Refining the Net Energy System

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Take Home Messages

- Because the composition of the total diet affects digestibility and metabolism, feedstuffs do not have net energy for lactation (NEL) values, only diets have NEL. This is a serious flaw in the NEL system (and all other currently used energy systems).
- Accurate estimates of NEL balance (intake minus use) are extremely important in dairy nutrition. It allows appropriate management of body condition of cows.
- Digestibility of neutral detergent fiber (NDF) averages about 50% but is highly variable. It is affected by lignin concentration but it also tends to decrease as starch digestibility increases and as NDF concentration of the diet decreases.
- Digestibility of starch averages about 90% and is variable but less so than NDF digestibility. Physical processing, grain species, and maturity of the grain are the major factors affecting digestibility.
- Nutritionists should not hesitate to adjust computer model generated NEL values based on experience, total diet composition, and feed intake of the cows.

Introduction

A feed energy system has two main purposes: ration formulation and economic evaluation of feedstuffs. For ration formulation, energy requirements for maintenance, pregnancy, milk production, and growth are estimated, feedstuffs are given energy values, and then linear programming is used to find the combination of feedstuffs that meet the energy requirement within a set of constraints. The logic behind balancing diets for energy is to provide a diet that has adequate energy for milk production while maintaining desirable body condition. Within a local market, nutritionists have dozens of different feedstuffs available to be included in diets. Usually one feed is chosen over another because it provides a nutrient or nutrients at a lower cost. Because energy is a primary nutrient for cows, the energy concentration of a feed has a major impact on its economic value. If a feed can be assigned an accurate energy concentration and if we know the value of a unit of energy, then economically wise decisions regarding feed choices can be made.

The most widespread energy system used for both these purposes is the net energy for lactation (**NEL**) system. On a theoretical basis the NEL system is far superior to other energy systems such as Total Digestible Nutrients. However, the current NEL system (and any other energy system) has serious flaws that should limit its value, especially in ration formulation. We need to continue to develop and eventually adopt better methods for ration formulation but until such methods are available we need to make the current NEL system as accurate as possible. The purposes of this paper are to: review the basics of the NEL system including its limitations and discuss adjustments in the current system, especially with regards to carbohydrates, that should make it more accurate.

▪ Review of the NEL System

The underlying basis of the NEL system is the first law of thermodynamics and all things, including cows, must obey that law. In terms relevant to animal nutrition, the first law of thermodynamics can be stated as: Energy input must equal energy output plus or minus any change in body energy. If we can accurately estimate the NEL of a diet and NEL requirements, then energy balance can be calculated and we can project changes in body energy reserves (i.e., body condition). The health and long term productivity of a cow depends on proper management of body condition. The NEL system attempts to account for all loses and use of energy by the cow. On average about one-third of the energy consumed is lost via feces, 10% is lost via urine and methane, one-fourth is lost via heat, and only about one-third of the energy consumed is used for something useful, i.e., NEL. In comparison, a gasoline-powered car converts about 15% of the chemical energy in gasoline to mechanical energy.

The NEL system uses the following terms to describe energy flow:

Gross energy (GE) is the total amount of chemical energy in the diet (Mcal/kg of diet dry matter) and is measured by completely burning a sample in a bomb calorimeter. This measurement is easy, precise, and accurate. The concentration of GE depends solely on the chemical composition. Ash, carbohydrate, fat, organic acids, and protein have different energy values per unit of mass and as the concentrations of these fractions change, GE changes. High protein and high fat feeds will have more GE than high carbohydrate feeds and feeds with high ash will have less energy than lower ash feeds.

Digestible energy (DE) is the energy remaining in the diet after fecal energy is subtracted. Because measurement of DE requires measurement of fecal output it is less accurate and less precise than measuring GE and can only be measured by feeding animals. The DE is a function of GE and all factors (animal and feed) that affect digestibility. The digestibility of the carbohydrate fraction of diets is extremely variable and has a substantial impact on DE. Dry matter intake is the major cow factor that influences energy digestibility; the marginal efficiency of digestion decreases as dry matter intake increases.

Metabolizable energy (ME) is the energy remaining after urinary and gaseous energy arising from fermentation (essentially methane) is subtracted from DE. Collection of urine, bomb calorimetry of urine, and measuring methane is difficult and prone to errors plus measurement of ME includes all the errors associated with measuring DE; therefore ME is less accurate and less precise than DE. Dietary fiber increases methane production and high protein increases synthesis of urea both of which reduce the efficiency of converting DE to ME. High starch diets and ionophores such as monensin reduce methane production and increase the efficiency of converting DE to ME.

