criterion; PubID = publications.

4. Discussion

Models created from this meta-regression study show that both DMI and specific nutrient intake from CS and ALF have an effect on MY, ECM, MUN, N_{MANURE} , and N_{EFF} . The recent NASEM Nutrient Requirements of Dairy Cattle [1] report that typical CS contains 7–8% CP, 30–35% starch, and 39–43% NDF. More mature CS has higher starch levels but lower NDF and CP than immature silages. It also reports that ALF has between 18 and 22% CP, 1.5 and 2.3% starch, and 37 and 46% NDF. The maturity of ALF does not appear to affect starch levels; however, CP decreases and NDF increases with advancing maturity [31]. This does not differ for ALF in the form of hay or silage. Corn silage and ALF can vary between farms, resulting in the variability of available nutrients [32]. Understanding the specific nutrients of the forages available are important to determine the effects on the response variables.

4.1. Milk Yield and Energy-Corrected Milk Yield

Both CS and ALF were shown to affect MY and ECM in similar ways. The DMI of both forages positively affected MY and ECM (see models ECM2 and MY2). Although it was beyond the scope of this meta-analysis, our models suggest the possibility that the maturity of the ALF and the changing nutrient content (i.e., CP, RDP, and NDF) can change specific nutrient intakes and impact MY and ECM [31]. More mature ALF has higher NDF, lower CP, lower RDP, and lower RUP than less mature ALF [1]. It is possible that changing the maturity of the ALF in the diet without changing the inclusion rate can alter the specific nutrient intake as suggested by Palmonari et al. [31].

Our study had a total DMI of 23.24 kg/d with 7.54 kg/d from CS and 3.97 kg/d from ALF. Work has been performed by different research groups on the combined effects of ALF and CS on MY and components at different inclusion rates. West et al. [33] substituted 33% of the dietary CS with ALF hay and found no effect on MY, but by substituting 67% of

the CS with ALF, MY decreased. Baxter et al. [34] reported a positive effect of both CS and ALF together on MY. Arndt et al. [10] reported the highest MY with diets containing CS and ALF haylage in a 60:40 ratio of the dietary forage. Milk fat was also highest in the diets where ALF made up 40% or more of forage DM, which would contribute to the increase in ECM that our models predicted. Dhiman and Satter [35] suggested a similar ratio of CS to ALF for maximum MY. Charmley et al. [36] showed that CS had a positive impact on milk components, which would influence ECM. Our study concurs with prior findings that both forages have a positive effect on MY and ECM. These effects are the result of having adequate CPI to meet the cow's needs. Previous studies show that optimum dietary CPI is approximately 16.5%, with increased production up to this level and no change above it [37–39]. Providing adequate energy in the diet allows the cow to utilize optimal CPI to maximize production [40].

4.2. Nitrogen Efficiency

Total dietary StarchI had a positive effect on N_{EFF} (see N_{EFF2} in Table 4). Chowdhury et al. [41] reported an increase in N_{EFF} with dietary starch supplementation when compared to a control diet. The researchers did have a reduced dietary CPI as well as a lower starch diet, which is consistent with N_{EFF2} (– for CPI and + for StarchI). The researchers also had two other treatments with lower CP levels with and without amino acid supplementation. These other diets also improved N_{EFF} compared to the high-CP diet, which aligns with our predictive models showing CPI having a negative effect (see N_{EFF1} , N_{EFF2} , and N_{EFF4}).

Another study by Ipharraguerre and Clark [42] produced complementary findings to those of Chowdhury et al. [41] and our predictive models. Three diets of low, medium, or high dietary CP were used with two different sources of starch. Starch levels and CP were inversely correlated in these diets; as CP increased, dietary starch decreased. The highest N_{EFF} was achieved on the low-CP and high-starch diets. The lowest N_{EFF} was recorded on the high CP and low starch diets. These findings are still consistent with our model N_{EFF2} .

A study conducted by Sun et al. [6] reported a similar positive interaction between StarchI and N_{EFF} . As StarchI levels increased, N_{EFF} also increased. A difference between this study and the previous two is that the CPI remained constant, but RDPI was reduced independently of StarchI with no effect on N_{EFF} . This is in agreement with our models as we found no effect of overall RDPI on N_{EFF} ; however, RDPI from ALF and CS both had a negative effect (see models N_{EFF4} and N_{EFF5}).

In a study looking at different ratios of ALF to CS in the diets, Arndt et al. [10] reported that lower ALF and higher CS in the diets increased the N_{EFF} in dairy cows. This is consistent with our findings. Our models show that DMI, CPI, and RDPI from ALF have a negative effect on N_{EFF} . Other studies also found a similar relationship between ALF, CS, and N_{EFF} . A study by Hassanat et al. [43] reported a consistent CPI and N intake as the ratio of ALF to CS changed, but an increase in MY and milk N as more CS was added. The difference in CPI was made up for by adding OTHER to the diet. The CPI from all three had a negative effect on N_{EFF} in our models. However, Arndt et al. [10] and Brito and Broderick [44] both reported an increase in CPI and N intake as more ALF was added to the diet. The increased N intake could decrease the N_{EFF} if the diet has insufficient energy to encourage microbial growth in the rumen. All three studies had a reduced N_{EFF} as the proportion of ALF increased in the diet, suggesting that ALF has a greater negative effect than CS.

