Manipulating Nonstructural and Structural Carbohydrates in Rations for Dairy Cattle

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Optimizing production performance in lactating dairy cattle depends on our ability to predict carbohydrate-energy available in the rumen to maximize microbial yield and still maintain normal rumen function. Microbial energy (VFA) and protein must then be supplemented with rumen undegradable starch, protein and fat to optimize the milk production response. Structural carbohydrates crude fiber, acid detergent fiber, (ADF) and neutral detergent fiber, (NDF) have been utilized in dairy ration formulations as negative indicators of energy density. NDF has been identified as a predictor of dry matter intake, and ADF related more to digestibility. However predictability of intake and digestibility from chemical parameters varies widely with forage. Nonstructural carbohydrates (NSC) are a major carbohydrate source in high producing cow diets and are more consistent in quantity and digestibility. Starch comprises the major portion of the NSC fraction. Processing can influence rumen degradability of starch to a large degree. Several enzymatic methods and difference equations have been developed to quantitate NSC. Production studies have shown there is an optimal level of NSC to maximize milk yield. Rumen degradable carbohydrate/starch as a qualitative measure in dairy ration formulation is emerging as data bases are developed. The synergism between protein and carbohydrate use at the ruminal, postruminal and mammary gland level will ultimately be key in maximizing efficiency of milk yield in dairy cattle.

QUANTITATIVE MEASURES OF CARBOHYDRATES

Acid Detergent Fiber

The acid detergent fiber (ADF) fraction of feedstuffs includes cellulose and lignin as primary components. ADF and lignin concentrations are related more to digestibility than to intake (-.75 and -.46 for ADF digestibility and intake, respectively (57). Relationship between ADF and digestibility is influenced by several factors including forage and variety, maturity at harvest, and storage conditions etc. (35, 55). Mathison (22) developed equations relating to ADF to digestible energy content in various forage types. They are as follows: alfalfa; r^2=.46; legume-grass; r^2=.58 grass; r^2=.34 and whole plant cereal; r^2=.34. Present systems to feed dairy cattle are based on a prediction of NE_L from ADF as well as NDF content.

Florida Ruminant Nutrition Symposium, January 13-14, 1993, Gainesville, Florida.

Presented at the 4th Florida Ruminant Nutrition Symposium, Gainesville, January 13-14, 1993

Neutral Detergent Fiber

Neutral detergent fiber (NDF) consists of cellulose, hemicellulose and lignin. NDF has been used to estimate the energy value of feed (26) as well as dietary bulk density and fill (28). NDF has also been identified as highly related to DMI and depression in digestibility associated with high intakes (27, 55).

The NDF Energy Intake System to formulate dairy rations has been proposed (28). The system is based on the concept that feed intake is regulated by two mechanisms: 1) rumen fill and 2) energy density. It is proposed that since NDF is related to both the filling effect and energy density of diets, it can provide a means to formulate rations. The objective is to identify optimal NDF contents that will maximize forage and fiber intake, in conjunction with meeting specific energy requirements at a given milk yield. It was identified that a challenge associated with this system is it assumes all NDF behaves equally in the cow. Density, particle size, dry matter content of forage have a significant effect on rate and extent of digestion, chewing time, and rate of passage of the fiber material.

A basic challenge with this system is the ability of NDF, as a single quantitative measure, to predict dry matter intake. Mathison (22) showed that voluntary consumption of forages was not predicted well by NDF content of forages, in that the percent of variation in DMI explained by NDF was only 8, 24, 6 and 4 for alfalfa, legume-grass, grass and whole plant cereal forages respectively. Others (14, 24, 40) have also demonstrated similar lack of a consistent relationship.

Briceno et al. (3) showed no constant relationship of NDF level with DMI and milk yield across a variety of forage sources, (DMI, r^2=.07 and milk yield, r^2= .09). They concluded that forage source should be considered individually if NDF is used to formulate dairy rations. Chandler (7) compared several equations to predict NE_L when compared to NRC values as a standard of comparison. Although, comparison to the standard NRC values may not be appropriate, since specific equations were developed with regional forages.

In theory, NDF should more accurately predict intake based on biological phenomena (28). However it is not a perfect nutritive entity as a single measurement and does not completely describe ruminal availability (cell wall content vs. digestibility, r^2=.45, 56).