NEL is the energy consumed by a cow that actually does something; it is the energy secreted in milk, retained in the body (fat, growth, fetus), or used to perform maintenance functions such as pumping blood. It is calculated as ME minus the heat generated by the inefficiency of transforming energy from one form to another (i.e., the heat increment). Heat increment cannot be measured directly; it is calculated from total heat production measured using a whole animal calorimeter. Because these instruments are extremely expensive and only a few are available in the world, measured NEL data are extremely limited. Type of carbohydrate and concentrations of dietary fat and protein affect the efficiency of converting ME to NEL. As fiber and protein increase, the efficiency of converting ME to NE usually decreases and as fat and starch increase, efficiency increases. Measurement of NEL is the least accurate and precise measure of energy because it includes all errors associated with measuring GE, DE, and ME plus the errors associated with measuring heat increment.

▪ Why We Should Stop Using the NEL System

The NEL system (as all current energy systems) has two serious problems. First, cows do not really have an energy requirement, they have requirements for ATP and the substrates that produce ATP. Energy was something we could measure and therefore energy systems were developed as proxies to the requirements for ATP-generating compounds. The second problem with the NEL system is that feeds do not have NEL, diets have NEL. We assign feeds NEL concentrations so that we can use linear programming to formulate diets. This approach assumes nutrients from different feedstuffs are additive (i.e., the ingredient and nutrient composition of the final diet has no effect on the nutrient value of the individual ingredients). The metabolizable protein (MP) concept is a good example of non-additivity. Urea is an excellent source of MP when added to a diet deficient in rumen degradable protein (RDP), but if urea was added to a diet with excess RDP it would contribute no MP. With the MP system, feeds are not given MP values, only the diet has an MP concentration. Similar to MP, NEL should be considered non-additive and only diets, not ingredients, should have an NEL value. Although difficult and expensive, we can measure NEL concentrations of diets. We cannot measure the NEL of individual feedstuffs within a diet, therefore, it is not possible to determine whether the value used for a feed is correct. However, with most ration balancing software, the only way a nutritionist can change the energy value of the diet is to adjust the NEL values of individual feeds. As our knowledge base, computing capacity, and analytical abilities increase, practical nutritional models will be developed that do not include energy.

▪ Living with What We Have: Application of the NEL System

Although the NEL system has flaws, it still has useful applications for feeding cows as the following example illustrates. A dairy farmer has a group of 100 Holstein cows. Actual body weights (BW) are not known but you estimate the average BW is about 640 kg. The farm has the ability to measure milk weights and the average milk yield for that group is 34 kg and milk from that pen averages 3.7% fat and 3.0% protein. The group averages about 150 days in milk (most cows are pregnant but at least 100 days from calving). Feed delivered to the pen and feed refusal is measured and average dry matter intake is 23 kg. To ensure cows get adequate nutrients, you formulate a diet that will support 40 kg of milk (20% more milk than the current average).

The daily NEL requirements (NRC, 2001) for the average cow are:

Maintenance: $636^{0.75}$ x 0.08 = 10.1 Mcal/day
Lactation: 34 kg x 0.70 Mcal/kg = 24.0 Mcal/day
Total NEL use = 34.1 Mcal/day

The diet was formulated to contain 1.69 Mcal NEL/kg because that will support 40 kg of milk without any change in body condition at an intake of 23 kg.

NEL intake = 23 kg x 1.69 = 38.9 Mcal/d
NEL balance = NEL intake - Maintenance - Milk energy = 38.9 - 10.1 - 24.0 = 4.8 Mcal/d

Cows in this example have an average daily surplus of 4.8 Mcal of NEL which should result in a daily increase in body energy reserves equal to about 0.9 kg of BW. Therefore, if the NEL system is accurate, cows in that group will on average produce 34 kg of milk per day and gain approximately 0.9 kg of BW and if cows continue to consume this diet for 110 days, body condition score will increase by an average of 1 unit. To project body condition changes, you must compare NEL intake to actual NEL expenditures (i.e., use actual mean milk production, not the target milk production).

