INTERRELATIONSHIPS OF DIETARY SODIUM, POTASSIUM AND CHLORINE AND CATION-ANION DIFFERENCE IN LACTATION RATIONS

by

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INTRODUCTION

Nutrition would be a simple science if the facts never changed. However, the more we learn about any one topic the more we have to adjust to the dynamic nature of this discipline. Macromineral nutrition is one area where new information is continuously available. One reason is that many of the macrominerals interact with each other. Due to the importance of these mineral interrelationships (Miller, 1981), dietary concentrations for optimal performance probably change depending on the presence of interrelating factors. Because sodium (Na), potassium (K), and chlorine (Cl) function together to maintain body fluid balance, osmotic regulation, and acid-base equilibrium (Kleinman and Lorenz, 1989) it would seem likely that they interrelate. Objectives of this paper are to review interrelationships of Na, K and Cl and demonstrate how they affect performance of lactating dairy cattle.

BASIC PRINCIPLES

In last year's Florida Ruminant Nutrition Symposium (Beede et al., 1990) we reviewed basic principles of macromineral electrolytes and their role in dietary electrolyte balance in late pregnant dry cow rations. In review it was noted that Na, K and Cl ions react according to their valences (or ionic charges). Because of this, their unit of expression is often converted to milliequivalents (meq) a measure of ionic charge. This standardizes the measurement so that comparisons can be made between and among ions that have different atomic weights but equal charge. The best example of this is in the reaction of 1 meq of hydrogen ions (1 gram atomic weight) with 1 meq of Cl ions (35.5 g atomic weight) in the reaction of H^+ plus Cl^- to yield HCl.

It also was noted that a major effect of Na, K and Cl is on acid-base status. Dietary cations, such as Na and K, are alkalogenic (base-forming) because they increase blood pH. Dietary anions such as Cl are acidogenic (acid-forming) because they decrease blood pH. Therefore, a diet with excess Na and K (relative to Cl) is alkalogenic and a diet with excess Cl (relative to Na and K) is acidogenic. Researchers have developed several expressions to quantify how acid or alkaline a diet is. The most common is the dietary

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electrolyte balance, or more specifically, the cation-anion difference (CAD) expression [meq (Na + K - Cl)/100g diet DM]. To convert mineral concentrations from percent to meq, divide the diet DM percent of each mineral by one-one hundredth of the atomic weight for that mineral (i.e., .023 for Na, .039 for K and .035 for Cl). For example a diet with .18% Na, .9% K and .25% Cl would have .18/.023 = 7.8 meq Na; .9/.039 K = 23.1 meq K; and .25/.035 = 7.1 meq Cl. The CAD [meq (Na + K - Cl)/100g diet DM] therefore would equal +23.8 meq/100g diet DM (7.8 + 23.1 - 7.1 = +23.8). If an ion with valence greater than one is considered in the expression divide the atomic weight by its valence before completing the calculation (Na, K and Cl have a valence of one so this step is ignored in the above expression).

To account for potential interrelationships among dietary Na, K and Cl, researchers have attempted to relate acid-base status and production responses to CAD. The initial evaluation of this concept was from studies in poultry reviewed by Mongin (1980) who concluded that in order to maintain acid-base homeostasis in the body, input and output of acid needs to be regulated. Net acid intake can be extrapolated from the difference between mineral cations and anions because they are "fixed" ions (i.e., they are not broken down during digestive or metabolic processes). The reason that Na, K and Cl are the only mineral ions included in the CAD expression is because they have the greatest effect on acid-base status (Mongin, 1980).

RESEARCH ON DIETARY CATION-ANION DIFFERENCE

It is obvious that CAD involves a three-way interrelationship among dietary Na, K and Cl. This interrelationship has been evaluated extensively in dry cows (see Beede et al., 1990 for review), but less thoroughly for lactating cattle. Several years ago Wheeler (1981) reviewed the potential influence of CAD on performance of lactating and growing cattle. From the limited data he surveyed, no clear relationship between CAD and lactation performance was detected. Growing cattle fed experimental diets with +50 meq/100g had greater weight gains compared with those fed control diets with +10. However, when growing cattle were switched to diets with +20 to +50 meq/100g DM, growth rate improved only slightly. Diets ranging from +78 to +118 meq/100g CAD resulted in either no improvement or a reduction in gain. Reviews of later lactation studies indicated that, in the range of +10 to +40 meq/100g, response to CAD was small (Coppock et al., 1982a; Coppock et al., 1982b; Coppock, 1986). Depressed feed intake and blood pH in lactating cows were observed when CAD values were negative (Escobosa et al., 1984).