Nonstructural Carbohydrates (NSC)

Nonstructural (NS) carbohydrates are composed of sugars, starches and pectins. Pectins are associated with the cell wall, but are not covalently linked to the lignified portions and are almost completely digested (90-100%) in the rumen. Galactans are unique to legumes in replacing starches as the carbohydrate reserve and fructusans are the storage material in temperate grasses (57, 58).

Beta-glucans are peculiar to the cell wall of grasses and the bran of oats, barley and rye (1). Starch is the major storage carbohydrate in most cereal grains and constitutes a majority of NSC. It is composed of two major molecules: amylose and amylopectin. Amylose is a linear polymer of alpha 1-4, D-glucose units. Amylopectin is a branched polymer with linear chains of alpha 1-4, D-glucose that has an alpha branch point every 20-25 glucose residues (11, 46). Amylose and amylopectin molecules are held together by hydrogen bonding. Starch granules are cold water insoluble and swell reversibly. Starch granules are "pseudo-crystals" that contain regions of organized "crystalline" form (primarily amylopectin) and also non-organized "amorphous" areas. The crystalline regions are quite resistant to water infiltration, whereas water moves freely through the amorphous areas (11, 46).

Various methods have been utilized to predict NSC. Enzymatic procedures have used amylase or taka-diastase (5, 12, 13, 21). Difference equations have been developed and are listed as follows:

Sniffen (51):

Total carbohydrate (TC)=100 - (crude protein + ether extract + ash)

Non-fiber carbohydrate (NFC) = total carbohydrate - NDF

Nocek (31):

Neutral detergent solubles (NDS) = 100 - NDF

Nonstructural carbohydrate (NSC) = NDS-(crude protein + ether extract + ash in NDS)

Figure 1 (a,b,c) illustrates the relationship among starch, TNS and NSC (Data base from #33). The enzymatic and difference procedures are only moderately correlated (r^2= .65 and .74). Much of the variation is associated with the specificity of enzymes used in the starch and TNC analysis. In addition, difference procedures usually account for more carbohydrate types (mainly pectins etc.) especially for forages and by-products.

Lactation Studies With NSC

deVisser and deGrott (10) fed early lactating cows grain mixes containing 20, 30, 40 and 50% sugar and starch. Grain intake decreased as level of starch in the concentrate increased, thus, total DM intake was lower for high starch treatments. Milk yield and fat percentage also decreased linearly with increased starch. The incidence of off-feed cases was 3, 13, 63, and 69% for 20, 30, 40 and 50% starch levels, respectively. MacGregor et al. (21) conducted a study where cows were fed low (24.9%) or high (32.9%) starch-containing diets. Cows fed high-starch diets increase in milk production (P<.08), SNF (P<.07) and DMI (P<.08) compared to the low-starch diet.

Three early lactation cow studies (31) were conducted to determine the appropriate level of NSC, determined by difference (26), for maximal milk production. Each study evaluated a different forage program as follows: 100% alfalfa silage (AS), 100% corn silage (CS) and 50% CS:50% AS. The NSC of the total rations in each experiment were manipulated through the grain mix and were dose responsed within the forage program. The results showed the optimal level of total ration NSC for maximal milk yield appeared to be the same level for each forage program. There were no significant differences in fat test among treatment within each forage program. These data suggest NSC may be a predictable nutritive measurement, relating to rumen degradable carbohydrate across a range of forage programs.

Hoover et al. (15) recently concluded from continuous culture studies that diets with an NSC level of about 37% of DM provided sufficient energy for optimum, microbial growth. Lactating cow studies indicated that diets formulated to contain 33 and 39% NSC with 11.9 and 13.7% of DM as degradable intake protein (DIP) had higher intakes, microbial protein flow, milk production and lower cost than a diet with 24% NSC and 8.4% DIP with added by-pass protein and fat.