Energy-corrected milk had a positive effect on N_{EFF} in the models where it was included. It can be influenced by the quality of ALF and quantity of both ALF and CS in the diet (see ECM2 and ECM3). The decrease in N_{EFF} as seen by adding more ALF into the diet could be related to the ECM, which decreased with increasing ALF or reduced ALF quality.

By reducing the ECM produced, a net loss in N_{EFF} occurs, meaning it does not increase as much as it could with greater ECM production. This suggests that the negative effect of ALF on ECM can affect N_{EFF} in the same way. More work is needed to determine if this conclusion is correct, as the relationship has not been discussed in the papers searched.

Our models show that RDPI from ALF and CS had a negative effect on N_{EFF} . Santos et al. [45] concluded that increasing the dietary RUP:RDP ratio decreased the N_{EFF} in the cows. Diets with a higher amount of RDP had greater N_{EFF} . This relationship was also shown by Savari et al. [46]. The researchers increased the RDP in the diet by adding soybean meal. This increase in RDP increased the N_{EFF} . Both research groups theorized that the increase in RDP increased the rumen production and intestinal flow of amino acids. Both also postulated that this increased flow of amino acids boosted milk production and increased the N_{EFF} of the cow compared to diets with higher RUP.

Model N_{EFF5} showed RDPI from CS and ALF having an inverse effect and reducing N_{EFF} . As more RUP from ALF and CS is added to the diet, the amount of RDP will decrease. Forage quality and source can change the RUP:RDP ratio [47]. Substituting ALF with CS in equal portions would decrease the total RDP in the diet unless added from another source [1]. The same relationship exists with CPI from ALF, CS, and OTHER, although a negative relationship exists with all three according to model N_{EFF4} . This conclusion agrees with those shown by other research groups [48–51].

4.3. Milk Urea Nitrogen

Milk urea nitrogen is a common measure of N_{EFF} . Both RDPI and RUP are the primary sources of dietary N, which influences N partitioning in the body. The N partitioning in dairy cows, including digestion and absorption, has been previously explored [50,52]. As the N intake increases, the body is unable to utilize the excess N up to a certain point at the current energy levels, so it is excreted in the urine and milk [14,53]. The excess unabsorbed N is excreted in the feces. As the N utilization increases, less is wasted as more is absorbed and used for growth, reproduction, and milk production. Higher N utilization resulting in more MY and/or components increases N_{EFF} . This can be seen when ECM is added to the predictive models (see model MUN2). Higher ECM suggests more N is used and less N is wasted in the milk and urine [54].

Naderi et al. [55] reported that diets containing ALF had decreasing MUN as CS was removed and replaced with beet pulp in the diet. This is contrary to our model MUN2 as DMI from CS had a negative effect on MUN, while DMI from ALF and OTHER had no effect. Work by Arndt et al. [10] agrees with this conclusion. However, it is possible that the beet pulp used in the study by Naderi et al. (2016) [55] contained similar energy and protein levels as CS, which would agree with our conclusions from MUN3. However, model MUN3 showed that RDPI from ALF and OTHER had a positive effect on MUN with both NDFI from CS and StarchI from OTHER having negative effects. The extra energy from increased StarchI and NDFI can improve N_{EFF} (see N_{EFF2}) by allowing the body to access more available protein N [52]. Improved N_{EFF} can result in lower MUN [48]. Our models agree with other conclusions in the literature that adding more CS into diets can lower MUN values while ALF tends to increase them.

4.4. Manure Nitrogen

The other measure of N_{EFF} that we evaluated was N_{MANURE} . Weiss et al. [13] reported that increasing ALF in the diet reduced N digestibility and increased N_{MANURE} . Our models concur with their findings. Model $N_{MANURE2}$ shows that RDPI from ALF, CS, and OTHER have a positive effect on N_{MANURE} . The RDPI content of ALF is much greater than for CS. As discussed previously, by substituting ALF for CS, the RDPI decrease from ALF

will be greater than the increase from CS, resulting in a net reduction in N_{MANURE} . This conclusion is based on nutrient values for these two forages [1].

A study by Wattiaux and Karg [14] supports our model conclusions from $N_{\text{MANURE}2}$ about RDPI from ALF and CS. Their study substituted ALF with CS as the primary dietary forage at two different levels of CP with comparable levels of dietary RDP. The diets with high ALF had higher N_{MANURE} than the high CS diets due to higher N intake. However, they found no impact of CPI on N_{MANURE} , whereas our model $N_{\text{MANURE}1}$ found CPI to have a positive effect. In contrast, Weiss et al. [13] reported that CPI had a positive effect on N_{MANURE} , agreeing with our models. Other work also concludes that CPI positively impacts N_{MANURE} [56,57].

5. Conclusions

This meta-regression demonstrates that varying the inclusion levels (proportions) of ALF and CS in lactating dairy cow diets leads to proportional shifts in nutrient intake. Those shifts, in turn, influence milk production, nitrogen utilization efficiencies, and nitrogen excretion. Our findings underscore the critical role that forage selection plays in precision nutrient and waste management strategies on dairies by optimizing nutrient intake and excretion. By tailoring forage choice and ration formulations, dairy producers can improve lactation performance, enhance nitrogen utilization efficiency, and promote the long-term sustainability of their dairy operations.

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