Rumen Degradable Protein in Feedlot Diets

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Take-Home Message

- Meeting degradable intake protein (DIP) requirements is essential for an efficient beef production process
- Requirements of DIP are a moving target that usually increases with feed intake and fermentability of the diet
- Diets formulated using corn as an energy source, as well as more extensively processed grains usually increase the risk of DIP deficits
- Meeting DIP requirements may result in increased energy value of the feed
- Actual DIP requirements are higher than estimated using the NRC (2000) software

Protein Requirements for Beef Cattle

In 1996, the National Research Council (NRC) released the newest version of the Nutrient Requirements of Beef Cattle, which was then updated in 2000 (http://www.nap.edu/catalog.php?record_id=9791). One of the most important differences between the previous and latest versions is the form in which cattle protein requirements are expressed. Previously, protein requirements were expressed on a Crude Protein (CP) basis while in the latest version requirements are expressed on a Metabolizable Protein (MP) basis.

Metabolizable protein represents the protein fraction that has been already digested and absorbed in the small intestine, and is therefore available for the animal to use in various metabolic functions. *Net protein* (NP) is the protein fraction that has undergone various biochemical transformations from absorption to utilization including protein synthesis, protein degradation, amino acid elongation, etc.; its value is determined from the efficiency of use of MP. The ***efficiency of use of MP*** depends on the biological value of the protein and the efficiency of use of an ideal protein or ideal mixture of aminoacids (Oldham, 1987) for maintenance, growth, gestation or lactation. The biological value (BV) of protein depends on the biological value of rumen undegradable protein or undegradable intake protein (UIP) of the diet and that of microbial protein. The BV of the former depends upon quality of feed protein and the metabolic process the protein is intended for. For example, UIP from corn grain is deficient in arginine while that from corn gluten is fairly adequate when compared to milk's arginine concentration. However, UIP from corn gluten is deficient in arginine when compared to muscle's arginine concentration (Van Soest, 1994). On the other hand, BV of microbial protein is fairly constant and deemed to be high, though deficient in methionine, histidine and tryptophan but adequate in lysine when compared to muscle amino acid (AA) composition(Van Soest, 1994). The fact that BV of protein is different for growth than for lactation implies that the efficiency of use of MP varies depending on the metabolic process (maintenance, growth, gestation, lactation). In addition, efficiency for growth is likely not constant across animal weight/age and rate of gain. Based on data from Ainslie et al. (1993) and Wilkerson et al. (1993), the NRC (2000) suggests an efficiency of use of MP of 49.2% for equivalent empty body weight (EQEBW) above 300 kg (662 lb), and greater MP efficiency for EQEBW below 300 kg (Efficiency = 83.4 – 0.114 x EQ Shrunk BW).

Changes in MP efficiency across BW or age might be related to a larger amount of actively proliferating and differentiating satellite cells in younger than older animals. The role of satellite cells is to fuse with the mature muscle fiber and provide the nuclei -DNA- necessary to control an additional portion of cytoplasm; thus, allowing for increased protein synthesis, accretion, and muscle hypertrophy. However, satellite cells fuse faster than they proliferate. Consequently, the number of satellite cells progressively decreases as the animal becomes older, and those that remain become quiescent, reducing protein accretion (M. White and W. Dayton, University of Minnesota, personal communication). Therefore, AA from MP intended for protein synthesis and final accretion (NP for growth) may decrease as cattle mature, thus decreasing efficiency of use of MP for growth. Effect of increased rate of gain on physiological age may also explain a decreased efficiency of MP use with increasing rate of gain.

Metabolizable protein balance results from the difference between ***MP supply*** and ***MP requirements***. Requirements of MP are estimated based on the factorial method and factors included are maintenance (metabolic fecal and urinary losses, and scurf losses), growth, fetal growth, and lactation. Estimations of MP requirements for maintenance and growth based on the NRC model are summarized in Table 1. To estimate true metabolic fecal losses (intestinal desquamations and digestive enzymes), indigested dietary nitrogen as well as microbial nitrogen (complete microbial cells or cell walls) have to be subtracted from total fecal nitrogen. True metabolic urinary losses account for protein turnover in body tissues and include creatinine, derivatives of nitrogenous bases (purine and pyrimidine), and urea. The NRC (2000) suggests a maintenance requirement of 3.8 g of MP/kg metabolic shrunk body weight ($SBW^{0.75}$). Net protein requirements for growth are estimated considering body weight, rate of gain, and targeted end point based on degree of intramuscular fat achieved (marbling; Table 1).

Table 1. Estimations of protein requirements for maintenance and growth suggested by NRC (2000).

	Metabolizable protein (MP), g/d	**Net protein (NP), g/d**
Maintenance	3.8 g/kg $SBW^{0.75}$	MP x 0.67[†]
Growth	If, • EQEBW < 300 kg, MP = NP / (83.4 – 0.114 x EQSBW)[†] • EQEBW ≥ 300 kg, MP = NP / 0.492[†]	SWG x [268 - 29.4 x (RE/SWG)]

[†] Efficiency of use of MP
SBW (shrunk body weight) = 0.96 x full weight
EQEBW (equivalent empty body weight) = 0.891 x EQSBW
EQSBW (equivalent shrunk body weight) = SBW x (SRW/FSBW)
SRW (standard reference weight) = 478 kg for animals finished at small marbling (28% fat)
= 462 kg for animals finished at slight marbling (27% fat)
= 435 kg for animals finished at trace marbling (25% fat)
FSBW, actual final shrunk body weight at the body fat endpoint selected
SWG, shrunk weight gain
RE = 0.0635 x $EQEBW^{0.75}$ x $EBG^{1.097}$
EBG = 0.956 x SWG

Based on the NRC model (2000), MP supply can be estimated as the summation of UIP and true ruminally synthesized microbial CP (MCP) digested and absorbed in the small intestine. Between 60 and 85% of total AA-N entering the small intestine is microbial protein synthesized in the rumen (van der Walt and Meyer, 1988). Crude protein concentration of a feed is calculated as nitrogen (N) concentration x 6.25. While part of that N is in the form of true protein, another proportion is in the form of non-protein nitrogen (NPN). Dietary NPN compounds such as urea, ammonia-nitrogen (NH_3-N; present in fermented feedstuffs), and nitrates (present in N-fertilized and stressed forages), and free AA, and small peptides are totally digested in the rumen (rumen degradable N) and transformed to MCP, while UIP reaching the small intestine is considered to be 100% true protein. On the other hand, 20% of MCP is considered to be NPN, this including mainly nitrogenous bases from microbial nucleic acids. Intestinal digestibility of UIP and MCP is considered to be 80%. Consequently, MP supply is estimated as [UIP x 0.8 + MCP x 0.8 x 0.8] or [UIP x 0.8 + MCP x 0.64].

Degradable Intake Protein Balance in Feedlot Cattle

As mentioned previously, MCP represents a high proportion of MP supply to the host animal. In addition, volatile fatty acids (VFA) produced as the result of feed ruminal fermentation, microbial growth and MCP synthesis, are essential to provide the animal with energy sources and fatty acid precursors (acetate, butyrate) as well as a glucose precursor (propionate). Consequently, adequate supply of nitrogen as well as carbohydrates and other growth factors to enhance ruminal microbial growth is essential for an efficient beef production process from both protein and energy supply perspectives.

As opposed to UIP, ***degradable intake protein*** (DIP) of a feedstuff represents the protein that is potentially degraded in the rumen by the action of ruminal microbes. Consequently, DIP can be used by ruminal microorganisms to synthesize their own proteins: MCP, which will be used by the ruminant once digested and absorbed in the small intestine. In this regard, it is important to estimate the DIP balance in the rumen in terms of the difference between DIP supply and DIP requirements. Based on Level 1 of NRC model (2000), ***DIP supply*** is estimated as dry matter intake (DMI) affected by DIP concentration in the diet. On the other hand, ***DIP requirements*** represent requirements for growth of ruminal microbes, which are estimated as total digestible nutrients (TDN) intake affected by ***microbial efficiency***, the latter being the units of MCP synthesized per unit of TDN. A similar expression is expressed in terms of organic matter (OM) fermented or digested in the rumen affected by microbial efficiency, where microbial efficiency is then defined as units of MCP produced per unit of OM fermented (Hoover and Stokes, 1991; Van Soest, 1994).

Level 1 of the NRC model (2000) assumes that, when present, DIP deficiencies (DIP requirements > DIP supply) are overcome by degradable protein supplementation. Therefore, DIP requirements represent the amount of MCP synthesized in the rumen.

The use of TDN to determine DIP requirements or MCP synthesis ignores the fact that ruminal microbes can only utilize ruminally available nutrients; that only glycerol from the lipid fraction can be used as energy source, and that only some microbes are able to grow on AA (Chen and Russell, 1988, 1989; Russell et al., 1988; Russell et al., 1992; Russell, 2002). In fact, most ruminal microorganisms are only able to use carbohydrates (digestible N-free extracts and digestible crude fiber) as an energy source (Nocek and Russell, 1988). That is probably why calculations of MCP synthesis based on digestible carbohydrates are less variable than those based on digestible OM (Nocek and Russell, 1988). To overcome some of the limitations mentioned above, Level 2 of the NRC model (2000) estimates DIP requirements or MCP synthesis by considering carbohydrate digestion in the rumen.

