DCAD: It's Not Just for Dry Cows

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Abstract

Dietary cation anion difference (**DCAD**) is an index of the relative proportions of the strong cations (potassium and sodium) and anions (chloride) in the diet. The dietary strong ions are virtually 100% absorbed from the diet and play a critical role in regulation of osmotic balance and electrochemical charge in rumen and digestive system, blood, and intracellular fluids, and urinary acid-base excretion in the dairy cow. Low and negative DCAD diets in dry cow diets have been used to prevent milk fever for more than 20 years. However, the importance of DCAD in the lactating dairy cow cannot be underemphasized. Inadequate DCAD in the milking cow diet can lead to impaired acid-base balance and reduced feed intake, milk production, and milk fat content. There is no minimum NRC requirement for DCAD. Meta-analysis of published literature on DCAD suggested that increasing DCAD from 0 to 400 mEq/kg diet dry matter (**DM**) would increase DM intake, milk production, and milk fat yield by 3.3, 2.2, and 0.33 lb/cow/day, respectively. Increasing DCAD from 0 to 400 mEq/kg increased DM digestibility by 3 percentage units, with the majority of the increase due to improved fiber digestibility. The manipulation of DCAD through ingredient selection and supplementation of mineral salts is discussed. The primary economic response to DCAD is milk fat yield and a practical suggested minimum DCAD appears to be about 300 mEq/kg.

Introduction

For more than 20 years, dairy producers have been using low DCAD diets in their transition cow feeding programs to prevent milk fever and subclinical hypocalcemia. The use of low DCAD diets in dry cows has virtually eliminated the incidence of clinical milk fever in most dairy herds. While dairy producers are well aware of the importance of proper DCAD concentrations in the dry period, relatively little attention has been paid to the effect of DCAD in lactating cows. We will review the principles of the strong ions in physiology and calculating and formulating for DCAD and then highlight the responses of lactating cows to DCAD.

What is DCAD?

The term DCAD stands for Dietary Cation Anion Difference. DCAD is an index of the relative balance between the principle cations (potassium; K and sodium; Na) and the principle anions (chloride; Cl and sometimes sulfur; S) in the cow's diet. Na, K, and Cl fall into a class of dietary minerals that are sometimes referred to as the "osmoregulators" because of the critical role that they play in maintaining osmotic balance in various body tissues (Table 2).

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In blood, Na is the primary cation and Cl, and to a lesser extent bicarbonate, ions are the primary anions. In the cell, K is the principal cation, while amino acids and proteins with a negative charge serve as the principle anions. Finally, in rumen fluid, a combination of Na and K are the principal cations, whereas volatile fatty acids (**VFA**) that are produced during rumen fermentation serve as the primary anions. These minerals are absorbed from the diet with nearly 100% efficiency and can readily move across the intestinal wall, blood, and cell membranes. Their relative content in these tissues is maintained by a Na-K-ATP pump. They are also important for maintaining osmotic balance in milk and the relatively consistent moisture content (85%) of feces in the cow. Na and K are the primary drivers of urine output. Thus, added intake of these minerals will also increase water intake in the cow. Finally, surpluses of these ions (Na, K, and Cl) in excess of the cow's requirements are regulated through urinary excretion.

There are 2 important principles with respect to the cations and anions: 1) the sum of the cations and anions (equivalent weight basis) should add up to about 300 to maintain a consistent osmotic pressure and maintain water balance between tissues; and 2) the sum of the cations should equal the sum of the anions to maintain neutral electrical charge. These 2 principles are important in understanding the role of DCAD in acid-base balance and urinary excretion of these minerals.