Results from the few experiments designed specifically to evaluate effects of CAD on lactational performance agree with these earlier conclusions. Data from three experiments are summarized and shown in figures 1, 2 and 3 for dry mattter intake (DMI), milk yield (MY) and blood bicarbonate, respectively. These figures include results from Florida, Kentucky and Georgia experiments. Regression lines were fit for each experiment and for all experiments combined.

Tucker et al. (1988) in Kentucky compared diets formulated to provide -10, 0, +10 and +20 meq/100g CAD. A diet with +20 improved DMI 11% (figure 1) and MY 9% (figure 2) compared with a diet with -10 meq/100g DM. Blood bicarbonate (the primary blood buffer) increased linearly with increasing CAD (figure 3) which indicated an improvement in acid-base status with high cation diets compared with low cation diets. Results of Tucker et al. (1988) suggested that by simply increasing the cation-anion difference from -10 to +20 meq/100g DM, lactational performance improved. Because lactation diets are typically above +20 meq/100g, the next question was whether or not responses continue to increase above +20 CAD.

West et al. (1990) in Georgia answered part of this question when they evaluated diets with up to +40 meq/100g DM. Their study compared +2.5, +15, +27.5 and +40 CAD for lactating dairy cattle. Increasing CAD improved DMI (figure 1), MY (figure 2) and blood bicarbonate (figure 3) from +2.5 to +27.5 but not from +27.5 to +40 CAD. These findings suggested that between +2.5 and +15 meq/100g performance was depressed. At +27.5, negative effects were overcome but no further improvements occurred above +27.5 meq/100g DM.

Sanchez et al. (1990) in Florida compared 15 treatments ranging from +12 to +62 CAD. As with the other studies, the diet near +10 depressed performance. Above +20 there was little overall effect of CAD on DMI (figure 1). Milk yield improved 8% between +12 and +37.5 (figure 2). Blood bicarbonate increased 8% between +12 and +37.5 (figure 3). These results indicated that milk production and acid-base status improved when CAD was increased from +12 to +37.5 but no additional improvements occurred above +37.5 meq/100g.

From the limited data available, no specific dietary CAD recommendation should be made at this time, but the optimum appeared to be somewhere between +27.5 and +40. This may depend on other factors such as the digestibility and acid producing potential of the diet, concentrations of other fixed ions in the diet, and rate of intake and production capacity of the animal.

We also should mention that with some of the CAD studies there is a confounding effect of dietary carbonate and bicarbonate content and CAD. Because sodium and potassium carbonate and bicarbonate salts are often used to vary the CAD, studies conducted thus far cannot separate CAD effects from potential ruminal and systemic buffering effects of these salts. Milk fat depression was not observed in studies reviewed in this paper (milk fat percent ranged from 3.33 to 3.60%) which implies that effects of Na, K and Cl may have been independent of ruminal buffering. An experimental approach to vary dietary CAD but keep carbonate and bicarbonate salts constant, is to begin with a relatively high CAD diet (i.e., high concentrations of Na and K) and then lower CAD by adding Cl. This can negatively affect performance and acid-base status of lactating dairy cows (Escobosa et al., 1984) and could lead to subclinical Cl toxicity. Perhaps this is what occurred with low CAD treatments in the studies reviewed in this paper (figures 1, 2, and 3).

