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Models for Estimating Energy and Protein Utilization for Feeds

Muhammad Fadel Wardeh
Utah State University

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MODELS FOR ESTIMATING
ENERGY AND PROTEIN
UTILIZATION FOR FEEDS

by

Muhammad Fadel Wardeh

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Animal Science

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To my wife, Rabeha, and my children, Linda, Rana and Fadel, for their love and forbearance, I dedicate this piece of work.

Muhammad Fadel Wardeh

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ABSTRACT

Models for Estimating Energy and Protein Utilization for Feeds

by

Muhammad Fadel Wardeh, Doctor of Philosophy
Utah State University, 1981

Major Professor: Lorin E. Harris
Department: Animal, Dairy and Veterinary Sciences

Data on the proximate nutrient content of feedstuffs, digestibility and energy utilization available from the International Feedstuffs Institute (Utah State University) were used to develop mathematical models for estimating energy and protein utilization of five classes of feedstuffs for various kinds of animals.

Classes of feedstuffs were subdivided into more related subclasses. Furthermore, data from all feeds were pooled together then subgrouped into more related subgroups in an attempt to gain high precision in prediction of digestible proximate nutrients and TDN from a single chemical entity by the use of simple regression models ($Y = bo + b_1x_1$).

Digestible percentages (Y) of crude protein, ether extract, crude fiber and nitrogen free extract were highly correlated with

their proximate contents (Xs) of most classes, subclasses and subgroups of feedstuffs for various kinds of animals. However, the use of linear multiple regression equation resulted in more precision in estimating each digestible nutrient (Y) from proximate analysis (X_1 = CP%, X_2 = EE%, X_3 = CF% and X_4 = NFE%) of the different classes of feedstuffs for various kinds of animals.

Prediction of digestible proximate nutrients made it possible to calculate TDN by the conventional equation:

$$\text{TDN} = \text{DCP\%} + \text{DCF\%} + \text{DNFE\%} + 2.25 \times \text{DEE\%}.$$

And to calculate digestible energy (DE) from the following equation:

$$\text{DE(Mcal/kg)} = \frac{5.72\ (\text{DCP\%}) + 9.5\ (\text{DEE\%}) + 4.79\ (\text{DCF\%}) + 4.03\ (\text{NFE\%})}{100}$$

TDN, DE and ME (Ys) were highly correlated with the digestible proximate nutrients (X_1 = DCP%, X_2 = DEE%, X_3 = DCF% and X_4 = DNFE%) and with proximate analysis (upon the use of multiple regression models).

However, TDN, DE and ME (Ys) were not predictable with high precision from any one single chemical entity (Xs) in most cases of the different classes of feedstuffs for various kinds of animals.

DE (Y) was highly correlated with TDN values (X), and ME (Y) was highly correlated with DE and TDN (Xs) values of the different classes of feedstuffs for various kinds of animals.

The inclusion of physical descriptions (qualitative factors) of feedstuffs along with chemical analysis (quantitative factors) gave promising results predicting TDN content of feedstuffs.

ME_n and NE_p for poultry were highly correlated with proximate analysis of the different classes of feedstuffs. NE_p was also estimated with high precision from ME_n. However, both ME_n and NE_p were not highly associated with single chemical entities.

The dissertation contains an extensive literature review on systems of evaluating nutritive value, and factors affecting digestibility of feedstuffs.

This dissertation also contains numerous equations which predict each digestible nutrient from its proximate content and from proximate analysis; TDN, DE and ME from each proximate nutrient, digestible proximate nutrients and proximate analysis; DE and ME from TDN; and ME from DE contents of different classes of feedstuffs for various kinds of animals. Moreover, there are complex equations to predict TDN from proximate analysis and their interactions and from proximate analysis plus physical descriptions of feedstuffs for various kinds of animals.

(504 pages)

INTRODUCTION

Animal nutrition is a science depending on information of nutrients that animals require for both the needs of their body systems (maintainance) and production (gain, milk, egg, wool, work, etc.), and on information of the nutritive value of feedstuffs. Nutrient requirements by the different kinds of animals can be estimated by metabolism trials. While the nutritive value of feedstuffs can be measured by digestibility trials.

Two factors besides management govern animal production. First is the animal itself, and second is the available feedstuffs.

The increase of feed costs, narrowing profit margins in livestock enterprises, the energy shortage, and growing concerns for increasing food production have refocused attention on the need of more effective evaluation for forage and food crops throughout the world. In many parts of the world, such as in the Middle East, nutritional information on feeds is scarce and the content of many nutrients in common feedstuffs is almost completely unknown. Protein and energy are the most prominent nutrients of the animal diet and some proximate analysis have been completed on feedstuffs.

To determine the utilization of the nutrients in feeds, it is necessary to have biological data. Considerable time, effort and capital must be expended in biological trials to determine the utilization of nutrients of feeds by animals. It is also practically impossible to obtain experimental biological data on all feeds for all kinds of economical animals because of the time factor and the expenses involved.

Schneider et al. (1952) developed regression equations to predict the digestibility of feedstuffs from their proximate analyses. There was more variation involved when predicting digestibility between feeds than within feeds. Variation in the proximate analysis accounted for more than thirty percent of the between-feed variance in digestibility (Schneider et al., 1950).

Harris et al. (1972) used the databank of the International Feedstuffs Institute (IFI) to develop mathematical models to predict the total digestible nutrients (TDN) from the proximate composition of the different classes of feeds for various kinds of animals. Cook and Child (1977) and Cook et al. (1977) also developed linear equations to predict nutrient digestibility from the nutrient content of plants and TDN and digestible energy (DE) values from proximate analysis of range plants for sheep and cattle.

A new method which approximately partitions dry matter of forages into cell wall and cell content by the use of a neutral detergent digestion was introduced by Van Soest (1963a). Fonnesbeck and Harris (1970a) modified this approach (prepeps in digestion and a detergent solution at pH 3.5) in order that high energy feeds and protein supplements could also be analyzed by the detergent technique.

Digestion trials and regression analysis indicate that the detergent technique is more accurate than crude fiber procedure in determining total feed fiber (Christiansen, 1979). However, that does not mean that we should throw out all of the accumulated data based on the old system of proximate analysis. Instead, better means for conversion from one system to another is needed.

There are many systems that describe the energy values of feedstuffs. The TDN system has traditionally been the most widely used system. There is presently a trend to shift from TDN to other energy systems such as to digestible energy (Swift, 1957) and to net energy for the various body functions (Moe and Flatt, 1969; Van Soest, 1971, 1973).

Regression equations were developed to predict digestible energy from various chemical components of diets for various species of animals (Fonnesbeck et al., 1975), for sheep (Christiansen, 1979) and for cattle and sheep on various seasonal range types (Cook and Child, 1977). ME was also predicted from the chemical composition of feedstuffs (Bickel and Landis, 1978; Van Es, 1978; Vermorel, 1978).

However, it is possible to estimate ME from DE by the use of regression equations that were developed by Harris and Asplund (1968).

The concept of "net nitrogen" can be of great importance in studying the nitrogen contribution to a certain ration (Harris and Asplund, 1968). Regression equations to determine digestible protein from crude protein were developed (Knight and Harris, 1966) for each class of feedstuff and kind of animal.

In view of the above, it is proposed to develop mathematical models to predict the utilization of energy and protein from the chemical analysis of feeds available from databank of IFI.

The objective of this study was: to develop models to predict the utilization of energy and protein of feedstuffs from information available in the "International Feedstuffs Institute Databank" at Utah State University.

LITERATURE REVIEW

Chemical Analysis to Determine the Nutritive Value of Feedstuffs

Chemical procedures are available to determine the concentration of most of the required nutrients in feedstuffs. However, there are some nutrient components that are very difficult to isolate chemically. These nutrients are often determined as combinations of nutrients that have some common property permitting a chemical analysis of the group. The nutritional significance of such nutrient groups depends on factors that are not indicated by the proportion of the feed comprising the group (Crampton and Harris, 1969).

The earliest animal nutritionists began to wonder what nutritive matter is and how the nutritive value of feed can be determined. Bergin (1781, cited by Tyler, 1975) tried to determine nutritive value by comparing the ability of a few common feeds to promote growth of swine and milk production in cattle.

The first attempt to chemically analyze feeds consisted of rubbing, sieving, and washing of the ground plant material with water in a sieve until no starch could be recovered in the water passing through the sieve. The material retained on the sieve was called fiber, and the material extracted was considered the nutritive matter (Einhof, 1905a, 1905b, cited in Fonnesbeck, 1976).

Davy (1813) described the isolation of fiber or wood as a repeated extraction of the plant material with boiling water and alcohol.

The term lignin was used for the substance remaining after extracting wood with dilute acid and alkali (Brande, 1836).

Johnston (1844) described the white fibrous mass remaining after boiling plant tissue in successive portions of water and alcohol as the "woody fiber", while Wolff (reproduced by Hamm, 1853) did not agree with the assumption that the woody fiber (cellulose, hemicellulose, lignin, and much of the protein in our present term) was non-nutritive matter (Tyler, 1975).

The crude fiber analysis and Weende system of proximate analysis were developed by Henneburg and Stohmann (1860, 1864). These analyses were improved and standardized by agricultural and feed control chemists to make the procedure more precise and compatible to routine analysis, but with little regards for the nutritive qualities of the proximate components (Fonnesbeck, 1976). The TDN system of feed was based on this analysis (Atwater, 1895; Henry, 1898).

The Proximate Analysis System. The proximate analysis was probably the most generally used chemical scheme for describing feedstuffs in spite of the fact that the information it gave might often be of uncertain nutritional significance or may even be misleading (Crampton and Harris, 1969).

Chemical analysis of feedstuffs serves two basic purposes. In conjunction with feeding traits, it helps researchers to elaborate and assess nutritional phenomena. It also provides a practical means of evaluating feedstuffs in the laboratory without the time and expense associated with feeding experiments (Van Soest, 1969). This scheme of analysis was devised by workers at the Weende Experiment Station in

Germany (Crampton and Harris, 1969). The proximate analysis partitions a feedstuffs into six fractions, namely: water, ether extract, crude fiber, nitrogen free extract, crude protein, and ash. The Association of Official Agricultural Chemists adopted the Proximate Analysis as an approved scheme for partitioning feed dry matter in 1891 (AOAC, 1891). Henry (1898) applied the proximate technique extensively soon after adoption.

Even though the proximate analysis system has been accepted throughout the world, there are certain limitations that were subject to criticism, namely, the determination of crude fiber, nitrogen free extract and ether extract.

Because crude fiber analysis depends on the collection of a residue which is not soluble in the reagents but merely less soluble than other constituents, variation in conditions under which the analysis is conducted are likely to lead to variation in the data resulting from the analysis (Schneider and Flatt, 1975). While this will apply especially to methods of crude fiber analysis, it is also likely to be true for cellulose and lignin determinations, for which standard methods have not yet been fully agreed upon.

Other factors can cause variation in crude fiber analysis by standard technique; for example, a difference in boiling temperature due to difference in altitudes of laboratories (Todd, 1951; Hallsworth, 1950).

Extreme fineness of grinding of samples results in lower CF values (Gallup and Hobbs, 1944). Fine grinding may occur in both feeds and feces in digestibility trails, but the accuracy should not depend on such "balancing of errors" (Schneider and Flatt, 1975).

Thus, the evidence suggests that many times analytical results from different laboratories, which may have been obtained by so-called standard method, may be be comparable with each other (Raymond, 1951).

The error in CF determination by imperical means leads to an error in nitrogen free extract since the latter is calculated as:

$$100 - (CF\% + CP\% + EE\% + Ash\%)$$

Theoretically, CF is considered to contain the less digestible portion of the plant, namely, cellulose, hemicellulose, and lignin. While NFE is thought to contain the readily available carbohydrate fraction. However, animal experiments have given contradictory digestion data, where CF is more digestible than NFE. Digestion coefficients calculated by Woodman and Evans (1930) for grass herbage fed to sheep, showed CF having greater digestibility than NFE and CP. Crampton and Maynard (1938) published a table with four feed types with percentage of cases where the digestibilities of CF were equal to or greater than those of NFE. Morrision (1956) published feed tables with contradictions of CF and NFE. Twenty to thirty three percent of the feeds listed show the digestibility of NFE to be less than CF.

Evaluating the effects of the acid and alkaline reagents used to determine crude fiber may explain the problem of the CF-NFE contradiction. Using brain, maize, and bean straw, Norman (1935) found that CF to be almost exclusively of cellulose and lignin. Cellulose recovery was 60-80% while that of lignin was highly variable, 4-67%. From comparisons of residue composition at different analytical stages, it was shown that lignin losses were brought about by sodium hydroxide treatment. Hemicellulose was also lost due to the sulfuric acid hydrolysis. Bondi and Myer (1943) supported their findings and observed that the large percentages of pentosans (hemicellulose) and lignin were extracted into the NFE portion of both feed and feces, while most of the hexoses (cellulose) remained in the crude fiber fraction.

Norman (1935) criticized the value of CF and NFE to evaluate feeds as NFE may be only more digestible than CF in some feeds and CF does not contain all of the non-nutritive matter.

Thus, CF, in spite of the name, did not include all of the most fibrous and coarse substances in the feed. In a general way, the CF% indicated the coarseness of a forage or a feedstuff (Schneider and Flatt, 1975).

Another critique of the proximate analysis was in the inaccuracies in the determination of EE. Since ethel ether did not completely extract the lipids, EE contained substances other than pure fats (Fonnesbeck, 1976). It contained all the non-nutritive lipids in the feed that were soluble in ether such as waxes, resins, chlorophyll, various pigments, the various steriods, carotene, phospholipids, etc., as well as certain essential oils that gave taste and odor to feeds and the true nutritive lipids (Jordan and Hall, 1900; Fraps and Rather, 1912; Cook et al. 1952; Crampton and Harris, 1969; Roberts et al. 1963). In green feeds, EE might contain very little true fat and it was mainly chlorophyll (Schneider and Flatt, 1975).

Many lipids were bonded to proteins with water molecules involved in the union. Lipids were released from lipo-protein molecule only if a dehydrating agent such as acetone, methanol or ethanol breaks the linkage (Hannahan, 1960). A 2:1 mixture of chloroform and methanol had been used to efficiently extract all lipids at room temperatures (Folch et al. 1951; Bligh and Dyer, 1959). Fonnesbeck and Harris (1974) modified the chloroform methanol method extraction procedure and made it easily adaptable as a routine laboratory analysis for total solvent extract to replace ether extract.

The crude protein analysis by the Kejeldahl method did not distinguish one form of nitrogen from another, thus, one cannot tell if a feed mixture has urea or the highest quality of protein such as casein. In addition, nintreate N was not converted into ammonium salts by this method so nitrogen in this form was not included (Church and Pond, 1976). From a nutritional point of view, data on protein analyses were applicable to ruminant species which could efficiently utilize almost all forms of nitrogen, but the information might be of little value for nonruminant species (such as man, swine, or poultry). Non ruminant species had specific requirements for various amino acids and did not efficiently utilize non-protein-nitrogen compounds such as amides, ammonium salts, or urea (Church and Pond, 1976). In addition, protein % was calculated by multiplying nitrogen by 6.25 assuming that all proteins were the same; and this was not the case.

Nitrogen free extract (NFE) was calculated by difference. 100 - (water% + ash% + crude protein% + crude fiber% + ether extract%). It was called NFE because it contains no nitrogen even though there was no extract involved in determining it. NFE was primarily made up of readily available carbohydrates such as sugars and starches, but it also contained most of the hemicellulose and lignin, particularly in feedstuffs as forages (Church and Pond, 1976). But NFE was not entirely nutritive matter (Fonnesbeck, 1976) nor was it a good evaluation for feed since it might be slightly more digestible than crude fiber in some feeds (Norman, 1935). Much of the lignin (nondigestible) and most of the hemicellulose (partially digestible) were found in the NFE portion (Van Soest, 1966b).

A more appropriate analysis would be one specifically for readily available carbohydrates--one in which starches were hydrolyzed to sugars and then an analysis is done for all sugars present. Nutritionally, the NFE fraction of grains was well utilized by nearly all species, but NFE from forages and other roughages are less well utilized (Church and Pond, 1976).

Ash determination was another subject of criticism for the proximate analysis. Ash was the inorganic residue from the ignition of organic matter. Ash content and composition depended on the nature of feed or food ignited and on the method of ashing. Ash was determined by weighing the dry mineral residue of organic materials which were ignited at a low red heat which is about 600° C (AOAC, 1965). About two hours are needed to burn off all organic matter.

Some of the possible inaccuracies of the ignition method of determining ash were that the ash might contain carbonates and sulfates which were formed by oxidation to organic compounds. The carbon and oxygen in them came from organic substances and from the air (Schneider and Flatt, 1975). Materials with high phosphorous to base ratio fuse to a dark melt in which carbon particles were trapped and did not burn (Pomerang and Meloan, 1971).

It should be noted that some mineral elements such as chlorine, iodine, and selenium, were volatile and were lost upon ashing (Church and Pond, 1976). Feeds with a high alkaline balance showed progressive decomposition of the carbonates and volatilization of chlorides (Pomerang and Meloan, 1971).

Thiers (1957) summarized reported losses during dry ashing. Iron volatilized as ferric chloride at 450° C, and when materials with a high phosphorous-to-iron ratio were ashed, an unidentified compound was formed which resisted solution or hydrolysis giving low results.

Phosphorous volatilized as one of the oxyacids, especially when sulfate was present, except in the presence of excess magnesium, volatilized as the chloride above 450° C (Thiers, 1957). In cases of silicates, the silica might be volatilized. However, ashing samples rich in silicon and aluminum might form as insoluble residue.

Some lead loss might occur in regular dry ashing above 550° C. However, dry ashing with H_2SO_4 as an ashing aid permited increasing temperature to 650°C with little lead loss (Gorsuch, 1959).

Another main objection against dry ashing was the interactions between components themselves or the receptacle material. The use of either silica or porcelain crucibles led to the absorption of certain trace elements by the vessels. If the temperature of ashing was not excessively high, the absorption loss might be greater than the volatilization loss (Pomerang and Meloan, 1971). Excessive heating might make certain metallic compounds such as those of tin, insoluble, and might cause salt (NaI) to be lost.

High hygroscopicity, lightness, and fluffiness of ash might sometimes present problems in determining precisely the total ash content or in handling the mineral residue for further analysis (Pomerang and Meloan, 1971).

Even though elements in ash present only a very small percentage of the total, little error was involved, researchers progressed in preventing such error to occur. Wet ashing was another way to prevent certain losses (Harris, 1970). Addition of a few drops of pure olive oil after drying and before ashing a carbohydrate rich sample would help prevent swelling and excessive foaming of the sample (Pomerang and Meloan, 1971). In cases of silicates, the silica might be volatilized by careful treatment with sulfuric and hydrochloric acids, taking special careful precautions to remove fluoride ions before subsequent determinations were made.

Dry ashing was the most commonly used procedure to determine water soluble, water insoluble and acid insoluble ash. It was also applicable to determine most of the common metals. It took a long time, but could be shortened by accelerated methods (Pomerang and Meloan, 1971) or by ashing over night.

The problem of error of crude fiber was further studied by many scientists. Crampton and Maynard (1938) developed methods to determine cellulose and lignin, but their methods were never widely adopted and did not solve all the objections to crude fiber, as the hemicellulose was still included in an undetermined fraction they called "other carbohydrate."

The use of detergents for extracting protein from plant cell wall constituents had proven to be an improvement over the acid and alkaline treatments of the crude fiber analysis.

Foster et al. (1950) obtained 85-95% protein extraction from corn by using detergent solution al alkyl benzine sodium sulfonate plus a reducing agent, bisulfite. Williams and Bevenue (1956) found that

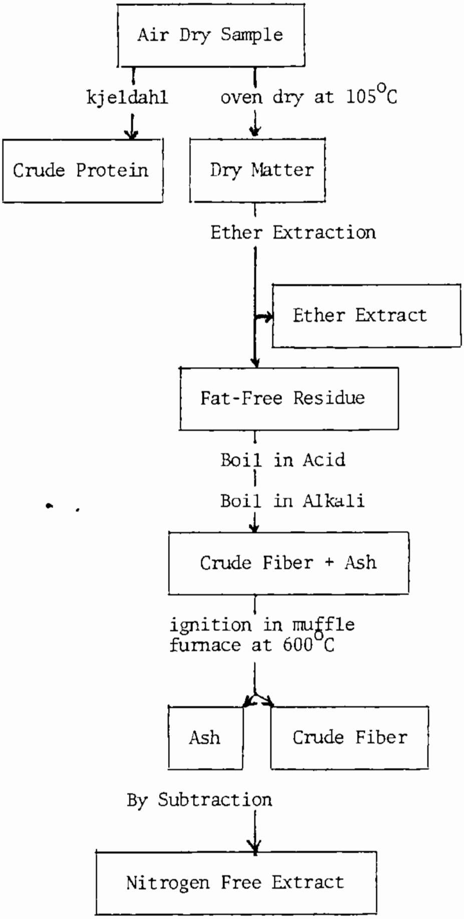

FIGURE 1 A flowchart of proximate analysis.

detergents could be used to seperate carbohydrate fibrous residues of protein without appreciable losses in plant fiber. Effective protein removed by detergents from bean and pea fiber was demonstrated by Bevenue and Williams (1959) who also showed that non-ionic detergents were not effective for protein extraction. However, 92-95% extraction of nitrogen constituents was accomplished by using an alkylaryl sulfonate sodium sulfonate detergent solution. Only a trace of hemicellulose loss was observed.

The Detergent System. Van Soest (1963 a,b) and Van Soest and Wine (1967) conducted experiments using alfalfa and grass forages, found out that a chemical digestion using a 3% buffered solution, neutral or slightly alkaline (pH 7.0-7.4), of sodium lavryl sulfate detergent yielded a low protein fiber residue. To increase protein removal, it was suggested that sodium sulfite be added (Van Soest and Wine, 1967). Sulfite reduced the protein content through its ability to cleave disulphide linkages in proteins. This capacity allowed it to be a very effective means of eliminating keratinaceous tissues from animal derived foods and of such excretions in fecal analysis (Van Soest, 1968). However, sulfite attacked lignin with a significant loss (Van Soest, 1978a).

Another way to reduce nitrogen content of fiber was through the use of detergent - stable proteases. However, the enzyme would not degrade resistant keratinized animal tissue; hence, it was proposed by Robertson and Van Soest (1977) to omit the use of sulfite except as required in specific instances.

The partitioning of plant dry matter into neutral detergent fiber (NDF) and neutral detergent solubles (NDS) had been presented as an accurate separation between cell wall constituents (cellulose, hemicellulose, and lignin) and the readily soluble portion contained within the plant cell (lipids, sugars, organic acids, nonprotein nitrogen, pectins, soluble proteins, etc.) (Van Soest, 1963a; Van Soest and Marcus, 1964; Van Soest and Moore, 1965; Van Soest, 1965a).

Van Soest (1963b), in addition to the neutral detergent separation, suggested that plant fiber can be prepared for alignin determination by using an acid detergent digest (1 normal sulfuric acid plus 2% cetyltrimethyl ammonium bromide). The acid detergent fiber (ADF) residue was composed primarily of lignocellulose since most of the protein and hemicellulose were removed by the acidic detergent (Van Soest, 1963b; Van Soest, 1965b; Colburn and Evans, 1967). This extraction was thought to reduce the probability of high lignin values due to protein and carboyhydrate artifacts (Van Soest, 1963b; Van Soest, 1965a; Van Soest and Moore, 1965). Lignin was determined by a 72% sulforic acid digest followed by ashing (Van Soest, 1963b; Van Soest and Moore, 1965). A potassium permenganate digest of ADF had also proven useful in calculating lignin percents (Van Soest and Wine, 1967). Whereas the 72% sulfuric acid lignin procedure dissolved the cellulose and any residual polysaccharides in acid-detergent residue, leaving the lignin. The permenganate procedure utilized the oxidation of aromatic rings by saturated potassium permenganate to solubilize the lignin and leave a residue composed mainly of cellulose. However, the analysis should be conducted at 20 to 25°C (Van Soest, 1978b).

The percentages of the individual carbohydrate components of the cell wall (cellulose and hemicellulose) could be calculated by difference (Keys and Van Soest, 1970; Van Soest and McQueen, 1973).

Hemicellulose was calculated by NDF% - ADF% and percent cellulose by ADF% - Lignin%. However, accuracy of these calculations was varied depending upon hemicellulose and protein residue in NDF and ADF (Christiansen, 1979).

Generally, acidic polysaccharides were more insoluble in acid detergent through precipitation as the quarternary ammonium detergent salts. Pectic acids from legumes, citrus, etc. tended to precipitate giving greater values for acid detergent fiber. The pectins of other plants such as Brassica remained soluble (Bailey et al. 1978). Tannin-protein complexes and biogenic silica are soluble in neutral-detergent but not acid-detergent; however, a reverse situation existed with regards to cell wall proteins which were soluble in acid-detergent but not in neutral-detergent (Van Soest, 1978a).

ADF was shown to retain residual protein and hemicellulose. The amount retained differed with feed type (Colburn and Evans, 1967; Kim, 1967). Some studies demonstrated ADF hemicellulose recovery to be 14-16% and protein recovery to be 5-16% (Colburn and Evans, 1967; Kim et al. 1967).

Tannins found in certain feeds and food materials precipitated protein or inhibit proteolytic digestion and formed a resistant tannin-protein complex that was passed on to the feces. An ordinary lignin analysis would usually measure such complexes as lignin (Van Soest, 1978a).

The main purpose of the detergent system was to provide a rational and practical alternative to the system of proximate analysis; the principle defects of crude fiber being the failure to recover unavailable and undigestible residues in lignin, cellulose, and hemicellulose

(Van Soest, 1978a). The neutral-detergent fiber (NDF) was shown to recover these fractions quantitatively in the case of ruminants and horses fed normal forage diets (Van Soest, 1967; Fonnesbeck, 1969). However, NDF fails to recover dietary residues in feces was characteristic of diets high in starch and tannin (Van Soest and Robertson, 1978).

Validity of partitioning of plant dry matter into NDF and NDS had been supported by animal digestion experiments together with chemical and regression analysis (Van Soest and Moore, 1965; Van Soest, 1965b; Van Soest et al. 1966). NDS% content was regressed against NDS% digestible amount, showed that the NDS fraction is chemically uniform $R^2 = .99$ (Van Soest and Moore, 1965; Van Soest, 1967; Fonnesbeck, 1969).

A literature review had shown Van Soest's detergent procedures to be a marked improvement over the crude fiber analysis in partitioning plant dry matter (Christiansen, 1979). Cell wall constituents were separated from soluble cell contents in different feed types without significant mispartitioning as had been shown between crude fiber and nitrogen free extract in the proximate analysis system (Christiansen, 1979).

Fonnesbeck and Harris Modified System. An improved method of a chemical system for partitioning plant dry matter was proposed by Fonnesbeck and Harris (1970 a,b) and was found to show certain advantages over the Van Soest systems of analysis (Christiansen, 1979).