The Strong Ion Theory

Na, K, and Cl are also referred to as the "Strong Ions" because they are absorbed from the diet with nearly 100% efficiency, they remain completely dissociated in solution and physiologically, and any surplus intake from the diet above and beyond the animal's needs will be excreted in the urine. The "Strong Ion Theory of Acid-Base Balance", first proposed by the Canadian physiologist Peter Stewart (Stewart, 1978) applies to virtually every mammal, including humans. Stewart (1978) referred to the sum of the strong cations minus the sum of the anions as the Strong Ion Difference (**SID**):

$$SID = Na^+ + K^+ - Cl^-$$

The SID equation is in fact identical to the simplest DCAD equation that was first developed for poultry and swine that is also referred to as the Mongin (1981) equation. Excretion of strong ions in the urine can be summarized by the following equation where the sum of the cations (Na^+, K^+, H^+) must equal the sum of the anions (Cl^-, OH^-) to maintain electrochemical neutrality:

$$Na^+ + K^+ + H^+ = Cl^- + OH^-$$

If an animal consumes a diet that is high in cations in relation to anions, (SID or DCAD is positive), its urine must contain additional anions to maintain electrochemical neutrality. Cattle routinely consume diets that are high in K, and the additional base (anion) excreted in the urine is usually the bicarbonate ion. In contrast, cattle consuming diets that are high in Cl relative to K and Na (DCAD or SID is negative), additional cations such as ammonium (**$NH4^+$**) and other titratable acids are needed to balance the negative charge of Cl. Because of this relationship, animals such as cattle which are typically are fed diets high in cations, will have an alkaline urine (pH > 7); whereas, animals that are fed diets that are low in cations will have acid urine (pH < 7). This concept is illustrated in Table 3 that compares lactating sows and dairy cows. Pigs, because they consume a low K diet, have an acidic urine; whereas, cows that consume a high K diet have an alkaline urine.

How Does DCAD Work in Preventing Milk Fever?

The initial work on use of DCAD was based on the observation by Scandinavian researchers that cows fed diets that were low in ash content resulted in reduced incidence of milk fever (Ender et al.,1971; Dishington, 1975). Since potassium is a major factor that affects dietary ash content (low ash diets were also low in K), it was found that diets with low DCAD (low K and Na, relative to Cl) reduced not only milk fever but also subclinical hypocalcemia. Since excess dietary Cl is excreted in urine, it requires a corresponding cation to maintain a neutral charge. Low K diets stimulated hydrogen ion (low pH) secretion and the "spilling of calcium" (Ca^{++}) in the urine. In turn, that increased loss of calcium in the urine also increased the cow's metabolic mechanisms for resorption of calcium from bone and intestinal absorption of Ca from the diet such that the cow was able to regulate blood calcium more effectively when the increased demand for Ca in milk production kicked in at the time of calving.

These observations stimulated numerous studies on the use of DCAD to prevent milk fever by Elliott Block (1984) at McGill University in Canada, Jesse Goff and Ron Horst (1997) at the USDA Animal Disease Laboratory in Iowa, and several others. The key points from their work were: 1) diets that were negative in DCAD were effective in preventing milk fever and subclinical hypocalcemia 2) selection of feeds that were low in K and Na along with addition of Cl and sulfate salts were required to achieve a low or negative DCAD diet, and 3) low urine pH was a very useful indicator of the cow's DCAD status.

Probably the most pivotal experiment was a study using Jersey cows by Goff and Horst (1997) where cows were fed diets containing 1.1, 2.1, and 3.1% K with either 0.5 or 1.5% Ca during the dry period. The DCAD across Ca levels was increased from -75 to 430 mEq/kg diet DM with increasing K. Incidence of milk fever increased from 0% in the 1.1% K, 0.5% Ca diet to 80% in the 3.1% K with either 0.5 or 1.5% Ca. It was clear that the low DCAD (low K) diets had a profound effect on incidence of milk fever. Subsequent work looked at the effectiveness of various Cl and sulfate salts to reduce urine pH and it was determined that dietary sulfur was about 60% as effective as Cl in reducing urine pH and preventing hypocalcemia (Goff et al., 2004).