QUALITATIVE MEASURES OF CARBOHYDRATE

Rumen Degradable Starch (RDS)

Starch is the primary NSC source fed to cattle. Table 1 shows several commonly used starch containing ingredients and their digestion profile (6). The range in rumen degradability ranged from 58% (corn) to 82.8% (barley). Processing (physical and chemical) can have a major influence on starch site of digestion (rumen or small intestine, 36). Table 1 illustrates the influence of grinding on ruminal starch degradability. Decreasing particle size from 6% to 8 mm increased corn starch degradability by 31.4%, whereas for barley, 8.8%. Table 2 shows the relative in vivo ruminal digestion of starch as influenced by various processing methods in dairy cattle.

Rumen Degradable Carbohydrate

Although starch is an important source of carbohydrate energy for microbial yield, the energy contribution from structural carbohydrates can be significant. Thus, the total contribution from NS and Structural CHO must be considered. Except for a few ingredients primarily corn or barley, there were very few estimates of ruminal carbohydrate digestibility found in the literature. Nocek and Russell (32) developed the following equation to account for both structural and non-structural carbohydrate digestion in the rumen:

$$\text{Rumen degradable carbohydrate (RDC)} = \frac{[0.9\ (\text{NDS} - (\text{protein} + \text{lipid}) + (\text{NDF} \times \text{NDF availability}]}{[(\text{NDF} - (\text{protein} + \text{lipid})) + \text{NDF}]}$$

where NDS = neutral detergent fiber and NDS = neutral detergent soluble (100-NDF). Unpublished work from our laboratory and others indicates that NSC, especially forages, is highly digested in the rumen by 24h, thus reference to the 0.9 value. Measurements for carbohydrate degradabilitites ranged from 54.6 to 87.3% for concentrates and 45.3 to 82.5% for forages (32).

Researchers from Denmark (16) use digestible carbohydrate (DCHO) as a determinate for microbial nitrogen yield (MN). This value is the sum of digestible nitrogen free extract (DNFE) and crude fiber (DCFi). The equation for primarily roughage is: MN = .037 (DNFE) + .059 (DCFi), r^2 = .96 for primarily concentrate diets is MN = .-35 (DNFE) - .021 (DCFi), r^2 = .77 They demonstrated that the inclusion of digestible crude protein revealed no significant contribution to the predictability of MN synthesis in the rumen and suggested that DCHO was a better determinate for microbial yield than RDOM.

Carbohydrate Use in Predicting Microbial Protein Yield

The National Research Council (30) has proposed a system of protein evaluation in ruminants where microbial crude protein (N x 6.25) yield is predicted by intake of Net Energy-Lactation. The prediction was derived from regression analysis of a data set where in vivo measurements of microbial N yield were made in dairy cattle. Several studies and 119 separate diet observations are included. Dry matter intake ranged from 3.5 to 20.0 kg/d.. The wide range is due to the inclusion of data from non-lactating animals. The regression analysis based on NE_L intake has an r^2 = .77.

We assembled a separate data base for the purpose of examining the effects of nutrient intake and digestibility characteristics on microbial protein yield in lactating dairy cattle. The microbial data base included in vivo data of 81 separate diets fed to cannulated lactating cows only (2, 8, 13, 17, 19, 20, 23, 25, 34, 37, 39, 42, 44, 45, 47, 48, 49, 50, 51). Microbial N yield was regressed on several measures including the in vivo measurement of organic matter truly digested in the rumen as well as nutrient intakes including NE_L. Dry matter intake ranged from 12.4 to 25.5 kg/d, organic matter digested ranged from 4.4 to 12.4 kg/d and microbial N flow from 100 to 480 g N/d. NE_L intake ranged from 19.2 to 42.5 Mcal/d.

Net energy intake regressed on MNY resulted in the following equation: MNY = 56.30 + (7.30*NE_L), r^2= .28. This differs considerably from the NRC equation (MNY = -30.92 + 11.45 * (NE_L), r^2 = .77 in its ability to account for variation in MNY. Due to the small r^2 value, alternative equations were tested. Stepwise multiple linear regression analysis indicated that the most satisfactory equation was: (Equ. 1) MNY (g/d) = 12.15 + 11.78 (NSC) + 77.9 (RDP) + 4.48 (RDS) + .76 (NE_L), r^2 = .41, where each component is expressed as kg NSC, RDP, RDS or Mcal (NE_L) intake per day. Clearly, there is a great deal more information needed concerning the prediction rumen microbial N yield in lactating dairy cows. Variation duet to marker sampling and analytical techniques may account for a significant portion of the variation in MNY. The remaining variation would presumably be due to other, as yet unrecognized or uncontrolled, dietary or animal effects.