ANOTHER VIEW OF INTERRELATIONSHIPS

The CAD concept helps us to understand part of the reason certain dietary concentrations of Na, K and Cl are optimal for lactating dairy cattle. However, it is evident that CAD is related only partially to performance of lactating dairy cattle and does not explain the entire effects of dietary Na, K and Cl. Cation-anion difference calculations will not be useful in situations with diet deficiencies or toxicities. For example, cows fed a diet with 5% NaCl will undoubtedly eat and milk less than cows fed .5% NaCl in the diet (NRC, 1989), even though CAD is identical in both diets. Even without toxicities or deficiencies, there are experiments that have found significant differences in MY of cows fed the same CAD (Mallonee, et al., 1982; Schneider et al., 1986). Part of the reason CAD does not completely account for differences in performance may be due to various interrelationships among minerals in the CAD expression.

Because of the similar physiological functions of Na, K and Cl it makes sense that the optimal dietary concentration of each macromineral depends on the concentrations of the others. We used response surface statistical techniques to better understand possible interactions of Na, K and Cl on productive output (Sanchez et al., 1990). Responses were plotted so that we could explore production relationships to dietary concentrations of Na, K and Cl from near minimal recommendations (NRC, 1989) to higher concentrations typically found in lactation diets in the field. Treatments consisted of concentrations that ranged from .31 to .85% Na, .86 to 1.71% K, and .32 to 1.15% Cl; basal diet was 54.5% concentrate, 5.5% cottonseed hulls and 40% corn silage (DM basis).

One of the main interrelationships discovered was the cation by anion interaction (figures 4, 5 and 6). This indicated a need to balance or couple additional dietary cations with anions (or vice versa). In general, responses to increasing dietary cation (Na or K) was most beneficial when coupled with an increase in dietary anion (Cl). If dietary Na or K was increased without an increase in Cl, or vice versa, negative responses resulted (figures 4, 5, 6). Response surface - predicted feed consumption for different dietary concentrations of Na and Cl was highest when both concentrations were raised in unison (figure 4). If dietary Na concentration was low and Cl was high (or vice versa) DMI was much poorer than when both were high (figure 4). Coppock et al. (1982a) proposed that a dietary ratio of Na:Cl was important, analogous to the Ca:P ratio. Hurwitz et al. (1973) reported maximal growth of chicks with a dietary Na:Cl ratio of 1:1, by weight.

In our study, Na by Cl interactive effects did not influence milk production. Yet, a coupling effect of cation and anion on milk production was still present. For milk production, K instead of Na, was the cation that interacted with Cl (figures 5 and 6). To our knowledge, interrelationships between K and Cl on milk production have not been reported previously. Data of Tucker et al. (1988) can be interpreted to provide evidence for a K by Cl interaction on MY. In their study with a diet relatively high in Cl (1.25%), there was a linear increase in MY with increasing dietary K (from .73 to 1.91% K). Lower concentrations of Cl were not tested in combination with that range of dietary K so a K by Cl interaction cannot be confirmed conclusively from their data. An interactive effect of dietary K by Cl on growth of weanling pigs recently was reported by Golz and Crenshaw (1990). In parallel with our lactational performance findings, they found a similar K by Cl interaction on growth performance of pigs. At low concentrations of K an increase in dietary Cl depressed performance, whereas at high concentrations of K the same increase in Cl improved performance. A possible explanation of the K by Cl interaction in our study may be derived from the findings of Belgium researchers (Paquay et al., 1969) who observed a positive correlation between K and Cl in the urine of cows. They suggested that because ruminants are herbivores they consume greater than required K from forage. The bovine kidney is adapted to eliminate excess K, but to maintain electrical neutrality of the urine an anion must accompany excreted K cations. The reason for the close correlation between dietary K and Cl is that Cl is the anion most often accompanying K in the urine.