Factors affecting TDN intake or OM digested in the rumen as well as microbial efficiency may potentially affect DIP requirements. For example, availability of branched-chain AA and therefore branched-chain VFA, rumen fermentable nitrogen (NH_3-N, AA, peptides) and carbohydrates, cobalt, sulfur, and other microbial growth factors (Hungate, 1966) may affect growth of ruminal microbes and OM digested in the rumen. A deficiency in ruminally degraded protein may cause a decrease in the efficiency of MCP synthesis (Russell et al., 1992). Similarly, diet composition, environmental factors, physiological stage, health status, and other intake-affecting factors may impact DIP requirements.

Microbial efficiency is largely affected by diet ***rate of fermentation*** and ***washout rate*** (Van Soest, 1994). Fermentation rate is an inherent property of the feed (Russell et al., 1992) which determines the amount of feed energy yield per unit of time for ruminal microbial growth. Thus, microbial efficiency increases with faster-fermenting diets. However, effects on VFA rate of production and accumulation and their impact on ruminal pH, and on microbial efficiency must also be considered (see later). Rate of washout from the rumen refers to the rate at which microbes are removed from the rumen towards the lower tract, in the liquid phase (dilution rate) as well as attached to indigested feed particles (rate of passage). Passage rates are regulated by feed intake, processing (particle size and surface area), and type of feed (e.g., forage or grain; Russell et al., 1992). While a slow rate of passage is usually associated with low DMI and/or low-quality diets, dilution rate is positively associated with rumination and saliva production as well as water intake. Slow rate of washout increases microbial maintenance costs by increasing microbial population age, microbial turnover (growth and death) inside the rumen and predation by protozoa. Lysed microbes and their nutrients are recycled within the rumen by other microbes, resulting in decreased efficiency of MCP synthesis because the amount of microbial protein reaching the small intestine is reduced; thereby reducing protein available for the host. With a slow washout rate, OM continues to be fermented to maintain mature microbial cells, while their rate of multiplication is largely reduced (Van Soest, 1994), thereby reducing MCP produced per unit of OM fermented. In addition, slow washout rate selects in favor of slow-growing, less efficient bacteria; slow washout rate sustains bacteria that reproduce at a rate consistent with a slow washout rate from the rumen by passage. In sum, fast washout rates result in increased microbial efficiency because mean age of microbial population is decreased and the younger population is subject to lower death and predation rates (Van Soest, 1994; Russell, 2002). Theoretically, on the other hand, extreme high washout rates may cause plateauing and even inefficiency through loss of unfermented feed and competition between washout and microbial cell generation time (Van Soest, 1994).

Although fast rate of fermentation can increase microbial efficiency, its effect on lowered **ruminal pH,** and on microbial efficiency, has to be considered. Strobel and Russell (1986) observed a decrease in microbial yield when pH decreased from 6.7 to 5.7. As VFA and/or lactic acid concentration in the rumen increases, ruminal fluid pH decreases. Decreasing pH results in increased proportion of un-dissociated VFA, which are lipophilic and able to cross microbial cell membrane (Russell and Wilson, 1996). Following a concentration gradient, un-dissociated VFA enter the microbial cell, where pH is higher (close to neutrality) than that of ruminal fluid, resulting in un-dissociated VFA to release protons in the interior of the cell (Russell and Wilson, 1996). To avoid a decrease in internal pH due to proton accumulation, the microbial cell is forced to pump out these protons, against a pH and proton gradient. Therefore, ATP is used to pump protons outside the cell, thus diverting ATP from growth to non-growth related functions, that is, increasing energy spilling (Strobel and Russel, 1986; Russell, 2007). Consequently, less

MCP is produced per unit of OM fermented. In addition, VFA anions (dissociated VFA) accumulate within the microbial cell because once deprotonated, VFA become hydrophilic and they cannot cross the cell membrane (Russell and Wilson, 1996). Klemps et al. (1987) observed that acetic acid-producing reactions (pyruvate oxidoreductase and acetate kinase) were strongly inhibited by increased internal acetate concentrations. This may result in a decrease in ATP production, which may further affect microbial growth. Similarly, ionophores, despite their potential effect on ruminal pH drop mitigation, increase energy spilling of sensitive bacteria (Russell and Strobel, 1989; Russell and Houlihan, 2003; Callaway et al., 2003), thus reducing overall microbial efficiency (Van Soest, 1994).

In general, microbial efficiency ranges from 8 to 13 g of microbial protein/100 g TDN intake, the latter value is considered as the maximum microbial efficiency (NRC, 2000). Given observations and discussions above, greater efficiency values are ascribed to forage-based diets and lesser values ascribed to grain-based diets. Level 1 of the NRC model (2000) estimates actual microbial efficiency as 13% (maximum microbial efficiency) affected by a coefficient called the "effective neutral detergent fiber adjusted" (eNDFadj) which depends on dietary effective NDF (eNDF) concentration. This value refers to the proportion of the NDF that is sufficiently large to be effective at stimulating chewing, salivation, and rumination. Thus, dietary concentration of eNDF is used by the model to predict ruminal pH and estimate eNDFadj coefficient. The model assumes that at 20% eNDF, microbial efficiency is maximized. Therefore, for diets containing as much or more than 20% eNDF the coefficient value is 1, while a reduction of 0.025 units per each percentage unit of dietary eNDF below 20% is integrated in the model. In sum, dietary degradable protein concentration, feed intake, fermentation rate of the diet, and ruminal pH may determine DIP balance, potentially affecting VFA production and MP supply and animal performance.

Due to high inclusion of rapidly-fermentable carbohydrates, feedlot diets can result in DIP deficiency. In addition, diets formulated using dry-rolled corn (DRC) or steam-flaked corn (SFC) as the energy source may be deficient in DIP because corn protein is considered to be approximately 60% UIP (Lardy et al., 1998; NRC, 2000). Concentration of UIP in high-moisture corn (HMC; 40%) is considered lower than in DRC or SFC due to positive effects of the ensiling process on protein degradability. Several efforts have been made towards determining DIP requirements of feedlot cattle under various feeding conditions. In that regard, scientists have investigated the effect of adding rumen-degradable nitrogen in the form of urea, to feedlot diets for which DIP deficits were expected. A summary of results from some of those studies are presented in Tables 2 (entire dataset), 3 (excluding results from studies where distillers grains was used) and 4 (excluding results from studies where distillers grains was not used). Studies included in the summary involved a control-type diet, to which a small amount or no urea was added; one or more additional dietary treatments with increased DIP concentration resulting from the inclusion of urea were included. Thus, dietary CP concentration increased while UIP remained fairly constant across treatments within study.

Estimation of Optimum DIP and MP Balance

Data from Tables 2, 3 and 4 were used to estimate optimum DIP and MP balance as defined by rate of gain and feed efficiency. Data were analyzed using the Mixed procedure of SAS; models tested were weighted by number of treatment replications per study.

Effects of DIP and MP balance on average daily gain (ADG) were evaluated simultaneously, as well as their interaction; a term for the effect of type of grain was also included in the model (ADG = DIP balance + DIP balance^2 + MP balance + MP balance^2 + DIP balance*MP balance +

Grain Type). Variables were retained in the model when $P < 0.10$ (Type III Tests). A similar analysis was performed for feed efficiency, which was analyzed as gain-to-feed. Grains used in studies 7-2 and 12-1 (Table 2) were analyzed as it they were DRC while that used in 5-1 was analyzed as if it was SFC.

a. Effects of DIP and MP balance on rate of gain

Grain type and the interaction between DIP and MP balances were non-significant ($P > 0.71$). Rate of gain followed a quadratic response with increasing each DIP (Figure 1) and MP balance (Figure 2). Within the range evaluated, the quadratic response demonstrates that ADG was more responsive to increased DIP balance when the latter was negative; that is, when there was an unmet demand of ruminal DIP. The fact that both DIP and MP balances were simultaneously significant, suggests that positive effects of restoring DIP balance in the rumen on rate of gain are significant even after considering the positive effects of MP balance, and vice versa. In other words, when modeling MP balance using the NRC (2000) software, increasing DIP balance through the inclusion of urea to a DIP-deficient diet results in increased MP balance, because it is assumed that more microbial protein is synthesized in the rumen, thus increasing its contribution to MP in the small intestine. Increased MP balance affects animal performance (Figure 2), which means that beneficial effects of increased DIP balance on rate of gain could be related to its effects on increased MP balance. However, due to the fact that *P*-value for DIP balance was significant in a model that already included MP balance as a factor, the effect of increased DIP balance on ADG might be beyond its potential effects on MP balance. Ceconi et al. (2013) observed that urea supplementation to a DIP-deficient diet resulted in increased total tract organic matter digestibility (OMD) and volatile fatty acid (VFA) concentration in the rumen without affecting DMI, which may partially explain improved ADG and feed efficiency observed in a concurrent feedlot performance study (Ceconi et al., 2012). Zinn et al. (2003) observed increased ruminal starch digestion and total tract starch and OM digestibility, DMI, and ADG with increased urea supplementation to steam-flaked barley-based diets.