Now comes the part that requires a good nutritionist rather than just a computer. You must evaluate estimated energy balance by asking: Is the value reasonable? Is it reasonable to expect a group of cows to produce an average of 34 kg of milk **AND** gain an average of almost 0.9 kg of BW per day with a feed intake of 23 kg? The probable consensus among nutritionists is that it is unlikely and therefore not reasonable. The focus of this paper is to discuss adjustments that a nutritionist may have to make to obtain reasonable projected energy balances. Measuring dietary concentrations of NEL is extremely difficult and measuring some NEL requirements is problematic. A good nutritionist should not hesitate to make appropriate adjustments to either feed NEL values or requirements based on apparent energy balance and experience.

▪ Incorrect Maintenance Requirement?

The past several versions of NRC has calculated maintenance requirement (Mcal NEL/day) as: $0.08\ BW^{0.75}$ where BW is in kilograms. That equation was derived from calorimetry data mainly from USDA, but because maintenance requirements cannot be directly measured, the accuracy of that equation is subject to debate. An analysis of calculated energy balances (Ellis et al., 2006) suggested that the average maintenance requirement was $= 0.096*BW^{0.75}$ (equivalent to a 20% increase of the NRC equation) and that maintenance changed from about $0.08*BW^{0.75}$ at calving to $0.098*BW^{0.75}$ at 15 weeks of lactation. The problem with that paper is that all the difference between estimated energy balance and BW change was assumed to be caused by an error in the maintenance requirement. Feed NEL concentrations were not measured and changes in BW in early lactation may not reflect change in body energy. Although an error of the magnitude (i.e., 20%) suggested by Ellis et al. is unlikely, the NRC equation may underestimate maintenance expenditure in many situations. With large pens and 3X milking, the distance some cows walk can be substantial and the NEL used for activity (included in the maintenance requirement) is probably underestimated. A typical Holstein cow needs about 0.3 Mcal of NEL to walk 1000 meters on flat surfaces so even with large pens, long distances between the pen and milking parlor, and 3X milking, a 3 to 5% increase in maintenance requirement will probably cover the NEL used for increased walking.

▪ Incorrect Estimation of Gross Energy of Feeds?

The nutrient fractions that have the greatest impact on GE concentrations are ash, crude protein (CP), carbohydrate, and fat. The ‘carbohydrate’ fraction as defined by NRC contains NDF, starch, simple sugars, organic acids, and several minor compounds. The GE concentration of starch and NDF is similar but simple sugars such as sucrose have about 10% less GE/kg than starch. This means NRC (2001) overestimates GE of feeds that contain substantial amounts of simple sugars (e.g., molasses). The major organic acids found in well-fermented silage have about 15% less GE than starch which means that silage will have less GE than the value estimated by NRC. The NRC value for GE of CP is a reasonable estimate for plant-based feeds that contain mostly true protein. A large proportion of the CP in silage can be nonprotein N which generally has less GE/kg than protein, therefore GE of silage CP is over estimated by the NRC system. The GE value for long chain fatty acids used by NRC is a reasonable average, but GE/kg increases as fatty acid chain length increases and saturated fatty acids have slightly more GE/kg than unsaturated fatty acids. Although several factors affect GE that are not considered in the NRC model, in practice most of these factors will not greatly affect the end results. The GE concentration of silage is probably overestimated by 1 or 2%. For feeds with a high concentration of simple sugars, GE may overestimated by about 6%, but those feeds generally make up a small proportion of the diet and the overall effect on diet NEL would be small.

▪ Variation in Energy Digestibility

Energy digestibility (86 treatment means) of mixed diets fed to lactating cows varied from 60 to 78% (mean = 68%) and DE concentrations varied from 2.8 to 3.4 Mcal/kg (mean = 3.04 Mcal/kg) (Wilkerson et al., 1997). The variation in DE concentration among diets is substantial and important sources of variation must be identified and modeled. For the purpose of estimating energy values, diets can be broken down into five fractions (NDF, starch, protein, fat, and ‘other’). Approximately 60% of the DE in a typical diet comes from NDF and starch, 20% from protein and 20% from fat and other components. The NRC assumes that digestibility of fatty acids is constant except for fat supplements. This probably is not true and better models of fat metabolism are being developed. The most important fine-tuning that should be done regarding the energy contribution of fat is to use accurate fatty acid concentration data. Feeds that contain appreciable concentrations of fatty acids should be assayed for fatty acids. The NRC has averages of measured digestibilities for several common fat supplements and the use of these values gave good estimates of measured diet DE (Weiss and Wyatt, 2004). If the NRC does not contain a digestibility value for a specific fat supplement, users should request the information from the manufacturer. Because fat supplements are only fed to provide NEL, I would not use a product if fatty acid digestibility (measured in lactating dairy cows) data were not available. The digestibility of CP is variable but the equations used by NRC (based on acid detergent insoluble CP) appear to account for most of the variation. This leaves starch and NDF as the major sources of variation in energy digestibility.