Most published Na by K interaction effects are related to nutrient absorption probably explaining why only DMI was influenced by Na by K interaction. In our study, increasing dietary Na resulted in a greater increase in DMI when dietary K concentration was low than when dietary K concentration was high (Na by K interaction; figure 7). This indicated a sparing of the two cations for each other. Other research supports this finding. In poultry and rats, additional dietary Na spared a portion of the K requirement (Kumpost and Sullivan, 1966; Burns, et al., 1953; Grunert, et al., 1950). Fontenot et al. (1960) reported that additional dietary Na depressed K absorption in lambs. Increasing dietary K intake in sheep resulted in an increase in fecal Na (Suttle and Field, 1967). Scott (1970) found that high dietary K impaired intestinal absorption of Na and low dietary K increased urinary Na excretion in cattle. Campbell and Roberts (1965) reported that apparent intestinal absorption of Na in heifers was impaired by high dietary concentration of K but lower concentrations of K increased urinary loss of Na. Scott (1967) observed that an increase in the ruminal fluid concentration of one of these ions is accompanied by a reciprocal decrease in the other, resulting in an almost constant concentration of the sum of Na plus K. Jackson et al. (1971) observed an interactive effect of dietary Na and K on microbial populations in the rumen.

In lactating cattle, studies on relationships between Na and K have not to this point revealed a sparing effect of dietary Na and K for each other. Erdman et al. (1980) found no benefit of additional Na (.52 versus .31%) with either low (.42%) or near adequate (.84%) K. O'Conner et al. (1988) also reported no benefit on lactational performance of additional Na (.24 versus .62%) with either 1.14 or 1.59% K. Chlorine was not equalized across diets in those studies which could explain the lack of response. Martens and Blume (1987) observed that Na and Cl absorption in sheep was coupled by a dual exchange mechanism of $Na^+/H^+ + Cl^-/HCO_3^-$ and was related to K concentrations in the rumen. An alteration in the relative amounts of dietary Na and K thus could affect acid-base status which in turn could affect lactational performance.

SUMMARY AND CONCLUSIONS

Data reviewed in this paper suggest that most of the effects of CAD on lactational performance are due to low CAD treatments. Tucker et al. (1988), West et al. (1990), and Sanchez et al. (1990) found that DMI, MY and blood bicarbonate were depressed in lactating cattle fed diets with CAD below +20 meq/100g, but above +20 CAD the relationship was less clear. Interrelationships among Na, K and Cl may be the reason that response above +20 CAD was variable. An investigation into this (Sanchez et al., 1990) found important interrelationships among Na, K and Cl. Increasing dietary cation (Na or K) was most beneficial when accompanied by increasing dietary anion (Cl). This means that optimal concentrations of dietary Na and K depend on the concentration of Cl. If Cl concentration is high then the diet should contain more Na and K (or vice versa). Sparing effects of cations (Na and K) on each other also were observed. A simple cation-anion difference expression of meq (Na + K - Cl)/100g diet DM implies that each ion is independent. As we discovered, these minerals do not act independently. The CAD expression correctly distinguishes cations from anions, but it assigns equal value to Na and K (on a milliequivalent basis). If dietary Na and K contributed equally to animal performance both would interact equally with dietary Cl. They did not. Therefore, with practical diets free of deficiencies and/or toxicities, actual dietary concentrations of Na, K and Cl are more important determinants of lactational performance than a linear CAD equation containing all three. Changes in recommendations for Na, K and Cl in lactation rations will have to wait until additional research is conducted on their interrelationships.

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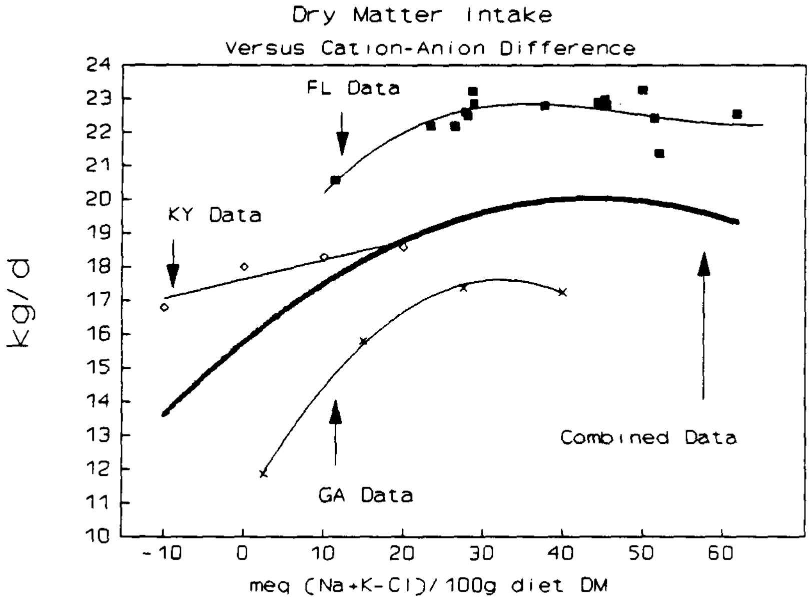

Figure 1. Mean dry matter intake versus dietary cation-anion difference. Means represented by symbols. Regressions represented by lines.