The neutral detergent procedures proposed by Van Soest (1963a) had been used to dissolve fiber protein when separating forage plant materials into cell wall and cell contents. However, studies showed that NDF might retain up to 30% of the protein in the sample (Colburn and Evans, 1967). This protein residue was counted as NDF and could result in significantly high cell wall estimates for high protein feeds (Christiansen, 1979). There were also filtering difficulties during the washing of NDF for protein supplements, energy feeds, mixed diets containing these ingredients, and feces from animals eating these diets (Van Soest, 1966b; Martin et al. 1975; Robertson and Van Soest, 1977). The filtering problems would give higher NDF results than expected.

Fonnesbeck and Harris (1970a) studied these analysis problems and proposed an improved chemical procedure in order that all feed types could be accurately analyzed for cell walls and cell contents by the same procedure.

A 24-hour preliminary pepsin digestion prior to sodium lauryl sulfate reflux to rid cell wall of residual protein was recommended (Fonnesbeck and Harris, 1970a). The addition of pepsinsted to high protein samples of alfalfa leaf meal and alfalfa hay resulted in the removal of above 95% of the protein while only 66% of the sample protein was removed with the use of detergent above. The increased removal of protein residues also helped overcome filtering problems experienced in analyzing energy feeds and protein supplements. Foods that were analyzed by the pepsin-detergent method resulted in high protein removal.

Fonnesbeck and Harris (1970a) observed that a sodium lauryl sulfate pH change from 7.0 to 3.5 was needed for maximum recovery of cell wall constituents. Barley straw was chosen to represent more mature cell walls and Kentucky Blue Grass, early vegetative, was used to represent younger growing cell walls. Detergent cell wall samples were determined over a pH range of 1 to 10. Maximum cell wall recovery was shown to occur at a pH of 3 to 4. A pH of 3.5 was chosen as a compromise for the pH values determined. More studies on alfalfa samples using pepsin-detergent method at pH 3.5 and pH 7.0 showed effective protein removal at a higher cell wall recovery at pH 3.5.

The use of 2-3% sodium lauryl sulfate detergent concentration for proper cell wall extraction was found sufficient (Van Soest and Wine, 1967; Van Soest, 1963a). Fonnesbeck and Harris (1970a) agreed with the results by showing that sodium lauryl sulfate concentrations ranging from 1.5-3% are adequate for plant cell wall determinations.

A one-hour detergent reflux for NDF determinations was recommended (Van Soest and Wine, 1967). Increasing the reflux time was found to significantly reduce cell wall recovery (Fonnesbeck and Harris, 1970a).

Plant cell walls were further quantitatively partitioned into fractions of cellulose, hemicellulose, and acid insoluble ash. Using a 4% sulfuric acid reflux for one hour, Fonnesbeck and Harris (1970b) observed an effective separation of hemicellulose from the cell wall residue. The cellulose portion of cell walls was determined by difference following a 3-hour 72% sulfuric acid digest of the 4% sulfuric acid residue. The lignin component of plant cell walls was calculated by difference after the 72% sulfuric acid residue had been ashed. Acid insoluble ash represented that portion of the total feed ash not absorbed by the animals digestible tract, primarily silica. The nutritive ash portion, soluble ash, was, therefore, calculated by subtracting acid insoluble ash from the total ash value.

To solve the filtering problems when digesting and washing the 72% sulfuric acid residue in Van Soest's 72% sulfuric acid lignin determination, Fonnesbeck and Harris (1970b) placed the lignocellulose containing crucibles in beakers of acid allowing the acid to seep up slowly through the filtered disc and wet the fibrous residue.

Fonnesbeck and Harris (1974) also modified the technique of chloroform: methanol extraction procedure to make it easily adapted as a routine laboratory analysis for total solvent extract to replace EE. The solvent extract could be further separated into nutritive lipids and non-nutritive lipids in a silicic acid column with ethyl ether in hexane. More refinement of the method to separate nutritive lipids was still needed as waxes and strols were carried into the fraction containing fat, fatty acids, and phospholipids remained in the column with the non-nutritive lipids (Fonnesbeck, 1976).

The solvent extract of all feeds and foods was greater than EE while nutritive lipid fraction was less than EE. The non-nutritive lipids of the leaves and stems of plants usually exceeded the nutritive portion (Fonnesbeck, 1976).

The ratio of non-digestible lipids to digestible lipids was highly variable among feeds (Fonnesbeck, 1976). When the quantity of the nutrient portion was low compared to the indigestible portion, extreme error in the calculations of other extract digestibility occurred.

The EE analysis probably had not been emphasized by most researchers because the ether extract content of most feeds was relatively small compared to other feed components, i.e. carbohydrates and protein (Christiansen, 1979).

Fonnesbeck (1976) further partitioned plant dry matter by calculation after determining total lipids. The quantity of available carbohydrates or carbohydrates readily digested by enzymes produced by an animal's digestive tract was calculated as cell contents minus crude protein minus total lipids minus soluble ash.

Christiansen (1979) reported that the chemical procedures by Fonnesbeck and Harris (1970 a,b) showed an improvement over the NDF procedure by reducing the residual protein in cell walls and by increasing the recovery of cell walls, hemicellulose, lignin and ash. The improved procedure could also be used in analyzing energy feeds, protein feeds as well as fibrous feeds without the filtering problems faced in the NDF method. The additional partitioning of plant material into more simplified components of cellulose, hemicellulose, lignin, acid insoluble ash, soluble ash, and available carbohydrates by simplified laboratory methods had also been shown by Fonnesbeck and Harris (1970 a, b; 1973).

Van Soest and Robertson (1978) also modified the procedure of the detergent system. These modifications were made in an attempt to overcome the problems of the contamination of fiber residues with protein and starch, difficulties in filtration and handling related problems in analysis of certain foods. These modifications were as follows:

1. Elimination of decalin originally added to overcome foaming, since it was found to increase the fiber yield and contributed to difficult filtering (Van Soest, 1973a). Decalin was not used in the preparation of neutral-detergent fiber any more.

2. Treatment of fresh sample of high lipid materials (more than 10%) with four volumes of acetone or ethanol to prepare a material that could be easily ground and was sufficiently low in lipid content to avoid interference in the detergent analysis. Thus, eliminating its use of heat which would affect the nitrogen content of the fiber (since the

detergents, at high levels of lipids, were soluble in the lipid phase and would not be adequate amounts in the water phase).

3. In samples high in proteins (more than 30%), the results of the analysis of detergent fibers might vary because the high protein content of such samples exceeded the capacity of the detergent to form soluble complexes. Addition of a protease might be employed. However, not all protein or other nitrogen could be removed from vegetable fibers by proteases. In fact, the resistant fraction more or less appeared in feces as an indigestible fraction which was composed of indigenous to the mature plants and of Millard reaction and heat damage to protein in cooking and baking as well as the tannin-protein complexes. Therefore, drying samples below 65°C was recommended to avoid Millard products.

4. The filtration problem encountered in the cell wall procedure due to protein, starch, mucillages, and gums could be eliminated. In samples high in proteins, the use of sodium sulphite was eliminated because it resulted in a loss of lignin which could more than compensate for the reduction in residual nitrogen. Sodium sulphite might also attack the Millard complex in heat damaged feedstuffs causing a further reduction in cell-wall value. Instead, an Oklahoma state filter screen (Labconco ^{R}) was used to help removal of the protein detergent complexes before filtering the neutral-detergent residues the crucible.

While in samples high in starch, filtration was a problem since starch geled as the content of the crucible cooled. Robertson and Van Soest (1977) proposed the use of a detergent stable α--amylase from Bacillus sublilis to eliminate the residual starch. The enzyme was type IIIA (eg. α--amylase, Type IIIA--Sigma Catalogue No. A6505) with an optimum activity at pH 6.9 and 80°C.

5. Lumping of the residue might create problems in lignin determination. The residue should be washed with hexanes after the water wash but prior to the acetone wash to overcome the problem.

A sequential analysis system (Figure 2) was proposed to be considered if there was a limited amount of a sample that contained some of the interfering substances, or if pre-extraction of the sample to enrich the fiber content was required (Van Soest and Robertson, 1978).

Barnes (1973) divided the chemical methods used in estimating some aspects of quality into: (1) definitive procedures identifying specific chemical entities or groups of related substances and (2) empirical procedures that solubilize forage dry matter with little attempt to define the actual chemical groups involved, as long as the results were correlated with some in vivo parameter. The first category involved the use of strong acids or solvents at high temperatures (crude protein, cellulose, and lignin analysis). The latter category of solubility indices involved the use of weak acids, aqueous solutions, or enzymes at moderate temperatures.

In definitive chemical procedures, crude protein percentage in herbage had an associative relationship with the amount of cell wall constituents, however, it is of little value in the prediction of energy availability. The second category of chemical methods that were used in estimating quality of herbage was the solubility indices. This method was based upon an estimation of the digestibility soluble fraction or an estimation of both the digestible soluble fraction and the digestible fibrous fraction of herbage. The difference from the conventional chemical procedures was that the soluble indices procedures

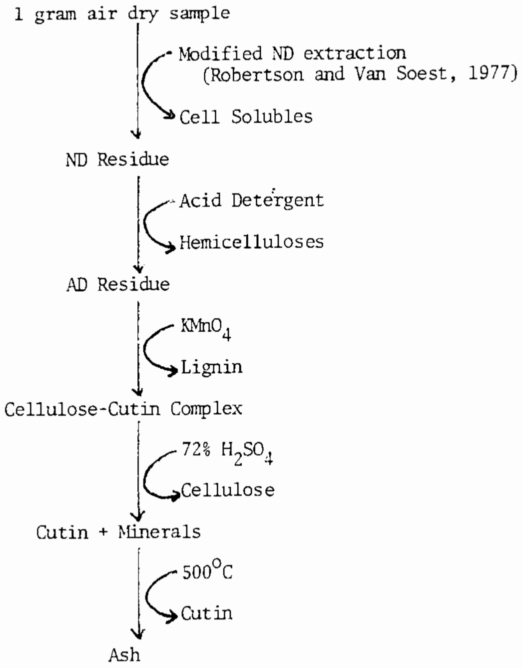

FIGURE 2 Flow diagram for sequential analysis (adapted from Van Soest and Robertson, 1978)

measured the loss of dry matter upon acid, solvent, or enzymatic treatment and no attempt was made to measure a specific chemical entity.

In summary, proximate analysis, Van Soest's method, Fonnesbeck and Harris's method, and the sequential method of analysis were a means for partitioning feedstuffs into their components; and they were methods for chemical evaluation of the nutritive values of feedstuffs as shown in the following scheme:

A Schematic Comparison could be drawn for the Van Soest, Harris and Fonnesbeck Methods:

Fraction	Components Included	
	Van Soest	Harris and Fonnesbeck
Cell Contents	sugars, soluble Carbohydrates, starch, pectin, NPN, protein lipids, other solubles	soluble carbohydrates, proteins, fats and fatty acids, soluble ash
Cell Walls	hemicellulose cellulose lignin heat-damaged proteins	hemicellulose cellulose lignin non-nutritive solvent extracted acid insoluble ash

The usefulness of chemical evaluation is that it could (1) compare recovery with standard substances, (2) compare the results by other methods, (3) compare to values obtained by proven methods and (4) make a comprehensive chemical analysis of the substances recovered and/or extracted (Fonnesbeck, 1976). However, further research is needed in determining these proposed analytical methods (Christensen, 1979).

Digestibility Trials or Biological Trials for the Evaluation of Feedstuffs

Feedstuff analysis usually involve chemical procedures to determine specific elements, compound or a group of compounds. These chemical procedures depend on the chemical properties of the various nutrients and nonnutritive components of feedstuffs.

Chemical methods involve drastic degradation of feeds with reagents such as concentrated acids or bases, extraction with concentrated solvents or other harsh treatments. Biochemical reactions that make feed nutrients available to the animal system proceed at animal body temperature catalyzed by specific enzymes and under control of the digestive system.

Chemical analysis could be the starting point for determining the nutritive value of feedstuffs. The nutritive value did not entirely depend upon the amounts of several nutrients it contained but on the amounts of these nutrients that the animal could digest and use (Schneider and Flatt, 1975). The chemical composition alone of any feedstuffs was usually an imperfect standard by which to judge nutritive value. Digestibility was one of the first considerations, since undigested or insoluble nutrients did not enter the body properly at all (Schneider and Flatt, 1975).

Since chemical methods often left questions regarding the availability of nutrients from feedstuffs, biological procedures or comparative feeding trials were used, although they were time consuming, tedious, and expensive (Church and Pond, 1976). Biological methods, however, might be a more accurate estimate of animal utilization. They determine how the animal utilized the nutrients of a feed.

Digestibility trials were used to estimate proportions of a feed that was available to an animal for absorption from the gastrointestinal tract. A diet of known composition was fed to animals over a time period of several days during which the feces were collected and analyzed for the components of interest. It was advisable to maintain a constant daily feed intake over several days to minimize day-to-day variation in fecal output (Schneider and Flatt, 1975; Church and Pond, 1976). Values of apparent digestibility of any desired nutrient could be obtained, but data may be meaningless for some nutrients such as the vitamins and minerals whose passage both from lumen of gastro-intestinal tract into the body and from body into the lumen of gastro-intestinal tract was quite variable and subject to change (Church and Pond, 1976).

Digestibility of a feed or its components could be estimated by two general ways; one way by total collection of feed and feces which allows a direct measure of apparent digestibility. It was computed as follows:

$$\text{Apparent Digestibility\%} = \frac{\text{nutrient intake - nutrient in feces}}{\text{nutrient intake}} \text{ X } 100$$

A problem in pasture arised from the animals selecting certain plants and refusing others (Church and Pond, 1976; Cook et al. 1952). Besides, equating actual consumption with assumed consumption based on analysis of clipping from a given area might be misleading. However, Crampton and Harris (1969) stated that "A regression equation determined for one set of conditions does not work under all sets of conditions." The regression might not be always linear or linear throughout the range of values. The steeper the slope, the more reliable the estimate would be. The percentage digestibility was not all that determined the value of feed. Two feeds might be equal in composition and equally digestible, yet one might be more valuable than the other because its digested matter could be used to better advantage by the body (Schneider and Flatt, 1975). The next step after chemical analysis was to accurately determine the percentage of each nutrient digested (Armsby, 1917).

Comparative feeding trials were being conducted to obtain data pertaining to either a feedstuff or to the needs of an animal. Regardless of what other criteria were also employed, most studies of the nutritive properties of foods include an examination of their digestibility and/or the biological nitrogen balance and/or carbon balance as fundamental criteria (Lloyd et al. 1978).

Digestion means all those processes that happen to a feed in the alimentary tract of an animal. Digestion depends on (1) presence of enzymes, (2) their physiological environments in which they function, (3) the properties of feeds including their susceptability to enzymatic hydrolysis and the action of inhibitory substances which the feeds may contain, and (4) total processing capacity of the animal's digestive tract (Schneider and Flatt, 1975).

As feed is taken into the alimentary canal of an animal, it is partly dissolved in water and acted upon by certain liquid agents such as the saliva in the mouth, the gastric juice in the stomach, and the juices in the intestines. In addition to these processes ruminant animals use, micro-organisms in the rumen have a very important role in ruminant nutrition. That part of feed which is dissolved, or digested, can be absorbed into the blood and lymph vessels. The undissolved, undigested, or unabsorbed portion of the feed is excreted from the body as the feces or dung, and thus constitutes one part of the feed which is useless for the purposes of nutrition of that particular animal (Schneider and Flatt, 1975).

There were very important differences in the digestibilities of feedstuffs and also of the nutrients within the same feed. Knowledge of the differences was of great importance to livestock nutritionists and to the national economy of any country (Schneider and Flatt, 1975).

The losses resulting from incomplete digestion and absorption were economically important, and nutritionists must understand them in order to use feeds correctly (Lloyd et al. 1978).

Digestible nutrients mean the difference between the amounts of each nutrient in the feed and the feces. Thus, digestible energy (DE) is energy of the digestible nutrients. The term digestible nutrient means the portion of a nutrient which is apparently digested and taken into the body (Schneider and Flatt, 1975).

The digestible percentage of any substance was called the digestion coefficient of that substance. The digestion coefficient of a nutrient might be defined as the percentage consumed in the ration which did not appear in the feces. It was an expression of how much of each nutrient had disappeared during the passage of the feed through the digestive tract (Schneider and Flatt, 1975).

The first step in assessing the energy values of the organic nutrients to the animal was considering the losses of these nutrients in the feces. The chemical composition was the basis, but the percentages of digestible carbohydrates, digestible fat, and digestible protein became the modified values that more nearly represented the benefit to the animal in terms of these substances. In addition to the digestion coefficients of crude protein, crude fiber, nitrogen free extract, and fat (ether extract), digestion coefficients were sometimes reported for organic matter in a feed or ration, or for the total dry matter (Schneider and Flatt, 1975). Also, most present-day digestion experiments and some older ones include the digestible energy.

The heat of combustion of both feed and feces was determined, and the difference was expressed as a percentage or digestion coefficient, or as the digestible energy per unit of feed (Mcal/kg). The amounts of certain vitamins, lignin, cellulose, etc., digested, have been estimated in relatively few experiments (Schneider and Flatt, 1975).

Fecal losses were the largest and most variable nutritive energy losses. Therefore, by taking the fecal losses into consideration in evaluating feedstuffs, a more comparable basis was provided and a better measure was obtained by which one feed could replace another (Schneider and Flatt, 1975).

Digestion trials were conducted as soon as the chemical methods were developed. The early work on losses of nutrients in the feces leading to evaluation of the energy values of feeds in terms of total digestible nutrients, began before 1860 (Hennenberg and Stohman, 1860, 1864; Wolff, 1870; Atwater, 1895; Hills, 1900). The earliest American report of digestibility experiments (Jordan and Hall, 1900) was published in 1884.

The percentage digestibility of feedstuffs could be determined only by trials with animals. Digestion coefficients were determined by means of these digestion or balance trials.

Most of the knowledge concerning animal requirements and values of feeds had been obtained through numerous and laborious experiments with animals. As data were accumulated from animal feeding experiments, it had become obvious that the quality of a ration could not be accurately ascertained in other ways. Emphasis in modern grassland thought was placed increasingly on herbage quality (Davis, 1950). The inability to measure the feeding value of a sample of herbage without digestibility experiments became increasingly evident (Crampton, 1950).

To make knowledge of the nutritional value of feeds more useful, it was necessary to compile, tabulate and publish all data that could be obtained or which had been previously reported into tables applicable for calculating rations for different kinds of livestock. These tables would be suitable for use by researchers, feed manufacturers and farmers (Schneider and Flatt, 1975; Harris, 1963).

Most of the data describing the grass nutrients make-up of foods and feedstuffs were obtained by chemical analysis. The average composition of commonly used feeds might be found tabulated in books and publications in the literature of nutrition. These chemically determined data were an adequate description of some of the nutrients in some feeds. But the grass composition of most sources of nutrients must be supplemented with figures indicating the extent of utilization figures obtainable only from experimentation with animals (Lloyd et al. 1978). Data for the quantities of nutrients needed by the body, and information concerning the digestibility and the biological usefulness of the energy and of the nutrient components of feedstuffs were necessary before a nutritionist can formulate a ration that meets specific nutritional needs.

In obtaining the required biological information, nutritionists employed various species of animals, including at least seven kinds of laboratory animals (Lloyd et al. 1978; Schneider and Flatt, 1975). For a limited number of problems, human subjects were also used.

Some feeds could not be fed alone. Horses and ruminants were not fed concentrates alone, without hay or other roughages. Pigs might be fed grain only; however, feeds such as tankage and linseed meal were too rich in protein to be fed alone. The digestibility of such feeds must be found by difference instead of directly (Schneider and Flatt, 1975; Crampton and Harris, 1969).

For example, in an experiment to determine the digestibility of oats for sheep, the sheep were first fed hay for several days, and the digestibility of hay was found. Then oat was added to the ration and the total amount of nutrients were determined that were digested from the combination of oats and hay. The amounts of the digestible nutrients coming from the hay were then subtracted from the total, leaving the amounts which were assumed to be digested from the oats (Schneider and Flatt, 1975).

Thus, two digestibility trials were conducted: the first (A) to determine the digestibility of the hay, and the second (B) to determine the digestibility of the mixture.

The assumption in this procedure, that mixing two feeds together did not alter the digestibility of either over what it would have been if fed alone, was often not true (Crampton and Harris, 1969). With poor-quality roughage, we might find that the digestibility of its dry matter was relatively poor. Much of the digestibility of such poor materials was largely dependent on the activity of microfloral breakdown of cellulose resulting volatile fatty acids readily available for the animal. It was conceivable that a meal supplement, especially one that contained suitable food for micro-organisms is fed with the roughage might result in a more complete digestion of the cellulose portion of the poor roughage (Crampton and Harris, 1969). This increase in digestibility of poor roughage was usually accounted for the meal supplement, whereas in reality, it might have been an improvement in the digestibility of roughage itself which was involved (Crampton and Harris, 1969). This kind of interaction between feedstuffs is referred to as associative digestibility (Crampton and Harris, 1969; Schneider and Flatt, 1975).

Therefore, animal or biological studies could (1) compare the nutritive value of the chemical components, (2) determine the digestibility of chemical methods to partition nutrients, and (3) demonstrate the ability to predict nutrient utilization from chemical analysis (Fonnesbeck, 1976). However, there were two main limitations to the interpretation of digestion coefficient values (Ranjhan, 1980). The first limitation was that nutrients excreted in feces were not representative of the undigested portion of food residues for which the digestion coefficients were determined. Part of the nutrients excreted in feces came from endogenous and bacterial origins.

Because it was assumed that feces were composed entirely of undigested food substance while the part of the nutrients coming from body itself the digestion coefficients were called apparent digestion coefficients. For the calculation of true digestion coefficients metabolic fecal losses were to be accounted. The true digestibility of protein in the feeds was not affected by increasing the indigestible matter by the apparent digestibility of protein would decrease because of the increase in metabolic fecal nitrogen (MFN).

The second limitation of the digestion trials was that the carbohydrates were degraded in volatile fatty acids (VFA), carbon dioxide (Co_2) and methane (CH_4). The later two gases did not yield any energy to the animals but were computed as digestible carbohydrates since they were not recovered in feces. Hence, digestible carbohydrates were over estimated.

Factors Affecting Digestibility of Feedstuffs

Schneider and Flatt (1975) assumed that there are more than fifty factors that affect digestibility of feedstuffs. These factors would then, affect the results of digestion coefficients used to evaluate feeds and supply data for feed tables.

Effect of Feeding Level. Farm animals digested a larger percentage of the nutrients in their feeds when fed a scanty ration than when they received a full ration. Schneider and Flatt (1975) concluded that there were variations between experiment stations and between trials within stations as far as feeding levels were concerned. However, most data indicated that apparent digestibility of feedstuffs was decreased as the level of feed intake increased.

Since most average digestibility coefficients of feeds were determined at the maintenance level or slightly higher, they might be 5 percentage units high when applied to full-feed animals (Mitchell, 1942). Therefore, the planes of nutrition which were employed in digestion trials might not be desirable if results were to be applied in practical feeding (Schneider, 1947).

Mitchell, et al. (1932) reported the most complete digestibility of all nutrients at the most of feeding. Digestibility of crude protein, dry matter, organic matter, and carbon of rations fed to steers, was highest at maintenance level (Forbes et al. 1937).

High roughage intake was found to decrease digestibility (Hogan et al. 1967). Timothy hay was fed at two levels, limited and ad libitum plus ten percent refusal. The mean energy digestion coefficient for all forages fed at the high level was significantly lower than that of the limited forage.

The digestibility of feeds seemed to be more affected by levels of feeding than by the place of nutrition. Mitchell (1942) found that digestibility was more depressed with high level of feeding mixed ration than with all-roughage ration. But, when fresh forage was fed, there was a small depression in digestibility. When Anderson et al. (1959) fed 700 grams, 1000 grams, and 1200 grams green, first growth and green, after-math forage per day to sheep, they did not observe a change in the digestibility of dry matter associated with feeding high levels of the green, first growth forage. However, at high level feeding of green, after-math forage depressed digestibility by 2.4 percent. Only three out of thirteen trials of depressed digestibility due to high level of feeding in comparison to medium level, were observed.

Animals indoors might not consume much cut grass as they might eat when grazing in a good pasture. Hutton (1962) observed in 120 digestion experiments in identical-twin cattle were fed clipped pasture herbage at two levels. One twin of each pair was fed at libitum, the second twin was fed about sixty percent of the amount consumed by the former.

Digestibility was lowered by .08 percentage unit by high levels of feeding.

Depressed digestibility of corn silage, when fed to steers at high levels, was reported by Watson et al. (1939), and in cattle and sheep (Colovos et al. 1970).

Blaxter (1961) put the following equation to express the changes in energy digestibility associated with feeding levels of roughages: Depression in digestibility of long roughage per unit increase in feeding level = 0.119 (100 - digestibility at maintenance). However, the constant in this equation changes to 0.152 when roughage was pelleted.

Thus, the extent of digestibility decline with increasing feeding levels was directly related to digestibility at the maintenance level. As feeding levels increased, a greater depression in digestibility (increment of maintenance) of a poor quality hay than of a good quality hay was reported (Blaxter, 1961). This difference was explained to be due to the necessity to consume more of poor quality hay for each energy unit increase in feeding level.

Total digestible nutrients of rations composed of concentrates and either early or late cut hay at various intake levels as percentages of total digestible nutrients (TDN) content was studied at maintenance (Moe et al. 1963). More than sixty observations were taken from cows producing from zero to 54.4 kilograms of milk per day. As feeding level increased from maintenance to six times maintenance, the relative total digestible nutrients decreased so that a diet which had a TDN value of 82 percent at maintenance would have a TDN value of 63 percent (that was 77 percent of the 82 percent) at six times maintenance.

Reid et al. (1966) expressed the multiple of maintenance needed for measuring the plane of nutrition or level of intake in terms of total digestible nutrients consumed, as follows:

$$\text{plane of nutrition} = \frac{\text{kilograms of TDN consumed}}{\text{kilograms of TDN for maintenance}}$$

The estimated plane of nutrition might be then 0.9 (for 90 percent of maintenance), 1.0, 1.5, 2.0, etc., to represent 0.9 x maintenance, 1.0 x maintenance, 1.5 x maintenance, 2.0 x maintenance, etc.

Lactating dairy cattle have the highest energy demand among ruminants. The response of dairy cows to increments of feed was one of diminishing returns in relation to milk production (Van Soest, 1978b). Balance trials at high levels of feed intake demonstrate that the decrease in digestion was very significant in dairy cows and involves structural carbohydrates and starch.

Cattle digested more of starch when the pH levels in the lower intestine range about 6.9 (Wheeler, 1980). Dry dairy cows fed at maintenance levels digested 10 percent more starch in the rations than those fed at the rate of two to three times maintenance levels during lactation. Digestibility of dietary starch decreased from 96 percent at maintenance levels to 86 percent during lactation.

The true digestibility of cellular content might decline with an increasing feed intake, especially in forages of high starch content (Karr et al. 1965). The bacterial endogenous excretion might not be constant with level of intake, and could have an important effect on the decline of apparent digestibility as the level of intake increased in dairy cattle (Brown, 1966; Van Soest, 1966a).

The depression in digestibility with the increased level of intake predicted a lower net energy for lactating cows than that which would be predicted from ordinary digestion trials. Tyrrell and Moe (1974) indicated variable lower net energy values for fibrous feeds at high levels of milk production. There was variability among feedstuffs in depression in digestibility per unit of maintenance intake and that variation depended on the relative rate of cell wall digestion and passage rates.