As shown in Tables 3 and 4, effect of urea supplementation on DMI is variable. Within studies that reported positive effects of adding urea on ADG, some of them demonstrated a concurrent increase in DMI. This resulted in varying effects on feed efficiency, depending on the magnitude of the change in ADG and DMI. The basis for increased DMI response with increasing dietary urea concentration is not clear. Theoretically, increased OM digestibility due to urea supplementation could explain an increase in DMI in diets whose intake is mostly regulated by gut fill or physical factors, which may likely not be the case for diets evaluated in the present studies. Urea has ruminal alkalizing effect which may attenuate ruminal pH drops when highly-fermentable diets are consumed, which in turn may positively affect DMI; however, this effect on ruminal pH is expected to be transitory.

Table 2. Summarized description of diets (U0: small amount or no urea added, and Ux: increased urea inclusion) used in various research studies to evaluate effects of increased degradable intake protein (DIP) through urea inclusion on feedlot cattle performance.

	Grain		Distillers grains		Urea inclusion, %		Dietary DIP, % [c]		Dietary crude protein, % [d]	
Ref. [a]	Type [b]	Inclusion, %	Type	Inclusion, %	U0	Ux	U0	Ux	U0	Ux
1-1	DRC	85.3	-	-	0.91	1.55	6.6	8.4	12.1	14.0
2-1	DRC	84.2	-	-	0	0.50 to 1.50	3.7	5.1 to 8.0	8.5	9.9 to 12.7
2-2	DRC	83.1	-	-	0	0.35 to 1.40	4.7	5.7 to 8.8	9.6	10.6 to 13.1
3-1	DRC	79.5	-	-	0	0.88 to 1.96	4.5	6.6 to 9.7	8.9	11.1 to 14.1
4-1	HMC	82.0	-	-	0	0.40 to 1.20	7.0	8.1 to 10.2	10.6	11.8 to 14.1
4-2	SFC	82.0	-	-	0	0.40 to 2.00	4.6	5.7 to 10.1	9.5	10.6 to 15.3
4-3	DRC	82.0	-	-	0	0.50 to 2.00	4.9	6.3 to 10.4	9.5	10.9 to 15.3
4-4	HMC	82.0	-	-	0	0.50 to 2.00	6.4	7.8 to 11.9	9.5	10.9 to 15.3
4-5	SFC	82.0	-	-	0	0.50 to 2.00	4.8	6.1 to 10.2	9.5	10.9 to 15.3
5-1	SFB	76.3	-	-	0	0.40 to 1.20	7.1	8.3 to 10.5	10.5	11.5 to 13.5
6-1	SFC	79.5	-	-	0.49	1.02 or 1.56	6.2	7.7 or 9.3	12.0	13.1 or 14.5
7-1	DRC	83.5	-	-	1.0	1.20 or 1.50	7.1	8.1 or 9.4	11.6	12.7 or 14.1
7-2	DRB	84.4	-	-	0	0.30 or 0.50	8.0	9.2 or 10.1	11.6	12.9 or 13.9
8-1	SFC	79.5	-	-	0.01	0.38 to 1.42	4.7	5.9 to 9.0	10.5	11.5 to 14.5
9-1	SFC	70.4	32:68 corn:milo wet	9.7	0.68	0.89 or 1.09	7.3	7.9 or 8.5	13.3	14.0 or 14.7
10-1	SFC	66.5	90:10 corn:milo wet	14.9	0	0.52 or 1.06	6.7	8.2 or 9.8	12.9	15.0 or 15.6

Table 2. (cont.)

Ref. [a]	Grain		Distillers grains		Urea inclusion, %		Dietary DIP, % [c]		Dietary crude protein, % [d]	
	Type [b]	Inclusion, %	Type	Inclusion, %	U0	Ux	U0	Ux	U0	Ux
10-2	SFC	52.6	90:10 corn:milo wet	29.7	0	0.52 or 1.06	8.6	10.2 or 11.7	16.6	18.1 or 18.9
10-3	SFC	65.8	76:24 corn:milo wet	15.4	0.54	0.80 or 1.06	8.1	8.8 or 9.6	13.7	14.5 or 15.3
11-1	DRC	76.0	corn dried	10	0	0.80	5.0	7.3	11.2	13.4
11-2	DRC	66.0	corn dried	20	0	0.63	6.0	7.8	13.4	15.1
11-3	DRC	59.5	corn wet	25	0	0.50 or 1.00	6.6	7.9 or 9.2	14.2	15.3 or 16.4
12-1	DRC+HMC	52 + 12	corn dried	20	0	0.40 or 0.60	6.4	7.5 or 8.0	14	15.1 or 15.6

[a] **1-1:** Milton et al., 1997a; **2-1 and 2-2:** Milton et al., 1997b; **3-1:** Shain et al., 1998; **4-1 to 4-5:** Cooper et al., 2002; **5-1:** Zinn et al., 2003; **6-1:** Gleghorn et al., 2004; **7-1 and 7-2:** Kennington et al., 2009; **8-1:** Wagner et al., 2010; **9-1:** Vasconcelos et al., 2007; **10-1 to 10-3:** Ponce, 2010; **11-1 to 11-3:** Jenkins et al., 2011; **12-1:** Ceconi et al., 2012.

[b] DRC: dry-rolled corn; SFC: steam-flaked corn; HMC: high-moisture corn; DRB: dry-rolled barley; SFB: steam-flaked barley.

[c] Estimated based on reported diet composition, and ingredients' crude protein (CP) and DIP book-referenced values (Lardy et al., 1998; NRC, 2000; Beef Magazine, 2012). DRC: 40% DIP and 9% CP; SFC: 38% DIP and 9% CP; HMC: 60% DIP and 9% CP; DRB: 67% DIP and 11.5 CP; SFB: 61% DIP and 12% CP; Corn dried distillers grains: 40% DIP, and 32.4 and 30.4% CP for Jenkins et al., 2011 and Ceconi et al., 2012, respectively (analyzed). Corn wet distillers grains: 49% DIP and 29.7% CP, except for Jenkins et al. (2011) where 30.1% CP was reported; 90:10 corn:milo wet distillers grains (Ponce, 2010): 49% DIP and 33.4% CP (analyzed CP); 76:24 corn:milo wet distillers grains (Ponce, 2010): 49 DIP and 32.5% CP (analyzed CP); Milo wet distillers grains: 49% DIP and 33% CP. DIP expressed on CP basis.

[d] Reported values.

Table 3. Summarized results from various research studies that evaluated effects of increased degradable intake protein (DIP) through the inclusion of urea to feedlot diets without distillers grains on dry matter intake (DMI), average daily gain (ADG), and units of feed consumed per unit of gain (F:G).

Ref. [a]		Urea inclusion, %	Dietary DIP, % [b]	DMI, kg	DMI, % BW [c]	DIP supply, g/d [d]	DIP req., g/d [d]	DIP balance, g/d	MP supply, g/d [e]	MP req., g/d [f]	MP balance, g/d	ADG, kg/d	F:G
1-1	U0	0.91	6.6	9.82	2.30	631	648	-17	823	701	121	1.35	7.30
	U1	1.55	8.4	9.33	2.30	807	643	164	838	671	167	1.24	7.69
	P			*NS*	-	-	-	-	-	-	-	*< 0.10*	*NS*
2-1	U0	0.00	3.7	11.1	2.57	410	796	-386	689	743	-54	1.52	7.30
	U1	0.50	5.1	10.5	2.41	538	749	-210	743	764	-21	1.60	6.54
	U2	1.00	6.6	10.9	2.49	715	773	-57	866	778	89	1.65	6.58
	U3	1.50	8.0	10.7	2.46	856	754	102	878	759	119	1.58	6.76
	P			*<0.10*	-	-	-	-	-	-	-	*0.10*	*<0.05*
	Cst			*C*								*Q*	*Q*
2-2	U0	0.00	4.7	9.14	2.11	432	601	-169	630	671	-41	1.21	7.58
	U1	0.35	5.7	9.05	2.08	519	593	-74	681	687	-6	1.27	7.14
	U2	0.70	6.7	9.32	2.12	628	608	20	744	689	55	1.28	7.19
	U3	1.05	7.7	9.50	2.18	736	618	118	752	673	78	1.22	7.75
	U4	1.35	8.8	8.78	2.08	768	568	200	671	634	37	1.07	8.20
	P			*0.11*	-	-	-	-	-	-	-	*<0.05*	*<0.05*
	Cst			*Q*								*Q*	*Q*

Table 3. (cont.)