Starch Versus Fiber

A typical diet fed to lactating cows contains about 70% carbohydrate (dry matter basis). Of that fraction, approximately 40 to 45% is NDF, 35 to 40% is starch and 15 to 20% is other compounds such as soluble fiber and simple sugars. We have conducted numerous digestion trials with lactating dairy cows fed a variety of diets. The primary NDF sources were corn silage and alfalfa silage but numerous byproducts were also fed. The primary starch sources were dry ground corn and corn silage. On average, starch was about twice as digestible as NDF (Table 1). Although diets in our studies contained about 1.2 times more NDF than starch, on average, starch provided about 1.6 times more digestible energy than NDF. Of the common nutrient fractions, digestibility of NDF is most variable (Figure 1).

Table 1. Average dietary concentrations and digestibilities of carbohydrates by lactating dairy cows. Data are from a large database (N = 237) we have been compiling over several years and represent a wide range of diets.

	Mean	SD
DM intake, kg/day	20.7	3.5
NDF, % of DM	32.1	5.1
NDF digestibility, %	46.0	10.9
Starch, % of DM	26.3	5.8
Starch digestibility, %	93.0	3.5
Digestible energy from NDF[1], Mcal/day	13.1	5.4
Digestible energy from starch[1], Mcal/day	21.2	5.2

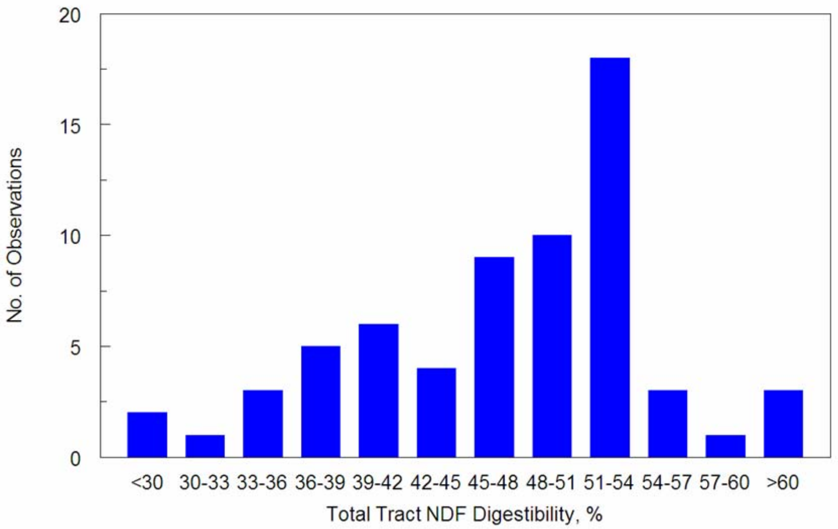

Figure 1. Variation in NDF digestibility by lactating dairy cows (Weiss, unpublished).

The concentration of lignin (as a % of NDF) is correlated with digestibility of NDF from forages and many nutritional models use lignin to account for variation in fiber digestibility. In vitro NDF digestibility (IVNDFD) can also be used to estimate in vivo NDF digestibility but generally IVNDFD overestimates variability as compared with in vivo (i.e., differences observed in vitro are usually much greater than differences observed in vivo). These two methods (lignin and IVNDFD) account for substantial variation in digestibility of forage fiber; however, those methods ignore the effect the diet has on NDF digestibility. On average, NDF digestibility is reduced as total diet NDF concentration decreases, i.e., low fiber diets tend to be inhibitory to fiber digestibility (Figure 2). This is most likely related to ruminal acidosis issues. Nutritionists usually will need to reduce estimated diet NEL concentrations in low fiber diets.