The apparent efficiency of an added increment of feed energy for dairy cows decreased with the increased intake, "but is certainly linear if regressed as metabolizable energy directly determined at each intake level. This would correct for decrease in digestibility which is a major part of the decreased response" (Moe and Tyrrell, 1973).

Net energy could be predicted at production levels of intake if the decrease in digestibility could be estimated, and rates of digestion and passage could be known. "The alternation of digestibility values with intake level is passed on to metabolizable and net energy values and constitutes the greatest single error in estimating them" (Moe and Tyrrell, 1973).

Blaxter et al. (1956) explained the reason for the lowered digestion at higher planes of nutrition. The rapid movement of feedstuff materials allowed less time for digestion or absorption. As the amount of fermentation and gestation was reduced due to increased rate of passage of feed materials, the overall nutritive value of the feed was reduced. Therefore, there would be a decline in enzymatic and microbic action especially on more fibrous substances (Campling et al. 1962). The fast movement of chyme through the digestive tract resulted in an incomplete absorption of nutrients, too.

The increased passage may have depressing effects upon digestibility or extent of fermentation in rumen if rates of passage were in competition with rates of digestibility (Van Soest, 1978b). If digestion (ks) and passage (kp) rates were first-order differentials, the theoretical fractions escaping digestion (E) would be:

$$E = \frac{Kp}{Ks + Kp}$$

Thus, from the equation, if passage and digestion rates were equal, one half of the potentially digestible matter would escape. The increasing intake of any feed increased the probability of rumen escape and that the effect would be more significant with less soluble and more slowly digested feed fractions (Van Soest and Robertson, 1978).

Escape from rumen was beneficial in cases as feed proteins, since the post-ruminal digestion of proteins was more efficient than that of the rumen. But escape was generally harmful in case of structural carbohydrates which would have little opportunity for further utilization (Van Soest and Robertson, 1978).

The decrease resulting from high level of feeding might be also due to the fact that certain feedstuffs had higher digestibilities. Thus, increasing proportions of such feeds in the ration would influence the digestibility (Mitchell et al. 1940; Stone and Fontenot, 1965). Changing the energy concentration of a ration and the level of feed intake of the same ration were two different factors that had an influence when more feed was consumed but at the same time the character of the feed mixture was altered.

Since digestibility depression had been directly estimated for only a relatively small number of feeds, values for feeds that were not evaluated must be interpreted from rate of digestion and passage estimates (NRC, 1978). This situation would leave judgment as the final resource in doubtful cases; hence, there was need for continued collection of rate of passage and digestion data (Van Soest, 1978b).

Not only ruminant animals (Mitchell, 1942), but other animals such as swine also digested some nutrients in their feeds somewhat less when fed higher levels (Mitchell and Hamilton, 1929).

Effect of Chemical Composition of Feedstuffs on Digestibility. Chemical composition determined the nutritive value of feedstuffs, and greatly affected the apparent digestibility of the chemical components. Schneider and Flatt (1975) suggested that digestion coefficients for a chemical or nutrient should never be reported for any feed without reporting the percentage composition of the same nutrient for which the coefficients had been determined. Digestion coefficients were of no value apart from information on the chemical content of the same sample or feedstuff.

Changes in chemical composition of feeds were due to (1) different treatments such as cooking, grinding or pelleting, (2) methods of preserving, (3) stage of maturity, (4) environments, (5) season, and (6) associative effect of one feed on another.

The apparent digestibility of the nutrient components of a feed depended on many factors. For example, change in crude protein and/or change in crude fiber exerted a change in digestibility of that feedstuff. The digestibilities of feedstuffs also differed because of different components of nutrients especially as some of these components lowered the chance for the digestive enzymes to come in contact with their substrates (Schneider and Flatt, 1975).

Schneider and Lucas (1950) observed that between 25 to 45 percent of the variation in digestibility of different samples from the same feedstuffs might be attributed to differences in the chemical composition. The chemical composition of a feed influenced its apparent digestibility (Schneider et al. 1950). Therefore, feeds of the same name but different in composition would show variations in digestibility.

It was very important to note the change of chemical composition in feedstuffs, especially of those feeds that change rapidly as they progress in growth and those feeds that were altered by milling processes resulting in different levels of proteins and still given the same name. Cereal grains had significant differences in chemical composition. Barley, for example, had 9 to 19 percent protein (Schneider and Flatt, 1975). A change in protein content of a feedstuff must be followed by a change of other components.

The protein level in feedstuffs greatly affected apparent digestibility coefficient. Protein also affected the growth and activity of microorganisms in ruminant animals. Harris and Mitchell (1941b) observed that when feedstuffs high in protein were added to balance the low protein rations, the microorganisms were stimulated and would degrade more fiber. Supplementing rations that contain low-nitrogen roughage with urea improved the digestibility of cellulose. Addition of protein to low protein diets of sheep increased the digestibility of dry matter at different levels of starch (Williams et al. 1953).

Since metabolic fecal nitrogen (MFN) was constant, the apparent digestibility of crude protein depended to a great extent on the protein level in the feedstuffs. In ruminants, the MFN was about three grams of crude protein per 100 grams of feed dry matter eaten (Schneider and Flatt, 1975). If a feed contains six percent crude protein, the apparent digestibility of this protein could not be more than 50 percent. If a feedstuff contained less than three percent crude protein, the digestible protein supply to the animal might be reduced (McDonald et al. 1973).

Metabolic fecal nitrogen was found to be 2.8 percent by Blaxter and Mitchell (1948) while Christiansen (1979) estimated it to be 3.5 percent when applied Lucas model in a study on sheep. Fonnesbeck (1969) reported a value of 3.2 percent for MFN in horses. As a result of metabolic crude protein, apparent digestibility of crude protein was shown to decrease with a decreasing crude protein content in the diet or increase with an increasing crude protein content in the diet (Christiansen, 1979).

As the nutritive ratio (ratio of apparent digestible nonprotein nutrients to apparent digestible protein) became wider, the apparent digestibility of all nutrients tended to decrease, particularly for the apparent digestibility of protein. This effect explained on basis of output of metabolic nitrogen (Schneider and Flatt, 1975). Hence, the apparent digestibility of protein was lower with a wide ratio even though the true digestibility might not be. In ruminants, the addition of protein or non-protein nitrogenous compounds to a ration with wide nutritive ratio increased the microbial digestion of structural carbohydrates (Schneider and Flatt, 1975). This digestion made other nutrients more digestible with mature fattening cattle and sheep.

A ration low in protein or the addition of non-nitrogenous feeds of any kind to a ration caused a greater excretion of nitrogen in the feces. The amount of the additional loss of nitrogen in feces depended chiefly on the amount of feed added and its digestibility. This extra excretion consisted not only of undigested protein, but of metabolic nitrogenous substances that had been assimilated and then excreted as a waste (Mitchell, 1924).

There was a negative correlation between the crude fiber content of feedstuffs and the digestibility of their organic matter (Axelsson, 1938; cited in Schneider and Flatt, 1975). Schneider (1947) observed that, with poor quality roughages fed to sheep, the effect of crude fiber and nitrogen free extract (NFE) on digestibility differed from that of better roughages. The greater the percentage of crude fiber, the lower its digestibility. Moreover, the digestibility of organic matter of such poor feeds decreased as the NFE increased. This decrease could be explained by the larger quantity of lignin that the usual chemical methods did not include in the fiber portion and became a part of the NFE as it was calculated by subtraction (Schneider and Flatt, 1975). Crude fiber depressed the apparent digestibility of crude protein because as the percentage of crude fiber increased, the percentage of crude protein decreased in the feed.

Differences in digestibility of crude fiber influenced the digestibility of all nutrients because undigested crude fiber hindered the action of digestive enzymes on the other nutrients especially in plant parts such as stems, seeds and seed coats, and also for cells with fibrous membranes (Schneider, 1947).

The nature and amount of crude fiber present were important factors affecting the digestibility of nutrients in feeds. Since the plant cell wall was the main fraction contributing to the depression in digestibility, the degree of the depression with increased intake was related to cell wall content (Robertson and Van Soest, 1977). However, it was inversely related to lignin content (Van Soest, 1970). High lignin content meant inherent low cell wall digestibility (Van Soest et al. 1978).

Since lignin was a primary factor limiting digestibility, lack of association with cellulose might cause crude fiber (mainly cellulose) to be poorly related to digestibility in tropical plants (Butterworth, 1967). Lignin and acid detergent fiber (ADF) were more associated with digestibility while other components such as hemicellulose and neutral detergent fiber (NDF) were related to voluntary intake (Van Soest et al. 1978).

The difference between rate of digestion by ruminal microbes increased as the cell wall and lignin content of forage increased (Koller and Hintz, 1978).

Forbes and Garrigus (1950a) showed relationships between organic matter digestibility and the crude protein, crude fiber and lignin content of forages grazed by steers and wethers in a total of 70 grazing trials averaging over three animals per trial. Similar digestive capacities were observed in steers and wethers. The best correlation between chemical composition and organic matter digestibility was obtained by lignin. The regression of organic matter digestibility with lignin content of the dry matter of the forage was presented in the following equations:

$$Y = 100 - 4.71x \text{ for steers}$$

$$Y = 100 - 5.24x \text{ for wethers}$$

where Y is organic matter digestibility and x is lignin content of dry matter of feed.

There was also significant correlation between digestible organic matter intake, and lignin content. Results from trials with steers and wethers showed a depression of 8.2 percent and 9.0 percent respectively of the maximum intake for each percentage unit increase in lignin content of the forage (Forbes and Garrigus, 1950a). Total digestible nutrient (TDN) content of several forages varied inversely with lignin content of forage (Forbes and Garrigus, 1948).

The efficiency with which digested energy was used for production was curvilinearly associated with cell wall content (Van Soest, 1973b). The decrease in efficiency relative to TDN content at maintenance would include the depression in digestibility and the energy cost of runimation which was porportioned to cell wall content of the ration (Van Soest and Robertson, 1978). Beside decreasing digestibility, crude fiber tended to exert a protective influence against the digestibility of all nutrients, since the undigested cell walls protect the nutrients that were found within the cell walls.

The fiber mass of plants was considered to be more bulky and more slowly digested than the nonfibrous parts (Balch and Campling, 1962). The amount of crude fiber desired in rations might depend on the size and anatomy of the animal's digestive tract. The bulkiness of rations might depend on the desired level of production. Too much bulk would not allow the animal to consume enough digestible nutrients. However, very low bulk combined with high feeding level might result in indigestion problems and animals might go off-feed.

Microorganisms in the rumen would utilize the more available carbohydrates instead of attacking the resistant celluloses and hemicelluloses that would be left partially fermented. Thus, digestibility of structural carbohydrates was reduced in rations high in easily digested carbohydrates. Glucose addition to a basal ration containing roughages markedly depressed the digestibility of crude fiber of the basal diet in cattle (Mitchell et al. 1940).

The addition of carbohydrates such as starch, glucose or sucrose to basal diet was also found to reduce digestibility of the basal ration (Ellet and Holiday, 1917). Corn feeding slightly lowered the digestibility of herbage (Brannon et al. 1954), while corn sugar (cerelose) added at six percent of ration decreased the digestibility of protein but had no effect on the digestibility of dry matter, organic matter, crude fiber or energy (Woods et al. 1956).

Molasses was found to have a favorable effect on digestibility of certain roughages (Paterson and White, 1912). When only one fourth of the nutrients of corn were replaced by those from molasses, the average digestibility coefficient of crude fiber was increased from 49.7 to 54.6 percent. However, Davis et al. (1955) observed no effect on protein digestibility at this level of molasses in the diet. More molasses was added to well balanced rations for ruminants might slightly reduce digestibility of nutrients in feedstuffs especially that of cellulose (Bohman et al. 1954), and of protein (King et al. 1956; 1957). Davis et al. (1955) observed a significant drop in the protein apparent digestibility coefficient when half or all of the nutrients from corn were replaced by TDN from molasses.

Komkris et al. (1965) found that digestibility of organic matter and NFE was greater at 19.7 percent than 13.0 percent molasses in rations fed to sheep. There was no significant difference in protein digestibility when the roughage and the concentrate, including molasses, were fed in a mixture. However, when the ingredients were fed separately. the digestibility of protein decreased in rations containing higher molasses levels (Komkris et al. 1965).

Nitrogen free extract (NFE) was significantly higher when molasses replaced all of the corn than when corn was fed alone in a ration (Davis et al. 1955). Swift et al. (1948) reported that the digestibility of NFE decreased as the percentage of this nutrient decreased in the diet. The amount of NFE also affected the digestibility of other nutrients adversely. This adverse condition might be caused by the decrease in the protein percentage or by the lignin content of NFE of some feeds. However, increasing NFE intake from 58 to 66 percent improves digestibility (Axelsson, 1949; cited in Schneider and Flatt, 1975).

The effect of rations high in carbohydrates or the addition of carbohydrates on digestibility depended to a certain extent on the nature of carbohydrates (Crampton and Maynard, 1938).

The addition of fats to diets might also have an effect on digestibility of nutrients. When corn oil was added to bring up the total ether extract from 2.8 to 6.4 percent in sheep rations, Swift et al. (1948) found that the apparent digestibility of all constituents of a mixed ration had increased. Then, when ether extract was increased to 9.7 percent, digestibility declined. Erwin et al. (1956) reported that increasing the amount of fat in rations lowered the digestibility of carbohydrates, especially that of crude fiber and dry matter. Fat addition also lowered cellulose digestibility (Summers et al. 1957).

Added fats might be more digestible than the ether extract content of certain feedstuffs (Schneider and Flatt, 1975), especially that of browse plants that were high in nondigestible fats such as waxes, pigments, essential oils and resins (Cook and Harris, 1968a).

Total lipid apparent digestibility was shown to vary considerably between all-hay and hay-corn rations, and was also affected by the addition of corn since the oil of corn increased the nutritive fraction of total lipids in the ration (Christiansen, 1979). Also, total lipid apparent digestibility was affected by an increase in lipid content in general due to effects of bile (metabolic lipid residue) (Schneider and Flatt, 1975).

The mineral content of diets influenced the digestibility of nutrients in feedstuffs, too. Minerals might aid digestion if the elements added were deficient in the ration and are essential for life and activity of micro-organisms in ruminants.

Adding 50 to 70 grams per day of each steamed bone meal and ground limestone to dairy cows rations, Schneider and Ellenberger (1927) observed a slight increase in digestibility. However, minerals increased dry matter digestibility when cows were fed at high level of milk production. Also, these minerals increased the digestibility coefficient of ether extract at maintenance levels.

Swift et al. (1952) observed increased digestibility upon addition of alfalfa ash to corn cob ration. The digestibility of all nutrients increased with alfalfa ash added to cotton seed hulls (Tillman et al. 1954). This increased digestibility was explained by increased activity of micro-organisms in the rumen. Such activity lead to higher efficiency in utilizing crude fiber and other nutrients in corn cobs and cotton seed hulls.

The estimated true digestibility for ash was high (Christiansen, 1979). The apparent digestibility of ash was also affected by changes in the ash content of the diet alone as a result of a high ash endogenous residue (Schneider and Flatt, 1975).

Thus, the nutritive value of forages was limited by composition. Use of compositional predictors of forage quality was a common practice and it was important that such analytical quality standards reflect the real factors that determine composition quality (Van Soest et al. 1978). The negative association of digestibility with lignin or fiber content was easy to realize, since it involved the nutritive availability of different chemical constituents of forages and factor affecting this availability such as lignification (Van Soest, 1965a).

Therefore, it might be practical to classify the effects of forage composition upon nutritive value according to how chemical constituents affect intake, digestibility and the relationship between them (Van Soest, 1965a). These classes could be: (1) the factors that affect intake, but had no direct reliable effect on digestibility, such as high moisture silages or toxic materials; (2) positive relationship between intake and digestibility was promoted such as fibrous, bulky feedstuffs, and (3) negative relationship between intake and digestibility was promoted, such as high quality feeds where fiber content was low and probably did not affect intake. In this case intake of digestible energy might be limited by the requirements of the animal. It could be concluded that fiber will positively relate to voluntary intake, since as fiber increases, digestibility decreases, and the animal had to consume more to meet energy requirements (Van Soest et al. 1978).

Effect of Stage of Maturity on Digestibility of Feedstuffs. Stage of maturity of forages affects digestibility by two ways. The first is due to a change in the chemical composition (Arnold and Dudzinski, 1978), and the second because of changes that occurred in physical state of the plants. As plants mature, their crude fiber contents increased and became less digestible than fiber of younger plants (Schneider and Flatt, 1975). Animals consumed less as plants became mature and less palatable (Cook and Harris, 1968a). The cell walls hardened through lignification and protein content reduced and other nutrients became less available to rumen micro-organisms (Dietz, 1972).

As grasses and broad leaved herbs mature, they decreased in crude protein and increased in crude fiber, lignin, cellulose and other carbohydrates. These were the actual changes in the plant as a whole and were further affected by changes in leaf-stem-fruit ratios (McIlvanie, 1942; Cook and Harris, 1950 ; Cook and Harris, 1968a).

Stage of maturity of plants was found to account for about eighty percent of variability in forage nutritional quality (Troelsen and Campbell, 1969). Reid (1957) observed a rapid decrease with advancing maturity in the digestibility of dry matter by dairy cows of first-cutting forage. Digestion coefficient declined from about 77 percent for early growth to approximately 52 percent later in the season.

Meyer et al. (1957) examined the maturity effect on the feeding value of oat hay which was harvested at seven different growth stages (51 percent jointing, 16 percent flagleaf, 12 percent boot, 1 percent flower, 8 percent flower, milk stage and dough stage). As growth progressed, holocellulose increased up to 52 percent in milk stage. Lignin also increased to the milk stage (9.0 percent). Lignin content of the hay decreased to about 8.4 percent at grain formation in dough stage. Decline in total digestible nutrients (TDN) was from 68 percent in the joining stage to 60 percent in the flowering stage; then to 50 percent during the milk stage followed by an increase to 53 percent with grain formation. The rate of gain of sheep fed the hay at the various stages followed TDN pattern closely. Sheep gained significantly higher in the joining stage, continued at a constant rate through the intermediate stages, then significantly gained less in the milk and dough stages. Lignin percentages were highly negatively correlated (-0.89) with TDN values.

Thus, not only did the digestibility of the structural carbohydrates of cell walls decline with stage of maturity of forage, but also these components tended to form an increasing proportion of the dry matter of the plant with age (Van Soest, 1967). Studies on the components of the cell wall showed that resolution of the cell wall into nutritionally uniform constituents was not possible. The consequence of this non-uniformity was to invalidate use of single fractions to predict the digestibility of dry matter in forage plants (Van Soest, 1967).

Stage of maturity was also found to affect the digestibility of dry roughages and silages. Experiments with cattle, sheep and horses showed that digestion tended to decline as crops advance in maturity. This was true with both grass and legume hays. Staples et al. (1951) observed that the protein content of hay was affected by time of harvest. Late cut hay had only 50 to 70 percent as much protein as early cut hay. Dry matter, ether extract, crude fiber and nitrogen free extract were found not to be affected by harvest time. However, the time of cutting of hay affected the apparent digestibility of the nutrients in the hay. Protein digestibility showed the largest decline with advanced maturity of hay, while digestibility of dry matter, ether extract, nitrogen free extract and fiber were slightly reduced when late-cut hay was compared with an early-cut hay.

The effect of maturity on in vitro digestibility of plant parts (leaves, heads and stems) in timothy, orchard, brome, reed canary, tall fescue, and mountain rye grasses, was studied by Pritchard et al. (1962). All grasses were cut at nine separate stages of maturity. In vitro digestibility was lower for stems than for leaves. At the same time, in vitro digestibility declined more rapidly with progress in maturity than did leaves. Due to species difference in rate of maturity, cutting date was not found to be a good indicator of maturity of grasses.

Johnson and White (1965) also concluded that since the contribution of leaf, stem, and sheath and head portions of grasses after heads emerged were 11 to 12 percent, 50 to 60 percent and 20 percent of the total dry matter, respectively. Thus, it might be that digestibility changes in grass stems determined to a certain extent the digestibility of the entire plant (Cook and Harris, 1950). Lignification of the leaves, sheaths, and stems followed digestibility patterns in which stems of lowest digestibility were more lignified than leaves or sheaths. Species variation in rate of maturity was also observed.

However, when Hogan et al. (1967) harvested one half of each plot of timothy hay on June 15, and the second half on June 25, significant differences were found in forage intake level between harvest dates. Harvest date had a significant difference in forage crude fiber content and energy digestibility when harvest date was delayed. Digestibility of energy was significantly decreased ($P < 0.01$) regardless of feeding level. The difference between the energy digestibility coefficient was 3.3 percent favoring the harvest at an early date.

Digestibility of corn silage with dairy cows was found to be 62.7 percent at dent stage and 56.7 percent at mature stage (Byers and Ormiston, 1964). While Bryant et al. (1965) obtained dry matter digestibility coefficients of 66.7 percent and 60.6 percent for corn silage harvested at milk and medium hard dough stages, respectively. However, Coloves et al. (1970) observed that maturity from soft dough through medium hard dough, early dent, and glazed and frosted stages of corn silage exerted no effect on digestibility in steers. Digestibilities of dry matter, gross energy and total digestible nutrients were significantly higher for the two most mature corn silages when fed to wethers.

Neutral detergent fiber (NDF) percentages in anclo clover were determined by Stanley et al. (1968) in a study of maturity effect on hay quality. In young vegetative forage, NDF was less than 40 percent of the total yield, and it increased to 47 percent then to 50 percent during flowering and at maturity stages, respectively. Combined forage production, cell wall and weather data indicated that during wet conditions forage yields increased rapidly; and forage quality as measured by cell wall percentages decreased more rapidly than forage under dry conditions with lower yields.

Stone et al. (1966) observed higher digestibility of early-cut than late-cut alfalfa and red clover-timothy mixed hay which was fed forms of long, chopped, ground and pelleted. All forms of early-cut hay showed significantly higher digestibilities of dry matter, protein and total carbohydrates. Anderson (1976) observed higher total dry matter with delayed cutting of alfalfa; however, chemical data showed that it was due to increased fibrous parts of the plants, namely neutral detergent fiber (NDF) and acid detergent fiber (ADF). It was also noted that crude protein and dry matter digestibilities declined with age of forage.

Cogswell and Kamstra (1976) observed maturity effects on the chemical composition and digestibility of certain range grasses. As maturity advanced, holocellulose content of plants increased. Similarly, hemicellulose increased but less than acid detergent fiber and cellulose. These results agreed with those of Murray et al. (1979). At latter stages lignin content increased the acid detergent fraction more than did cellulose. It was also demonstrated that lignification increased and crude protein and dry matter digestibilities decreased in all grass species with maturity. These results were in agreement with those of Cook and Harris (1968b) who found that in summer ranges, grasses had the lowest protein percentage and highest energy content while shrubs had the highest protein and phosphorous contents as summer advances.

Besides, the digestibility of cellulose decreased with plant maturation. The same decline occurred in the case of hemicellulose, but this fact was not well-recognized because the ready solubility of hemicellulose in dilute acids and bases and its long standing inclusion in the NFE (Van Soest, 1967).

Christiansen (1979) showed forage maturity to be a significant factor in altering apparent digestibilities for most of the nutrients in feedstuffs with lambs. Treatments included two forage types (grasses and legumes) and three stages of maturity. There was no significant difference in apparent digestibility of cell walls between late vegetative and mid-bloom stages. However, the full bloom stage was significantly lower than late vegetative or midbloom stages in cell wall digestibility. This pattern held true for neutral detergent fiber (NDF) and acid detergent fiber (ADF) apparent digestibility as well.

Comparing maturity effects on the apparent digestibility of cellulose, hemicellulose and lignin; Christiansen (1979) observed no significant maturity effects for hemicellulose apparent digestibility between any of the maturity levels. This was in agreement with Van Soest (1967) and Cross et al. (1974). However, maturity significantly affected the apparent digestibility of cellulose in the same pattern as that of cell walls, NDF, and ADF. Lignin apprent digestibility was shown to be significantly higher (23.5 percent) in mid-bloom than in the late vegetative stage (13.9 percent) or full bloom (12.9 percent) stages. This difference could be due to rain damage or heat damage to baled hay. No significant difference was observed between late vegetative and full bloom stages.

It was also observed (Christiansen, 1979) that the apparent digestibility of cell walls, NDF, or ADF was much greater in midbloom grass than in late vegetative or full bloom stages of maturity. However, in alfalfa, cell wall, NDF and ADF apparent digestibility declined as maturity advanced. Lignin in midbloom grass was high in apparent digestibility (37.6 percent). Crude protein was significantly lower in apparent digestibility in diets containing full bloom forage than in diets containing late vegetative or midbloom stages. Crude protein apparent digestibility was not significantly different between late vegetative and midbloom stages. The decrease in crude protein content was relatively small between late vegetative and midbloom stages within alfalfa or grass diets. However, a large decrease in crude protein content for the full-bloom stage resulted in a slightly lower crude protein apparent digestibility in full bloom stage in both alfalfa and grass forage types.

Available carbohydrates digestibility was demonstrated to be significantly lower in midbloom than late vegetative or full bloom stages (Christiansen, 1979). The available carbohydrate difference between late vegetative and full bloom stages was not significant. The principle cause of the significant decrease in available carbohydrate apparent digestibility in midbloom diets, was the significantly low carbohydrate content in mid bloom grass. Even though dry matter and gross energy digestibilities decreased with advancing stage of maturity, differences were not significant.

Murray et al. (1979) found that in all grass species that were studied, the total nitrogen content exceeded three percent (18.8 percent protein) in April, then declined to less than one percent (6.2 percent protein) by the end of the grazing season. Nitrogen levels in desert wheatgrass fell below the maintenance level by early June.

All grass species under consideration provided insufficient protein by August.

Murray et al. (1979) also reported an increase in the percentage of NDF in all species under consideration with plant maturity. Cell content decreased with increased maturity, while NDF increased in the forage. Wheatgrass digestibility (cell wall contents) values were erratic and no trends with plant maturity could be shown, even the NDF percentage was correlated to plant maturity. The rate of decline in cell wall digestibility was greatest in the basin wild rye, followed by desert cheatgrass, squirreltail, needle-and-thread grass, and blue grass. These species became less digestible with increasing maturity. By September, all species except cheatgrass and blue grass were less than 50 percent digestible. The estimated true dry matter digestibility (TDDM) was a measure of the digestible cell contents and digestible liquified cell wall corrected for silica content (Murray et al. 1979). The NDF percentage subtracted from 100 gives the cell content. The digestible cell wall percentage (100 - NDF percentage) minus the silica correction gives the TDDM. TDN or the expected apparent dry matter digestibilities are about 13 units less than TDDM because of the loss of metabolic matter in feces (Murray et al. 1979). The TDDM follows similar trends to digestible cell walls and the rates of decrease are similar. By September, most species were lower than 60 percent digestible. Olsen and Slinger (1968) found that dry matter digestibilities were 72, 63, and 65 percent for mid-July, mid-August, and early September, respectively.