Ref. [a]		Urea inclusion, %	Dietary DIP, % [b]	DMI, kg	DMI, % BW [c]	DIP supply, g/d [d]	DIP req., g/d [d]	DIP balance, g/d	MP supply, g/d [e]	MP req., g/d [f]	MP balance, g/d	ADG, kg/d	F:G
3-1	U0	0.00	4.5	11.6	2.77	527	765	-238	750	689	60	1.43	8.13
	U1	0.88	6.6	11.9	2.74	771	766	5	915	719	196	1.54	7.69
	U2	1.34	8.1	11.6	2.74	953	762	191	908	719	189	1.50	7.81
	U3	1.96	9.7	11.8	2.74	1135	757	378	901	719	182	1.55	7.63
	P			*NS*	-	-	-	-	-	-	-	*<0.01*	*<0.01*
	Cst											*U0vsU*	*U0vsU*
4-1	U0	0.00	7.0	12.3	2.58	853	871	-18	893	825	69	1.70	7.24
	U1	0.40	8.1	12.1	2.57	988	871	117	914	830	84	1.72	7.03
	U2	0.80	9.2	12.1	2.55	1114	871	243	920	856	64	1.82	6.65
	U3	1.20	10.2	12.1	2.54	1240	871	369	935	864	72	1.85	6.54
	P			*NS*	-	-	-	-	-	-	-	*<0.03*	-
	Cst											*L*	
4-2	U0	0.00	4.6	10.3	2.30	469	753	-285	708	738	-30	1.44	7.15
	U1	0.40	5.7	10.8	2.31	611	790	-179	818	817	1	1.74	6.21
	U2	0.80	6.8	11.0	2.27	745	805	-40	919	886	33	2.00	5.50
	U3	1.20	7.9	11.0	2.27	868	805	63	965	886	79	2.00	5.50
	U4	1.60	9.0	11.3	2.33	1017	827	190	990	891	99	2.02	5.59
	U5	2.00	10.1	11.0	2.26	1112	805	308	971	896	75	2.04	5.39
	P			*0.01*	-	-	-	-	-	-	-	*<0.01*	-
	Cst			*Q*								*Q*	

Table 3. (cont.)

Ref. [a]		Urea inclusion, %	Dietary DIP, % [b]	DMI, kg	DMI, % BW [c]	DIP supply, g/d [d]	DIP req., g/d [d]	DIP balance, g/d	MP supply, g/d [e]	MP req., g/d [f]	MP balance, g/d	ADG, kg/d	F:G
4-3	U0	0.00	4.9	9.9	2.48	496	703	-207	688	709	-21	1.54	6.43
	U1	0.50	6.3	9.6	2.43	634	703	-68	779	736	43	1.64	5.85
	U2	1.00	7.7	10.0	2.48	772	703	69	833	709	124	1.54	6.49
	U3	1.50	9.0	10.6	2.36	911	703	208	836	780	56	1.80	5.89
	U4	2.00	10.4	10.4	2.41	1049	703	346	846	747	99	1.68	6.19
	P			*NS*	-	-	-	-	-	-	-	*<0.05*	-
	Cst											*L*	
4-4	U0	0.00	6.4	10.5	2.35	628	706	-77	647	747	-100	1.68	6.25
	U1	0.50	7.8	9.6	2.41	763	706	57	699	717	-18	1.57	6.11
	U2	1.00	9.1	9.7	2.39	898	706	192	709	725	-16	1.60	6.06
	U3	1.50	10.5	9.9	2.34	1032	706	327	712	752	-41	1.70	5.82
	U4	2.00	11.9	9.5	2.44	1167	706	461	722	701	21	1.51	6.29
	P			*NS*	-	-	-	-	-	-	-	*<0.05*	-
	Cst											*C*	
4-4	U0	0.00	6.4	10.5	2.35	628	706	-77	647	747	-100	1.68	6.25
	U1	0.50	7.8	9.6	2.41	763	706	57	699	717	-18	1.57	6.11
	U2	1.00	9.1	9.7	2.39	898	706	192	709	725	-16	1.60	6.06
	U3	1.50	10.5	9.9	2.34	1032	706	327	712	752	-41	1.70	5.82
	U4	2.00	11.9	9.5	2.44	1167	706	461	722	701	21	1.51	6.29
	P			*NS*	-	-	-	-	-	-	-	*<0.05*	-
	Cst											*C*	

Table 3. (cont.)

Ref. [a]		Urea inclusion, %	Dietary DIP, % [b]	DMI, kg	DMI, % BW [c]	DIP supply, g/d [d]	DIP req., g/d [d]	DIP balance, g/d	MP supply, g/d [e]	MP req., g/d [f]	MP balance, g/d	ADG, kg/d	F:G
4-5	U0	0.00	4.8	8.1	2.07	386	593	-207	554	660	-107	1.36	5.96
	U1	0.50	6.1	10.1	2.40	619	739	-120	781	758	23	1.72	5.87
	U2	1.00	7.5	9.5	2.27	713	695	18	817	750	67	1.69	5.62
	U3	1.50	8.9	10.0	2.31	887	732	155	862	793	69	1.85	5.41
	U4	2.00	10.2	8.5	2.08	870	622	248	742	717	25	1.57	5.41
	P			*<0.05*	-	-	-	-	-	-	-	*<0.05*	-
	Cst			*Q*								*Q*	
5-1	U0	0.00	7.1	6.77	2.20	483	446	37	468	649	-182	1.37	5.00
	U1	0.40	8.3	6.98	2.24	577	458	119	473	666	-192	1.43	4.76
	U2	0.80	9.4	7.30	2.30	686	477	210	486	693	-208	1.53	4.76
	U3	1.20	10.5	7.34	2.33	773	477	296	479	680	-201	1.48	5.00
	P			*<0.01*	-	-	-	-	-	-	-	*<0.05*	*NS*
	Cst			*L*								*L*	
6-1	U0	0.49	6.2	9.05	1.96	571	618	-47	791	783	8	1.67	5.39
	U1	1.02	7.7	9.28	1.94	710	613	97	790	805	-15	1.75	5.27
	U2	1.56	9.3	9.15	1.95	850	608	242	776	797	-20	1.72	5.30
	P			*0.11*	-	-	-	-	-	-	-	*0.06*	*0.12*
	Cst			*Q*								*Q*	*L*
7-1	U0	1.00	7.1	9.8	1.99	692	663	29	780	843	-63	1.77	5.54
	U1	1.20	8.1	10.0	2.03	807	676	131	803	843	-41	1.77	5.65
	U2	1.50	9.4	9.9	2.01	927	668	259	802	870	-68	1.87	5.29
	P			*<0.05*	-	-	-	-	-	-	-	*<0.05*	*NS*
	Cst			*Q*								*L*	

Table 3. (cont.)

Ref.[a]		Urea inclusion, %	Dietary DIP, %[b]	DMI, kg	DMI, % BW[c]	DIP supply, g/d[d]	DIP req., g/d[d]	DIP balance, g/d	MP supply, g/d[e]	MP req., g/d[f]	MP balance, g/d	ADG, kg/d	F:G
7-2	U0	0.00	8.0	9.4	1.99	747	616	131	669	763	-95	1.47	6.39
	U1	0.30	9.2	9.1	1.92	834	596	238	653	763	-111	1.47	6.19
	U2	0.50	10.1	10.2	2.15	1031	668	363	737	870	-134	1.57	6.50
	P			*<0.05*	-	-	-	-	-	-	-	*<0.05*	*NS*
	Cst			*Q*								*L*	
8-1	U0	0.01	4.7	9.54	1.91	451	625	-174	729	842	-113	1.73	5.50
	U1	0.38	5.9	9.54	1.91	561	623	-62	788	839	-52	1.72	5.53
	U2	0.73	6.9	9.83	1.96	680	640	40	848	852	-4	1.77	5.54
	U3	1.08	8.0	10.1	1.98	800	652	148	862	873	-11	1.85	5.39
	U4	1.42	9.0	10.1	2.00	908	652	256	862	868	-6	1.83	5.51
	P			*0.06*	-	-	-	-	-	-	-	*0.03*	*NS*
	Cst			*L*								*L*	

[a] **1-1:** Milton et al., 1997a; **2-1 and 2-2:** Milton et al., 1997b; **3-1:** Shain et al., 1998; **4-1 to 4-5:** Cooper et al., 2002; **5-1:** Zinn et al., 2003; **6-1:** Gleghorn et al., 2004; **7-1 and 7-2:** Kennington et al., 2009; **8-1:** Wagner et al., 2010.

U0: control-type diet to which small amount or no urea was added; U1 to U5: diets with greater DIP than U0 due to greater addition of urea.

P: *P*-value for means contrast. NS: $P > 0.15$.

Cst: Contrast. L: linear; Q: quadratic; C: cubic; U0vsU: U0 versus [(U1+U2+U3)/3].

[b] Estimated based on reported diet composition, and ingredients' crude protein (CP) and DIP book-referenced values (Lardy et al., 1998; NRC, 2000; Beef Magazine, 2012). Dry-rolled corn (DRC): 40% DIP and 9% CP; Steam-flaked corn (SFC): 38% DIP and 9% CP; High-moisture corn (HMC): 60% DIP and 9% CP; Dry-rolled barley (DRB): 67% DIP and 11.5 CP; Steam-flaked barley (SFB): 61% DIP and 12% CP. DIP expressed on CP basis.

[c] Estimated as {DMI / [(Initial BW + Final BW) / 2]} x 100. When not reported, final BW was estimated as initial BW + ADG x days on feed.

[d] Estimated using Level 1 of the NRC model (2000), estimated dietary DIP, reported DMI and diet composition, and book-referenced (Lardy et al., 1998; NRC, 2000; Beef Magazine, 2012) ingredients' total digestible nutrients (TDN) values. DRC: 88% TDN; SFC: 93% TDN; HMC: 91% TDN; DRB: 84% TDN; SFB: 90% TDN. TDN from fat sources was disregarded for DIP requirement calculations.