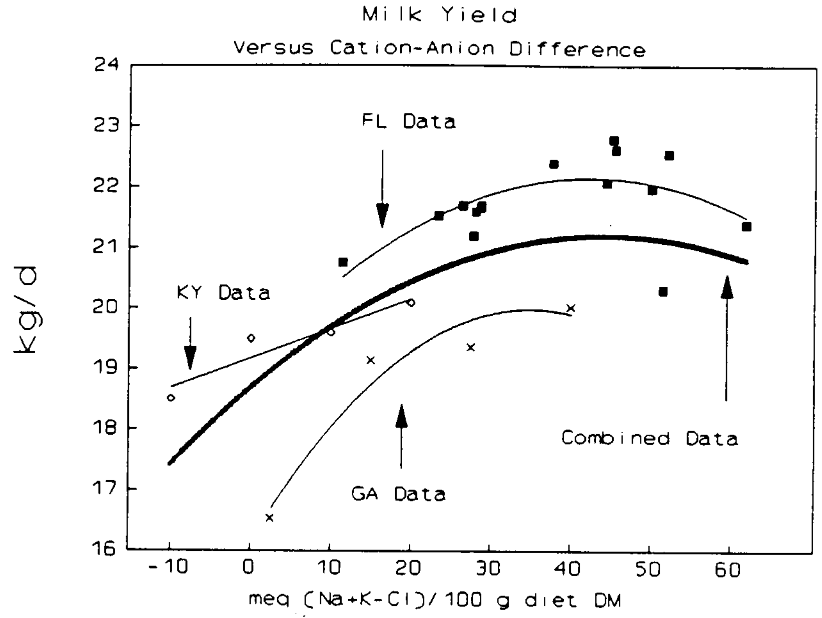

Figure 2. Mean milk yield versus dietary cation-anion difference. Means represented by symbols. Regressions represented by lines.

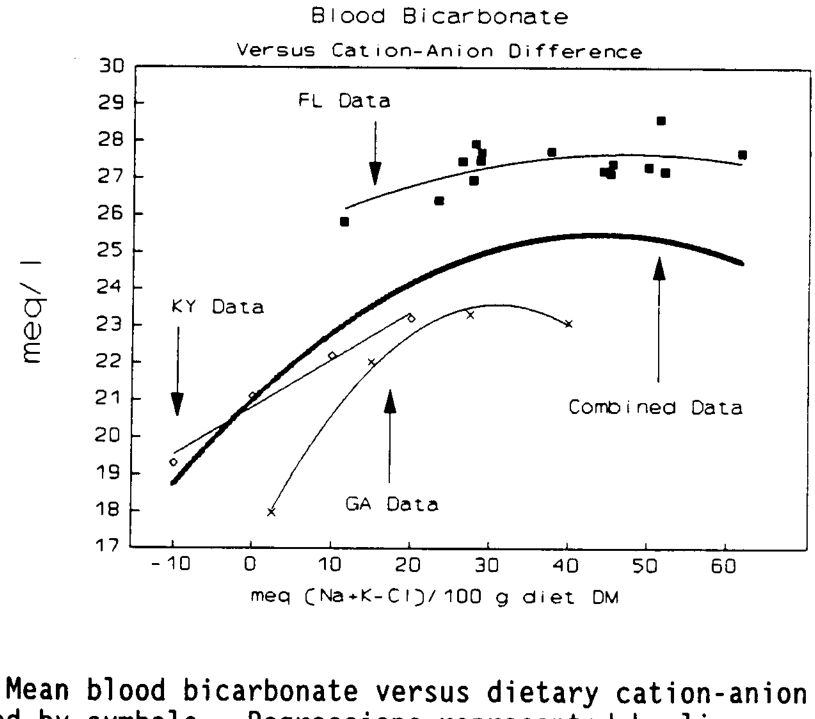

Figure 3. Mean blood bicarbonate versus dietary cation-anion difference. Means represented by symbols. Regressions represented by lines.