In a comparison study of the nutritive value of forbs, grasses, and shrubs, Cook (1972) and Cook et al. (1977) demonstrated that in range forages the digestibility of protein may vary from 70 percent in early growth to about 10 to 15 percent in the quiescent stages. Thus, it was more logical to evaluate diets of grazing animals on the basis of digestible protein rather than a total protein unless standards had considered the high variability in digestibility of protein as plants mature. The digestibility of gross energy in range forages followed a similar trend, but digestibility of mature forages, even when dry, seldom goes below 45 percent (Cook et al. 1977).

Cook (1972) also observed that grass species declined in digestible protein rapidly and generally fail to meet the lactation requirements at about the time they come into full anthsis. This was a result of a rather rapid loss of total protein. Hence, a more rapid decrease in digestibility of protein as growth advanced. Grasses in general, lost about 75 percent of their protein during the period from early growth to seed formation; on the other hand, browse lost only about 40 percent of their protein during a similar period. As a result, grasses that had matured were considered poor sources of apparent digestible protein.

Shrubs, however, were considered good sources of digestible protein during most of their active growing period; and even after they reached full maturity they continued to meet gestation requirements (Cook and Harris, 1968a).

Forbs were found to be intermediate between browse and grasses with respect to protein content during most seasons. Most forb species failed to furnish adequate digestible protein to meet the requirements of animal gestation after reaching the fruit stage (Cook, 1972).

Since shrubs had high contents of essential oils, resins, or waxes that give high energy content, but their materials were not available for livestock metabolism, neither the grass energy nor the digestible energy of shrubs was considered a good index of true energy values of forages (Cook and Harris, 1968b). Thus, shrubs were not considered good sources of energy, especially after they reached the phenological stage of fruit development. Thereafter, they generally failed to meet the energy requirement for animals in gestation. While grasses were generally considered good to excellent sources of energy primarily because of their high content of cellulose. Even when grasses reached maturity, they seldom failed to furnish the energy requirements of lactation (Cook, 1972; Cook and Harris, 1968b).

However, digestion trials carried out by Biswell et al. (1945) showed that older, more mature, fall and winter shrub material was less readily digested than newer, tender, spring growth. Thus, protein deficiency in the fall and winter might be much greater than shown by routine chemical analysis. While Cook and Harris (1968a) demonstrated that the change in the chemical content of forage plants on winter ranges was small during the grazing season. Browse showed the least seasonal changes and grasses the greatest.

Van Soest (1964) concluded, in a review of chemical composition of forage plants, that digestibility variations in forages due to maturity changes was a result of quantitative changes between non-digestible and readily digestible chemical components for all forage plants. As plants mature, lignin and fiber increase while crude protein and other cell wall components decrease. These conclusions were in agreement with those of Crampton and Forshaw (1939); and Crampton and Jackson (1944) who showed that young pasture was much more digestible than the same pasture at later stages of growth. Young plants differed from those which were more mature by being tender and having much less fiber and lignin on dry basis than later stages of maturity. This was in agreement with Cross et al. (1974) who observed that immature forage digested 68 percent more rapidly than mature forage fiber. Immature forage cell walls, hemicellulose and cellulose digested faster than these components in mature forages ($p < .01$). The digestibilities of cell wall, hemicellulose, and cellulose of immature forages were 76 percent, 75 percent, and 85 percent, respectively. While the digestibilities of these components of mature forages were 52 percent, 50 percent, and 64 percent, respectively. During growth the hemicellulose and particularly the xylan fraction which contained uranic acid in its side chain became progressively less digestible (Waite et al. 1964).

Cross et al. (1974) also observed that the digestibilities of cellulose were different for species ($p < .05$), stage of maturity ($P < .01$), and fiber preparation ($P < .01$). Young unlignified forage cell walls were light and had a high bulk volume that decreased with age as cell walls thickened and became more lignified (Van Soest et al. 1978). Feed volume and cell wall content have been factors associated with lower intake of forage. The association of lignin with intake might be confined to the secondary association with date-of-cutting studies, where lignin and cell wall increased with plant maturity while intake and digestibility declined (Van Soest et al. 1978). Such associations disappeared when forages of similar maturity were collected and compared (Van Soest, 1965a).

Hardison et al. (1957) found that dry matter in the bottom portion of the alfalfa plants was only 87 percent digestible as that of the top portion. As the stage of maturity advanced, digestibility of dry matter in the base decreased at a rate of 0.6 percent per day, but digestibility of the top portion remained unchanged.

The effect of variation in chemical composition of the forages on organic matter digestibility was investigated by use of correlation and regression analysis (Forbes and Garrigus, 1950a). Organic matter digestibility was used, rather than dry matter since a widely variable content of ash was noted in the feces; animal grazing young forages were likely to have 20 to 25 percent ash in their feces while feces from animals grazing more mature forages usually contained 12 to 5 percent ash (Forbes and Garrigus, 1950a).

Murray et al. (1979) demonstrated that forage moisture, certain mineral components, and certain ratios exhibited trends with advancing plant maturity. Forage moisture, N,P,S,K,Zn,Cu,N:S, and K/(Ca + Mg) declined. The Ca - P ratio increased, even though the Ca contents were not related to forage maturity.

In most plant species studied by Murray et al. (1979) Ca, Mg, Na, Ma, and Fe contents were not related to date of maturity.

Schneider et al. (1950) showed that the apparent digestibility of a feed was influenced by its proximate analysis. Hence, that feed of the same name but different in chemical make-up would show different digestibility. This factor would be important with all feeds, but certainly notable with forages where chemical composition changed largely with stage of maturity, although the feed might still be called the same name.

Hence, the precision of equations used to predict forage digestibility from chemical composition should be negatively affected by changes in forage maturity.

Effect of Forage Type on Digestibility of Feedstuffs. The seasonal variation of forage nutrient quality on rangelands was closely related to plant species characteristics and the growth stage of the vegetation (Cook et al. 1977). The kind of forages (legumes versus grasses) also accounted for variations in reported results of digestibility (Schneider and Flatt, 1975). Separate equations were used for the forage type and were shown to be significantly different (Tomlin et al. 1962). It was also shown that lignin was significantly correlated to in vivo cellulose digestibility for grasses and legumes.

Johnson et al. (1962) reported high correlations (R = .95) for the in vitro cellulose digestibility with in vivo measurements for grasses. When alfalfa data were included, correlations dropped (R = .86). Regression equations were developed using in vivo and chemical data as independent variables used were extremely variable between feed classes suggesting differences between grasses and legumes.

Rohweder et al. (1978) reported high correlations between acid detergent fiber concentration and in vitro digestible dry matter in alfalfa, temperate grasses, and subtropical grasses. However, prediction equations for digestibility of dry matter from ADF percent were different between alfalfa and grasses (Table 1).

TABLE 1 Regression Equations for Predicting In Vivo Digestible Dry Matter (DDM) From Acid-Detergent Fiber (ADF) and Dry Matter Intake (DMI) from Neutral-Detergent Fiber (NDF), Correlation Values (R) and Standard Deviation (SD) Values for Alfalfa, Temperate Grasses and Subtropical Grasses

Description		R^2 (%)	SD^2
1. In vivo digestible dry matter (DDM)			
a. Alfalfa n = 40			
North only	DDM = 71.1 + .593 ADF% - .0221 ADF%^{2}	71	3.61
North and South	DDM = 65.5 + .975 ADF% - .0277 ADF%^{2}	68	3.50
b. Grasses			
Temperate	DDM = 41.9 + 2.15 ADF% - .0433 ADF%^{2}	53	4.98
With aftermath	DDM = 49.7 + 1.67 ADF% 0 .0364 ADF%^{2}	46	5.23
With pangolagrass	DDM = 44 + 2.01 ADF% - .0412 ADF%^{2}	49	4.96
With bahiagrass	DDM = 34.8 + 2.56 ADF% - .0491 ADF%^{2}	58	4.81
With bermudagrass[b]	DDM = 59.2 + 1.32 ADF% - .0338 ADF%^{2}	48	5.74
2. Dry matter intake (DMI)			
a. Alfalfa			
North only	DMI = 86.7 + .425 NDF% - .0164 NDF%^{2}	56	6.13
North and South	DMI = 39 + 2.68 NDF% = .0410 NDF%^{2}	39	7.95
b. Grasses			
Temperate	DMI = 95.3 + 6.70 NDF% - .0668 NDF%^{2}	89	3.04
With aftermath	DMI = 118 + 7.41 NDF% - .0723 NDF%^{2}	56	6.79
With pangolagrass	DMI = 92.5 + 6.39 NDF% - .0623 NDF%^{2}	64	6.75
With bahiagrass	DMI = 54.8 + 1.22 NDF% - .0176 NDF%^{2}	58	7.64
With bermudagrass	DMI = 123 + 1.22 NDF% - .00385 NDF%^{2}	35	8.71

[a] Standard deviation from regression.

[b] 'Suwannee' bermudagrass (adapted from Rohweder et al. 1978).

Crude protein was correlated with dry matter digestibility and with its own digestibility in legumes; however, it did not estimate digestibility in grasses satisfactorily (Martin et al. 1975).

Correlations between holocellulose and the in vivo digestibility of organic matter in grass and legumes were determined by Gaillard (1962, 1966). Low correlations for both chemical fractions were observed when forage types were not distinguished. However, high, significant correlations were shown when forage groups were separated. Gaillard (1962) proposed that the differences between forage types were mainly due to digestibility differences between forage hemicellulose, since holocellulose contained a considerable amount of hemicellulose. These differences were possibly due to differences in the structure of hemicellulose of the different types of forages.

Gaillard (1965) checked his suggestion by a study of the monosaccharide composition of the three main hemicellulose polymers (the linear polymer from hemicellulose A and the linear and the branched polymers from hemicellulose B fraction) from Gramineae and Leguminosae. Distinct structural differences were found between corresponding polymer fractions from each group, especially in linear xylan from the hemicellulose A fraction and in the branched polymer form the hemicellulose B.

The action of rumen microbial enzymes on the isolated polymer fractions of hemicellulose, from grass and clover was studied in vitro (Gaillard et al. 1965). The three polymers from grass were hydrolyzed at a rate higher than that of the corresponding polymers from clover. While the branched B polymers from both grass and clover were the most resistant to action of the enzyme. The rate of hydrolysis of the linear A polymers was somewhat greater and the linear B polymers were degraded the most rapidly. Therefore, the hemicelluloses from roughages were better digested when they contained more of the linear B polymer. It was also found that the ratio of hemicellulose A to B differs between various plants at different stages of maturity (Gaillard, 1966).

Legumes were characterized by low content and digestibility of hemicellulose, while grasses were high in both respects (Sullivan, 1966; Van Soest, 1967). Individual regression slopes did not reveal these differences. While grasses and legumes tended to have similar cellulose content, grasses may contain up to four times the amount of hemicellulose found in legumes. The use of cellulose to estimate structural carbohydrates was particularly dangerous when applied in mixed species of plants (Van Soest, 1967).

The hemicelluloses were found to be lower in legumes than in grasses, when expressed either as percent or dry matter or in relation to cellulose (Sullivan, 1966). There were also significant species differences in hemicellulose content among grasses, but there might be a higher ratio of hemicellulose to cellulose in Kentucky bluegrass and fescue than in other grasses. Sullivan (1966) reported a higher ratio in the samples of feces in comparison with the corresponding forages, indicating a lower digestibility of hemicellulose than that of cellulose.

The correlation between percent hemicellulose and the digestion coefficient of dry matter was significant for alfalfa (-.59), orchardgrass (-.48), and highly significant for timothy (-.80). The hemicellulose: cellulose ratio (H:C) was positively correlated with digestibility in many species and in the total population, except for timothy (Sullivan, 1966).

Differences in fiber digestibility between grasses and legumes, including fractions of hemicellulose, cellulose, neutral detergent fiber (NDF), acid detergent fiber (ADF), and crude fiber, were observed (Van Soest, 1964; Donker et al. 1976).

Christiansen (1979) observed highly significant apparent digestibility differences between forage types for nearly all of the fibrous components. Cell walls, NDF, ADF and cellulose were shown to be more digestible in grasses than alfalfa ($p < .01$). Hemicellulose was also found to be more digestible in grasses than alfalfa by sheep, but was not significantly different in digestibility. These results were in agreement with results obtained by Moir (1972) who reported that on the average grass cell walls were 40.0 percent digestible versus 19.8 percent digestibility for legume cell walls of temperate and tropical species of grasses and legumes fed to sheep.

Christiansen (1979) also observed a considerable amount of variability between lignin digestibility coefficient within and between forage types. Grass lignin was shown to be more digestible (25.4 percent) than alfalfa lignin (8.2 percent) for all maturity stages. The cell walls digestibility in alfalfa followed the classic pattern by decreasing with increasing lignin content. However, the digestibility of grass cell walls closely followed the digestibility pattern of lignin. Van Soest (1962) reported marked differences in the relationship of lignin and digestibility in plant species, particularly between grasses and legumes. Correlations between lignin and digestibility for grasses, legumes and both forages combined were -.82, -.74, and -.40, respectively.

Alfalfa had a higher lignin content than grasses of equal digestibility. Such differences might be explained by supposing grass lignin to be combined with carbohydrates in a way to cause more inhibition of digestion (Van Soest, 1964). But, grass lignin was more dissolved than that of alfalfa. The ratio of lignin to cell walls in alfalfa was greater than in grasses, thus higher digestibility of the grass cell walls (Keys et al. 1969).

A greater proportion of total grass lignins was dissolved by alkali than with lucerne lignins, but digestion increased this proportion with both species. Compared with the grass alkali lignins, the lucerne lignin had more total but less aromatic protons (Gordon, 1975). The correlation between amount of lignin in the cell wall and rate of cell wall digestibility was reported (Smith et al. (1972) to be -.89 for grasses but only -.35 for legumes. Thus, legume lignins appeared to have a smaller effect on digestion of cellulose and hemicellulose than did grass legumes.

Reid et al. (1962) conducted in vitro fermentation for cellulose digestion and gas production at 12, 24, and 36 hours. When the in vitro fermentation was used, alfalfas were characterized by a high initial gas production followed by a leveling off, while grasses ferment at a slower rate and did not level off to the same extent.

Legumes were expected, because of a large available fraction (about 60% dry matter), to have a rapid burst of fermentation followed by a leveling off as soluble cell contents were used up (Van Soest, 1965a). With grasses, a slower start was observed because of the smaller quantity of highly digestible cell contents, and the fermentation continues steadily as the lightly lignified holocellulose continues to ferment at an appreciable rate.

Keys et al. (1969) and Donker et al. (1976) observed no significant differences between grass and alfalfa dry matter apparent digestibilities by sheep but showed significantly higher apparent digestibility for crude protein of alfalfa. While Christiansen (1979) found that crude protein, available carbohydrates, dry matter and gross energy were to be significantly more digestible in alfalfa than in grass.

The digestibility of proximate nutrients of forage by horses was studied by Fonnesbeck et al. (1967). Pennscot red clover, Atlantic alfalfa, Timothy, Lincoln brom grass, Reed Canarygrass, and Alta fescue hays were evaluated in one experiment. In a second experiment, Atlantic alfalfa, Lincoln bromgrass, Reed canarygrass, orchardgrass, Alta fescue, and Midland bermuda grass hays were evaluated.

The legume forages contained significantly ($P < .01$) higher digestible dry matter and TDN (Fonnesbeck et al. 1967). Alfalfa hay had lower digestible crude fiber and digestible ether extract contents than all other forages. The bromgrass had the most digestible crude fiber content ($P < .05$).

Results reported by Fonnesbeck et al. (1967) suggested that there were among and within plant species differences in digestibility of forages when fed to horses. The nutritive value of legume hays was superior to all grass hays studied. The Nutritive Value Index was highest for red clover (68.0), followed by alfalfa (56.8 and 62.5), timothy (52.8), bromgrass (48.1 and 48.8), canarygrass (46.9 and 46.0), orchardgrass (45.2), bermuda grass (44.0), and fescue (36.8 and 44.6) in both experiments.

The digestibility of Sudan grass was shown to be higher than that for timothy and equal to that of barnyard millet for sheep (Lindsey et al. 1917). The in vitro cellulose digestibility of bromgrass was found to be 52.9 and 43.1 percent for two stages of maturity. While in vitro cellulose digestibility for orchardgrass was 66.3 and 53.3 percent for the two stages of maturity (Quicke et al. 1959).

The percent of hemicellulose and cellulose was significantly ($P < .01$) correlated in every plant species studied except Reed canary grass and Kentucky bluegrass, and in all total samples (Sullivan, 1966). These results suggest that the species of plant was an important factor in determining the proportions of the different cell wall constituents, especially the proportion of lignin to the structural carbohydrates.

The interrelationship between intake, digestibility, and chemical composition were highly species oriented (Van Soest, 1965a). Tall fiscue was consumed more when mature. Results with two different sets of alfalfa from Utah and West Virginia agreed in that there was not a consistent relationship between intake and digestibility or chemical composition.

Horses consumed significantly ($P < .05$) greater intake of legume than of grass hays when fed ad libitum (Fonnesbeck et al. 1967). Rohweder et al. (1978) used NDF to estimate voluntary intake which was a function of the rate of digestion, that in turn affected the rate of passage and hence the amount of forage the animal can consume.

Different equations were reported for different types of forages (Table 2).

Comparing alfalfa to a mixture of weed plants, Martin and Andersen (1975) found that the dry matter digestibility was not different, but the weeds contained more NDF and less ADL and crude protein than alfalfa. Thus, while the weed mixture contained more fiber, this fiber was less lignified and more digestible than the fiber of alfalfa. Ten out of the twelve weeds studied had higher digestibility than that of oats forage.

Linn et al. (1975) reported that the digestibility of dry matter and crude protein of aquatic weeds (Myriophyllum exalbesins Fern) and (Potamogeton pectinatus L.) were lower than those for dehydrated alfalfa.

Browse species on all ranges were higher in protein, calcium, phosphorus and lignin, while grasses were higher in crude fiber, cellulose, and energy-yielding components (Cook and Harris, 1968b). Generally, forbes were intermediate to browse and grass in nutritive content in the spring and summer ranges.

Legume forage required as much water per unit of dry matter for ingestion as the grass forage, but because of the higher digestibility, more water was absorbed from the intestines and less water was excreted in feces of horses (Fonnesbeck, 1968). A greater volume of urine was excreted from horses consuming legumes. The ash content had an apparent influence on water intake and water excretion. Thus, kinds of forages, grain mixtures, hay-grain rations, and other environmental factors might also account for a part of the variations in reported results of digestibility of feedstuffs (Schneider and Flatt, 1975).

Animal Effects. Nutrients of various feedstuffs were not equally digested by the different kinds of animals because of the variations in the digestive systems and feeding habits. Herbivores, especially ruminants, digested fibrous feeds more than carnivores or omnivores (Schneider and Flatt, 1975). Horses and pigs digested less fiber than cattle and sheep. Pigs had lower digestive power than ruminants but higher than poultry; however, poultry digested feeds that were low in fiber as well as cattle and sheep (Fraps, 1932). The main variation in the digestibility among animals was usually in the case of roughages because they were higher in fiber content. The ability of ruminants to utilize large amounts of roughages was great and they can consume rations which were only partially digested and still get enough nutrients for body functions. Swine and poultry on the other hand, should have highly digestible rations in order to meet their nutrient requirements (Schneider and Flatt, 1975).

Swine digested some concentrates more and roughages less than cattle. Concentrate digestibility was about 100 percent by swine. Hence, calculating rations for swine could not be based on digestibility trials of sheep or cattle. Calculated digestible crude protein and total digestible nutrients for farm gains shown by Crampton and Whiting (1943) were significantly lower than those tabulated by Morrison (1936), which were largely obtained using ruminant animals (Schneider and Flatt, 1975). Monogastric animals digest more hemicellulose than cellulose (Keys et al. 1969; Fonnesbeck et al. 1974), while ruminants had a great ability to digest more cellulose. The digestion coefficients for hemicellulose were greater than those for cellulose in both swine and rats (Keys et al. 1969). However, in sheep trials, hemicellulose in grasses was more digestible than cellulose while the reverse was true in the case of alfalfa.

Fonnesbeck et al. (1974) compared the apparent digestibility of plant cell wall contents for sheep, rabbits, swine, rats, and chickens. Eleven diets were formulated that increased in cell wall content from 1 to 55 percent. Sheep diets contained 28.7 to 55.0 percent cell wall; rabbits received 25.0 to 55.0 percent cell wall containing diets; swine and rats received 1.0 to 34.3 percent cell wall containing diets; and chickens received 1.0 to 41.9 percent cell wall containing diets. The apparent digestibility of cell wall constituents, cellulose, hemicellulose (Table 3) lignin, and acid insoluble ash, by sheep was 30.0, 40.3, 5.1, and -7.3; by rabbits 16,1, 24.7, -7.4, and -7.4; by swine 30.4, 46.4, 2.0, and -7.7; by rats 20.7, 25.9, -1.2, and 00.1; and by chickens 9.6, 4.2, 5.64, and -5.0 percent, respectively. Cellulose and hemicellulose were partially digested in swine and rats as well as herbivorous animals such as sheep (ruminal digestion) and rabbits (cecal digestion). Chickens digested the cell wall components to a much lesser extent (Table 4). Lignin and acid insoluble ash were found essentially indigestible or nonnutritive matter for all the animals mentioned (Fonnesbeck et al. 1974).

The cell wall carbohydrates were digested by enzymes produced by microflora within the digestive tract rather than enzymes produced by the digestive systems. The differences in digestibility of cell wall carbohydrates among species of animals could be due to conditions favoring or reducing anaerobic bacterial fermentation. Bacterial

TABLE 2 Apparent Digestibility of Hemicellulose by Animals

Diet No.	Diet Hemicellulose Content	Digestibility by species				
		Sheep	Rabbits	Swine	Rats	Chickens
	%	%	%	%	%	%
1	0.4	--	--	67.4	51.8	57.1
2	4.6	--	--	62.5	45.1	24.7
3	7.7	--	--	56.3	44.2	7.4
4	9.2	--	--	53.0	32.2	4.5
5	10.2	37.8	23.3	43.0	28.7	4.4
6	11.4	45.9	26.4	46.4	25.6	1.3
7	12.2	41.7	27.0	43.2	17.3	-7.2
8	14.7	49.8	29.0	--	--	0.4
9	15.3	35.1	21.4	--	--	--
10	16.3	34.7	21.3	--	--	--
11	18.0	37.4	24.7	--	--	--

Adapted from Fonnesbeck et al. (1974)

TABLE 3 Apparent Digestibility of Plant Cell Walls by Animals

Diet No.	Diet Content	Digestibility by species				
		Sheep	Rabbits	Swine	Rats	Chickens
	%	%	%	%	%	%
1	1.0	--	--	66.5	59.4	60.6
2	8.6	--	--	40.4	33.9	22.8
3	15.0	--	--	46.9	31.4	13.6
4	20.4	--	--	37.1	18.8	11.7
5	25.0	--	18.2	31.0	18.2	13.5
6	28.7	29.4	16.5	31.8	20.6	7.1
7	34.3	29.9	18.8	33.8	17.1	5.8
8	41.9	34.8	17.3	--	--	3.9
9	47.0	26.9	16.7	--	--	--
10	50.2	27.2	16.5	--	--	--
11	55.0	28.6	18.0	--	--	--

Adapted from Fonnesbeck et al. (1974)

fermentation of cell wall carbohydrates produced volatile fatty acids namely acetic, propionic, and butyric acids. In addition, this fermentation produced methane and carbon dioxide, with a loss of free energy as heat (Fonnesbeck et al. 1974). Since ruminants pass the fermented diet through the true stomach they could get the energy within the microbial cells as well as that of nutrients in solution. However, microorganisms living beyond the gastric stomach might not be digested and pass in the feces. The organic matter of those microbial cells might reduce the absorbed energy into the animal. The cell wall carbohydrate as apparently digested by rabbits, swine, rats, and chickens might be absorbed at a low efficiency to provide metabolizable energy (Fonnesbeck et al. 1974).

Equines are herbivorous animals which utilized forages as a sole part of their diets. . However, unlike ruminants, results of digestion trials showing their efficiency in digesting the constituents of forages were scarce (Schneider, 1947). This lack of information lead Morrison (1956) to use digestion coefficients obtained from ruminant studies on various feedstuffs that were common to both species as a guide in computing rations for equines.

Vandernoot and Gilbreath (1970) reported that the fibrous portion of feeds was more digested by ruminants than equines. Steers digested all components in grass hay better than gelding with exceptions of protein and NFE. While the components of alfalfa hay were digested to the same extent by steers and gildings, with exceptions of crude fiber and cellulose.

Darlington and Hershberger (1968) observed that horses, apparent capacity to digest dry matter, crude protein, fiber, NFE, and energy was inversely related to the percentage of crude fiber in the diet.

The greater digestion of fiber in ruminants could be due to the slower rate of digestion than in equine and thus fiber was exposed longer to microbial activity (Vandernoot and Gilbreath, 1970). In equine, feed was partially digested in the stomach and small intestines before it went to the cecum and colon (Hintz et al. 1971) where most fermentation occurred. Thus, the prolytic activity of bacteria in the terminal intestine might be more important in the horse than in the steer for maintaining body nitrogen balance when similar diets were offered (Kern et al. 1973).

Even though identical diets were fed to steers and horses, the ingesta entering the equine cecum varied from that entering the rumen of the steer. This variation might partially account for the difference in the digestibility of various components of forages by horses and steers (Vandernoot and Gilbreath, 1970).

Steers' rumen and horses' cecum had similar cellulolytic bacterial count per gram ingesta when oats were fed or not. However, addition of oats to forage diets increased the proteolytic bacterial count in ponies' cecal ingesta but not in the steers' ruminal ingesta (Kern et al. 1973). This increase might suggest that cecal bacteria might have a potential to provide nitrogen to the horses.

Using the Lucas test, Fonnesbeck (1969) found that the crude protein of forage had an average true digestibility of 81.7 percent compared to only 51.2 percent apparent digestibility (Figure 3) while

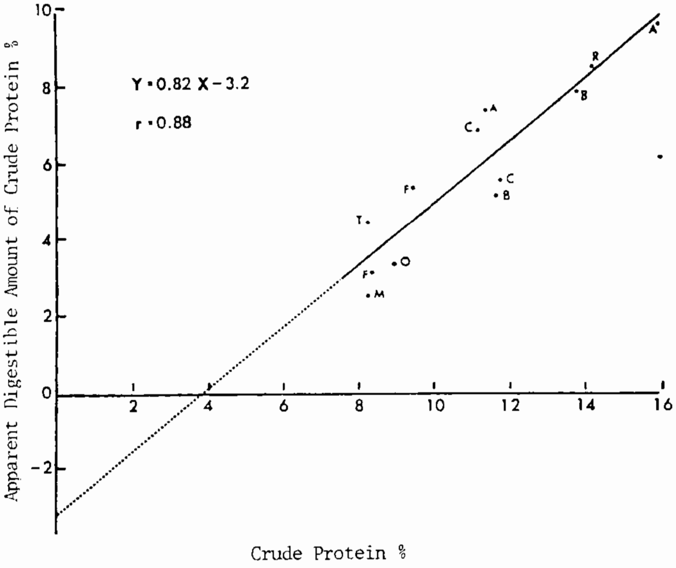

FIGURE 3 Regression of digestible amount of crude protein with the crude protein content of forage. Treatment means (6 trials) are plotted for Atlantic alfalfa (A), Lincoln bromegrass (B), Reed canarygrass (C), alta fescue (F), Midland bermudagrass (M), orchardgrass (O), red clover (R) and timothy (T). (Adapted from Fonnesbeck, 1969)

the average true digestibilities of forage protein estimated by Lucas test for cattle were 87 percent (Colburn et al. 1968) and 93 percent (Van Soest, 1967). The less efficient utilization of protein might be expected in the horse due to the fact that feed protein was digested more directly by enzymes of the intestinal tract, and microbial protein formed in the cecum may not be as efficiently utilized, since enzymes are not secreted later by the large intestine and colon (Fonnesbeck, 1969). The metabolic fecal protein was estimated by regression constant to be 3.2 percent of the dry matter intake (Fonnesbeck, 1969). While that of ruminants was 2.8 percent (Blaxter and Mitchell, 1948).