The DCAD Equations

The simplest calculation of DCAD is referred to as the Mongin (1981) equation that was originally developed for formulation of poultry and swine diets. The formula includes the Na, K, and Cl contents of the diet and an example of DCAD calculations for a diet that meets the minimum (NRC, 2001) requirements for K, Na, and Cl in lactating dairy cows is in Table 1. DCAD is most frequently expressed as either mEq/kg or mEq/100 g feed DM. The difference in magnitude is a factor of 10.

Table 4 shows the various DCAD equations that have been used by dairy nutritionists in diet formulation programs. Each equation is very similar in that they all account for the strong ion (K, Na, and Cl) contents of the diet. The first equation suggested for use in formulating dry cow diets was proposed by Ender (1971). This equation includes dietary sulfur (**S**), which has a +2 valence and therefore in this equation, the sulfur content divided by the atomic weight is multiplied by 2. The inclusion of S in the DCAD formula is only important when dietary S varies. Typically, this is not an issue unless distillers grains (**DDGS**) are a major component of the cow's diet. As stated earlier, the Mongin (1981) equation is the simplest equation and is equally effective as long as dietary S does not vary substantially. The NRC (2001) equation is perhaps the most precise and is based on the relative rates of absorption of each of the minerals in the equation. However, very few nutritionists utilize that equation. Finally, the Goff et al. (2004) equation with a 0.6 coefficient for S is based on the relative effectiveness of sulfate salts in reducing urine pH compared to Cl salts. In our opinion, this is probably the most precise of all of the DCAD equations. However, the Ender (1971) DCAD equation still remains the most commonly used one, in spite of the fact that it probably overemphasizes the role of dietary sulfur.

DCAD in Lactating Dairy Cow Diets

Although negative DCAD diets have been fed to dry cows for many years, relatively little work was done on the effect of DCAD in lactating dairy cows until the late 1980's and early 1990's. Work by Tucker et al. (1988) demonstrated that in contrast to dry cows, negative DCAD diets should not be fed to lactating cows and negative DCAD diets resulted in reduced feed intake and milk production. A series of experiments at Georgia (West et al., 1992) and Florida (Sanchez and Beede, 1996) examined the effects DCAD during heat stress. They suggested that increasing DCAD improved feed intake, milk production, and milk fat concentration during heat stress. The importance of DCAD was extensively discussed in the 2001 NRC publication, but no minimal DCAD requirement was established. There simply had not been enough experiments conducted with varying DCAD concentrations to establish a requirement at the time of publication. If one were to feed diets at the minimal requirements for K, Na, Cl, and S, the implied requirement would be around 179 mEq/kg DM using the Ender (1971) equation that includes dietary S and about 304 mEq/kg DM using the Mongin (1981) equation that does not include S in the formula.

The first meta-analysis of DCAD studies in lactating dairy cows was published by Hu and Murphy (2004), where the results of 12 papers involving 17 experiments and 54 treatment means were summarized. Hu and Murphy (2004) estimated that maximum feed intake, milk production, and 4% fat-corrected milk (**FCM**) production occurred at DCAD of 40, 34, and 49 mEq/100 g of feed DM, respectively using the Mongin (1981) equation to calculate DCAD. This study conclusively demonstrated the importance of feeding positive DCAD diets to lactating cows. However, the number of experiments and treatment means available for the analysis were limited. Further, many of the diets in that summary were DCAD negative, with more than 50% of the treatment means from cows fed diets containing less than 304 mEq/kg DM, the theoretical requirement for cows fed diets with the minimum requirements for K, Na, and Cl. Because Hu and Murphy (2004) had chosen to use a quadratic equation to explain the data, only a maximal response to DCAD rather than an optimal response could be determined.