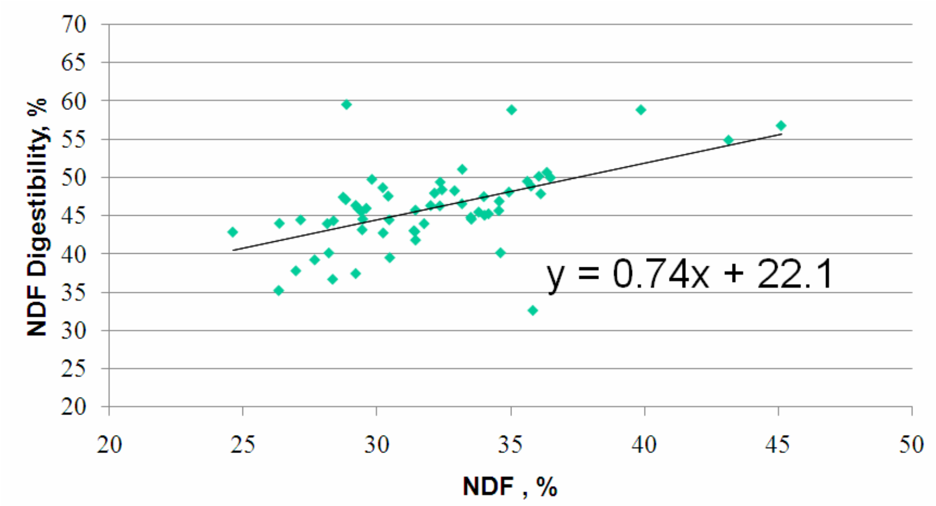

Figure 2. Effect of concentration of dietary NDF on NDF digestibility in lactating dairy cows (Weiss, unpublished).

Lignin and IVNDFD have problems estimating energy value of byproducts. Typically these feeds have low concentrations of lignin and high IVNDFD but when fed to cows, in vivo NDF digestibility is often low. These ingredients have small particle size and often pass through the rumen quickly resulting in lower digestibility. Very often feed efficiency is low (kg milk/kg of intake) but milk yields are high when cows are fed diets high in byproducts. The calculated energy concentrations of byproducts often are too high and must be discounted because they often promote high intakes.

Starch digestibility is less variable (Figure 3) than NDF digestibility but the variation still is important. The major sources of variation in starch digestibility are: plant species (e.g., corn, wheat, sorghum, etc.), physical processing (particle size after grinding, steam-flaking), maturity of the grain (grain in corn silage versus high moisture corn versus dry ground corn) and interactions among those factors (Figure 4). Increasing starch digestibility is often, but not always, associated with increased dietary energy. In diets that contain marginal fiber concentrations, increasing starch digestibility often can reduce fiber digestibility (i.e., an effect of acidosis) which may equal or exceed the beneficial effects of increasing starch digestibility. We have found that in marginal fiber diets a 10 percentage unit increase in starch digestibility was associated with a 10 percentage unit decrease in NDF digestibility (Figure 5). This means that as you add sources of highly digestible starch to diets (e.g., replace dry ground corn with high moisture ground corn) you need to ensure diets have adequate fiber or you will not change energy concentration of the diet as much as you anticipated.

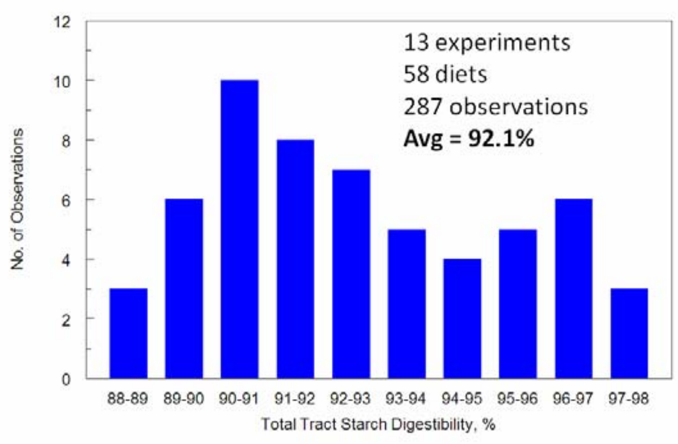

Figure 3. Variation in starch digestibility by lactating dairy cows (Weiss, unpublished).