[e] Estimated based on DIP balance, considering 64% of metabolizable protein (MP) supply from DIP is missing when DIP balance results negative.

[f] Estimated using Level 1 of the NRC model (2000).

Table 4. Summarized results from various research studies that evaluated effects of increased degradable intake protein (DIP) through the inclusion of urea to distillers-grains-containing feedlot diets on dry matter intake (DMI), average daily gain (ADG), and units of feed consumed per unit of gain (F:G).

Ref. [a]		Urea inclusion, %	Dietary DIP, % [b]	DMI, kg	DMI, % BW [c]	DIP supply, g/d [d]	DIP req., g/d [d]	DIP balance, g/d	MP supply, g/d [e]	MP req., g/d [f]	MP balance, g/d	ADG, kg/d	F:G
9-1	U0	0.68	7.3	9.25	1.92	673	668	5	869	793	76	1.66	5.59
	U1	0.89	7.9	8.99	1.88	709	648	61	855	793	62	1.63	5.56
	U2	1.09	8.5	8.72	1.83	737	626	111	835	794	41	1.56	5.59
	P			*0.02*	-	-	-	-	-	-	-	*NS*	*NS*
	Cst			*L*									
10-1	U0	0.00	6.7	9.47	1.96	632	649	-17	874	813	61	1.68	5.67
	U1	0.52	8.2	9.78	2.01	801	670	131	964	840	124	1.78	5.50
	U2	1.06	9.8	9.83	2.02	959	673	286	890	831	59	1.75	5.62
	P			*<0.05*	-	-	-	-	-	-	-	*<0.07*	*<0.07*
	Cst			*L*								*Q*	*Q*
10-2	U0	0.00	8.6	9.46	1.97	817	651	166	1016	811	205	1.68	5.63
	U1	0.52	10.2	9.46	1.97	960	651	309	1019	812	207	1.66	5.69
	U2	1.06	11.7	9.77	2.04	1145	672	473	994	811	183	1.68	5.85
	P			*<0.05*	-	-	-	-	-	-	-	*NS*	*<0.09*
	Cst			*L*									*L*
10-3	U0	0.54	8.1	8.47	1.78	672	554	118	728	748	-20	1.52	5.57
	U1	0.80	8.8	8.30	1.78	735	551	184	732	748	-16	1.51	5.52
	U2	1.06	9.6	8.26	1.78	798	549	248	731	748	-17	1.51	5.50
	P			*NS*	-	-	-	-	-	-	-	*NS*	*NS*
11-1	U0	0.00	5.0	11.1	2.40	555	708	-152	908	809	99	1.59	6.99
	U1	0.80	7.3	11.3	2.43	811	702	109	992	809	183	1.67	6.76
	P			*NS*	-	-	-	-	-	-	-	*NS*	*NS*

Table 4. (cont.)

Ref. [a]		Urea inclusion, %	Dietary DIP, % [b]	DMI, kg	DMI, % BW [c]	DIP supply, g/d [d]	DIP req., g/d [d]	DIP balance, g/d	MP supply, g/d [e]	MP req., g/d [f]	MP balance, g/d	ADG, kg/d	F:G
11-2	U0	0.00	6.0	10.9	2.35	666	707	-41	1086	809	277	1.61	6.76
	U1	0.63	7.8	11.2	2.41	868	703	165	1099	809	290	1.63	6.85
	P			*NS*	-	-	-	-	-	-	-	*NS*	*NS*
11-3	U0	0.00	6.6	10.7	2.13	704	672	32	1080	869	211	1.91	5.59
	U1	0.50	7.9	10.8	2.15	840	672	169	1065	869	196	1.90	5.65
	U2	1.00	9.2	10.7	2.12	977	672	305	1050	869	181	1.93	5.52
	P			*NS*	-	-	-	-	-	-	-	*NS*	*0.11*
	Cst												Q
12-1	U0	0.00	6.4	12.6	2.43	802	898	-95	1283	858	425	1.91	6.53
	U1	0.40	7.5	12.6	2.45	942	88	44	1343	846	498	1.88	6.81
	U2	0.60	8.0	12.9	2.47	1037	919	118	1370	954	416	2.12	6.06
	P			*NS*	-	-	-	-	-	-	-	*0.06*	*0.07*
	Cst											Q	Q

[a] **9-1:** Vasconcelos et al., 2007; **10-1 to 10-3:** Ponce, 2010; **11-1 to 11-3:** Jenkins et al., 2011; **12-1:** Ceconi et al., 2012.
U0: control-type diet to which small amount or no urea was added; U1 to U5: diets with greater DIP than U0 due to greater addition of urea.
P: *P*-value for means' contrast. NS: $P > 0.15$.
Cst: Contrast. L: linear; Q: quadratic; C: cubic; U0vsU: U0 versus [(U1+U2+U3)/3].

[b] Estimated based on reported diet composition, and ingredients' crude protein (CP) and DIP book-referenced values (Lardy et al., 1998; NRC, 2000; Beef Magazine, 2012). Dry-rolled corn (DRC): 40% DIP and 9% CP; Steam-flaked corn (SFC): 38% DIP and 9% CP; High-moisture corn (HMC): 60% DIP and 9% CP; Corn dried distillers grains: 40% DIP, and 32.4 and 30.4% CP for Jenkins et al., 2011 and Ceconi et al., 2012, respectively (analyzed). Corn wet distillers grains: 49% DIP and 29.7% CP, except for Jenkins et al. (2011) where 30.1% CP was reported; 90:10 corn:milo wet distillers grains (Ponce, 2010): 49% DIP and 33.4% CP (analyzed CP); 76:24 corn:milo wet distillers grains (Ponce, 2010): 49 DIP and 32.5% CP (analyzed CP); Milo wet distillers grains: 49% DIP and 33% CP. DIP expressed on CP basis.

[c] Estimated as {DMI / [(Initial BW + Final BW) / 2]} x 100. When not reported, final BW was estimated as initial BW + ADG x days on feed.

[d] Estimated using Level 1 of the NRC model (2000), estimated dietary DIP, reported DMI and diet composition, and book-referenced (Lardy et al., 1998; NRC, 2000; Beef Magazine, 2012) ingredients' total digestible nutrients (TDN) values. DRC: 88% TDN; SFC: 93% TDN; HMC: 91% TDN; Corn dried distillers grains: 88% TDN; Corn wet distillers grains: 90% TDN. 90:10 corn:milo wet distillers grains (Ponce, 2010): 89.6% TDN; 76:24 corn:milo wet distillers grains (Ponce, 2010): 89.1% TDN; Milo wet distillers grains: 86%. TDN from fat sources was disregarded for DIP requirement calculations.

[e] Estimated based on DIP balance, considering 64% of metabolizable protein (MP) supply from DIP is missing when DIP balance results negative.

[f] Estimated using Level 1 of the NRC model (2000).

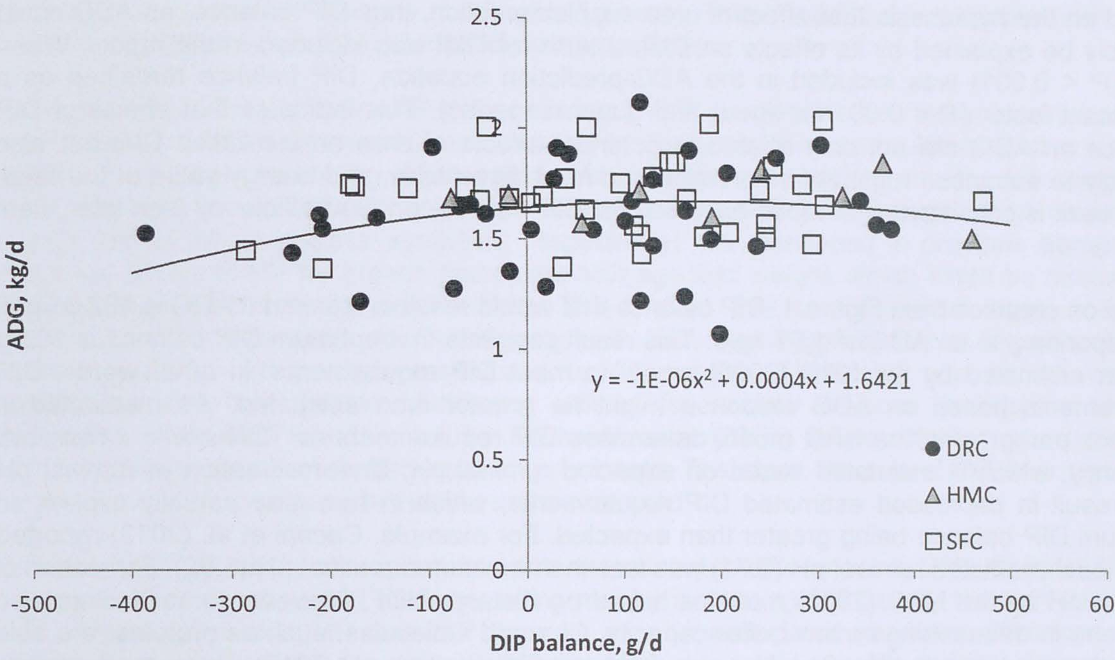

Figure 1. Average daily gain (ADG) as affected by degradable intake protein (DIP) balance in dry-rolled corn- (DRC), high-moisture corn- (HMC) or steam-flaked corn- (SFC) based finishing diets (from various studies reported in Tables 2 to 4).