Dietary buffers containing bicarbonate and carbonate salts of K and Na will increase DCAD, and they have been common feed additives in dairy cow diets for more than 50 years. We reasoned that the numerous feeding studies on the use of buffers in the early lactation period and to increase milk fat in low forage diets (Erdman, 1988), along with studies published since 2004 could be used to augment the dataset of Hu and Murphy (2004). Although some of the older publications did not have complete mineral analysis to calculate DCAD, we were able to show that book values from the 2001 NRC software could be used to fill in the missing mineral concentrations and accurately predict DCAD (Iwaniuk and Erdman, 2015).

The calculated DCAD from those publications was the basis for our recent meta-analysis of DCAD effects in lactating dairy cows (Iwaniuk and Erdman, 2015). A total of 43 articles published between 1965 and 2011 that included 196 treatment means and 89 DCAD treatment comparisons were included in the analysis. The range in DCAD was from −68 to +811 mEq/kg of diet DM (Ender equation), but the vast majority of diets contained between 0 and 500 mEq/kg of diet DM, which we considered to be the practical range of inference.

Figure 1 (A to D) shows a summary of the dry matter intake (**DMI**), milk production, and milk composition responses to DCAD from that analysis that were fitted to curvilinear and linear response equations. For DMI (Figure 1A), the maximum response was 1.92 kg/day (4.2 lb/day) and 66% and 80% of the maximum DMI responses were achieved at DCAD concentrations of 290 and 425, respectively. Maximum milk production responses (Figure 1B) were small (1.1 kg/day; 2.4 lb/day) with very little response to DCAD above 300 mEq/kg diet DM. For milk fat percentage and yield (Figures 1C and 1D, respectively), the responses were linear. Every 100 mEq/kg increase in DCAD resulted in a 1 point (0.1 percentage unit) increase in milk fat percent and a 38 g/day (0.08 lb/day) increase in fat yield. This suggests that fat yield will be the primary economic response to DCAD. Consequently, the 3.5% FCM response was much greater than for milk production alone, and 66% and 80% of the maximum FCM response (4.8 kg/day, 10.8 lb/day) occurred at DCAD concentrations of 450 and 675 mEq/kg DM, respectively. We consider the 675 mEq/kg DCAD to be outside of the range of inference of this data set. There were no effects of DCAD on milk protein percent or yield (data not shown). In summary, clearly there are intake, milk production, and milk composition responses to DCAD, and these effects need to be accounted for in diet formulation for lactating dairy cows.

We also looked at the effects of DCAD on rumen pH (data not shown). A 100 mEq/kg DM increase in DCAD resulted in a linear 0.003 unit in rumen pH, such that increasing DCAD from 0 to 500 mEq/kg DM was projected to increase mean rumen pH from 6.31 to 6.46. These results are very consistent with earlier studies on the use of buffers to increase rumen pH and correspond to changes in milk fat percent (Iwaniuk and Erdman, 2015).

With respect to digestibility, increasing DCAD from 0 to 500 mEq/kg DM resulted in a 3.5 percentage unit increase in DM digestibility and a 7.5 percentage unit increase in NDF digestibility (Figure, 2A and B). About two thirds of the increase in DM digestibility was due to increased NDF digestibility. Changes in NDF digestibility of this magnitude are huge and exceed those expected with substitution of brown midrib corn silage for traditional corn silage. Oba and Allen (1999) suggested that a 1-percentage unit increase in NDF digestibility resulted in 0.17 and 0.25 kg/day increases in DMI and 4.0% FCM, respectively. Using Oba and Allen (1999) coefficients and assuming a 7.5-percentage-unit increase in NDF digestibility by increasing DCAD from 0 to 500 mEq/kg, the expected increase in DMI and 3.5% FCM would be 1.3 and 1.9 kg/day (2.9 and 4.2 lb/day), respectively and would account for 75% of the expected increase in DMI and 55% of the expected increase in 3.5% FCM. We concluded that one of the primary modes of action of DCAD is the increase in rumen pH and NDF digestibility.

What is the Optimal DCAD for Lactating Dairy Cows?