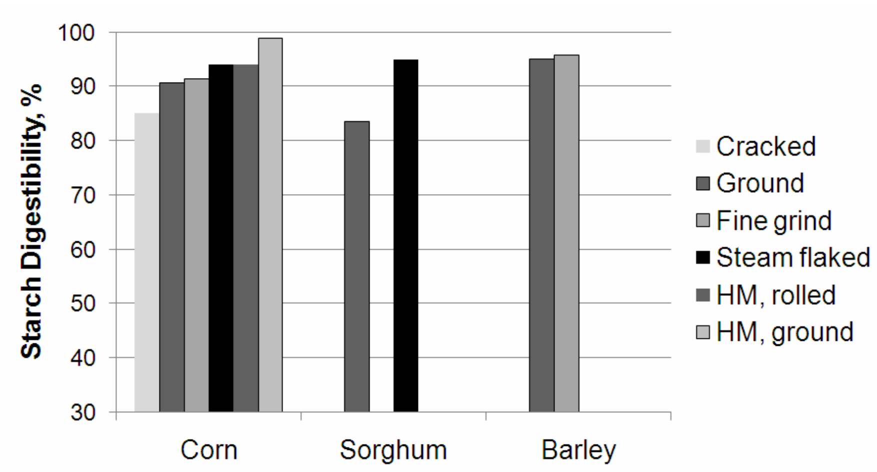

Figure 4. Digestibility of starch from different sources (Firkins et al., 2001). Generally finer grinding, steam-flaking and high moisture (HM) are associated with increased starch digestibility in corn and sorghum. Barley has high inherent starch digestibility and is less responsive to processing.

▪ The Total Diet

Many of the available computer models used to formulate or evaluate diets (e.g., NRC, CPM, etc.) are reasonably accurate at estimating total diet NEL (since feeds do not have NEL values we cannot conclude anything about the accuracy of NEL values assigned to feedstuffs). The models are more accurate for diets that are well-balanced with respect to rumen degradable protein (RDP), total protein, NDF, starch, and minerals. Diets with inadequate RDP can inhibit fiber digestibility whereas diets with excessive protein (including RDP) require additional energy to excrete the extra nitrogen. Diets with inadequate fiber and/or excessive digestible starch do not promote optimal fiber digestibility and usually have less NEL than many models estimate. Although rarely an issue, diets with inadequate minerals (especially sulfur, phosphorus, and magnesium) may result in reduced fiber digestibility. Lastly, nutritionists must be aware of the interdependency of dietary NEL concentrations and DM intake. Changing dietary NEL concentrations often affects DM intake and changing DM intake often changes NEL concentrations. Adding digestible fat to a diet usually increases NEL concentrations but often is associated with reduced feed intake so that the net effect on NEL intake (Mcal/day) is less than anticipated. Conversely, increasing the digestibility of fiber usually increases DM intake which is associated with reduced NDF digestibility resulting in little change in the NEL concentration of the diet (Mcal/kg) but usually increases NEL intake. A good nutrition model (and a good nutritionist) must consider the effects of changing dietary NEL on DM intake and remember that usually the goal is to increase NEL intake.

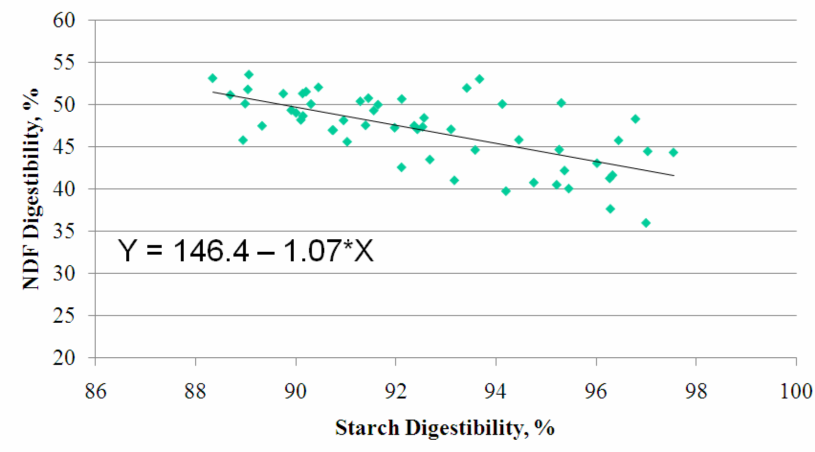

Figure 5. Relationship between total tract starch digestibility and NDF digestibility in lactating dairy cows (Weiss, unpublished).

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