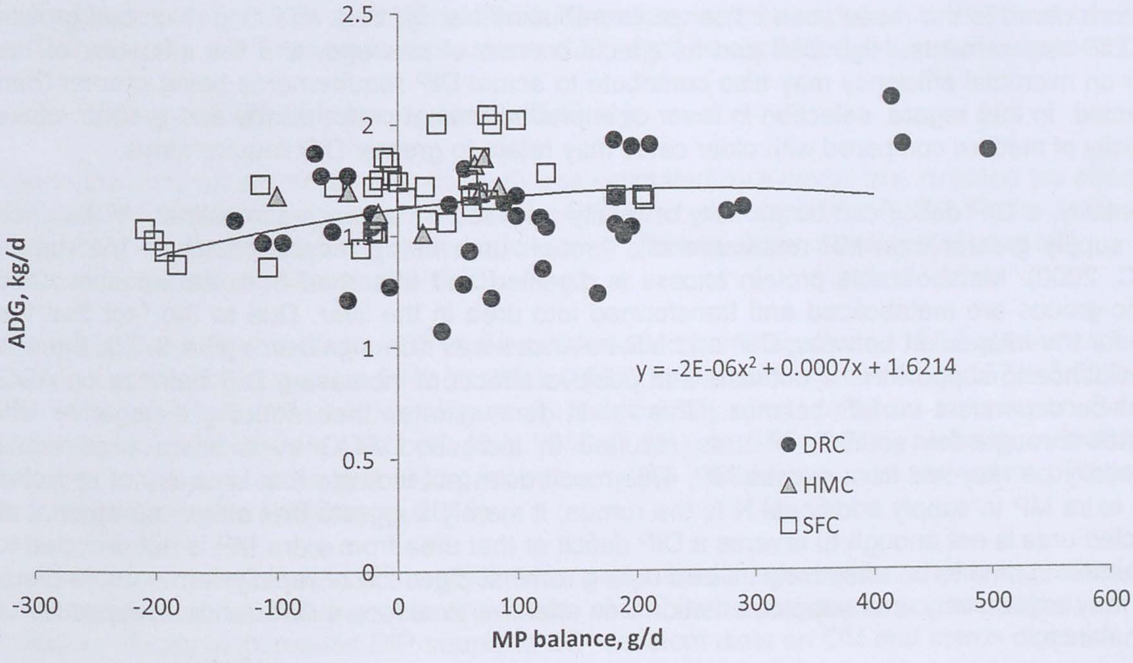

Figure 2. Average daily gain (ADG) as affected by metabolizable protein (MP) balance in dry-rolled corn- (DRC), high-moisture corn- (HMC) or steam-flaked corn- (SFC) based finishing diets (from various studies reported in Tables 2 to 4).

Based on the hypothesis that effect of urea supplementation, thus DIP balance, on ADG could possibly be explained by its effects on DMI, a term for DMI was included in the model. When DMI ($P < 0.001$) was included in the ADG-prediction equation, DIP balance remained as a significant factor ($P < 0.001$ for linear and quadratic terms). This indicates that effects of DIP balance on ADG are not only related to potential effects of urea on increased DMI but also possibly to enhanced ruminal fermentation and feed digestibility, and energy value of the feed. This result is consistent with those observed for DIP balance on feed efficiency (see later, Item b).

Based on equation from Figure 1, DIP balance that would result in maximum ADG is 182.05 g/d, corresponding to an ADG of 1.67 kg/d. This result suggests that optimum DIP balance is 182 g greater estimated by the NRC (2000) model to meet DIP requirements. In other words, DIP requirements based on ADG response might be greater than estimated. As mentioned in previous paragraphs, the NRC model determines DIP requirements as TDN intake x Microbial efficiency, which is estimated based on expected ruminal pH. Underestimation of ruminal pH may result in decreased estimated DIP requirements, which in turn may partially explain an optimum DIP balance being greater than expected. For example, Ceconi et al. (2013) reported that model-predicted ruminal pH (5.71) was less than measured ruminal pH (5.82). Estimation of ruminal pH by the NRC (2000) model is based on dietary eNDF. However, other factors also intervene in determining rumen buffer capacity. Charged molecules, such as proteins, are able to exchange cations (K, Ca, Mg) for protons (Dijkstra et al, 2012). Increased protein concentration in distillers grains-containing diets, as the ones evaluated by Ceconi et al. (2013), may result in ruminal pH being higher than the pH estimated based only on eNDF. As reported by Zinn et al. (2003), there is evidence that feeding urea in excess of that required to meet DIP requirements may enhance growth performance of feedlot cattle. They suggested that the basis for this effect may relate to the alkalizing effect of urea within the rumen. However, as mentioned before, this effect is usually transient. In addition, other factors besides pH, which are not considered in the model, can influence microbial efficiency, thus affecting microbial growth and DIP requirements. High DMI and its effects on rate of passage, and the influence of the latter on microbial efficiency may also contribute to actual DIP requirements being greater than expected. In that regard, selection in favor of improved animal performance and greater intake capacity of modern compared with older cattle may relate to greater DIP requirements.

Potentially, a DIP deficit can be partially or totally reversed by a positive intestinal MP balance (MP supply greater than MP requirements), through urea being recycled back to the rumen (NRC, 2000). Metabolizable protein excess is digested and absorbed from the intestine, and amino-groups are metabolized and transformed into urea in the liver. Due to the fact that the term for the interaction between DIP and MP balances was non-significant ($P = 0.72$), there is no evidence to support the hypothesis that positive effects of increasing DIP balance on ADG might be dependent on MP balance.. This result demonstrates that reducing a negative DIP balance through the addition of urea resulted in increased ADG even when urea could potentially be recycled from excess MP. This result does not indicate that urea is not recycled from extra MP to supply additional N to the rumen; it merely suggests that either the amount of recycled urea is not enough to reverse a DIP deficit or that urea from extra MP is not recycled to the rumen in time to be effectively utilized during ruminal digestion of rapidly-fermentable diets. This may explain why urea supplementation was effective to reduce a DIP deficit, irrespective of MP balance.

Similarly, ADG increased when MP balance increased from negative to an estimated value of 247.7 g/d (Figure 2), which corresponded to an ADG of 1.71 kg/d, very close to the maximum

ADG estimated from DIP balance (1.67 kg/d; Figure 1). These results are consistent with those observed by DiCostanzo (2007) for a different set of data.

As mentioned above, optimum MP balance is about 250 g/d greater than the amount needed to meet estimated MP requirements (maintenance and growth). This can be interpreted in terms of actual MP requirements being greater than expected or the possibility of extra AA being used for a metabolic function other than protein accretion (ketogenic and glucogenic AA used as an energy source or for glucose synthesis, respectively). As mentioned in previous paragraphs, efficiency of use of MP for growth decreases with age and weight, which might be related to a reduced number of muscle satellite cells. This implies that as the animal ages, a smaller proportion of MP is transformed into NP for growth. This also suggests that as the animal ages, protein accretion will be less responsive to AA supply.. Therefore, unused AA may be catabolized and their carbon backbones utilized for another purpose (energy or glucose synthesis). Published reports cited by Markantonatos (2006) indicate that in ruminants, 25 to60% of the glucose can be derived from propionate. Therefore, the role of MP as a significant contributor to gluconeogenesis may be underestimated.

Differences in MP balance across treatments are related to differences in DMI, dietary UIP, DIP requirements, and amount of the latter being met by increasing DIP supply through addition of urea. This implies that MP and DIP balance can be associated variables; therefore, when simultaneously included in the model to predict ADG, one could override the significance of the other. That is, if mechanisms behind ADG response to increased DIP and MP balance are the same, inclusion of one of these variables when the other one is already included in the model should not further contribute to explain a significant proportion of ADG. When modeling ADG response to MP and DIP balance, MP balance remained in the model after including DIP balance as another factor, but it didn't remain as significant ($P > 0.14$) when DMI ($P < 0.001$)) was included as another variable in the model. DiCostanzo (2007) reported a significant association between DMI and MP balance. Therefore, and as opposed to what was observed for DIP balance, ADG response to increased MP might be explained in terms of increased DMI.

b. Effects of DIP balance on feed efficiency

Feed efficiency (analyzed as gain-to-feed) was estimated by a model that included the effect of DIP balance (linear and quadratic terms; $P < 0.01$) and grain type ($P < 0.001$; Figure 3). Terms for DMI, MP balance (linear and quadratic terms), and interaction between DIP and MP balances were not significant ($P > 0.26$).

Feed efficiency improved when DIP balance increased from negative to 157.6 g/d. As expected, gain-to-feed was greatest for SFC (0.175 ± 0.004), intermediate for HMC (0.157 ± 0.005), and lowest for DRC (0.155 ± 0.004; Figure 3). Additionally, the coefficient of variation for feed efficiency decreased from DRC (12.1%), HMC (7.0%), to SFC (6.8%), probably reflecting the effect of intensity of grain processing on reducing the variability in rate and extent of digestion among batches of grain (Owens, 2013).