There is no NRC requirement for DCAD, but feeding at the minimal requirements for Na, K, Cl, and S would result in a DCAD of 304 and 179 mEq/kg DM using the Mongin (1981) and Ender (1971) equations, respectively. The difference being the incorporation of S in the DCAD calculation.Table 5 shows a comparison of the maximum DMI milk, and FCM responses from our summary (Iwaniuk and Erdman, 2015) and the earlier analysis of Hu and Murphy (2004). First, the primary economic response to DCAD is milk fat yield, which in combination with a slight increase in milk production drives increased FCM. Secondly, an optimal DCAD concentration is not necessarily the concentration at the maximal response. We prefer to look at DCAD concentrations somewhat below maximum because there is a cost of added mineral supplements to increase DCAD and the cost of increased feed intake caused by increased DCAD. We view a practical minimum as a DCAD of 300 mEq/kg DM (Ender, 1971 equation). This corresponds to two-thirds of the maximum response in DMI and will garner nearly all the added milk production and achieve the majority of the increase in FCM production. After that point, the decision to feed higher DCAD will depend on the cost of supplementation and the added value of the extra milk fat produced.

Formulating for DCAD

Diet formulation for DCAD begins with feed ingredient selection. Table 6 shows a comparison of selected feed ingredients and their relative mineral and DCAD concentrations. The first thing that is apparent is that most feeds have a relatively low Na content and vary substantially in K, and to a lesser extent, Cl and S. Feeds that are high in DCAD, where the cations (K and Na) are greater than the anions (Cl and S), are usually feeds that are high in K. Feeds like soybean meal, alfalfa haylage, barley, and grass silages that are high in K are also high DCAD feeds. Corn silage, because it is a mixture of the corn plant (stalk and leaves) and grain, is intermediate in DCAD content. Protein supplement, such as DDGS and canola meal are intermediate in K content and are low DCAD feeds because of their relatively high S content. Thus, in selection of feed ingredients for high DCAD, you will normally look for feeds that are high in K content. Feeds like soybean meal and forages, especially alfalfa and small grain silages, will increase DCAD.

Generally, high NDF feeds (forages) are also high DCAD feeds because of their K content. One side benefit of increasing fiber (**NDF**) in the diet to increase milk fat is that this also indirectly increases DCAD. While dairy producers frequently attribute the increase in milk fat when NDF is increased to the added NDF, part of the response is likely due to increased DCAD caused by substitution of low fiber and low DCAD feeds like corn for high fiber and high DCAD feeds like grass or small grain silages.

Supplements that can be Used to Increase DCAD

Once DCAD has been increased through feed ingredient selection, further increases can be achieved by use of mineral supplements. There are a variety of Na and K carbonate and bicarbonate salts that can be used to raise DCAD. Table 7 shows some commonly supplemented K and Na mineral salts used in dairy cattle diets. Please note that common salt (**NaCl**) and potassium chloride (**KCl**) are DCAD neutral since the cation (Na or K) is balanced by a corresponding anion (**Cl**). While salt and KCl are highly available sources of Na, K, and Cl, supplementing with these minerals will have no effect on DCAD. In order to raise DCAD, nutritionists must select from mineral supplements, such as potassium carbonate, sodium bicarbonate, or sodium sesquicarbonate. Surprisingly, there is very little difference among these in their relative DCAD content (Table 7). Adding 0.75, 0.83, or 0.75% of commercially available potassium carbonate, sodium bicarbonate, or sodium sesquicarbonate, respectively, to the diet DM will increase DCAD by 100 mEq/kg diet DM. At that point, the choice of supplement is based on cost unless the minimum requirements for sodium and potassium have not been met.

Summary

DCAD is not only important in dry cows but also lactating cows. Optimal DCAD for dry cow diets is typically zero or negative, while feeding low DCAD diets to lactating cows will depress feed intake, milk production, and milk fat concentration. A suggested minimal DCAD for lactating cows is most likely about 300 mEq/kg feed DM (30 mEq/100 g DM). However, the optimal DCAD will be dependent on the value of the increased milk and milk fat yields, including the primary economic responses to DCAD, the cost of increased feed intake, and the cost of increasing DCAD above the diet's inherent DCAD concentration using mineral supplements.