In vitro studies showed that the rate of digestion of alfalfa was rapid when incubated with inocula from steer rumen or from horse cecum. The rate of digestion of other hays, however, was faster when samples were incubated with inocula from the rumen rather than from the cecum (Kern et al. 1973).

Because of the rumen reticulum that cattle have, they probably digested fibrous forages better than deer of genus Odoceilus (Short, 1963). The rumen population might also adapt to substances which were normally antimicrobial. For instance, while cedar oils inhibited fermentation by the rumen microbes of a steer on an alfalfa corn-concentrate ration, but did not inhibit the microbial activity from a deer adapted to a diet of cedar, leaf spray (Short, 1963).

Sheep and cattle might have different nutrient digestion according to many workers. Others believe that sheep and cattle digest feeds essentially the same assuming that both species have the same way of utilization. Forbes (1950) obtained widely different constants for each species for an equation showing the relationship between protein digestibility and protein content of the dry matter of forages.

Wethers digested more mature corn silage better than steers; hence, data obtained with sheep could not be applied to cattle in all cases (Colovos et al. 1970). There were also significant differences between sheep and cattle in the digestibility of organic matter, crude fiber, nitrogen-free extract, ether extract, and in the TDN contents of dry roughages (Cipolloni et al. 1951). There was also a significant species-by-feed interactions for the digestibility of protein in dry roughages and digestibility of ether extract in concentrates, indicating that cattle digested certain nutrient better in certain feeds and sheep digest them better in other feeds. Cattle tended to digest roughages and silages better than sheep (Bartlett, 1904; Cipolloni et al. 1951). However, Forbes (1950) illustrated that protein of low-protein forages to be better digested by sheep than by cattle and that this difference disappeared with high-protein forages. Cattle digest high protein forage better. These results were similar to those reported by Devendra (1978) who concluded that with decreasing quality of roughages, the digestibility of the fiber component increased, and that the efficiency of utilization was higher in goats than in sheep. Under situations where feedstuffs were high in fiber content, goats could utilize the nutrients much better than sheep or cattle. Sheep also digested low quality grass, hay or low protein better than cattle (Alexander et al. 1962).

Protein was reported to be digested better by cattle than by sheep (Watson et al. 1948), while Swift and Bratzler reported a slight advantage in protein digestion by sheep and higher dry matter digestibility coefficients with cattle than with sheep. Steers had higher digestion coefficients than wethers for all nutrients except for protein in prairie hays (Jordan and Staples, 1951). Crude protein was also more digested by goats than by steers (Byers et al. 1961) although both species digested dry matter, cellulose, and energy of four alfalfa hays to the same extent.

Van Dyne and Heady (1965) developed separate correlations for dietary components of roughage for sheep and cattle because the two species did not select many botanical and chemical constituents to the same degree with decreasing amounts of herbage available. Cook and Child (1977) showed that the various predictor factors varied in accountability of variation in digestible protein between cattle and sheep and among various seasonal range types.

On summer mountain ranges the predictive equation for digestible protein when using total protein and lignin was slightly better than using total protein alone for both sheep and cattle. The variation in Y accounted for R^2 in sheep diet was 0.72 compared to 0.48 for cattle. This result was not expected since sheep diets during the summer varied more in species diversity among forage classes than did cattle diets (Cook and Child, 1977).

Either total protein or gross energy for predictors of digestible energy were highly variable among seasonal range types and between sheep and cattle on different seasonal ranges which varies from 0.10 to 0.70 for R^2 (Cook and Child, 1977).

On Saltbush (Atriplex confertifolia) ranges. The diet of sheep averaged about sixty percent browse and forty percent grass. Cattle on the same range would consume about forty percent browse and sixty percent grass. Composition of the sheep diet contained more digestible protein and phosphorous than the diet of cattle on similar ranges. However, cattle consumed more energy than sheep because cattle grazed more grass (Cook et al. 1977). The same trend was true on summer mountain ranges in Utah (Cook and Harris, 1968a).

Animal preference for certain classes of forages affected the nutrient content of the diet. Both sheep and cattle changed their herbage preference as the season progresses (Cook and Harris, 1968b). Preference for grasses by both species decreased while it increased for browse. Cattle preference for forbes increased during early season and remained intermediate for grasses and browse during the season. While sheep preference for forbes was higher during the whole season.

Generally speaking, diets of sheep were higher in protein, phosphorous, and lignin and cattle diets were higher in cellulose. Sheep digested protein better than cattle but cattle digested cellulose better than sheep. Hence, sheep diets were higher in digestible protein and cattle diets were higher in digestible energy and TDN (Cook and Harris, 1968b).

In vitro microdigestion studies (Van Dyne and Weir, 1964) showed that there was no difference in percent cellulose digestibility (PCD) between cattle and sheep except for alfalfa (Solka-flak) digested with inocula from animals on range. However, in vivo microdigestion showed that cattle had significantly higher digestion than sheep for alfalfa

(Solka-flock). On the range, sheep had higher in vivo digestibilities than cattle for many samples resulting from the fact that sheep grazed higher quality forage than cattle (Cook and Harris, 1968b; VanDyne and Weir, 1964), thus, sheep should have developed a denser and more vigorous microbial population (VanDyne and Weir, 1964). In vivo percent dry matter digestibility for Solka-flock was significantly lower for cattle than for sheep. However, cattle digested significantly cellulose higher than sheep according to lignin ration technique (VanDyne and Weir, 1964).

Bartlett (1904) suggested that if sheep were to be used to determine coefficients for bovines, great care should be taken to select strong animals that were good feeders and would eat coarse fodders readily. Otherwise, results which were too low were likely to be obtained.

Devendra (1978) concluded from a list of reports from tropical conditions that under identical feeding and management conditions, distinct differences existed between goats and other ruminants in the digestibility of dietary constituents (Table 4). Twelve of nineteen references showed statistically significant differences in favor of better digestion by goats, five no differences, and three showed higher digestibility by sheep. Goats differed from sheep feeding behavior and rumination when fed hay, silage, or mature rye grass. The digestion in the goat was essentially dependent on nature of diet, level of feed intake, salivary secretion, pattern of rumen fermentation, and movement along the alimentary tract.

Calculations of efficiencies of energy and protein production in meat and milk production in goats showed that meat production was

TABLE 4 Summary of Digestibility Studies in Goats Compared to Other Ruminants

Species Compared	Location	Diet	Differences in Digestibility	Magnitude of CFD Difference Favouring Goats (%)**	Reference
1. Goats vs Bullocks	Pakistan	Pipal leaves (Ficus religiosa) ad lib.	Higher OMD and CFD by goats	10.2	Hossain (1960)
2. Goats vs Bullocks	India	Bardad leaves (Ficus Bengaisensis) ad lib.	Higher DMD and CFD by goats	9.8	Mia et al. (1960a)
3. Goats vs Bullocks	India	Bardad leaves (Ficus religiosa) ad lib. (i) leaves only ad lib. (ii) leaves + rapeseed cake	Higher DMD and CFD by goats	9.8 4.7	Mia et al. (1960b)
4. Goats vs Steers	Canada	Alfalfa	No differences	--	Byer et al. (1961)
5. Goats vs Bullocks	Pakistan	Bargad leaves (Ficus Bangalensis) ad lib	Higher DMD, CFD and COP by goats	25.5	Hossain (1961)
6. Gaots vs Sheep	India	Grazing + concentrate supplement	Higher cellulose digestibility by goats	16.9	Pant et al. (1962)
7. Goats vs Steers	Canada	Vernal alfalfa bromegrass forage	DCP higher in goats	--	Baumgardt et al. (1964)
8. Goats vs Sheep	Nigeria	Napier grass ad lib (Pennisetum purpureum) 3.6 and 9 weeks growth	Higher DMD and OMD by sheep no difference	--	Ademosum (1970)
9. Goats vs Sheep	France and Guadeloupe	Pangola grass (Digitaria decumbens) 30 or 50 days growth ad lib.	No difference in digestive ability	--	Chenost (1972)
10. Goats vs Sheep	Texas	Roughage Concentrate diet	No differences in DMD	--	Gallagher and Shelton (1972)
11. Goats vs Sheep vs Cattle vs Buffalo	India	Speargrass (Andropogon contortus) + groundnut cake fed on metabolic live weight basis	Goats and sheep utilized nutrients better than cattle and buffalos, however there was no difference between goats and sheep	--	Jang and Majumdar (1972)
12. Goats vs Sheep vs Heifers	Canada	Alfalfa hay ad lib.	Higher cellulose digestibility by goats compared to heifers	24.0	Jones et al. (1972)
13. Goats vs Sheep	Guadeloupe	Hay or silage of rye grass with or without urea and molasses	No differences in digestible ability	--	Geoffrey (1974)
14. Goats vs Sheep	Nigeria	Cocoa husk in concentrate diets based on live weight	Higher CFD by sheep	--	Adeyan et al. (1975)
15. Goats vs Sheep	Trinidad	Napier grass ad lib. (Pennisetum purpureum) 4.5 and 6 weeks growth	Higher DMD and CFD by goats	3.7-12.9	Devendra (1975)

TABLE 4 (CONTINUED)

Species Compared	Location	Diet	Differences in Digestibility	Magnitude CFD Difference Favouring Goats (%)**	Reference
16. Goats vs Sheep	Australia	Casuaring cristata-Heterodendrum oleifoluin woodland community, grazing	DCP higher in sheep	--	Wilson et al. (1975)
17. Goats vs Sheep	Sudan	Berseem hay (Medicago sativa), lokh grass (Dianthum annulatum) and desert grasses (Dactyloctenium aegyplium, Shoenefeldia gracilis. Eragrostis pilosa, Aristida funiculata and Aristida sp.) la lib.	Higher DMD, CFD and CPO by goats	5.4	El Hag (1976)
18. Goats vs Calves	India	Concentrate + Lucerne (Medicago sativa) or Berseem (Trifolium alexandrinum) led ad lib.	Higher DMD and OMD by goats	29.1	Mudgal and Dalgit Kaur (1976)
19. Goats vs Sheep	Malaysia	Guinea grass ad lib. (Panicum maximum var Serdang) 16-19, 21-28, 28-35, 35-42 and 42-49 days growth	Higher DMD and CFD with increasing age of grass by goats	8.6 - 10.9	Devendra (1977)
20. Goats vs Sheep	Australia	Tree leaves A. pendula C. cristata	Higher CFD by goats	6.5^2-3.9^3 6.2^2-9.1^3	Wilson (1977)

* DMD, OMD, CFD and CPO refer to dry matter organic matter, crude protein digestibility, respectively.

** The digestibility units indicated refer only to statistically significant differences.

1 In vitro.

2 Acid detergent fibre.

3 Neutral detergent fibre.

(Adapted from Devendra, 1978)

comparable to sheep and cattle, but with milk production, the efficiency was higher in goats (Devendra, 1975). It was also demonstrated (Gallagher and Shelton, 1972) that efficiency of feed conversion to fiber in goats was 3.7 to 3.2 times higher than that of sheep. The fact that goats had higher digestibility of crude fiber suggested that this would influence metabolizable energy value of feeds. On high fiber diets, the metabolizable availability could be higher with goats than with sheep or cattle (Devendra, 1978).

Wilson et al. (1975) noted that the nitrogen intake was higher in goat's diets than that of sheep. When fed similar diets goats had a lower level of rumen ammonia, blood urea concentration and higher nitrogen retention than did sheep (El-Hag, 1976). Nitrogen balance was significantly higher in goats than in sheep when both were fed Guinea grass at different stages of maturity (Devendra, 1977). It could be concluded that differences in the intake and utilization of dietary nitrogen were associated with differences in digestive efficiency between goats and other species.

Variation of digestibility among breeds of animals and within breeds have been reported in many cases. In comparing zebu cattle (Bos indicus) with European cattle (Bos taurus), Phillips et al. (1960) reported an average dry matter digestibility of 67.7 percent for Zebu and 65.0 percent for mixed breeds grade European steers. Zebu was also found to have shorter rumen retention time. The effect of varying crude fiber contents of fodder on digestibility as found in digestion trials in India, United States, and Europe was statistically compared (Duckworth, 1946). The regression coefficients indicated that in Bos taurus an increase of one percent in the crude fiber content of fodder results in a decrease of the digestibility of organic matter by about 0.9 percent, while in Bos indicus cattle the decrease in about 0.5 percent.

Howes et al. (1963) found that Brahman cattle had higher digestibility coefficients for all nutrients except fat than Hereford cattle. However, only protein digestibility was significantly higher ($P < 0.05$). These results were true whether animals were allowed to eat ad libitum or feed intakes were equalized. Ether extract was better digested by Herefords, but the difference was not significant. Brahman ate more of low-protein feeds and hence more protein intake.

Variations among individual animals with breeds were also reported in cattle and sheep (Bartlett, 1904; Alexander et al. 1962). Where variation among individual animals was slightly greater for sheep than cattle. The greatest difference among horses was in their ability to digest crude protein. Horses differed significantly in their digestion of nitrogen-free extract, dry matter digestibility, and TDN obtained from forages (Fonnesbeck et al. 1967).

Significant or slightly significant differences were observed among sheep and among cattle in digestive power as measured by three microdigestion techniques (VanDyne and Weir, 1964). The range among cattle was greater in late summer than early or mid-summer, while the range among sheep was relatively constant throughout the summer. However, the range among cattle was greater than among sheep for standard forage samples (Solka flock alfalfa), while the range of microdigestion for grazed forages among cattle was comparable to that among sheep.

The degree of between animal variation also differed by type of herbivore (VanDyne, 1962). Many other workers did not note significant differences in digestibility of feedstuffs among species or breeds within species. French (1940; cited in Schneider and Flatt, 1975) concluded that there were no significant differences in digestibility of feedstuffs between Zebu (Bos indicus) and high-grade European cattle (Bos taurus). This was in agreement with Fonnesbeck et al. (1980) who found that there were no significant differences in digestibility of dry matter, gross energy, plant cell wall, cellulose, hemicellulose, neutral detergent fiber, or crude protein between breeds of cattle (Hereford and Charolais heifers). Digestibility trials with Medicago sativa, Cenchrus cilaris, chaffed wheaten-hay, and combinations of these diets, showed no significant difference in the digestion of dry matter of these feeds by cattle and camels (Newman, 1975).

Swift and Bratzler (1959) indicated no significant difference between the digestion efficiencies of cattle and sheep. There were highly significant correlations between cattle and sheep digestion coefficients for dry matter (R = 0.86), protein (R = 0.77), crude fiber (R = 0.95), nitrogen-free extract (R = 0.87), ether extract (R = 0.83), energy (R = 0.85) and TDN content (R = 0.89) when 17 different results were averaged. The wethers, steers, and cows were maintained under the same environmental conditions and fed the same feeds (2 of oat silage, 4 of corn silage, and 11 of coastal bermudagrass hay) (Alexander et al. 1962). These results are in agreement with those reported by Blaxter and Wainman (1961), Langlands et al. (1963) and Swift and Bratzler (1959).

Cipolloni et al. (1951) could not state that sheep had poorer or better digestive powers than cattle or the two species of animals were identical in this respect. It could be possible that significant differences exist between data from cattle and sheep digestion trials. However, the direction and magnitude of these differences may be functions of the feed and of the nutrients involved (Cipolloni et al. 1951). Also individual nutrient species-by-feed interaction has been found. This interaction meant that cattle digest a certain nutrient significantly better than sheep with certain feeds and the reverse was true with other feeds (Cipolloni et al. 1951; Keating et al. 1965; Barnes, 1977).

Age of animal was debated whether it affected the digestibility of feedstuffs or not. Thompson et al. (1972) reported that advancing age and maturation of ruminant digestive processes were accompanied by increased efficiency of utilization of dietary carbohydrates, resulting in increased TDN and net energy per unit dry matter consumed. Young sheep did not digest fiber as well as old sheep (Lindsey et al. 1917).

Raymond et al. (1954) concluded that digestibility increased on an average of one unit for an increase of each year in age of sheep. Crude protein was higher in apparent digestibility in older sheep. This result was not true for all eight experiments run by Raymond et al. (1954). However, the results were surprising since positive nitrogen balance tended to be higher in younger animals (Schneider and Flatt, 1975).

Age of animal did not significantly affect the digestibility of pasture forages with three age groups of grazing sheep (Schneider et al. 1953). The interaction between stage of maturity of grass and age of animal was not significant either. Hence, all of the three age groups of sheep were equally efficient in digesting the forage grazed at all three different stages of maturity.

Smaller ruminants could not eat or digest very much roughages until their digestive tracts (especially the rumens) were developed. The ability of old animals to digest feed was often impaired by poor teeth, which made chewing difficult. Health problem could affect digestibility adversely as age of animal advances (Schneider and Flatt, 1975).

To give an opinion whether there were variations in digestibility of feedstuffs among animal species, it was necessary to give a concurrent definition of the type and number of animals used, age, condition, variability of animals within species, variations in the feedstuffs fed, and level of feeding (Devendra, 1978). Besides, season of the year and the reproductive status of the test animals could affect feed utilization and should be minimized through experiment design (Short, 1963). Increasing replicates could also minimize within species and within feed class variations.

Effect of Physical Form of Feed and Processing on Digestibility of Feedstuffs. Change in the physical form of feedstuffs might influence the digestibility of the nutrients in feedstuffs. Moreover, the methods by which feedstuffs were handled exert a great effect on their digestibilities.

When fresh grass was offered to sheep, Osuji (1973) found that the rate of dry matter intake was slow even though they eat wet matter rapidly. This slow rate was mainly due to the high moisture content of the grass which was ingested. The energy cost of eating (Calories per gram dry matter) the same grass was about twice as great when fresh than when it was given in a dry form. The work of digestion involved in handling the bulky fresh grass might account for the high fraction of the total heat increment of feeding observed in ruminants (Osuji, 1974).

Drying of green forage was most common and may not lower digestibility much if there was no waste in leaves and if fermentation was prevented during the drying process. But there would always be losses of finer and more nutritious parts during and after drying process. Moreover, fermentation and leaching will remove nutrients and hence, digestibility was lowered. More energy was needed to digest dry forages than green forage (Schneider and Flatt, 1975) and concentrates (Young, 1966). The storage of dry feedstuffs for many months, even under favorable conditions, decreased their digestibility (Schneider and Flatt, 1975).

Under intensive feeding conditions, however, the greater part of the ration carbohydrates might be in the form of starch. The extent of fermentation of a particular carbohydrate would depend on the ease with which it could be attacked by microbial enzymes and its rate of passage through the rumen (Hobson, 1969). The rate of passage might depend on the physical nature of the diet and the way in which it was fed. The extent of fermentation depends on the solubility of that carbohydrate. In plant materials the availability of even soluble carbohydrates may depend on their position in the plant material and on the degree of lignification. The ease of hydrolysis and solubilization of polysaccherides also depended on the treatment of feed. Crushed starch granules were more easily attacked than whole starch granules, and a finely chopped hay would present a larger surface area for cellulolysis than would long-fiber hay (Hobson, 1969).

The first step in producing food or feed from its raw source was to isolate certain part or parts to be fed. This part was usually changed during isolation, or was subsequently altered to make it more useful as a feed ingredient. Certain changes were employed to improve the keeping quality or to make the feed physically compatible with other ingredients in the ration (Harris et al. 1968b).

Feed processing could be physical and/or chemical. Physical alterations resulted from things like moisture addition or removal, heat, pressure, agglomeration, and particle size reduction. Chemical changes might include structural changes in the starch and disrupting the protein matrix, resulting in changes in digestibility and metabolic and products (Ensminger and Olentine, 1978). Feed processing referred to performing all the operations necessary to achieve the maximum potential nutritive value of feedstuffs (Ensminger and Olentine, 1978).

Processing methods might be classified as follows (Ensminger and Olentine, 1978; Harris et al. 1968b):

1. Mechanical: dehulling, extracting, grinding, rolling (dry and steam).
2. Heat treatments: dry heat process (cooking, exploding), flaking (steam flaking and pressure flaking), pelleting

(crumbling), moisture alteration (bran mash, drying, high moisture grain), reconstituted grain, watered feeds.

3. Blocks.
4. Liquid supplements.
5. Fermenting.
6. Hydroponics (sprouted grain).
7. Unprocessed (whole) grains.

Particle size was an important physical characteristic of fiber. Reduction of particle size would be a promising method for upgrading forage quality. It was generally observed that the lower the quality of a forage, the greater the nutritive advantage gained by reduction of its particle size (Donefer, 1972). Finer grinding increased the possibility that fiber particle will flow with liquid while coarser fiber would tend to mat and become a block through the filtration effects (Van Soest and Robertson, 1976). Fine ground fiber could pack more densely and therefore, has a reduced bulk effect. These filtration and bulk effects became the mechanism for differential passage of residues through the digestive tract.

Upon grinding, digestibility of hay was lower than that of long or chopped hay. Pelleted feedstuffs were first ground then pelleted. Hence pelleting had the same effect on digestibility of feedstuffs as grinding. In mixed rations where a forage was supplemented with a whole or ground, high energy feed such as corn or barley, the crude fiber digestibility was depressed by pelleting (Schneider and Flatt, 1975).

The digestibility of the entire ration, however, was often not affected or might be slightly higher than unpelleted diets (Campling et al. 1963; Anderson et al. 1975; Johnson et al. 1964; Waldo et al. 1971). Moore (1964) described the following significant changes in ruminant digestive processes as a result of feeding ground or pelleted forages:

a. Prehension (Jensen et al. 1962; Jorgensen et al. 1978; Sudweeks and Ely, 1979; Sudweeks et al. 1979) and rumination time was reduced (Van Soest, 1976).

Kick et al. (1937) found that steers required for the prehension of equal amounts of whole hay, two inches cut and one-fourth inch cut, and ground hay, 153, 130, 90 and 78 minutes, respectively. Rumination time was 402, 437, 418, and 227 minutes, respectively. Horses also consumed the pelleted ration more rapidly than the meal (76.7 vs 107.9 minutes; Ott, 1972).

b. Saliva secretion was reduced. Ground or pelleted forage results in more rapid comprehension with less mustication; which results in less salivation with less secretion or buffer salts into the rumen. Since the feed particles were fine, there was less rumination and probably less stimulation of saliva secretion. Balch (1958) showed a three-fold increase in saliva secretion during mustication and swallowing of the same weight of hay as compared to concentrate.

c. pH of rumen contents decreased (Qrshov et al. 1974) resulting from rapid fermentation that lead to rapid production of organic acids. There was an increased concentration of volatile fatty acids (VFA) and a consequent lowering of pH further intensified because of the lower amount of buffer from saliva being present.

Rumen pH was reduced from 6.9 to 6.0 when dairy cows were fed dehydrated alfalfa pellets as compared to alfalfa hay as the only feed

(Hinders et al. 1961). Cullison (1961) fed rations containing 30 percent constal bermuda grass (Cynodon dactylon (L) pres.) hay in the form of long, ground and pelleted feed and found that pH was lower (5.22) in the animals fed pelleted ration than those fed long hay (6.28). Providing straw to animals receiving pellets increased pH from 5.22 to 6.45. This change in pH might be due to the increase of salivation due to stimulation of rumination.

d. Rate of fermentation in the rumen was increased because within the reticulorumen, fine particles of feeds were easily wetted and there were more of bacterial attack, hence a more rapid fermentation. Disappearance of dry matter was found to be more rapid after feeding pelleted forages (one and half hours) in comparison with coarsely chopped forages (four hours) (Meyer et al. 1959a).

e. Concentration and proportion of volatile fatty acids (VFAs) increased the proportion of propionic acid to acetic acid in the rumen also increased at one and a half hour and four hours after feeding either ground or pelleted forage in comparison with either chopped or long forage (Van Soest, 1955; Moody, 1962). Generally, propionic acid increases upon feeding ground forages (Qrshov et al. 1974).

The volatile fatty acid concentrations (μ moles/ml of rumen fluid) were 51, 80, 44 for acetate; 8, 23, 12 for propionate; and 10, 14, 7 respectively for butyrate for diets of corn silage that was chopped into 0.62, 1.27, and 1.91 centimeter (Sudweeks et al. 1979). The concentration of each acid was highest on the 1.27 centimeter cut silage, followed by 0.62 and 1.91 centimeter cut diet. However, Jorgensen et al. (1978), ensiled a second alfalfa harvest that was chopped at three particle sizes. The silage was fed with 40 percent concentrate to lactating cows. No difference in VFA production acetate: propionate ratio, or milk fat percentage were noted that could be attributed to particle size. Moe and Tyrrell (1977) found, however, that milk fat was reduced upon feeding diets containing 45 percent corn grain (whole, cracked, or ground), 40 percent timothy hay, and 15 percent grain mix (protein, minerals, and vitamin mix).

f. Rate of passage was increased when ground or pelleted forages were fed (Osuji, 1973; Blaxter et al. 1956; King et al. 1962; Meyer et al. 1959a; Ott, 1972). Since gound and pelleted forages had finer particle size than long or chopped hays, rate of passage from the reticulo-rumen was enhanced; and therefore, the amount of digestion was lower especially that of cellulose and crude fiber fractions. Coarse particles tended to pass through the digestive tract slower than fine particles, and elimination of coarse fiber might reduce the differential sorting of feed residues (Moore, 1964).

The processing of grain, particularly small grained cereals, appeared to reduce tactile stimulation of the rumen, which in turn reduced the rate of rumen fluid passage and restricted intake (Weston, 1974).

However, plant cell wall was the factor most highly related to animal efficiency. That was because plant cell wall determined intake, and the level of intake above maintenance was the largest single factor influencing efficiency (Van Soest, 1976). The effect of cell wall upon intake was not linear but decreased, increasingly as cell wall of a feedstuff increased. The level of cell wall intake affected the rate of passage and rumination, which constitute energy losses. Increased passage as a result of intake of fiber caused a decline in digestibility with level of intake expressed mainly in the fiber fraction.

The combined effect of increased rumination, lowered fiber digestibility at productive level of feeding were responsible for the lower efficiencies of high cell wall forage. Grinding or pelleting dried forage, can help eliminate the reduced efficiency due to high cell wall content by reducing rumination and increasing intake (Van Soest, 1976). However, grinding did not eliminate the decline in digestibility of the fibrous fraction but may actually increase it. Animal studies showed that fine grinding of the fiber increased the feed density and altered passage and the character of the gastro intestinal fermentations (Moore, 1964). Grinding of wheat bran decreased its bulk volume primarily through collapse and demolition of the cell structure. Hydration capacity was a more complex function of the surface area, which was increased upon grinding, and the interior cell space, which was decreased upon grinding (Van Soest, 1974).