Relationship Between Microbial Protein Yield and Milk Yield

In order to explore relationships between microbial protein yield and milk yield, a production data base was assembled from the literature (4, 5, 9, 12, 13, 15, 17, 18, 23, 29, 34, 38, 43, 53). A total of 16 studies consisting of 62 diets were included and the protein and carbohydrate fractions of each diet were calculated. Dry matter intake was used to calculate intakes of various nutrients. Milk yield averaged 34.8 kg/d.

Equation 1 was used to predict microbial N yield for each diet in the production data base. Milk yield was regressed on microbial protein yield (kg/d) and rumen escape protein (kg/d) with NE_L intake (Mcal/d) as a covariate. Escape protein was based on actual in vivo measurements for 24 diets and available degradability data for the other diets. Quadratic components were included in the model (Figure 2, r^2 = .64, P<.01, CV = 9.0%).

Although this regression is to some degree an extrapolation, it points out some important relationships. At low microbial yields and low intakes of rumen escape protein, milk yield is projected to be very low. There was a general increase in milk yield as the quantity of rumen microbial protein increased. When microbial yield is low, a linear response to escape protein would be expected, because of the deficiency in overall protein supply. As the microbial protein contribution increases, less escape protein would be required in order to meet the net protein requirement of the host animal.

Relationship Between Qualitative Carbohydrate Measures on Production Performance in Lactating Dairy Cattle

In order to identify relationships between chemical carbohydrate measures and production performance in lactating dairy cows, a production data base was assembled from the literature (4, 5, 9, 12, 13, 15, 17, 18, 23, 29, 34, 38, 41, 58). A total of 14 studies consisting of 62 diets were included. The NE_L, ADF, NDF, Starch and NSC intakes were calculated. Milk yield averaged 34.8 kg/d.

The correlation coefficient between NDF concentration and ruminal digestibility was .45 (Table 3). This relationship suggests that the digestibility of NDF and, therefore, the ruminal energy contribution from NDF varies with source. NSC and starch concentrations were positively related to ruminal starch availability (r = .71 and .92, respectively).

Table 4 shows the relationship between rumen degradable CHO variables and production performance. The amount of rumen degradable NDF intake was not related to DMI. However, the amount of rumen escape NDF was highly correlated to DMI (r = .77), which would suggest as more NDF is cleared from the rumen, a greater capacity for intake exists. Although rumen degradable NDF and starch separately were not highly correlated to DHI, the combination of these variables incorporated into the RDCHO equation was highly related to DMI. This may reflect the greater proportion of rumen available energy accounted for in this calculation. Rumen degradable CHO was more highly correlated to milk yield and milk protein percentage (r = .54 and r = .57, respectively) than the separate entities of NDF or starch. Nocek and Russell (32) developed a data base with cows producing greater than 30 kg/d of milk. Total carbohydrate was calculated as [NDS - (protein + lipid) = NDF]. The RDC equation previously described was used to evaluate rumen degradable carbohydrate intake. Using the intake values obtained from these cows, their diet would contain 78% carbohydrate and 53% RDC, as a percent of CHO intake.

Effect of Site of Starch Digestion on Milk Yield

A major determinant in identifying whether or not manipulating site of carbohydrate digestion is feasible in production performance. To date, most studies have evaluated ingredient effects, with the basic premise that concepts such as rumen degradable starch, escape starch and carbohydrate degradability would follow. There may be inherent factors which will not allow specific ingredients to conform to a conceptual framework.

Table 5 shows recent studies that have dealt with manipulating the site of dietary starch digestion in dairy cattle. These four studies provide no consistent evidence that increasing post-ruminal starch enhances milk yield and/or alters composition. In two of the studies (38, 53) increased ruminal starch digestion resulted in increased milk production. Three of the studies were confounded by differences in dry matter and energy intake associated with site digestion. Starch intakes in these studies ranged from 24 to 44% of DM, and Rumen Degradable Starch from 49 to 85% of starch intake. It appears that diets with total tract starch digestibilities of 85% and greater resulted in the highest level of milk production.