As previously mentioned, DIP balance was a significant factor when explaining variation in ADG, even after considering potential effects of DIP balance (urea supplementation) on DMI. Possible effects of increased DIP supply to DIP-deficient diets on OM and starch digestion, VFA production, and microbial crude protein synthesis may relate to the observed improved feed efficiency.

Present information reveals that optimizing DIP balance is an important factor to improve feed efficiency (Figure 3). But, how does that information translate into field applications?

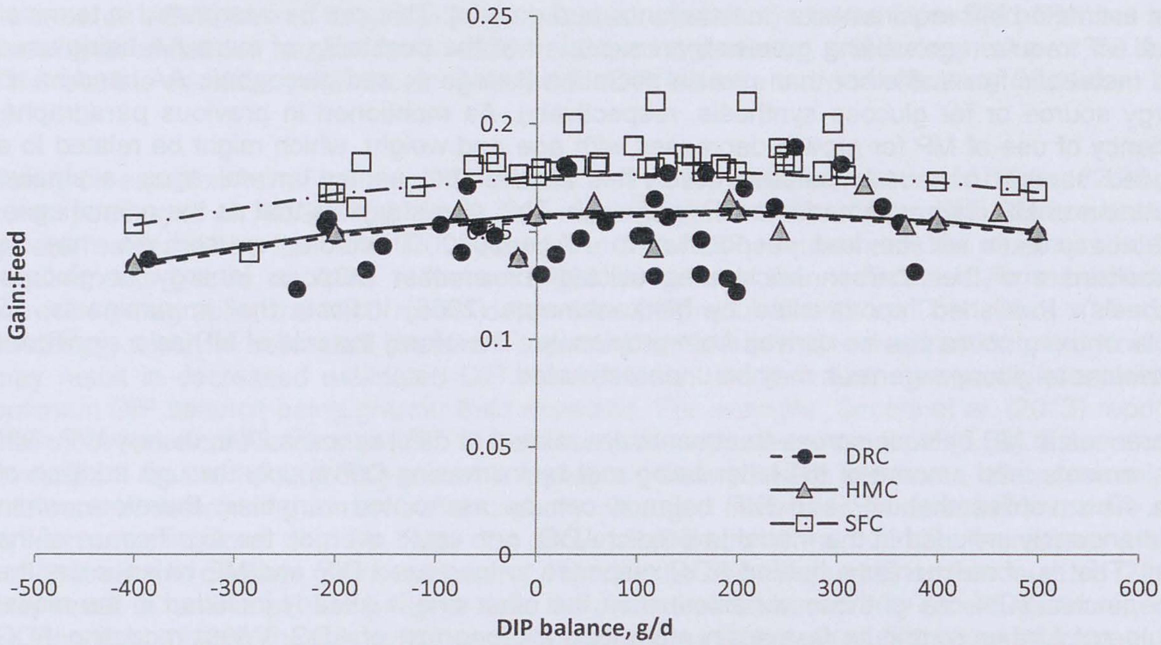

Figure 3. Feed efficiency (kg gain:kg feed) as affected by degradable intake protein (DIP) balance in dry-rolled corn- (DRC), high-moisture corn- (HMC) or steam-flaked corn- (SFC) based finishing diets (from various studies reported in Tables 2 to 4).

Recognizing a potential DIP deficit

a. Dietary DIP concentration and grain type

Optimum DIP balance was shown to be around 160 g/d, which corresponded to the greatest feed efficiency (0.158, 0.160, and 0.178 for DRC-, HMC- and SFC-based finishing diets; Figure 3). As mentioned previously, increased rate of fermentation can potentially increase microbial efficiency, which in turn may increase DIP requirements and affect DIP balance. Providing adequate DIP is necessary for maximum microbial CP synthesis, which depends largely on carbohydrate digestion in the rumen (Russell et al., 1992). Thus, requirements for DIP should be greatest with high-grain diets that are based on extensively processed starch (e.g., steam-flaked grains). Therefore, dietary DIP (as a % of diet dry matter) that would correspond to the highest feed efficiency was estimated by modeling feed efficiency in terms of dietary DIP, grain type, and their interaction. Based on the hypothesis that replacement of corn in distillers grains-containing diets may result in decreased dietary rate of fermentation, mainly in SFC-based diets, terms for distillers grains inclusion, and its interaction with dietary DIP and grain type were included in the model as well. Only dietary DIP (linear and quadratic terms, $P < 0.01$) and its interaction with grain type ($P < 0.001$) were retained in the model (Figure 4).

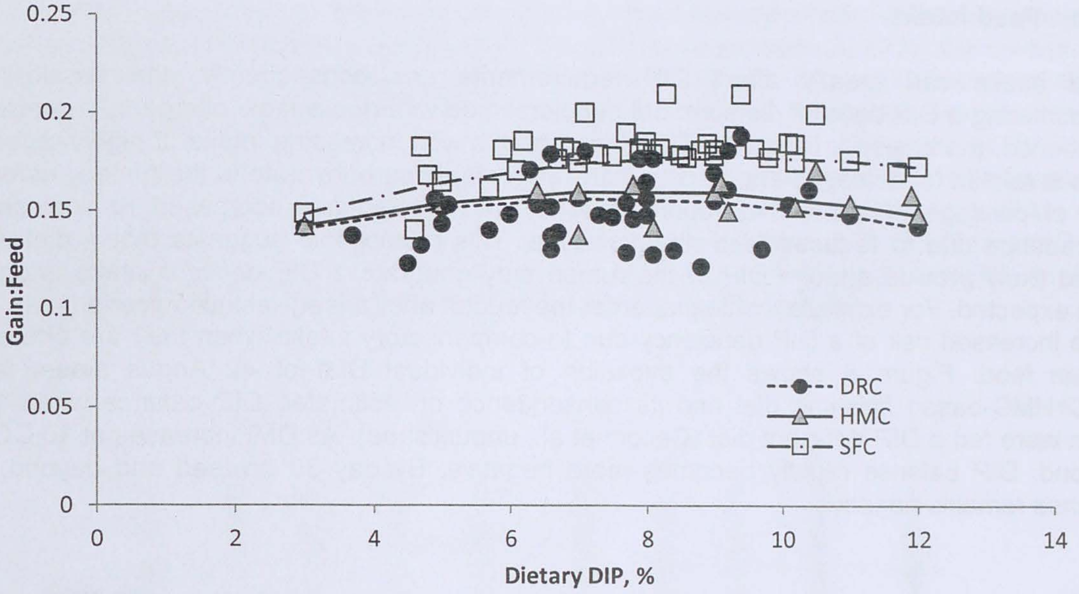

Figure 4. Feed efficiency (kg gain:kg feed) as affected by degradable intake protein (DIP) balance in dry-rolled corn- (DRC), high-moisture corn- (HMC) or steam-flaked corn- (SFC) based finishing diets (from various studies reported in Tables 2 to 4).

The fact that the effect of dietary DIP on feed efficiency was the same for diets with as that for those without distillers grains indicates that factors that potentially affect DIP requirements may compensate between those diets. For example, based on the hypothesis that replacing basically starch by NDF and protein in distillers containing diets, rate of fermentation was speculated to be slowed down, thus reducing microbial efficiency and DIP requirements. However, this proposed effect could be compensated by positive effects resulting from reduced particle size of distillers grains on fermentation rate, as well as possible increased intake, and therefore increased DIP requirements when replacing 10 to30% corn by distillers grains. In a meta-analysis, Klopfenstein et al. (2008) reported a quadratic increase in DMI with increasing distillers inclusion in DRC- or HMC-based diets; DMI being maximized at 30% distillers inclusion. Similarly, Luebbe et al. (2012) observed highest DMI with 15 to 30% distillers inclusion in SFC-based finishing diets. Finally, potential beneficial effects of protein from distillers grains on ruminal pH (ion exchange within ruminal fluid; Dijkstra et al., 2012) may help compensate expected differences in terms of DIP requirements between diets.

Figure 4 shows that maximum feed efficiency is achieved when dietary DIP is 7.68, 8.03 and 9.41% for DRC, HMC, and SFC, respectively. Based on differences in rate of fermentation between diets, the observed difference in dietary DIP to achieve maximum feed efficiency was expected. Microbial protein synthesis potential increases with increasing starch degradability; therefore, DIP required for maximal feed efficiency increases with more extensively processed grains (Spicer et al., 1986; Brake et al., 1989; Barajas and Zinn, 1998; Cooper et al., 2002). As opposed to the present analysis, Cooper et al. (2002) reported a smaller optimum dietary DIP for SFC- (8.3%) compared with HMC-based diets (10.0%). This result might be partially related with reduced DMI and possible negative effects of the high fermentability of SFC on ruminal pH compared with HMC, which in turn may result in reduced DIP requirements.

b. Feed intake

Feed intake can greatly affect DIP requirements and consequently, the possibility of encountering a DIP deficit if diets are not supplemented with degradable nitrogen. As previously mentioned, the basis for increased DIP requirements with increasing intake of highly-digestible diets is related to increased supply of rapidly-fermentable carbohydrate to the rumen, increased rate of passage (increased microbial efficiency), and potentially decreased ruminal protein degradation due to reduced feed retention time. This relationship suggests that a diet which would likely provide enough DIP to the rumen may generate a DIP deficit if intake is greater than expected. For example, cattle that enter the feedlot after a feed-restriction period may likely have increased risk of a DIP deficiency due to compensatory intake when they are offered *ad libitum* feed. Figure 5 shows the evolution of individual DMI of 42 Angus steers fed a DRC+HMC-based finishing diet and its consequence on estimated DIP balance when 14 of them were fed a DIP-deficient diet (Ceconi et al., unpublished). As DMI increases at 10 DOF or beyond, DIP balance rapidly becomes more negative. By day 30 on feed and beyond, DIP balance remains negative.