Slinger (1972) fed pelleted wheat bran and shorts to rats. Results showed a marked increase in feed intake, which led to increased weight gain and decreased feed per gain ratio. Part of this improvement was probably due to higher bulk density of feed with less amounts of time and energy expended for comprehension of feed (Jensen et al. 1962). Olsen and Slinger (1968) showed that when wheat bran was pelleted and reground to the consistancy of mach, feed intake, weight gain, and protein and amino acid digestibilities were markedly enhanced in rats.

g. Dry matter digestibility was depressed especially that of the crude fiber fraction. However, very fine grinding increased cellulose digestibility in vitro but decreased it in vivo (Minson, 1963). Blaxter and Graham (1956) reported decreased digestibility of dry matter, crude fiber, nitrogen free extract, crude protein and cellulose when fed at 600 grams per day and at 1500 grams per day of pelleted (medium and finely ground) compared with chopped hay. The degree of fines of ground feedstuffs could be responsible for the main variation in results among researchers (Blaxter and Graham, 1956; Rodrigue and Allen, 1960). Feeding lactating cows ground or pelleted forage as the only feed in comparison with long or chopped forage, resulted in increased dry matter intake, increased milk production, decreased milk fat percentage, decreased digestibility of crude fiber, and increased rate of passage of Cr_2O_3 (Keith et al. 1961).

Christiansen (1979) showed that pelleting the diet significantly lowered the apparent digestibility of cellulose, lignin, cell walls, NDF and ADF. Hemicellulose apparent digestibility was not significantly affected by pelleting, though hemicellulose values were lower in pelleted diets. The apparent digestibility of ash was also significantly lowered by pelleting. This low value was not expected since the significant digestibility difference was not shown for the soluble ash fraction between texture levels (Table 5).

Digestion of dry matter, organic matter, crude protein, and nitrogen free extract was not affected by pelleting for horse feeds (Haenlein et al. 1966). This was in agreement with results reported by Ott (1972) who also found that the digestion of ether extract was

TABLE 5 Treatment Means of Apparent Digestion Coefficients (Texture)

	Cell Content				Cell Wall Constituents									
Treatments	Crude Protein (%)	Available Carbohydrate (%)	Soluble Ash (%)	Total Lipids (%)	Cellulose (%)	Cellulose (%)	Lignin (%)	Acid Insoluble Ash (%)	Cell Walls[a] (%)	Neutral Detergent Fiber (%)	Acid Detergent Fiber (%)	Ash (%)	Dry Matter (%)	CE (%)
Texture														
Coarse	62.1^{b}	80.9^{b}	50.9^{b}	45.3^{b}	59.3^{f}	53.3^{b}	20.4^{f}	-11.2^{b}	44.4^{b}	45.7^{b}	44.6^{b}	39.9^{f}	61.5^{b}	61.4^{b}
Pelleted	64.0^{b}	82.8^{b}	54.4^{b}	44.3^{b}	46.2^{g}	51.7^{b}	13.1^{g}	9.5^{b}	42.0^{c}	41.6^{c}	39.6^{c}	47.1^{g}	61.2^{b}	60.8^{b}

[a] Plant cell wall as determined using detergent procedures by Fonnesbeck and Harris (1970a).

[b,c] Means of the same nutrient component and the same factor with the same superscript are not significantly different; $P < .05$

[d,e] Means of the same nutrient component and the same factor with the same superscript are not significantly different; $P < .01$

[f,g,h] Means of the same nutrient component and the same factor with the same superscript are not significantly different; $P < .001$

(Adapted from Christiansen, 1979)

more digested in the pelleted ration. Crude fiber was significantly decreased by pelleting horse rations (Haenlein et al. 1966). This decrease in crude fiber digestibility and the variance of Cr_2O_3 excretion, which had been related to the different forms of hay, suggested that the pelleted alfalfa moved through the digestive system more rapidly than loose hay.

Although total TDN of the hay was apparently not influenced by pelleting, the increased consumption resulted in an increase in the nutritive value index. Hence, the pelleted and wafered hay had a greater value to the horses on a free-choice basis (Haenlein et al. 1966). The apparent digestibilities of crude protein and available carbohydrates were shown not to be significantly affected by feed pelleting (Christiansen, 1979). That could be due to the fact that crude protein and available carbohydrate digestibilities were primarily affected by a change in the crude protein and available carbohydrate composition of the diet only.

Allerd et al. (1957), noted a growth response to pelleting even when the pellets were ground to a particle size and density similar to mash in rat diets. Thus, some chemical change due to pelleting as the major beneficial effect could be postulated. However, there was no improvement in protein digestibility when cereal grains were pelleted and reground (Olsen and Slinger, 1968). Grinding was found to increase the nutritive value of rice straw (Willis et al. 1980) by apparent disrupting the encrusting materials such as lignin, and allowing micro-organisms direct access to the cellulose fibers (Wainman and Blaxter, 1972). Grinding and pelleting mature grasses increased by 47 percent and digestibility of dry matter by 27 percent. However, reduction of the bulk factor by mechanical grinding increased the requirement for dietary nitrogen (Minson and Milford, 1968).

The theory of incrustation had been supported by evidence that ball milling of lignified tissue greatly increased the in vitro digestibility by cellulose (Dehority et al. 1962). Explanation of this phenomenon on the basis that milling broke away incrusting lignin did not allow for the very probably degradation of carbohydrates by ball milling. Ball milling of cotton, which had no lignin, greatly increased the rate of digestion by cellulytic organisms (Van Soest, 1969). Very fine grinding by ball milling also exposed degraded cellulose to attach by B-glucanase. Extensive milling reduced chain length, and was a method of degrading cellulose and separating it from lignin (Van Soest and Robertson 1976). Harkin (1973) used ball milling to prepare lignin without the use of harsh treatment of hydrolytic reagents.

h. Net energy values of feedstuffs were not affected upon grinding or pelleting (Blaxter and Graham, 1956; Meyer et al. 1959a). However, Blaxter and Graham (1956) reported differences between DE and ME of ground and pelleted forage compared to chopped forage. The same trend was reported when the same feeds were fed at low (600 grams per day) and high (1500 grams per day) levels.

Osuji (1973) found that visceral heat increased due to aerobic gut metabolism in sheep accounted for about 66 percent of the increased heat production of the portal drained viscera disregarding the type and physical form of the diet. However, the eating pelleted diets did not result in appreciable measures in heat production attributed to grinding during eating (Osuji, 1973). Pelleting wheat middlings caused no significant increase in ME but resulted in marked improvement in feed intake and performance (Cave et al. 1965).

Improvement in animal productivity upon grinding and pelleting forages depended largely on the increase in intake of the digestible energy afforded by grinding and pelleting (Van Soest, 1978b). Fine grinding produced a faster passage and a decline in digestibility reflected mainly in the structural carbohydrates. In addition, there was an increased intake. Hence, the improvement in animal response was likely restricted to quality forages in which the digestion rate was not very slow as to cause excessive losses of potentially digestible carbohydrates that would affect the advantage of a higher intake (Van Soest, 1978b).

It should be warned, however, that these physical properties as measured might not be representative of those occurring in the lower gut (Van Soest, 1978b). Because bacteria might ferment components contributing to the ration exchange or hydration capacity. Bacteria may also cause a reduction in fiber structure through fermentive digestion, which was altered by production of microbial cell mass which had its own hydration and apsorption capacities (Fitt et al. 1972). The bacteria, therefore, replaced fiber which had been fermented. Wafers were another form into which long hay could be processed. Results tended to follow those of pelleted diets with increased intake coming from their greater acceptability to livestock and increased digestibility over that of unprocessed feedstuffs (Michalk and Saville 1979). Results conflicted concerning the effect of feed wafers to lactating cows. These conflicts could be due to animal variations and wafering procedures (Moore, 1964). Ronning and Dobie (1962) reported increased consumption and milk production on a wafered alfalfa ration, while Bringe et al. (1958) did not find any advantage in feeding wafers in terms of lactation. Wafer feeding did not increase consumption of forage dry matter in dairy cows and heifers (Veltman et al. 1962), in growing sheep (Meyer et al. 1959b) or in weaned Hereford calves (Wallace, 1961). Cooking could also alter the physical properties of feedstuffs through gelation, softening of the fiber (McConnell et al. 1974) and production of the heat damage products of the Millard reaction (Van Soest and Robertson, 1976). The more easily gelled fraction probably were more fermentable and might disappear in the lower gut to be replaced by microbial matter. However, cooking allows less feed selection by pigs and lowers digestibility of some of the nutrients especially that of the proteins (Ensminger and Olentine, 1978). While cooking cereals for mink improved the carbohydrates digestibility of wheat, corn, and barley but has little effect on digestibility of oat groats (Stout, 1972). Flaking caused gelatinization of starch granules, rendering them more digestible. Flaking corn seemed to improve the digestibility of dry matter, protein, crude fiber, nitrogen-free extract, and energy for steers (Arnett and Bradley, 1961). Steam processing milo improved the digestibility of innprotein organic matter for both steers and sheep although it depressed nitrogen digestion (Buchanan-Smith et al. 1968).

Dry rolled wheat was found to be as digestible as steam flaked or micronized flaked wheat for steers and sheep (Cornett et al. 1977).

However, steam processing and flaking milo increased the digestibility of certain nutrients (Hale et al. 1966; Mehen et al. 1966; Husted et al. 1968). This increase in digestibility could be attributed to a gelatinization of the starch granules, that were, hydration and rupturing of the complex starch molecules, rendering them more digestible and causing more colatile fatty acid production (Ensminger and Olentine, 1978).

Although Osman et al. (1966), found that starch digestion in vitro of barley and milo appeared to vary with the amount of steam and pressure and was improved by flaking. Garret et al. (1968) found that amount of pressure used in steam processing milo influenced dietary intake and feed efficiency in cattle, but there was no significant effect of steam processing on digestibility. There was a consistent effect of steam processing barley on its digestion by steers (Parrott et al. 1969) although complete gelatinization of mixed barley and milo diets decreased protein digestion by cattle (Riley et al. 1965). Crude fiber and protein digestion was decreased upon heat treatment of sorghum fed to steers (Ward and Morrill, 1966) and protein digestion by lambs but improved nitrogen free extract digestion in lambs (Keating et al. 1965).

Chapman and Matsushima (1970) compared the digestibility and feed lot performance of cattle fed dry and wet extruded, flaked, and whole shelled corn for fattening cattle. Think-flaked corn was more highly digestible. It seemed that processing performed a different effect in each case, and thus the proper method of processing could well be different for each kind of feedstuffs (Slinger, 1972).

The ME values of the soybean meal diets processed at high temperature (90°C) were significantly lower than that for the lower temperatures (70 and 80°C) in chickens (Bayley et al. 1968). However, Henstrom et al. (1959) used cattle to determine the digestibility of nutrients of growing and fattening diets that contained corn dried at different temperatures. There were no significant differences in the digestion of dry matter, organic matter, crude protein, ether extract, crude fiber, nitrogen free extract or energy between diets in either the growing or fattening phase. The influence of dehydration temperature on the digestibility of protein and energy in citrus pulp was studied by Ammerman (1972) and Ammerman et al. (1965). Protein and energy in a diet containing citrus pulp dehydrated at lowest temperature were ($P < 0.05$) more digestible than the same nutrients in diets containing citrus pulp dried at higher temperatures (Ammerman, 1972). Depending on temperature of drying, citrus pulp was commercially classified as light, gray and black in color. These colored meals were fed as 72.5 percent of the total diet in digestibility trials with sheep. The protein digestibility ranged from 70.3 percent for the diets containing light citrus meal (low dehydration temperature) to 56.5 percent for the black citrus meal (high dehydration temperature) ($P < 0.05$). Similar differences related to color were observed in energy digestion (Ammerman et al. 1965). Energy in diets containing light citrus meal was 77.2 percent digestible, while that in diets containing black meal was 64.9 percent digestible ($P < 0.05$).

In vitro studies on dehydrated alfalfa showed that protein digestibility was decreased upon dehydration (Booth et al. 1972). This digestibility of cellulose and pentosans was considered to be possible affected in the same manner as protein. Plant sugars and proteins condense by heat treatment to form end products that were totally indigestible by cattle (Byers, 1979). When evaluated for evidence of heat damage, protein content was normally reduced for level of nitrogen in the acid detergent fiber fraction. The feed digestible energy was also reduced for level of nitrogen in the acid detergent fiber. The digestible energy of feed was reduced by heating. Beef cattle gained slower and less efficiently on heat-damaged dehydrated alfalfa meal than on pelleted sun-cured alfalfa hay, indicating a reduction in digestible energy (Byers, 1979). Since, in alfalfa, energy was more limited than protein for beef cattle. The reduction in available energy was more critical than that of protein per se.

Protein in dehydrated alfalfa became less available for microorganisms in rumen on bypass into the true stomach. The rumen microorganisms, however, needed a certain amount of nitrogen in the form of ammonia, and feeding slowly degraded protein as a sole source of nitrogen might have lead into nitrogen deficiency in the rumen. As a result, there would be less efficient utilization of other dietary nutrients (Klopfenstein et al. 1979). Such a situation could be corrected by the supplementation of urea to meet microbial requirements.

Oven drying of forages (at $100^{\circ}C$) appeared to reduce in vitro digestibility by increasing the content of the lignin-like compounds (Van Soest, 1964). Drying may also create physical impediments to microbial attack in some plant materials. Eriogonum became cottony and almost imprevious to wetting when dried and mechanically ground

(Urness et al. 1977). Soaking, washing, and ensiling were processes that had been suggested for improving the digestibility of straw (Kehar, 1953).

Ensiling lowered the ratio of hemicellulose to cellulose in alfalfa and legumes, suggesting that some hemicellulose may be lost by ensiling (Sullivan, 1966). Digestion trials and laboratory studies (Baker, Jr., 1972) with sorghum grain showed increased digestibility of ensiled, reconstituted, high-moisture grain than dry grain, possibly because the ensiling process of a protein compound surrounding starch granules.

Ensminger and Olentine (1978) gave a summary about the effect of sprouting on the nutritive value of grains. Sprouting resulted in an average loss of 83 percent of dry matter of oat grains. TDN was reduced from 75.7 percent in the oat grain to 70.2 percent of sprouted oats. Besides digestibility of dry matter, energy, protein, ether extract, and nitrogen-free extract was lower for sprouted oats than for oat grain. However, when sprouted oats were added to an adequate ration, dairy cows yielded more milk. Processing seemed to influence mineral utilization differently. Calcium from all available sources appeared to be well utilized by animals, and feed processing had little influence (Loosli, 1972). Steam-pelleting of feedstuffs that did not contain added phosphorous supplements increased the utilization of phosphorous for chickens and pigs (Loosli, 1972). Methods of processing rock phosphates for defluorination might greatly affect the availability of phosphorous. Magnesium utilization was not known to be affected by feed processing (Loosli, 1972).

Range feeds had sometimes been modified by being chopped after clipping, by being dried, milled and pelleted to be easily fed, sampled and chemically analyzed. The resulting data represent the processed materials rather than the range plants (Short, 1963). The digestion coefficients obtained from feeding freshly clipped forages in dry lot were meaningful indicators of range forage quality if, however, the test feeds were identical in composition to forages selected by the ruminant animals.

Chemical treatment was a method used to improve the nutritional quality of crop residues and by-products that are characterized by a high fibrous content and lower digestibility. Lignification of the cell wall component of these roughages seemed to be responsible for the low digestibility. Lignin encrusted the energy-rich carbohydrates, cellulose and hemicellulose and kept the microbes in the rumen from breaking them down to release energy (Ensminger and Colentine, 1978).

There were many chemical ways to delignify and increase digestibility of poor-quality roughages. Treatment with NaOH, $NaHCO_4$, $Ca(OH_2)$, $KCOH_2$, NaS, NH_4, acid hydrolysis (H_2SO_4 AND HCl), and pressurized heating (Ensminger and Olentine, 1978; Schneider and Flatt, 1975; Van Soest and Robertson, 1976) were practiced. Graminaceous lignin appeared to be composed of polymerized substituted phenolpropanoic acids esterified to xylan hemicelluloses (Van Soest and Robertson, 1976). Treatment with alkali saponified this link without reducing lignin content, but increasing digestibility. Clawson et al. (1970) concluded that treatment of rice straw with caustic alkali brought about extensive delignification and increased digestibility of cellulose and the supposedly inert lignin. Others, however, concluded that lignin content was generally not reduced by chemical treatment (Klopfenstein et al. 1972; Rexan and Thomsen, 1976). The increase in the extent of digestion might probably be due to breaking of bonds between lignin and hemicellulose without actual removal of lignin (Klopfenstein, 1978).

Treatment of rice straw with NaOH resulted in an increase in apparent digestibility and utilization of energy, dry matter consumption and daily gains (Chandra and Jakson, 1971; Garrett et al. 1974). There was a significant increase (10.1 percent) in the digestibility of dry matter of rice straw, and (8.1 percent) for that of bagasse, however, energy digestibility did not increase significantly in sheep (Stone et al. 1966).

Willis et al. (1980) showed that NaOH treatment of rice straw increased dry matter digestibility in vitro and in vivo. There was also an improvement in the coefficients of energy digestibility, increased dry matter intake and a more positive response of nitrogen retention suggesting that chemical treatment of rice straw increased the utilization of energy by steers. Hence, NaOH seems to facilitate the activity of microbial enzymes thus improving the feeding value of rice straw in ruminants (Willis et al. 1980).

Digestibility of crude protein was slightly superior in the control silage compared to NaOH treatments (Willis et al. 1980). NaOH alone gave the least negative nitrogen balance, followed by NaOH plus enzyme treatment. However, the control group had the most negative balance of the treatments. Weight loss and negative nitrogen retention indicated that the diets might have been deficient in metabolizable energy, increased digestible energy and the subsequent reduction of negative nitrogen balance, suggested that improved energy was due to the chemical treated diets (Willis et al. 1980).

Berger et al. (1980) used ruminally fistulated lambs to measure the effect of sodium hydroxide treatment on rate of passage and rate of ruminal fiber digestion. Corn cobs were raised to 60 percent moisture and treated with different levels of NaOH concentrations (0, 2.5, 5.0, 7.5 and 10.0 percent) on dry matter basis. Eighty percent corn cobs was mixed with 20 percent supplement, giving a complete mixed diet containing 0, 2.0, 4.0, 6.0 and 8.0 percent NaOH on dry basis. As level of NaOH treatment increased, rate of passage increased linearly ($P < .05$). Mean ruminal retention time decreased from 32.4 hours for the control diet to 20.7 hours for the 8 percent NaOH diet. Nylon bags containing .15 grams cotton were used to estimate ruminal digestion. As level of NaOH increased, the rate of ruminal cotton digestion decreased linearly ($P < .05$). When rate of cotton digestion was regressed against NaOH level, the slope of the line was -.488 percent per hour per unit NaOH, with $r^2 = .934$.

The addition of five percent NaOH (dry matter basis) as a 50 percent solution to alfalfa hay ground through a two-inch screen, followed by cubing in a stationery cuber. Forage composition was generally similar whether chemically treated or not, except for an increase in hemicellulose (Byers, 1979). In vivo digestibility at ad libitum intake was similar between treatments for cellulose, lignin and solubles while digestibility of hemicellulose was increased about 20 percent with NaOH addition. There was also a 20 percent increase in ad libitum intake with NaOH treatment, hence an increased intake of digestible forage carbohydrates and energy (Table 6). Dehydrated alfalfa meal contained 30.7 and 45 percent acid detergent fiber (ADF) and cell wall, respectively. With NaOH treatment, ADF and cell wall content were 29.1 and 42.6 percent. Nitrogen in the ADF fraction was 0.45 percent and 0.36 percent for control and NaOH treated dehydrated alfalfa, respectively. Hence, NaOH treatment seemed to be effective in reversing some of the heat damage by reducing ADF-bound nitrogen by about 20 percent while simultaneously reducing overall protein solubility (Byers, 1979).

Experiments with beef cattle showed that NaOH treatment with cubing of alfalfa increased digestibility of forage carbohydrates and energy, consumption of dry matter and digestible nutrients or both (Byers, 1979).

TABLE 6 In Vivo Digestibility of Cubed Alfalfa Hay Fed to Growing Steers at Similar Intakes,a

Item	Control	5% NaOH	SEM
Number of observations	27	27	--
ADF	31.1	40.1	0.96
NDF	36.8	46.5	1.09
Cellulose:			
ADF	47.8	55.4	0.87
Crampton and Maynard	43.0	47.6	1.0
Hemicellulose	61.0	64.4	2.7
Cell solubles	66.2	68.8	0.54

a. Least squares means at 6.2 kg dry matter per day; 215 kg steers. (Adapted from Byers, 1979)

Environmental Factors Affecting Digestibility of Feedstuffs. Environmetal conditions of plant growth determined the plant composition which controled the limits of the nutritive value (Van Soest et al. 1978). Studies of environmental conditions indicated that increasing light intensity tended to increase soluble carbohydrate content and digestibility of grasses through photosynthetic accumulation of carbohydrates. Increasing temperature, however, caused more conversion of photosynthetic products into structural matter (Deinum et al. 1968). Legume plants might follow the same pattern (Kalu, 1976).

Environmental temperature increased lignification in a dominant effect in comparison with plant maturity and light intensity (Van Soest et al. 1978). Differences between tropical and temperature forages could be the result of both environment and management, however, the fast maturation of tropical forages exerted a greater pressure upon management to maintain the nutritive value.

The differences between tropical and temperature forages and the environmental interactions upon lignification were relevant to the evaluation of forages (Van Soest et al. 1978). The correlation between lignin and cellulose in tropical grasses was significant, while that of temperate grasses was in the order of +.80. Lignin was an important predictor of digestibility. Simple correlation coefficients from the composition data showed permenganate lignin to be the best predictor (R = -.74) of in vitro dry matter digestibility (IVDMD) for all grasses, while protein gave the best positive correlation (R = .70). When grasses were subgrouped, the correlations changed. The correlation coefficient between protein and IVDMD was high for tropical grasses (R = .90) but low for the temperate grasses (R = -.17). Lignin was highly negatively correlated with IVDMD (R = -.72) for tropical grasses and (R = -.67) for temperate grasses (Barton et al. 1976). Differences in the cell wall matrix of tropical and temperate grasses could cause discrepancies in predicting digestibility from chemical composition data, however (Barton et al. 1976). Multiple linear regression analysis were shown in Table 7.

The fiber from tropical plants tended to be less fermentable because of the effect of environmental temperature upon lignification (Deinum et al. 1968; Deinum, 1976). Cellulose was the main component of ADF and its association with digestibility depended on its association with lignin. This association was in turn dependent upon environmental temperature and the nature of plant species (Van Soest et al. 1978). However, the ADF fraction from tropical grasses was found to be more digestible than that isolated from temperate species (Barton et al. 1976).

Rohweder et al. (1978) found that alfalfa grown in Florida had similar concentrations of ADF and NDF to that grown in Wisconsin, Indiana, and Pennsylvania at similar stages of maturity. However, crude protein was higher in alfalfa grown in Florida at all stages of maturity. Crude protein concentration in alfalfa, timothy, and oats increased at warmer temperatures while dry matter digestibility remained constant (Smith, 1969; Vough and Martin, 1971).

ADF concentration was highly correlated with in vivo digestible dry matter in alfalfa, temperate grasses, and subtropical grasses (Rohweder et al. 1978). However, NDF concentrations in subtropical grasses were higher than in temperate grasses. Hemicellulose seems to be the major important composition difference between tropical and temperate grasses. Hemicellulose was found to be higher in tropical grasses (30-35 percent) than in temperate grasses (22-27%) as shown

TABLE 7 Equation, Coefficients of Determination and Residual Standard Deviation Obtained from Multiple Linear Regression Analysis

Equation	Coefficient of Determination (R^2)	Significance of R^2 (P)	Residual Standard Deviation
Tropical and temperate			
$Y_1 = 79.89 - 4.52X_8{}^b$	.55	.0005	3.88
$Y_1 = 94.25 - .56X_6 - 4.29X_8$	.76	.0001	2.94
$Y_1{}^c = 81.87 - .42X_1 - .47X_6 - 3.36X_8$	.80	.0001	2.73
Tropical			
$Y_1 = 41.88 + 1.18X_1$	.81	.005	3.12
$Y_1 = 61.15 + 1.04X^1 - .26X_4$	.83	.02	3.24
$Y_1 = 121.42 + 1.77X_1 = 5.27X_3 = 82X_4$	.90	.02	2.78
$Y_1{}^c = 70.81 + .72X_1 - .36X_6 = 2.49X_8$	.85	.05	3.46
Temperate			
$Y_1 = 76.46 - 3.49X_8$	.45	.05	2.86
$Y_1 = 47.28 + 88X_5 - 3.16X_8$	.74	.01	2.06
$Y_1 = 31.26 + 1.43X_2 + 1.06X_5 - 2.32X_8$	.86	.01	1.69
$Y_1{}^c = 93.24 - .13X_1 - .64X_6 - 3.20X_8$	.67	.05	2.45

[a] Compositional data used for regression analysis is tabulated in Table 1.

[b] X_1 = Crude protein; X_2 = Ether extract; X_3 = Ash; X_4 = Neutral detergent fiber; X_5 = Acid detergent fiber; X_6 = Hemicellulose; X_8 = Permanganate lignin.

[c] The same parameters are used for these three equations with the different data sub-sets.

(Adapted from Barton et al. 1976)

by the higher NDF values (tropical average 66.2 percent versus temperate average 56.9 percent that were reported by Barton et al. (1976). Van Soest (1973a also reported results that showed higher NDF content of tropical and subtropical grasses than that of temperate grasses.

The average in vitro dry matter digestibility (IVDMD) of four week summer regrowth tropical and temperate grasses were 61.6 percent and 63.4 percent, respectively and did not reflect a significant difference in digestibility. These results could be related to immature stage of all the grasses and to the manner in which they were handled in this particular study (Barton et al. 1976; Barton and Akin, 1977).

Comparing of first cutting and aftermath of tropical forages, Van Soest et al. (1978) found lignin and cellulose to be positively associated in first cuttings and negatively associated in aftermath cuttings. This contrary effect might reflect the tropical nature of temperate summers and the interaction of regrowth rate and date of aftermath cuttings.

The nutrient content among grass species varied widely depending on the length of time required to mature (Cook and Harris, 1968a). Cool weather grasses usually start growth in the fall and mature early in the summer while warm weather grasses mature and set seeds in late summer or fall. As a result, the warm weather grasses were higher in nutrients during late summer but the cool weather grasses were more suited to early summer and spring grazing (Table 8).

The negative association of temperature with forage quality might predict improvement of forage quality with date of fall cuttings since later leaves develop at lower temperatures. Whether or not such

TABLE 8 Average Nutrient Content of Cool Weather and Warm Weather Grasses on Mountain Range During Early (July 1) and Late (September 1) Summer

Forage Type	Season	Digestible Protein (%)	Cellulose (%)	Digestible Energy (kcal/lb)	TDN (%)	P (%)
Cool weather grasses[1]	Early	6.9	40.3	1266	64.1	.24
	Late	2.4	44.5	959	53.2	.16
Warm weather grasses[2]	Early	8.8	38.5	1183	61.2	.30
	Late	4.7	40.6	1091	57.4	.23

[1] Cool weather grasses consisted of mountain brome, slender wheatgrass, and blue wildrye grass.