If the lower gut is provided with large quantities of starch (4.7 kg, #23), increased dietary glucose may be available to support increased lactose synthesis for milk production. However, the mechanics may be through sparing endogenously synthesized glucose from oxidative metabolism rather than an increase in net glucose from absorbed dietary sources (33).

Guidelines for Inclusion of Different Carbohydrate Fractions in Rations of Lactating Dairy Cows

Based on studies with lactating dairy cows producing greater than 30 kg of milk, general guidelines for different carbohydrate fraction concentrations can be considered (% of total ration DM):

NDF: 25-30%
NSC: 35-40%
Starch: 30-40%

When considering rumen degradability parameters, the following general guidelines can be considered:

Rumen Degradable Starch: 50-75% of total starch
Rumen Degradable NDF: 50-60% of total NDF
Rumen Degradable CHO: 50-55% of total CHO

These guidelines should only be considered after total ration energy (NE_L) requirements (NRC) are met for the specific animals in question.

Method of starch and NSC determination and rumen degradability procedure utilized can have a significant influence on the analytical measure developed. Particle size, processing method and moisture content can also significantly influence rumen availability determinations. Particle size of structural carbohydrate fractions to maintain normal rumen function is a key consideration not addressed here. In addition, storage and processing procedures of both structural and NS CHO can dramatically influence rumen degradability. It must also be realized that appropriate nitrogen fractions must be provided with these various carbohydrate fractions in order for optimal microbial synthesis and carbohydrate utilization to occur.

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Table 1. Effect of feed type and fineness of grind on in situ starch degradation.

Feed	Fineness of grind (mm)	Proportion of Total Starch: Rapidly degradable	Slowly and potentially degradable	Unde-gradable	Rate of degrad. (%/h)	Rumen Degradability
Barley	.8	8.20[a]	18.0[a]	0	.571[a]	98.3[a]
Corn	.8	26.5[b]	73.5[b]	0	.071[b]	57.8[b]
Oats	.8	94.5[c]	5.5[c]	0	.071[b]	97.4[ca]
Peas	.8	55.9[d]	44.1[d]	0	.207[c]	90.0[d]
Wheat bran	.8	82.8[a]	16.8[a]	.3	.254[c]	96.4[c]

Means with different superscripts in the same column are significantly different (P<.05).

Barley	.8	82.0[a]	18.0[a]	0[a]	.571[a]	98.3[a]
	3.0	50.8[b]	49.2[b]	0[a]	.490[b]	94.6[ab]
	6.0	46.6[b]	53.0[b]	.4[a]	.304[c]	90.6[b]
Corn	.8	26.5[a]	73.5[a]	0[a]	.045[a]	57.8[a]
	3.0	30.5[a]	66.2[a]	3.3[b]	.055[a]	61.0[a]
	6.0	0.0[b]	99.3[b]	.7[a]	.048[a]	44.0[b]

Means with different superscripts in the same column within feed are significantly different (P<.05). Cerneau and Michalet-Doreau, 1991 (6)

Table 2. Effects of starch source and processing on site and extent of starch digestion in dairy cattle.

Ingredient/Process	N	Starch intake (kg)	Ruminal digestible starch (RDS)	Ruminal escape	Post-ruminal digestion (as % entering)	Total Tract (% of starch) intake
Corn:			- - - % of starch intake - - -			
Ground (Grd)	25	8.30	60.5	39.5	62.4	85.2
Rolled/grd	2	9.62	60.9	39.1	59.6	84.2
Steam rolled	1	6.7	65.0	35.0	51.5	83.0
Steam flaked/grd	1	10.94	60.6	39.4	62.8	85.3
Barley:						
Ground	11	7.07	71.0	29.0	59.8	88.4
Rolled	1	6.23	71.2	28.8	79.6	94.3
Rolled/grd	2	5.9	56.3	43.7	57.6	81.5
Milo:						
Ground	2	6.5	56.1	43.9	55.6	80.6
Rolled/grd	2	5.4	45.0	55.0	62.2	79.2
Reg rolled	1	6.73	48.0	52.0	45.4	71.6
Steam flaked	1	6.37	84.8	15.2	38.9	90.7
Oats:						
Whole	1	4.36	64.1	35.9	77.7	92.2
Rolled	2	4.85	64.3	35.7	85.5	94.7
Wheat:						
Rolled	1	6.93	72.2	27.8	86.5	96.2