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Table 1. Calculation of dietary cation anion difference using K, Na, and Cl.[1]

Element	% of DM	g/kg	Atomic Wt., g	Eq./kg	Eq/kg
K	1.06	12	39.1	0.271	271
Na	0.23	2.3	23.0	0.100	100
Cl	0.24	2.5	35.5	0.067	67

[1]DCAD = mEq K + mEq Na – mEq Cl; DCAD = 271 + 100 – 67; DCAD = 304 mEq per kg DM = 30.4 mEq per 100 g DM.

Table 2. Principle cations and anions (mEq/L) in body fluids.

Ion$^{(charge)}$	Blood	Intracellular	Rumen Fluid
Sodium (Na^{+})	145	12	84
Potassium (K^{+})	4	139	27
Chloride (Cl^{-})	116	4	8
Bicarbonate($HCO3^{-}$)	29	12	6
Amino acids and proteins^{-}	9	138	(VFA's) 105
Magnesium (Mg^{++})	1.5	0.8	4.2[1]
(Ca^{++})	1.8	<0.0002	3.5[1]
Milliosmoles/L	290	290	315[1]

[1]From Bennink et al., 1978.

Table 3. Comparison of strong ion requirements for lactating dairy cows and sows using the 2001 Dairy NRC and 2012 Swine NRC.

Mineral	Lactating Sow Requirement, % As Fed	Lactating Cow Requirement, % of DM
Na	0.20	0.23
K	0.20	1.06
Cl	0.16	0.24
DCAD[1], mEq/kg	93	303
Expected urine pH	6.5	7.5 to 8.0

[1]DCAD = Dietary cation anion difference.

Table 4. Examples of various DCAD equations used in dairy cattle feeding programs when minerals are fed at NRC (2001) minimum requirements.[1]

Equation	Elements Included:	DCAD, mEq/kg DM
Ender (1971)	Na + K - Cl - S	179
Mongin (1981)	Na + K - Cl	304
2001 Dairy NRC	(Na + K + 0.15 Ca + 0.15 Mg) − (Cl + 0.6 S + 0.5 P)	284
Goff et al. (2004)	Na + K - Cl - 0.6 S	228

[1]DCAD = Dietary cation anion difference.

Table 5. Comparisons of maximum responses to dietary cation anion difference (**DCAD**); (Ender 1971 equation) from the meta analyses conducted by Iwaniuk and Erdman (2015) and Hu and Murphy (2004).

Item	Maximum Response, kg/day	66% of Maximum	80% of Maximum	Hu and Murphy (2004)
		------------- DCAD mEq/kg DM Required ----------------		
DMI	1.92	290	425	275
Milk	1.11	150	225	215
FCM	4.82	450	675	No Maximum

Table 6. Comparison of cation (K, Na) anion (Cl, S), and dietary cation anion difference (**DCAD**) concentrations (mEq/kg DM), along with crude protein (**CP**), and NDF of feed ingredients. DCAD was calculated using the Ender (1971) equation that includes dietary S.

Feed Ingredient	K	Na	Cl	S	DCAD	CP, %	NDF, %
Shelled corn	107	9	-23	-63	31	9.4	9.5
Dried distillers grains	281	130	-28	-275	109	29.7	38.8
Soybean meal	775	13	-155	-244	389	53.8	9.8
Canola meal	361	30	-11	-456	-76	37.8	29.8
Corn silage	307	4	-82	-88	142	8.8	45
Alfalfa haylage	775	13	-155	-188	445	22.8	36.3
Grass silage	795	22	-181	-131	505	18	49.9
Barley silage	621	57	-203	-106	369	12	56.3

Table 7. Composition of sodium and potassium mineral supplements.