Dry Matter intake (kg/d)

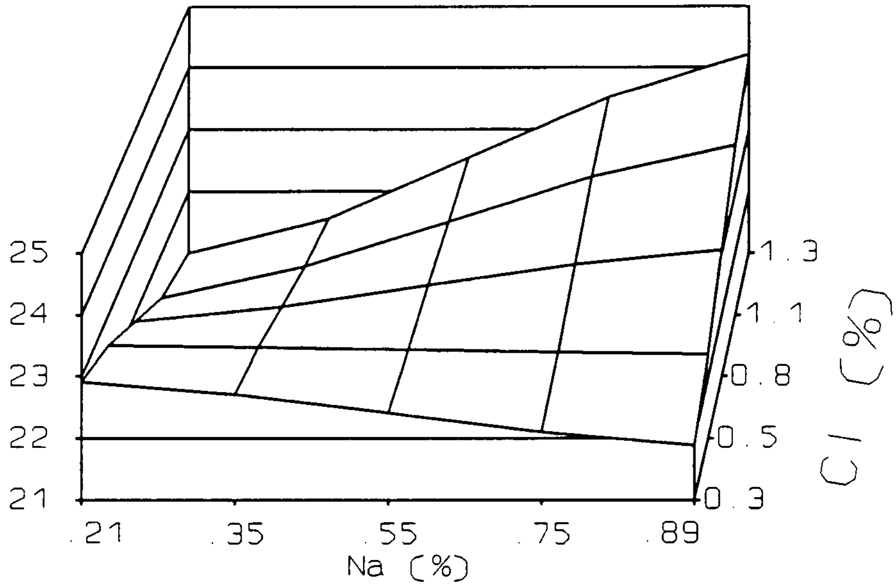

Figure 4. Response surface for dry matter intake (kg/d) plotted against dry matter concentrations of dietary sodium and chlorine.

Milk Yield (kg/d)

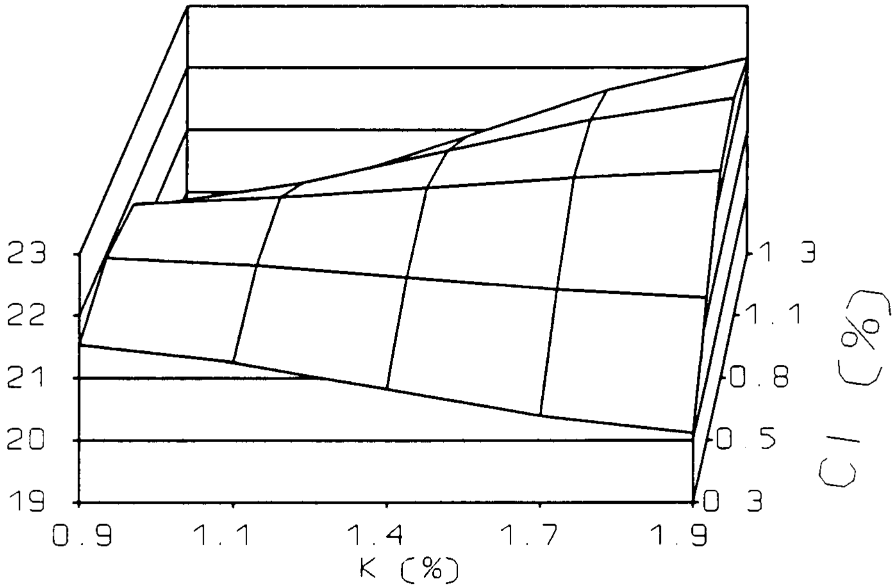

Figure 5. Response surface for milk yield (kg/d) plotted against dry matter concentrations of dietary potassium and chlorine.