Table 3. Relationship between carbohydrate and rumen degradable carbohydrate intake variables.[1]

Rumen Degradable (RD) Intake Variables (kg/d)	Carbohydrate Intake Variables (kg/d)		
	NDF	NSC	Starch
NDF	.45*	.31	.46*
Starch	.09	.71*	.92*
CHO[2]	.42*	.82*	.69*

*P<.01
[1]Data base: 14 lactation studies: Mean DMI = 20.9 kg/d
[2]RDCHO = [(.9 (NSC) + RD (NDF))/(NSC + NDF)] x 100

Table 4. Relationship between rumen degradable carbohydrate variables and production performance in dairy cattle.[1]

Performance Variables (Kg/d)	Rumen Degradable Intake Variables (kg/d)		
	NDF	Starch	Carbohydrate
DMI	-.03[2]	.43*	.77*
Milk Yield	-.31	.40*	.54*
Protein	-.48*	.52*	.57*
Fat	.13	.03	-.10

*P<.01
[1]Data base: 14 lactation studies, Mean DMI = 20.9 kg/d. Mean Milk Yield = 31.9 kg/d
[2]NDF escape vs DMI: r=.77

Table 5. Effect of starch source on site and extent of starch digestion and production performance in Holstein cows.

Reference	Main carbohydrate source	Dry matter intake kg/d	Starch intake kg/d	Starch Rumen degradation kg/d	Starch Rumen degradation % of intake	APRD[1] kg	APRD[1] % of intake	APRD[1] % esc. rumen	ATID[2] kg/d	Milk kg/d	FCM %	Protein %	kg
McCarthy et al. (23)	GSC[3]	23.8	10.6	5.2	49.1	4.7	44.3	87.0	93.2	35.6[a]	28.4	3.18	1.13[a]
	SRB[4]	20.7	8.4	6.5	77.4	1.6	19.0	84.2	96.7	32.5[b]	27.3	3.16	1.02[b]
Herrera-Saldena & Huber (12)	DRB/CSM[5]	25.3	8.3[a]	6.2[a]	74.7	1.5	18.1	69.0	92.2	37.4[a]	34.3[a]	2.90	.99
	DRB/BDG[6]	23.7	7.1[b]	4.9[b]	69.0	1.3	18.3	60.9	87.8	34.9[b]	31.4[b]	3.00	.94
	DRM/CSM[7]	24.3	7.4[b]	4.6[b]	62.2	1.4	23.0	48.6	80.5	34.2[b]	33.6[a]	3.00	1.01
	DRM/BDG[8]	23.8	5.8[c]	2.8[c]	48.3	1.9	32.7	62.3	80.5	34.6[b]	34.8[a]	2.80	.97
Olivera & Huber (34)	SRC[9]	26.3[a,b]	6.73	4.4	65.0	1.2	17.8	51.7	83.0	30.2	31.0	3.01[b]	.93
	DRM[10]	26.1[a,b]	6.73	3.3	48.0	1.6	23.8	45.4	71.6	29.4	30.6	2.95[b]	.90
	SFM[11]	24.8[b]	7.11	6.0	85.0	.4	5.6	38.9	90.8	31.0	30.8	3.10[a]	.95
	50% DRM/ 50% SFM	29.4[a]	8.32	5.6	67.0	1.4	16.8	4.95	83.3	30.9	29.7	3.06[a,b]	.91
Poore et al. (38)	DRM	20.7	6.7	3.3	49.2	2.2	32.8	62.8	80	28.1[b]	28.2	2.90[a]	.82
	SFM	20.3	6.4	4.7	73.9	1.6	25.0	91.8	97	31.5[a]	29.8	2.98[b]	.89

[1]Apparent postruminal digestion
[2]Apparent total tract digestibility
[3]Ground shelled corn
[4]Steam rolled barley
[5]Dry rolled barley/cottonseed meal
[6]Dry rolled barley/brewers dried grain
[7]Dry rolled milo/cottonseed meal
[8]Dry rolled milo/brewers dried grain
[9]Steam rolled corn
[10]Dry rolled milo
[11]Steam flaked milo
[abc]$P<.05$