[2] Warm weather grasses consisted of Kentucky bluegrass, green needle-and-thread grass and Idaho fescue.

(Adapted from Cook and Harris, 1968a)

improvement with age occurred, was dependent on the fact that temperature was more important than light and plant maturity (Van Soest et al. 1978). Such conditions could occur in midwest and Atlantic states where temperatures are tropical in midsummer and decline in fall down to freezing. Hence, improvement in forage quality would be dependent mainly on vegetative regrowth (Kalu, 1976).

The range in digestibility declines from first growth to maturity as affected by the altitude where forages were grown. The digestibility of first cuttings is very high and constant north of 30° latitude. North of this line, perenial forages usually regrew after frost, while to it south growth occurred after cutting or dry winter conditions of warmer temperatures (Van Soest et al. 1978). Digestibility at maturity declined progressively towards the equator. As the mean temperature increased, the average forage digestibility decreased (Minson and McLeod, 1970).

In addition, the greater morphological differentiation of leaves and stems within tropical grasses as compared to temperate grasses was evidence showing a greater range of digestibilities within the plant parts of the tropical grasses (Van Soest et al. 1978).

Cook and Child (1977) found that using both total protein and lignin was slightly better to predict digestible protein than total protein alone on summer mountain ranges. The same trend was true on desert ranges. In mixed grass areas of northern Colorado during the grazing season from May 15 to September 15 digestible protein could be predicted from total protein which accounts for as much as 88 percent of total variability in digestible protein. By using both total protein and dry matter digestibility as predictors, 96 percent of the variability in digestible protein could be accounted for. In short grass plains in Colorado, however, predictive equations for digestible protein showed that total protein alone gave R^2 values of 0.92. By using total protein and digestible energy as predictors, .96 percent of variability in digestible protein in diets of steers could be accounted for (Table 9).

Nitrogen fertilization and water availability have marked effects on forage composition. Light-induced photosynthesis promoted reduction of nitrate and its conversion with carbohydrate to amino acids and protein (Van Soest et al. 1978). Nitrogen fertilization did not improve digestibility of grasses because increased nitrogen compounds were used for a reduction in soluble carbohydrates and increased lignification. The proportions of lignin and hemicellulose were altered upon nitrogen fertilization (Deinum, 1976; Deinum et al. 1968).

Pieper et al. (1974) did not find a significant difference in dry matter digestibility between fertilized and unfertilized plants at every stage of maturity. Dry matter disappearance declined markedly from the full-bloom stage to the stem cured stage for both fertilized and unfertilized plants. However, crude protein of a mixture of weed plants was low because soil, in which the mixture was grown, was nitrogen difficient (Martin and Andersen, 1975).

Other factors such as water stress and infestation of alfalfa weevil (Liu and Fick, 1975) may cause a higher digestible plant of lower yield. That could be due to promotion of the maintenance of forage quality for a longer time by stress factors that hinder plant development (Van Soest et al. 1978).

TABLE 9 Nutrients Shown in a Predictive Linear Equation for Determining Digestible Protein in Range Plants for Three Seasonal Range Types for Sheep and Cattle

Predictive factors (b's)	R^2 x 100
Sheep, Spring (seeded foothills)	
- 4.10 + 0.97 (TP%)	92.9
19.49 - 1.97 (Lig%)	61.9
84.80 = 0.64 (Lig^2%)	72.0
0.77 + 0.82 (TDP%) - 0.51 (Lig%)	94.9
108.60 - 0.50 (Lig^2%) - 0.03 (Cellu. % x CHO%)	82.0
Cattle, Spring (seeded foothills)	
- 2.79 + 0.84 (TP%)	90.0
21.63 - 2.11 (Lig%)	44.7
- 3.45 + 0.85 (TP%) + 0.08 (Lig%)	90.4
-10.42 + 10.17 (TP%) - 0.35 (TP^2%)	90.9
81.07 + 13.19 (TP%) + 1.52 (Cell.%) - 0.43 (TP^2)	93.4
Sheep, Summer (mt. range)	
- 3.32 + 0.69 (TP%)	60.3
10.56 - 0.50 (Lig%)	31.6
1.27 + 0.60 (TP%) - 0.32 (Lig%)	72.0
Cattle, Summer (mt. range)	
- 0.77 + 0.48 (TP%)	34.1
6.57 - 0.27 (Lig%)	25.5
1.93 + 0.40 (TP%) - 0.20 (Lig%)	48.0
Sheep, Winter (desert range)	
- 3.02 + 0.84 (TP%)	84.0
3.64 - 0.01 (Lig%)	00.7
- 1.59 + 0.87 (TP%) - 0.14 (Lig%)	87.6
Cattle, Spring-Summer (mixed grass)	
- 1.98 + 0.86 (TP%)	88.3
- 7.32 + 0.21 (DDM%)	52.7
9.61 - 0.002 (GE kcal/lb)	0.4
- 7.38 + 0.011 (DE kcal/lb)	54.6
- 6.27 + 0.710 (TP%) = 0.094 (DDM%)	95.6
Cattle, Spring-Summer (short grass)	
- 2.01 + 0.91 (TP%)	91.9
16.84 - 0.006 (GE kcal/lb)	3.4
- 3.54 + 0.16 (DDM%)	24.5
4.99 + 0.009 (DE kcal/lb)	43.7
- 4.55 + 0.80 (TP%) = 0.003 (DE kcal/lb)	94.9
.13 + 0.76 (TP%) - 0.003 (GE kcal/lb) + 0.004 (DE kcal/lb)	95.5

(Adapted from Cook and Child, 1977)

Humidity tended to lower quality of forages. Plants grown under arid conditions have better quality than that from humid conditions (a probability was, everything else being equal). Water stress depressed plant development and improved digestibility while cloud cover reduced light and hence digestibility (Van Soest et al. 1978).

Chemical composition and in vitro digestibility of forages consumed by sugora goats were compared on heavily-stocked, fair-condition range and lightly-stocked, good condition range in the Edwards Plateau region in Texas (Malechek and Leinweber, 1972). There was a great variability in chemical composition and in vitro digestibility of forages depending on season. However, as a general trend, forage on lightly stocked range was higher in crude protein, cell wall constituents, cellulose, lignin but was lower in hemicellulose content and in vitro digestibility than that on the heavily-stocked range.

However, Pieper et al. (1959) and Cook et al. (1952) found that digestibility of nutrients in the diet was seriously reduced by heavy grazing on typical desert range from October to April. The nutrient intake of animals grazing winter ranges varied from area to area and was influenced by many factors of which intensity of grazing was most important (Cook and Harris, 1968a). As degree of utilization increased, the content of desirable nutrients in the diet decreased and digestibility of nutrients decreased because animals would eat the less nutritious portion of plants. These results were in agreement with those reported by Vavra et al. (1973) and Armstrong et al. (1959).

Frost could be a factor that might cause a reduction in digestibility of feedstuffs (Whiting and Bezeau, 1954; Woodman and Oosthuizen, 1934).

Thus, environmental factors influence forage composition and quality and account for regional and seasonal differences in forage crops (Van Soest et al. 1978). Such information was related to the practical problem of forage evaluation as experienced in a laboratory receiving samples from different sources, in the compiling of an NRC publication, or by the establishment of hay grading standards (Rohweder et al. 1978). The principal animal evaluation consisted of digestibility and voluntary intake measurements of unsupplemented forages.

Associative Effects. The digestion of a single nutritive component of a feed was not sufficient to explain the variability in the digestibility of feedstuffs (Van Soest, 1967). Differences in digestibility of a feed might arise because the combination of feeds might represent a higher or a lower plane of nutrition than individual feeds fed alone (Schneider and Flatt, 1975). When proper amount of a nitrogenous supplements or essential minerals were added to a mixed ration, cellulose digestion in that ration may be increased. The microorganisms in the rumen attacked fiber more vigorously and hence, fiber digestibility was enhanced (Harris and Mitchell, 1941a).

Apparent associative effects might arise because of the variations of average digestion values found in feed tables. Digestion coefficients of ration obtained by digestibility trials carried with these rations often differed significantly from calculated digestibilities using table values. Whatever the cause of these combination effects, their degrees were much influenced by the relative quantities and relative digestibilities of the basal diet and the added feed. The digestibility of which was to be determined by difference (Schneider and

Flatt, 1975). The combination effect plus the results of all errors and imperfections of experimentation were, by the difference procedure attributed to the added feed.

The digestibility of a mixture was not necessarily the average of the values for its constituents determined separately or indirectly. Each feed might affect digestibility of the other (Maynard and Loosli, 1969). Although it was very difficult to determine the specific factors involved in this associative digestibility, the influence of crude fiber content and the nutritive ratio made it easy to understand that marked variations from computer average might occur.

Experiments indicated that in some cases one feed did not influence the digestibility of the individual nutrients of another feed with which it was fed. While in other cases, it made the nutrient more or less digestible than when the feed was fed alone (Schneider and Flatt, 1975).

Variations associated with digestion coefficients for energy feeds could also be high. Energy feeds such as grains were usually not fed alone to ruminant animals to determine their digestibility values. These feeds were fed along with fibrous (high cell wall) basal feeds of known digestibilities. The digestibility of the basal feed was assumed to remain constant when fed alone or mixed with a test feed. Again, the variation from combination effect as well as from error of experimentation were attributed to the added energy feed (Schneider and Flatt, 1975; Swift, 1947).

Staples et al. (1951) observed that the associative effect might be greater when a feed was of poorer quality. The addition of oat and soybean meal to hays improved the digestibility of medium and late cut hay rations to a relatively greater extent than that of an early-cut hay ration. However, studies by Houser et al. (1975) and Chimwano et al. (1976) showed that increasing levels of grain in ruminant rations lowered cellulose digestibility.

The kind and amounts of the combined feeds had an effect on the digestibility of these feedstuffs (Titus, 1926). Hence part of the improved digestibility in goats was probably due to the associative effects due to compositions of feeds consumed. This was particularly distinct in goats in view of their wide feeding habits of a variety of feeds (Devendra, 1978).

Associative digestibility of nitrogen-free extract, ether extract, and crude protein were observed in sheep fed diets containing different ratios of corn grain to dehydrated alfalfa (Clemens, 1968). The apparent digestibility of crude protein decreased lineary with the increase of corn in the diet. The curvilinearity of the digestible crude protein, ether extract, and nitrogen-free extract indicated that the digestibility of these nutrients increased with an increase of concentrates in the diet (Figure 4).

When starch was fed in excessive amounts, it seemed to exert a depressing effect upon the digestibility of the nitrogen and crude fiber even when the excess was not great. When 47.3 percent of the net energy of the ration was supplied in the form of starch, there was also a depression in the digestibility of the total ash. These depressions in digestion of nitrogen, crude fiber, and ash were accompanied by a rise in the digestion of fat, which was high in the high starch rations (Ewing, 1915).

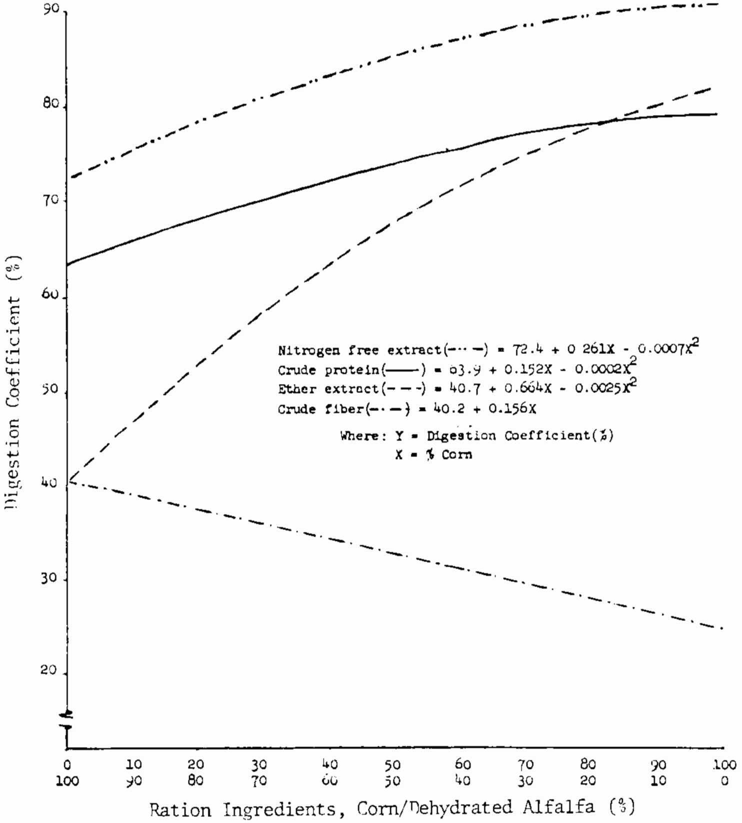

FIGURE 4 Linear and curvilinear relationships between the digestion coefficient and percent ration ingredients. (Adapted from Clemens, 1968)

In studies with steers, Slyter et al. (1971) reported that 13 percent starch in the ration reduced both the number of cellylytic bacteria and total cellulose digested. Despite no reduction in cellulolytic numbers, there was a depression in the cellulose activity of the bacteria when grain was added to a rumen innoculum source (Slyter and Weaver, 1972). Furthermore, the change in proportion of volatile fatty acids in equine cecal fluid or bovine rumen fluid when grain was added to a forage diet indicates a change in bacterial activity (Kern et al. 1973).

The feeding of grain rich in protein with corn meal apparently increased the digestibility of the ration, particularly that of the protein (Bartlett, 1904). Clanton et al. (1966) and Cook and Harris (1968b) found that energy supplements (barley and corn) reduced the digestibility of protein in the forage while protein supplements (cotton seed meal and soybean meal) increased the digestibility of cellulose and protein in the diet under range conditions.

Asplund and Harris (1971) studied the associative effects of equal parts of alfalfa hay and dried molasses beet pulp with sheep. The EE and CP digestibilities were lower and NFE digestibility was higher in the mixed diet than as calculated from values of the individual feeds. The digestion coefficients for gross energy (GE) and NFE in beet pulp and dry matter (DM), CP, CF, and NFE in alfalfa hay were higher when determined by difference than when determined directly on feed. Digestion coefficients at intakes below maintenance were greater than above. It was emphasized that an individual feedstuffs expressed its nutritive value only as it was part of a ration (Asplund and Harris, 1971).

However, supplying carbohydrates should be done with care since the provision of easily digested carbohydrates can depress the utilization of fiber (Topps, 1972). A useful rule was to supply enough energy supplement to increase forage consumption, but not to replace it.

Dry matter and organic matter in potato-bean silage with hay were highly digestible than in the two rations containing cabbage silage (Barth and Gelaye, 1980). Adding hay to cabbage silage decreased its organic matter digestibility, probably because apparent ash digestibility was higher in cabbage silage than in hay. Crude protein digestibility was higher and not significantly different among the three rations (78.4), (75.3) and (75.4) for potato-bean silage and hay, cabbage silage, and cabbage silage and hay ration, respectively. Crude fiber digestibility of all rations was high, especially when cabbage silage alone was fed (89.2). Addition of hay depressed fiber digestibility of 82.2.

Kromann et al. (1977) observed a linear increase in the digestibility of nitrogen-free extract, ether extract, and dry matter when the level of pea scalping increased in the diets that consisted of varying proportions of pea scalping and straw, and fed to wether and ewe lambs. Crude fiber digestibility was not affected by the diet rations since crude fiber content was not significantly different among the four rations. Digestible energy (DE) and metabolizable energy (ME) were shown to have a third order relationship with percent pea scalpings in the diet. NEm+p showed only a linear relationship to the peastraw rations.

The digestibility of gross energy, crude protein, dry matter, and ether extract was greater for the urea-treated corn silage diet than the hay crop silage diet while the mixture of both silages were intermediate. There was no positive associative effects between these forages when fed to Holstein heifers (Johns and Holter, 1975).

The interactions of plant species and method of harvesting was revealed in the efficiency of feed utilization. A statistically highly significant interaction of plant species (alfalfa and trefoil orchard grass) and method of feeding (soilage or pasture) was found when the amount of feed per 100 pounds of grain was analyzed (Hull et al. 1957). Greater increase in efficiency of feed utilization occurred when alfalfa was pastured rather than soiled.

For feed consumption by the steers, however, a highly significant interaction was present for method of feeding versus kind of forage. Feed consumption of the steers given alfalfa pasture was much lower than that of the other lots. It seems that feed consumption of steers or pasture was influenced by the kind of forage offered. This effect was not noted in sheep (Hull et al. 1957). Christiansen (1979) reported the following findings on associated effects on digestibilities:

a. A significant forage-by-maturity interaction was found to affect on the apparent digestibility of neutral detergent fiber (NDF) and lignin. The apparent digestibilities of cell wall, neutral detergent fiber and acid detergent fiber in alfalfa decreased with increasing maturity; however, this trend was not maintained in grass. Cell walls, neutral detergent fiber, and acid detergent fiber in midbloom grass were much more digestible than in the late vegetative and full bloom grass stages.

The available carbohydrate content in mid-bloom grass was much lower than in the late vegetative and full bloom grass. As a result, digestibility of the available carbohydrate was extremely low in midbloom grass. Hence, a highly significant ($P<.001$) forage-by-maturity interaction was observed to affect available carbohydrate apparent digestibility. Besides, a forage-by-energy level interaction significantly affected available carbohydrate apparent digestibility only. The extremely low available carbohydrate content of the midbloom grass was probably primarily responsible for the forage-by-energy level interaction effect on available carbohydrate digestibility.

b. A significant maturity-by-energy level interaction affected the apparent digestibility of crude protein, available carbohydrates, cellulose, neutral detergent fiber, and acid detergent fiber. It was also observed that, though fibrous components in the hay-corn diets tended to be of greater digestibility than in the all-hay diets at the late vegetative and full bloom stages, the opposite was true at the midbloom maturity stage. The fibrous constituents in midbloom grass were much more digestible than in late vegetative or full bloom grass. This condition was probably the major cause of the significant maturity-by-energy level differences among the fiber constituents.

c. Hemicellulose and cell wall apparent digestibilities followed the same trend as other fibrous constituents though differences were not significant.

d. The pattern of apparent digestibility of crude protein between all-hay and hay-corn diets was altered by an increase in crude protein content in the full bloom hay-corn diet. The full bloom grass was very low in crude protein. The addition of corn with full bloom grass signicantly increased the crude protein content of the ration. Crude protein became more digestible in the hay-corn rations at the mature level.

e. A significant decrease in apparent digestibility of cellulose, hemicellulose, cell walls, and neutral detergent fiber was observed with pelleted diets. The energy level-by-texture interaction was shown to affect digestibility of fibrous constituents of the diets. Combining corn with coarse hay also reduced considerably the fiber apparent digestibility. However, the opposite phenomenon was observed for hay-corn pelleted diets. Fiber digestibility increased when pelleted hay-corn diets replaced pelleted all-hay diets. Significant differences in the apparent digestibility of fibrous constituents due to the addition of corn to the diet were cancelled out when differences were averaged over coarse and pelleted diets.

f. The energy level-by-texture interaction also affected the apparent digestibility of crude protein, soluble ash, ash, dry matter, and gross energy significantly. However, no significant maturity-by-texture nor forage-by-texture interaction effects were observed.

Other Methods to Predict the Nutritive Value of Feedstuffs

The Ratio Technique.

The digestibility of grazed forage could not be determined directly because the forage intake of the grazing animal could not be measured (Harris et al. 1968b; Streeter, 1969). The indirect techniques had been employed to estimate the digestibility of grazed forages by many workers.

Bergeim (1926) computed digestion coefficients from the ratio of the concentration of iron oxide added to rat rations to the concentration of iron oxide in the feces. However, the use of iron as an indicator of digestibility of grazed forage was limited because digestion coefficients were often variable (Gallup and Kuhlman, 1931).

Chromogens were first used by Reid et al. (1950) as internal indicators in digestion studies. Certain oils present in desert range plants might carry some chromogens through the intestinal wall and caused substantial urinary excretion of chromogens and thus negative digestibilities were obtained (Cook and Harris, 1951). However, Connor et al. (1963) reported that chromogens proved to be a more reliable indicator than lignin in studies involving desert range plants with a low ether extract content. Chromogen also appeared to be a good indicator for succulent green forages during the summer (Reid et al. 1952); while lignin appeared to be a good indicator for winter range plants (Cook et al. 1951).

Lignin was a substance found in plant cell wall material which was insoluble in a solution of 72% sulfuric acid. Lignin ratio was extensively in studies on Utah ranges by Cook and Harris (1968a); Cook et al. (1951). Hill et al. (1961) compared the recovery of ingested lignin by confined heifers by using five procedures for collecting feces: (1) 24-hour fecal bag collection, (2) 4-hour fecal bag collection, (3) 6-hour fecal bag collection, (4) 4-hours on a concrete platform and (5) 6 hours on a concrete platform. Percentage lignin recoveries for the five procedures were: 117.4, 104.9, 105.7, 79.6, and 75.5, respectively. Part of the high recovery of lignin using 24-hour fecal bag collection was probably due to sampling. Also, the procedures might have resulted in increased excretion of feces during the short test period.

Hill (1965) also used lignin as an indicator of digestibility and 4- or 8-hour fecal collections by means of harness and bag to measure fecal output of cows on desert rangeland. The forage sample was hand-plucked by a technician while observing a cow during the daylight hours of a 24-hour grazing observation period. There were no significant differences between two cows within each breed (Hereford and Santa Gertrudis) nor among samples within cows. Digestibility estimates of Hereford cows grazing appeared satisfactory; however, this method did not provide reliable estimates of the organic matter intake of Santa Gertrudis cows because the estimate of fecal output were too low. The Santa Gertrudis cows were very active and it was difficult to catch and restrain them which resulted in fecal losses both before and after the collection bags were attached.

The lignin content of the forage was consistently higher in samples collected through a rumen fistula than in hand-plucked samples. Because lignin was used as the internal indicator, all digestibility values based on the lignin content of rumen samples were abnormally low. Thus, organic matter intakes based on rumen samples were unreliable as they considerably underestimated the organic matter intake necessary to support the cows (Hill, 1965). However, the organic matter digestibility or range plants was similar among breeds when calculated by using the lignin-ratio method with samples of hand-plucked forage and collecting feces for 4 or 8-hour periods with harnesses and bags.

Fonnesbeck et al. (1974) found that the apparent digestibility of lignin was near zero for all species of animals tested (Table 10). These results justify lignin as a non-nutritive matter for all species.

TABLE 10 Apparent Digestibility of Lignin by Animals

Diet No.	Diet Lignin Content	Digestibility by species				
		Sheep	Rabbits	Swine	Rats	Chickens
	%	%	%	%	%	%
1	0.1	--	--	3.1	--	--
2	0.6	--	--	-4.5	-4.8	--
3	1.0	--	--	2.9	4.7	--
4	1.9	--	--	2.0	2.9	-4.3
5	2.6	-1.1	-13.2	4.2	-4.6	-1.8
6	3.0	4.6	-7.8	4.4	-2.3	-9.4
7	4.0	14.5	-10.0	--	-3.1	-1.4
8	4.9	4.6	-7.5	--	--	-6.3
9	5.6	3.8	-8.9	--	--	--
10	6.5	7.2	-2.3	--	--	--
11	7.1	2.5	-19.2	--	--	--

(Adapted from Fonnesbeck et al. 1974)

In nature, only a few fungi product enzymes digested lignin. The small amount of lignin in the ration and expected variation among individual animals combined with the limited precision of the experimental methods to yield digestion coefficient near zero (Fonnesbeck et al. 1974). When lignin was less than one percent, the limited precision of the chemical analyses gave wild digestion coefficients that are not reported (rations 1-3).

Calculated digestibility of dry matter by the use of lignin ratio compared well with digestibility results obtained by many workers on similar forages (Cook and Harris, 1951). This trend was not true for determinations made by the chromogen method. Forbes and Garrigus (1950a) found that the digestion coefficient for steers calculated by conventional method and by the lignin ratio were reasonably close. The most significant correlation between organic matter digestibility and forage composition was related to the lignin content of the forage. Regression equations to predict organic matter digestibility from lignin content were not statistically different between the conventional calculations and the lignin ratio calculations for either steers or wethers.

However, the digestion coefficients for forages fed to wethers, determined by the two methods of calculations were not in such a good agreement as were those shown for steers due to the less satisfactory apparent digestion coefficients for lignin (Forbes and Garrigus, 1950b).

The following sources of error could result from lignin methods employing 72 percent sulfuric acid: (1) contamination with nitrogenous substances; (2) incomplete hydrolysis of carbohydrate; (3) formation of reversion products from carbohydrates; and (4) removal of lignin by preliminary treatment with organic solvents, boiling water, and boiling dilute acids (Phillips, 1940).

Contaminating proteins could be removed by trypsin in a sodium carbonate buffer (Armitage et al. 1948) or sodium carbonate (Thacker, 1954). However, more than sixty percent of the lignin might be dissolved in high pH solutions such as sodium carbonate solutions (Van Soest, 1964). NaOH solutions would also dissolve lignin while dissolving protein from crude fiber (Norman, 1935). Thus, a major problem in the chemical partitioning of fibrous plant tissues was the efficient separation of protein from lignin (Van Soest, 1964).

Moreover, lignin analyses were also complicated by the effect of drying and heating during the preparation of laboratory samples. Heating forage samples at temperatures above 50°C significantly increased the lignin and insoluble nitrogen content (MacDougall and Delong, 1942; Hodge, 1953). Lignin content of moist samples such as freshly harvested green chop forage, ruminal fistula samples, and fecal samples were 11.5, 53.2, and 28.8 percent greater, respectively, when dried at 60°C than when freeze-dried (Bohman and Lesperance; 1967). This increase could be attributed to the condensation of carbohydrate degradation products with proteins and amoni acids via the non-enzymatic browning reaction (MacDougall and DeLong, 1942; Hodge, 1953; Van Soest, 1962) which was enhanced greatly by water (Van Soest, 1965b).

Immature high-protein grasses were particularly sensitive to heat damage. The combination of low lignin content and susceptibility to heat damage might increase the apparent lignin content by about three times the true value because of heat applied during ordinary drying procedures at 80-100^{o}C (Van Soest, 1964). Feces were relatively less susceptible to heat damage, lignin would appear to have a significant digestibility, especially in young grasses. Negative lignin digestibilities might appear if heat damage to feces was more than that of feed. This latter effect could be found in digestibility trials with silage or with hays that have not been heat-dried (Van Soest, 1964).

Christiansen (1979) observed that in all-hay diets, the grass lignin digestibility coefficients were high, ranging from 7.1 to 25.8 percent with a mean of 20.8 percent. No negative digestion coefficients were observed for the grass diets while several negative lignin digestibility coefficients were calculated for the alfalfa diets. The lignin digestibility of alfalfa ranged from -1.3 to 17.1 percent with an average of 4.5 percent. Procedure of Fonnesbeck and Harris (1970b) was used by Christiansen (1979) to determine lignin composition.

Not only the different chemical procedures of lignin extraction was accounting for the variations in lignin digestibility. These variations could also be attributed to feed lignin reacting differently to the chemical extraction than lignin in feces (Christiansen, 1979).

Scales et al. (1974) reported that the lignin ratio technique and forage lignin determined by KMno4 procedures gave unsatisfactory estimation of in vivo digestibility. However, forage lignin determined by the 72 percent sulfuric acid procedures was satisfactory (R = .94).