3.5% FCM Yield (kg/d)

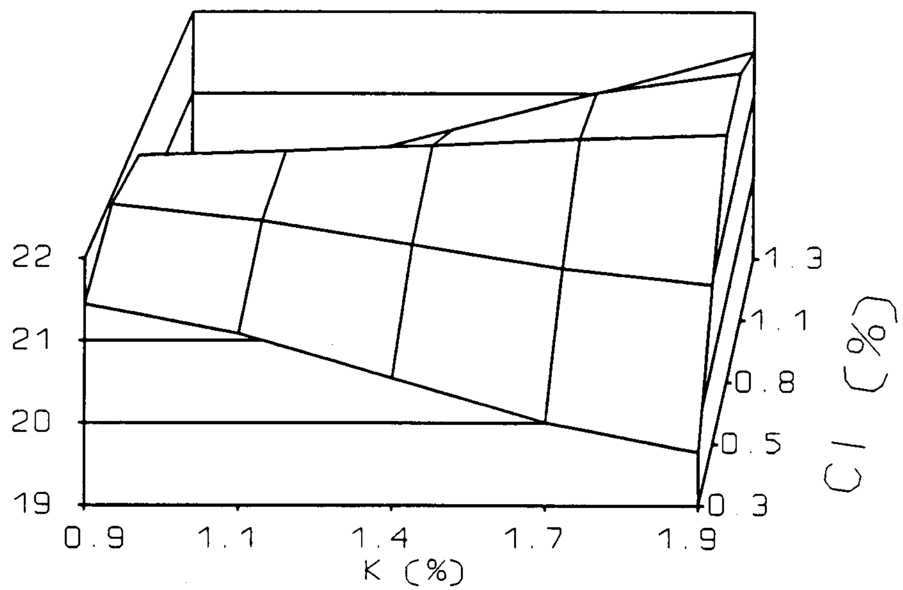

Figure 6. Response surface for 3.5% FCM yield (kg/d) plotted against dry matter concentrations of dietary potassium and chlorine.

Dry Matter Intake (kg/d)

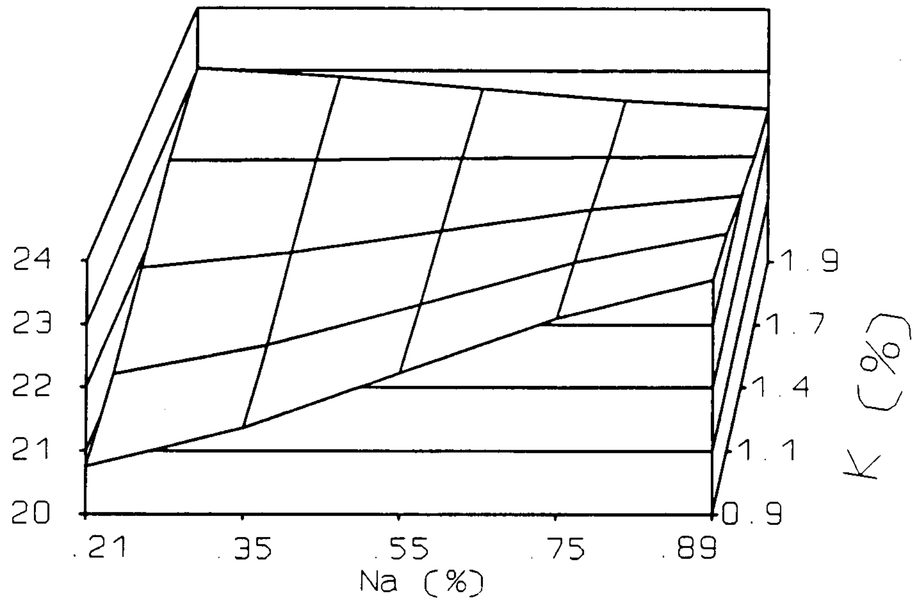

Figure 7. Response surface for dry matter intake (kg/d) plotted against dry matter concentrations of dietary sodium and potassium.