Mineral Supplement	K, %	Na, %	Cl, %	DCAD,[1] Eq/lb	DCAD, Eq/kg	DCAD
Salt (NaCl)	0.0	39.3	60.7	0	0	Neutral
Potassium Chloride (KCl)	52.4	0.0	47.6	0	0	Neutral
Potassium Carbonate (K_2CO_3)	52.4	0.0	0.0	609	1340	Positive
Sodium Bicarbonate ($NaHCO_3$)	0.0	27.7	0.0	547	1203	Positive
Sodium Sesquicarbonate ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$)	0.0	30.5	0.0	602	1325	Positive

[1]DCAD - Dietary cation anion difference.

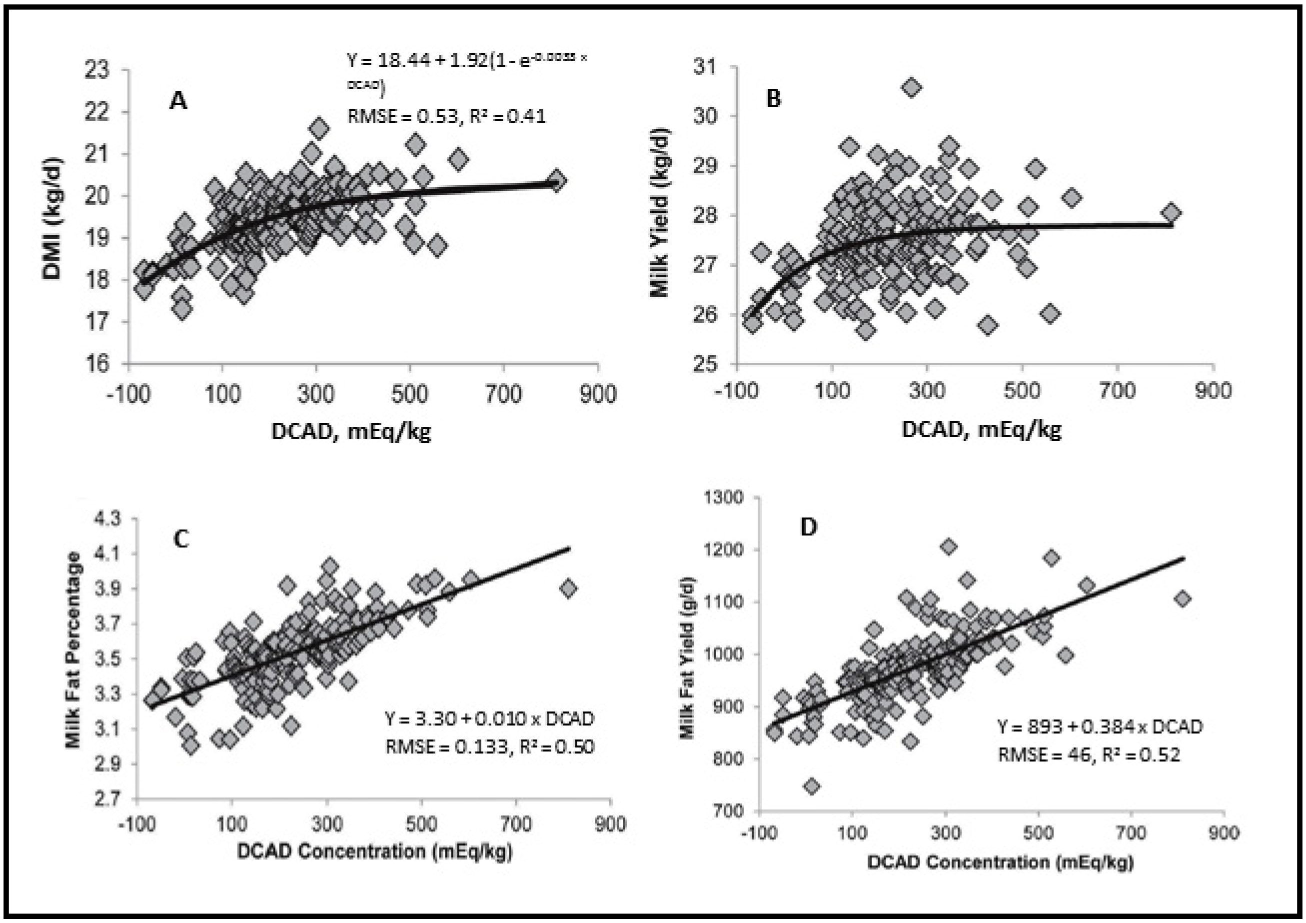