FIGURE 1. Relationship Between Quantitative Measures of NonStructural Carbohydrate

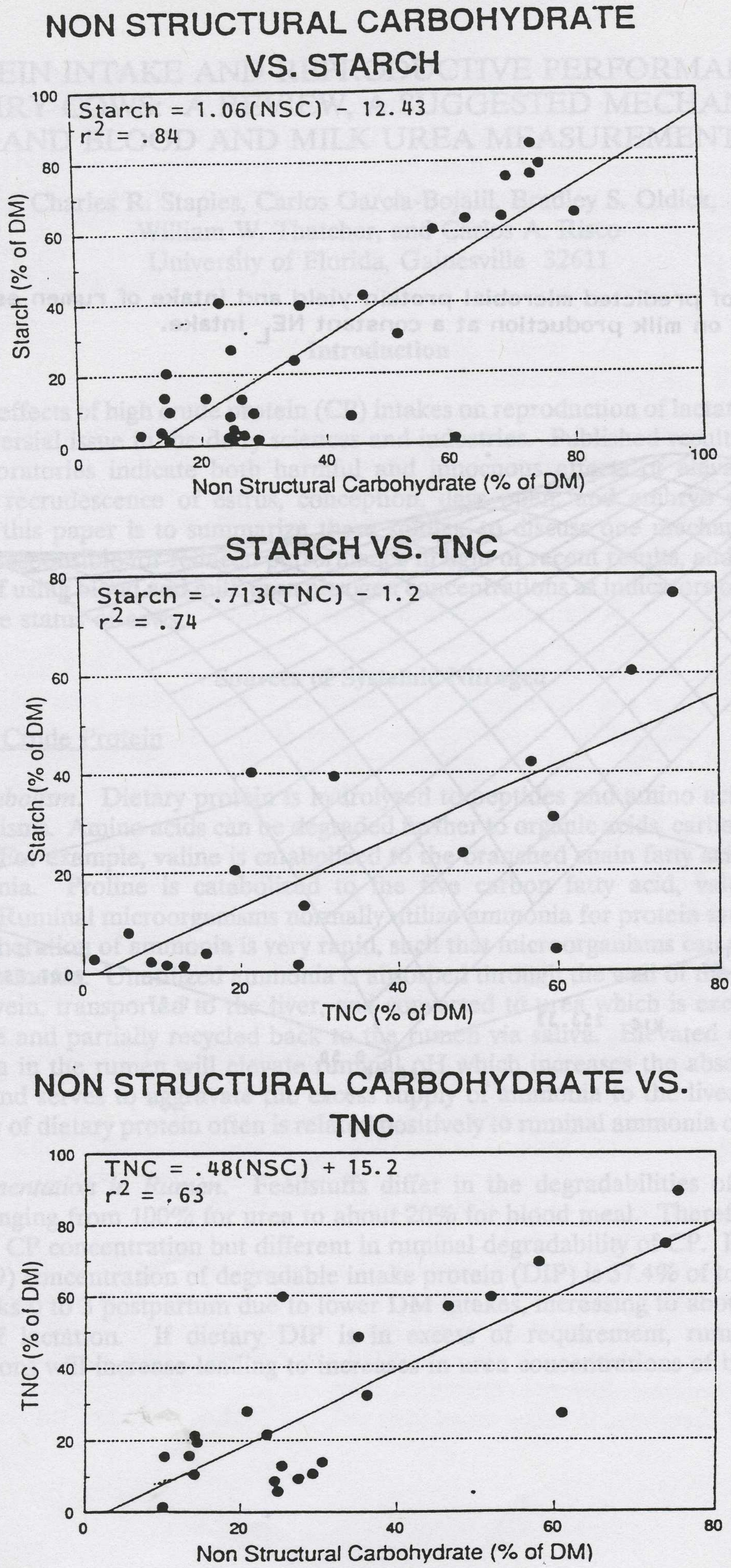

Figure 2. Effect of predicted microbial protein yield and intake of rumen escape protein on milk production at a constant NE_L intake.