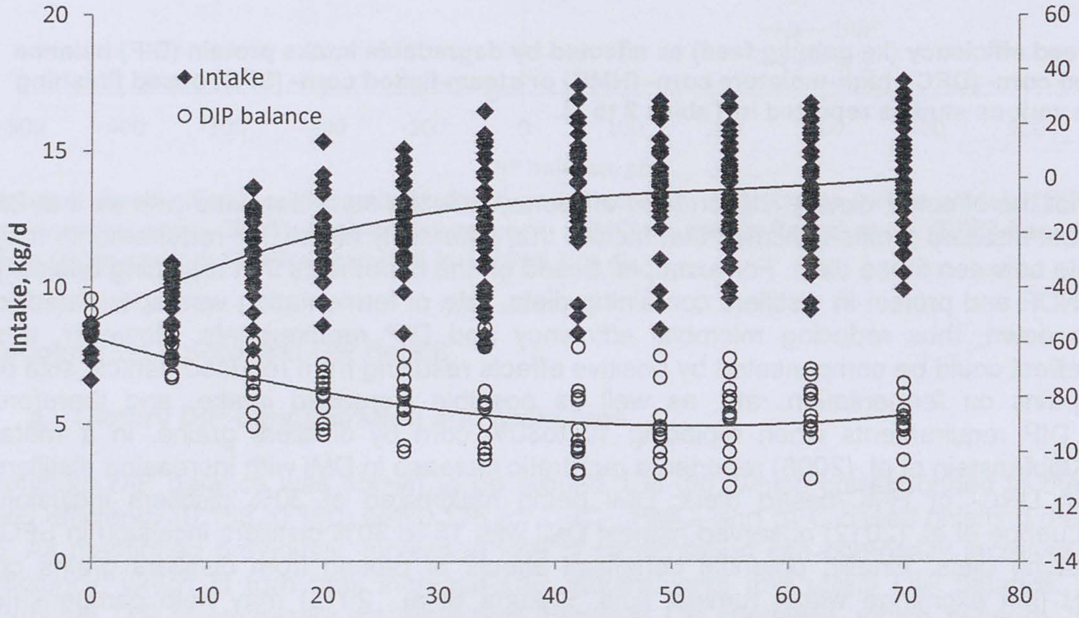

Figure 5. Individual DMI by 42 steers, and estimated degradable intake protein (DIP) balance for 14 steers fed a DIP-deficient diet as affected by days on feed (DOF). Ceconi et al., unpublished.

These results suggest that chances of producing a DIP deficit should be greater at the end than the beginning of the feedlot finishing period. However, NRC Level 1-based DIP balance does not account for potential effects of relative intake (%BW) on rate of passage and consequently on microbial efficiency and DIP requirements. Considering data from Figure 6, opportunity for a DIP deficit may be greater after 20 days of the beginning of the feeding period, when relative intake is greatest. Similarly, decreased initial body weight may increase chances for a negative DIP balance, as lighter animals usually express greater relative intake.

Finally, a model was tested to determine the relative intake beyond which ADG would positively respond to urea supplementation. Within study, the difference between ADG for the control-type diet and each of the urea supplemented treatments was calculated. This variable was regressed against relative intake (kg DMI/kg BW)for each treatment and the interaction between relative intake and grain type. The model was evaluated using the Mixed procedure of SAS and weighted by number of treatment replications per study. Both relative intake and its interaction with grain type were significant ($P < 0.03$). As guidance, relative intake beyond which urea supplementation may have a positive effect on ADG was 2.20% and 1.76 %BW for DRC and SFC, respectively. This translates into 8.4 kg (18.4 lb) and 6.7 kg (14.7 lb) of DRC- or SFC-based diet, respectively, for a 380-kg-in-BW-yearling steer (837 lb in-BW).

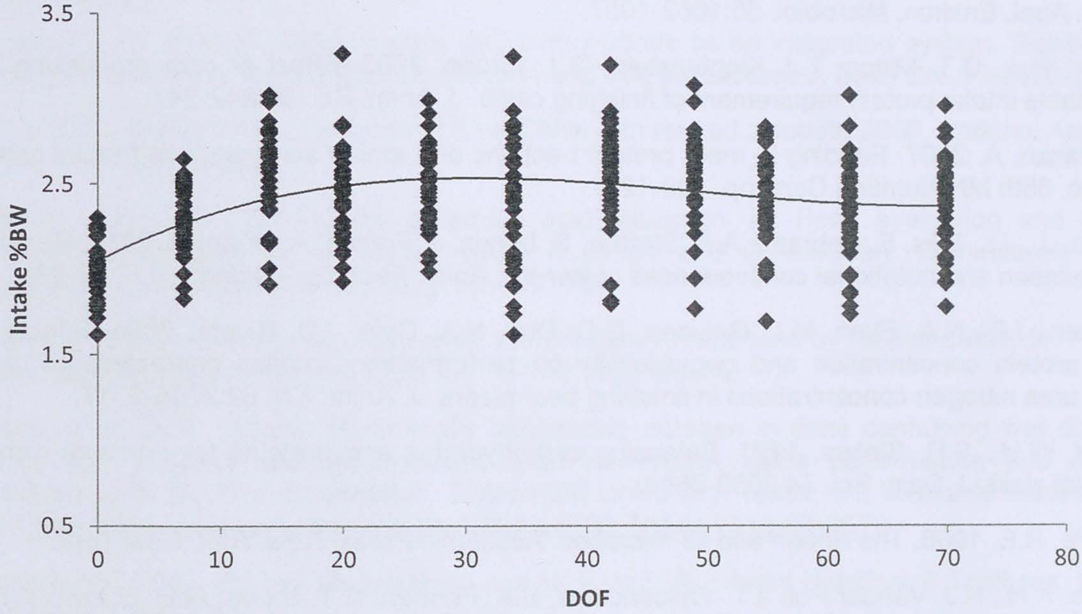

Figure 6. Dry mater intake, as a percentage of body weight (%BW), of 42 steers as affected by days on feed (DOF). Ceconi et al., unpublished.

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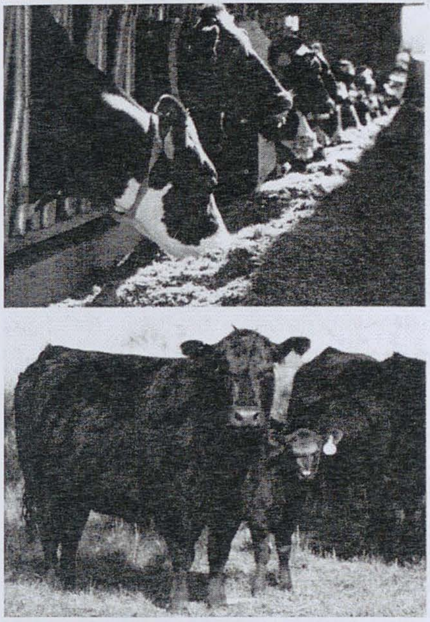

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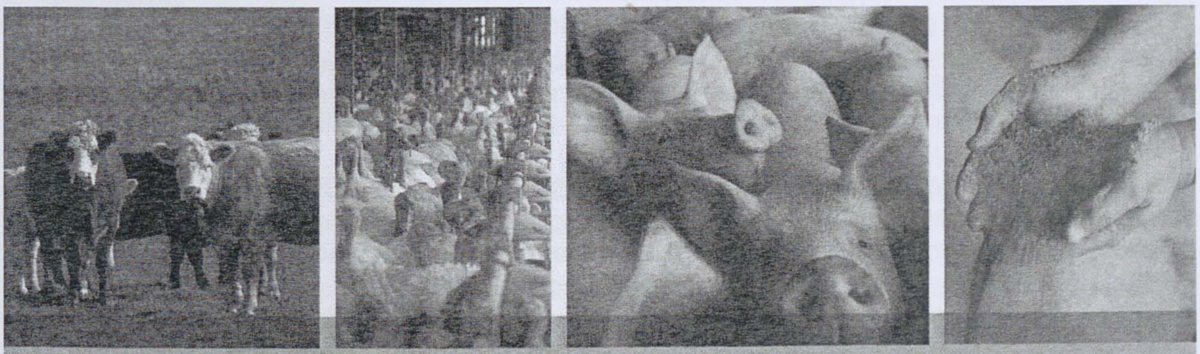

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