Figure 1. Dry matter intake (A), milk production (B), milk fat percent (C) and fat yield responses (D) to increasing dietary cation anion difference (**DCAD**: Iwaniuk and Erdman, 2015; RMSE = root mean square error).

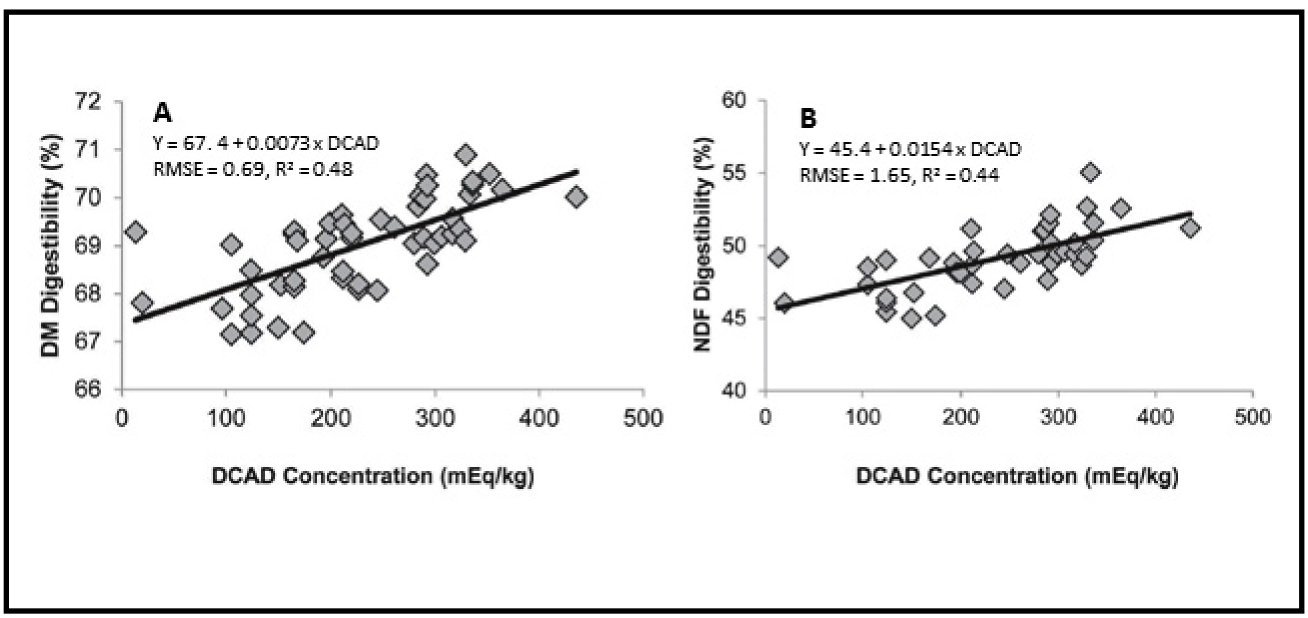

Figure 2. Effect of dietary cation anion difference (**DCAD**) on dry matter (**DM**) (A) and NDF digestibilities (B). (Figures from Iwaniuk and Erdman, 2015; RMSE = root mean square error).