Wallace and Van Dyne (1970) reviewed the apparent digestibility of lignin in various forages by different analytical procedures. The conclusions was that lignin might be digested to a large extent, particularly in immature forages.

Barnes and Marten (1979) listed the following problems associated with the use of lignin concentration as a predictor of digestibility: (1) the complex and incompletely known structure of lignin; (2) the lack of an efficient and reliable procedure to determine lignin; (3) the inherent variation in lignin content among forages; and (4) variations in the relationship between indigestible lignin and partly digestible cellulose, depending on environmental conditions.

These facts would prevent effective use of conventional lignin as a marker in digestibility trials (Van Soest, 1964). However, more accurate experimental techniques were needed to prove or disprove the indigestibility of lignin.

The fecal nitrogen index was also used as an alternative to methods that required sampling of forage consumed to determine digestibility (Cordova et al. 1978). Mitchell (1924) found a constant relationship between the feed consumption of rats and metabolic fecal nitrogen. Raymond (1948) demonstrated that the percent nitrogen in sheep diets could be predicted from the nitrogen content in the feces. A relationship was found between fecal nitrogen (N) and organic matter digestibility (Y) of $Y = 1 - 0.80/N$ for forages containing over 15 percent protein and $Y = 1 - 0.67/N$ for forages containing less than 15 percent protein (Lancaster, 1949a,b). A linear regression between digestibility and fecal nitrogen was found (Raymond et al. 1954).

Errors associated with regression equations found in many studies have indicated that their application could be limited to cases where very large differences in intake or digestibility exist. Variability in digestibility coefficients ranged from 9 percent (Lancaster, 1949b) to 13 percent (Jeffery, 1971).

Feed nitrogen index regression also varied with season (Minson and Raymond, 1958; Langlands et al. 1963). The seasonal variations were mainly due to the differences in the leaf-to-stem ratios between the herbage clipped for conventional digestion trials and that was actually consumed by grazing animals (Lambourne and Reardon, 1963).

The consumption of a variety of plant species by grazing animals would result in different relationships between fecal nitrogen and the feed-to-feces ratio (Streeter, 1969). Feed consumed (Mitchell, 1924), body weight (Schneider, 1943), and the fiber content of feed (Blaxter and Mitchell, 1948) had an effect on the amount of metabolic fecal nitrogen which in turn affected the fecal nitrogen index.

However, the assumption that fecal nitrogen was related to metabolic fecal material which was related to the feed-to-feces ratio seems weak (Virtanen, 1966). The fecal nitrogen was mainly of bacterial origin rather than metabolic. The non-bacterial fraction of fecal nitrogen would be present in the lignin molecule (Van Soest, 1967).

Fecal nitrogen method was found to be better suited for digestibility than for intake estimates (Cordova, 1977). Fecal nitrogen was also an exceptionally valid estimator of digestibility of sandhill range forages (Wallace and VanDyne, 1970; Scales et al. 1974).

Other internal markers such as iron (Gallup and Kuhlman, 1931), silica (Gallup and Kuhlman, 1936; VanDyne and Lofgreen, 1964), Methoxyl groups of forage (Richards and Reid, 1952), crude fiber content of feces Richards and Reid, 1952; Raymond et al. 1954), and soluble fecal fraction (Owen and Ingleton, 1963) were also used to estimate the digestibility and intake of forages.

External indicators were a second kind which was fed to the animals to estimate fecal output without the use of feces bags and include chromic oxide (Chromium sequioxide), orinoxide, monastral blue (Church and Pond, 1976; Crampton and Harris, 1969; Schneider and Flatt, 1975), and rare earth compounds (Kays et al. 1980; Kotb and Luckey, 1972).

It was obvious that an indicator should be non-toxic, palatable, easily measured, should be insoluble and should pass out of gastro-intestinal tract at a uniform rate.

If the digestibility of a component of a diet was known, and if its fecal output of a grazing animal could be measured by fitting an animal with a feces bag to collect the total output, or by feeding an external indicator to the animal. Therefore, the only purpose of the external indicator was to permit estimation of the fecal output without using feces bags (Crampton and Harris, 1969). Calculation of the fecal output by using an external indicator was as follows:

$$\text{Fecal dry matter output (grams)} = \frac{\text{\% external indicator in feed X 100}}{\text{\% external indicator in feces grap}}$$
$$\text{sample dry matter}$$

Forage intake and digestibility by grazing animals could be estimated by the use of the ratio technique and by the fecal index technique (Crampton and Harris, 1969):

$$\text{Dry matter consumption} = \frac{\text{weight of internal indicator in feces}}{\text{\% indicator in forage}}$$

or

Dry matter consumption =

$$\frac{\text{(units of dry matter in feces/day)(amount of indicator/unit of dry feces)}}{\text{amount of indicator/unit of dry matter in feed}}$$

(Schneider and Flatt, 1975). Apparent digestibility of a particular nutrient could be calculated as follows:

$$\text{Apparent digestibility} = 100 - \frac{\%\ \text{indicator in feces}}{\%\ \text{indicator in feed}} \times \frac{\%\ \text{nutrient in feces}}{\%\ \text{nutrient in feed}}$$

Such a ratio provided an estimate of digestibility of a particular nutrient without knowing either total intake of feed or the total excretion of feces (Church and Pond, 1976; Schneider and Flatt, 1975). Then it was possible to estimate the dry matter as follows:

$$\text{Indigestible dry matter} = 100 - \%\ \text{digestible dry matter}$$

$$\text{Dry matter consumption} = \frac{\text{dry matter in feces (g)} \times 100}{\%\text{indigestibility of dry matter}}$$

(Crampton and Harris, 1969).

The ratio technique needed accuracy in collecting samples of the forage consumed by the animal and a completely indigestible indicator (Crampton and Harris, 1969).

The most widely used internal indicators for the ratio technique were chromogen and lignin. Chromogen appeared to be a good indicator for succulent green forage during the summer (Reid et al. 1952); while lignin appeared to be a good indicator for winter range plants (Cook et al. 1951).

It was necessary to clip forage and feed it in a conventional digestion trial in which the forage intake and fecal output of a few animals were quantitatively measured using a digestion stall (Crampton and Harris, 1969). Analyses of feed and feces for an internal indicator (grass energy, organic matter, nitrogen, silica-free dry matter or dry matter) were necessary.

While the conventional digestibility trial was being conducted, animals equipped with fecal bags or animals fed an external indicator to calculate the total fecal output were grazed on the pasture, and the concentration of the internal indicator in feces was determined (Cook et al. 1951). Regression equations for the data on the animals fed in the conventional trial were developed and used to calculate digestibility of forage pasture on range (Crampton and Harris, 1969).

When both external and internal indicators were used together in grazing animals, both the parameters, namely, consumption and digestibility of pasture forage could be measured without the total collection of feces for 24 hours by feces bags (Reid et al. 1951; Reid et al. 1952). The internal indicator gave the indigestibility of the consumed dry matter. A mathematical relationship between the internal indicator (Chromogen in this study) - dry matter ratio was established between the fecal output and the forage consumption. This relationship allowed the circumvention of sampling of the forage. The forage consumption might be determined from the following formula:

$$\text{Dry matter consumed (g)/day} = \frac{\text{external indicator fed}}{\text{(g) external indicator in feces}} \text{ X } \frac{\text{(g) dry matter in feces}}{\text{\% indigestibile dry matter}}$$

<u>In Vitro Methods</u>. The invitro methods, in which organisms or enzymes which were similar in function to those present in the digestive tract of ruminants, were used to estimate the digestibility of feeds in the laboratory. The two-stage technique for the in vitro digestion of forage crops was described by Tilley and Terry (1963). The method involved incubation of small (0.5 gram) samples of dried forages with rumen liquor first, then with acid pepsin. A regression equation

was developed to predict in vivo digestibility (Y) from the in vitro dry matter digestibility (X): $Y = 0.99 X - 1.01$.

Van Dyne and Meyer (1964) also proposed an in vitro technique to measure in vivo forage digestibility of grazing animals. The first phase of the method involves the determination of the in vivo and in vitro cellulose digestion of several hard-fed forages. The in vivo cellulose digestion coefficients of the hard-fed forages were lineary regressed on the in vitro cellulose digestion coefficients of the hard-fed forage.

The second phase involved grazing trials in which samples of the diet and feces were obtained. In vitro digestion was conducted on these samples. A sample of a hand-fed forage used in the first phase must be included in the vitro study and inoculated with inoculum from each of the grazing animals in order to permit the adjustment for differences in the relative fermenting capacity of different in vitro trials. The adjusted in vitro cellulose digestibility was calculated by dividing the in vitro cellulose digestibility of the dietary samples by the in vitro cellulose digestibility of the respective hand-fed forage samples.

The in vivo digestibility of cellulose of the dietary samples was then predicted from the adjusted in vitro cellulose digestibilities using the equation developed in the first phase. The in vivo digestibility of the dry matter consumed could then be computed by subtracting the in vivo cellulose digestibility from the percent cellulose in the ration and dividing the remainder by the percent cellulose in the feces.

Van Dyne and Meyer (1964) assumed in this technique that (1) the relationship between cellulose digestibility in vivo and cellulose digestibility in vitro must be the same for the grazed and the hand-fed forages; (2) this relationship was not affected by different sources of inoculum; and (3) dietary samples were of the same composition as the total forage consumed by the grazing animal.

Testing the applicability of the micro-digestion techniques range digestion studies, Van Dyne and Meyer (1964) found that the ratio between the overall mean digestion coefficient for cellulose as calculated by the lignin ratio technique and the microdigestion technique was 101 and 111 percent for cattle and sheep, respectively. The higher digestion coefficients as calculated by the microdigestion technique were related to partial digestibility of lignin based on the in vitro digestion of lignin of approximately 4 percent.

In vitro digestibility of feedstuffs could be influenced by source of inoculum (Van Dyne and Weir, 1966; Eikenberry, 1963), length of fermentation (Van Dyne, 1962; Teri et al. 1963; Van Dyne and Meyer, 1964) and stage of maturity of forage (Wallace et al. 1961a,b).

The in vitro methods of forage analysis to estimate the digestibility of the fibrous fraction (usually cellulose) were criticized by Van Soest (1969). Apart from poor analytical precision, the difficulties with the in vitro rumen fermentation techniques were that cellulose was only a part of the cell wall and a small part of the forage dry matter, and that factors affecting the availability of cellulose might not be the same of those affecting other constituents. Thus, in vitro fermentation was not a suitable mean of evaluating concentrate feeds.

Moreover, one might expect the two-stage in vitro (Tilley and Terry, 1963) digestibility to be higher than digestibility in vivo due to the fact that there was no in vitro endogenous excretion (Van Soest et al. 1966). On the other hand, the in vitro indigestible residue may contain bacterial residue or forage digestion might not be as complete as that in the animal.

Van Soest et al. (1966) modified the Tilley and Terry (1963) in vitro digestion technique. The modified method consisted of two stages. The first stage was a 48-hour in vitro rumen fermentation as in Tilley and Terry (1963) procedure. The second stage was replaced by a cell wall determination, using the neutral detergent procedure. Percentage of dry matter disappearance was also calculated.

Digestibilities resulted from this method were higher than those of Tilley and Terry (1963) technique. The in vitro digestibility by cell walls yielded values nearly equal to those of true digestibility in vivo. The matter comprising the difference between the two techniques was not of forage origin but of bacterial residues resisting acid pepsin digestion.

The modified in vitro digestion technique could be used to ascertain true digestibilities and apparent digestibilities with slightly less precision. It was also shorter by two days and requires fewer manipulations (Van Soest et al. 1966).

The cell wall in vitro digestion resulted in slightly less accurate predictions of in vivo digestibility, but like the summative equation technique (Van Soest, 1967) was within acceptable limits of accuracy (R = .85) (Scales et al. 1974).

When acid-pepsin was employed in the second stage of the in vitro procedure, the technique combined all three components of the summative equation: DCC, DCW, and MFOM. Substituting neutral detergent for acid-pepsin resulted in an estimate of true organic matter digestibility (DOM) and required a correction for MFOM in order to predict DOM. Major problems associated with the use of in vitro methods for routine hay evaluation programs were precision and cost under commercial operations, and time that was required for the analysis of samples (Barnes, 1975).

Another in vitro technique for the estimation of digestibility and metabolizable energy content of ruminant feedstuffs was carried by measuring the gas production when they were incubated with rumen liquor in vitro (Menke et al. 1979). Gas production in 24 hours from 200 milligram feed dry matter was well correlated ($R = .82$) with digestibility of organic matter, determined in vivo with sheep. $DO = 7.65$ ($\pm$ 0.59), where DO = digestible organic matter (DO, gram per kilogram organic matter). Gb = gas production in 24 hours. Since gas production reflected more the content of digestible carbohydrates than of protein and fat, a multiple regression analysis including these crude nutrient contents was carried out ($R = .96$).

$DO = 13.3(\pm 0.22)\ Gb - 0.05\ (\pm 0.002)\ Gb^2 + 511\ (\pm 25.0)\ XL + 91.2$ ($\pm$ 0.31), where XP = crude protein and X = ether extract (gram per gram dry matter).

When multiple regression analysis included data from proximate analysis, it resulted in an equation ($R = .98$) for prediction of metabolizable energy content (based on 30 experiments with ration varying in protein and crude fiber content, and 59 other experiments with concentrates):

$ME_r = 0.118(\pm 0.0009)$ Gb $+ 8.72(\pm 0.087)$ XP $+ 19.21(\pm 0.303)$ XL $+ 3.38\ (0.103)$ XX $+ 9.691(\pm 0.0038)$, where ME_r = metabolizable energy (MJ/kg dry matter), XP = crude protein, XL = ether extract, and XX = nitrogen-free extract. The relationship between in vitro and in vivo was: ME (in vitro) = 0.949 ME (in vivo) + 0.565; $R^2 = 0.95$.

The critical points of the gas production technique were: (1) the low sample weight which might lead to errors. (To overcome this problem, it was recommended to use more samples instead of using larger samples); (2) the difficulties in keeping a standard feedstuff for correction for deviations caused by changes of the rumen liquor, and (3) that feedstuffs that showed a significantly slower gas production than the majority might have higher digestibilities in vivo than was indicated by the gas production method.

When time of incubation increased to 26 hours, the expected improvement in correlation predicted from the mathematical correlation was not achieved. The feeds that showed an early maximum in gas production showed almost the same increment in the last two hours as those with slower increase. The difference between in vivo and in vitro measurements with those feeds might be due to either the differences in passage rate and retention time in the rumen, or to higher utilization in the small intestines of nutrients that bypass rumen fermentation.

Other possible interferring factors were the atmospheric pressure, the pH of sample, and the organic acids present in the feed. In silages the content of organic acids might cause deviations because the metabolizable energy (ME) content was higher than indicated by the production of carbondioxide (Co_2) in rumen liquor. Hence, a separate equation for silages should be developed (Menke et al. 1979).

The reason for high correlation between gas production in vitro and digestibility (and metabolizability) in vivo could be to the fact that this method was not based on a filtration process to separate the digested and undigested materials. Such a separation might not lead to full information on digestibility, partially because some partially digestible and/or indigestible substances might pass through the filter, and partly because some digestible matter might not be extracted from the indigestible fraction on the fiber.

Barnes (1973) described two types of errors associated with the in vitro procedures. The random errors which involved those factors contributing to the variability in the in vitro results. The magnitude of the random errors reflecting the precision of the in vitro methods were those associated with the within and between trial variability. The failure of the investigator to handle each sample similarly contributed to the random variation. More variation between trials than within trials had been reported.

A study was conducted among 19 laboratories where a standardized two-stage in vitro rumen fermentation technique was used (Barnes, 1973). In vitro dry matter disappearance from duplicate determinations within each of three runs was obtained for the same 12 herbage samples by each laboratory. The mean in vitro dry matter digestibility among laboratories averaged over herbages ranged 57.1 to 64.2 percent with a mean standard deviation within runs of 1.3 and among runs of 2.0.

The second type of errors was the prediction errors that result from the failure of the in vitro data to estimate accurately the in vivo parameters due to an inaccurate mathematical model. The correlation coefficients could be high and significantly greater than zero. However, the predictive equations derived from in vivo - in vitro relationships might have limited value if the standard errors of the estimate (Sy.x) were large (Barnes, 1973).

The In Vivo Nylon Bag Digestion. The in vivo nylon bag digestion was another method for digestibility estimation. Harris et al. (1968b) summerized factors affecting the results of the nylon bag technique, sample preparation and fermentation time (Van Dyne, 1962; Gallinger and Kercher, 1964) and type of diet (Van Dyne, 1962; Van Dyne and Weir, 1966; Gallinger, 1965; Hopson et al. 1963) were the factors that would influence the results of digestion carried by the nylon bag technique. Particle size of forage kept in the bags would influence digestibility. The finer the particle of forage put in the nylon bag, the greater would be the disappearance (Hopson et al. 1963). Moreover, the dietary regime of fistulated animals would influence the disappearance of test forages put in the nylon bags.

Small Animal Bioassay Techniques. Small animal bioassay techniques to evaluate forages were used (Barnes, 1977; Barnes and Marten, 1979). Small animals like hamsters, guinea pigs, rabbits, and meadow voles, had been used. Satisfactory prediction of ruminant intake and digestibility had been obtained with the vole, using tropical and temperate forage species (Shenk and Barnes, 1974). The weanling meadow vole (a common herbivore in the grasslands of most of North America and Europe) was successfully used to predict milk production potential of alfalfa for dairy cows (Shenk et al. 1975).

Insects such as crickets had also been proposed and used for bioassays of forage quality for certain forage species (Pfander et al. 1964).

Near-Infra-Reflectance Method. Recently, a new technique had been proposed as a rapid assay for chemical constituents of feedstuffs. Near-infrared-reflectance spectra (1.4 to 2.4 μm) were recorded for 87 samples of ground dry forages (Norris et al. 1976). Temperate and tropical forage species were included in the study. Laboratory analysis of crude protein, acid detergent fiber, neutral detergent fiber, lignin, and in vitro dry matter disappearance, as well as in vivo digestibility, dry matter intake and digestible energy intake were determined for the same samples. Reflectance (R) spectra were recorded as log (1/R) versus wave length and transformed to the second derivative of log (1/R) versus wave length for correlation with composition and nutritional data. Multiple-linear-regression techniques were used to determine the optimum wave lengths for predicting each of the chemical in vitro and in vivo analysis. By use of nine wave length points for the prediction equations, the correlation coefficients were .99, .98, .96, .96, .95, .88, .80, .85 for crude protein, neutral detergent fiber, acid detergent fiber, lignin, in vitro dry matter digestibility, dry matter digestibility, dry matter intake, and digestible energy intake, respectively.

The low-protein samples were characterized by a broad absorption band at 2.1 μm while the high-protein samples exhibited almost a straight line in the same region.

Lignin content was determined by permanganate and sulphuric acid procedures. The simple correlation coefficient between the two procedures was .95. Infrared reflectance gave a correlation coefficient of .96 with the permanganate method so that the standard error of .80 percent may reflect errors equally from the chemical procedure and from infrared reflectance.

Norris et al. (1976) also found that errors in predicting animal responses were greater than those in predicting chemical composition because these errors could have originated from animal response data since appeared that much of the errors might be in only a few samples.

Barnes (1977) and Barnes and Marten (1979) predicted that infrared reflectant spectroscopy of forages and other feedstuffs might replace many routine laboratory quality assays. The potential existed for this procedure to predict the animal nutritive responses without the need to predict the chemical composition first.

The greatest source of variation was sample preparation. Uniformity, finness, and temperature fluctuations during assay were known to affect infrared reflectance (Barnes and Marten, 1979).

Other physical methods to estimate forage quality and animal response included approaches to such as: artificial mustication of forage tissue in order to measure the relative tissue breakdown into particles of a certain size (Troelsen et al. 1970). Measurement of a fibrous index based upon the electrical energy required to pulverize a given size sample of hay (Chenost, 1966), and anatomical-histological observations (Monson et al. 1972; Chatteron and Powell, 1974; Shenk and Elliot, 1971).

A comparison of laboratory methods in attempts to determine the most reliable procedures of evaluating the nutritive value of feedstuffs (Oh et al. 1966; Sullivan, 1964; Van Soest, 1964), was reported by Barnes (1973).

Lignin was often cited as the most promising for estimating in vivo digestibility, especially when individual species were evaluated (Sullivan, 1964; Van Soest, 1971). The inability of a single chemical entity or solubility index to accurately predict various in vivo parameters was inherent in the complex biological systems. The difference between grasses and legumes was one of the main problems. Grasses and legumes with similar digestibility values might differ significantly in chemical composition. Legumes had a higher lignin content and usually lower hemicellulose than grasses. Therefore, the calculation of separate regression equations for different species would reduce the residual error in the prediction of digestibility with most laboratory methods. A summative chemical equation was effective for prediction of digestibility, if all the correct constituents were analyzed (Barnes, 1973). However, the expense and time required for all the analyses in a summative equation might not be practical.

The two-stage in vitro rumen fermentation technique was reported superior to other laboratory methods in predicting in vivo digestibility (Barnes, 1966; Deinum and Van Soest, 1969). The sensitivity of the digesting microorganisms to undetermined factors accounted for much of the superiority of the in vitro system. However, the many sources of variations inherent with the method made it difficult to standardize, especially with respect to the source and handling of inoculum (Barnes, 1973).

Mathematical Methods to Predict Digestibility of Feedstuffs

Regression Equations. Regression studies showed that significant relationships existed between the chemical analysis and the digestion coefficients of the different nutrients. The regression of apparent digestibility on one or more of these independent variables, the percentages of proximate nutrients, was very significant in most cases (Schneider and Flatt, 1975). The proximate analysis and other chemical entities could be used to predict the digestibilities of nutrients. These predictions were more accurate than fixed average coefficients multiplied by the composition values of a sample or by the average composition of a feed.

Feedstuffs differed considerably in their chemical and physical characteristics depending on their species, stage of maturity, disease and insect damage, genetic and environmental variation and harvesting, processing, and feeding procedures (Barnes, 1973). Hence, the digestibility of feeds was related to their chemical composition (Schneider and Flatt, 1975). 25 to 45 percent variance in digestibility between samples of a given feed was associated with proximate composition was found in a statistical study of digestibility data (Schneider and Lucas, 1950). Thus, the use of the adjustments which took into consideration the chemical composition of a certain sample would lead to more precise estimates of digestibility than would the use of tabulated averages. However, feeds for which there were missing digestibility data, equation for estimating digestion coefficients and total digestible nutrients (TDN) from the chemical analysis of a given feed was developed (Schnieder et al. 1952): $Y = C + b_1X_1 + b_3X_3 + b_4X_4$ where C was a constant specific for the nutrient and the class of feed under consideration. b_1, b_2, b_3 and b_4 were the partial regression coefficients, and X_1, X_2, X_3, and X_4 were the moisture-free percentages of the crude protein, crude fiber, nitrogen-free extract, and ether extract, respectively, for the sample of feed for which it was desired to estimate the digestibility. Schneider and Flatt (1975) gave the constants and partial regression coefficients for the several nutrients in each feed class for cattle and sheep.

The use of crude fiber in feedstuff analysis was based on the assumption that the amount of crude fiber was negatively related to the available nutrient content in forages. However, the crude fiber content often gave an inaccurate estimate of nutrient availability and the analytical procedures used lack precision (Barnes, 1973). A correlation coefficient of R = -.65 (Sy.x = 4.1) between crude fiber and dry matter digestibility was obtained with a group of 65 samples of grass (Sullivan, 1964). A correlation coefficient of R = -0.49 (Sy.x = 4.8) was obtained with a group of 98 samples of grass, alfalfa, and grass-alfalfa mixtures. Crampton (1950) and Crampton and Jackson (1944) also reported that little correlation could be obtained between crude fiber and digestibility of roughages (Crampton et al. 1940).

High correlations, however, had been obtained between crude fiber of roughages and digestibility of the organic matter (Axelsson, 1949; McMeekan, 1943; Walker and Hepburn, 1955). Meyer and Lofgreen (1956) used the crude fiber content (S) to estimate TDN (Y) in 152 digestion trials on 31 samples of alfalfa hay of variable quality: Y = 79.7 - 0.84X. The correlation coefficient was -0.86, (Sy.x = 2.96).
Barnes (1977) reported that correlations between crude fiber and in vivo dry matter digestibility had been cited as ranging from an R = .50 to R = 0.94. The lack of agreement among workers might be due to the mixture and species of the roughages studied (Meyer and Lofgreen, 1956).

Many other analytical precedures had been developed for predicting forage quality, such as anhydro-uronic acid solubility, cellulose, methoxyl, modified crude fiber, and normal acid fiber. However, these procedures had shown little or no improvement over crude fiber (Barnes, 1977).

Lignin had been successfully used to predict energy or organic matter digestibility (Lancaster, 1943; Forbes and Garrigus, 1950a, 1950b; Walker and Hepburn, 1955). The regressions of organic matter digestibility on lignin content (X) for cattle were:

$Y = 95 - 4.10X$ (for conventional calculations) and,

$Y = 100 - 4.33X$ (for the calculations made up by lignin ratio).

These equations were not statistically different by the (t) test (Forbes and Garrigus, 1950a). The regression of organic matter digestibility (Y) or lignin content (X) for wethers were:

$Y = 9 - 5.32X$ (for the conventional calculations) and,

$Y = 101 - 4.92X$ (for the calculations made up by lignin ratio).

Results of the digestion trials carried by Meyer and Lofgreen (1956) showed a great range in alfalfa quality (36.2 - 63.4 percent TDN). The regression equation of TDN (Y) or lignin content (X) was:

$Y = 84.57 - 3.21X$.

Both the regression coefficient ($b = 3.21$) and the correlation coefficient ($R = -0.88$) were statistically highly significant. Correlations of nitrogen content with TDN was 0.77.

When organic matter digestibility was related to lignin, crude fiber, or nitrogen content, the correlation coefficients were practically identical to those relating TDN to lignin, crude fiber, or nitrogen.

A multiple regression of TDN on lignin and nitrogen did not prove to be more significant than a simple regression of TDN or lignin.

Another study of regression equations relating total digestible nutrients (TDN) and digestible protein to lignin, crude fiber, crude fiber plus silica, and protein revealed that the modified crude fiber was most satisfactory for predicting both TDN and digestible protein (Table 11) (Meyer and Lofgreen, 1959). The inclusion of silica as a part of the crude fiber seemed desirable. Since fibrous portion of the hay had less nutritive value than the non-fibrous portion, inclusion of silica with the fiber might give a better indication of hay quality than treating it as part of the non-fibrous portion.

TABLE 11 Regression and Correlation of Alfalfa Constituents With TDN and Digestible Protein[a]

Item	Regression Equation[b]	Standard Error of Estimate	Correlation Coefficient
	Total digestible nutrients		
Lignin	$Y = 79.1 - 2.67X$	3.13	-.84**
Crude fiber	$Y = 78.7 - 0.8027X$	2.84	-.87**
Modified crude fiber	$Y = 81.07 - 0.8558X$	2.52	-.89**
Protein	$Y = 1.142X + 33.33$	3.41	0.80**
	Digestible protein		
Lignin	$Y = 30.6 - 1.21X$	1.94	-.85**
Crude fiber	$Y = 29.5 - 0.5168X$	1.95	-.85**
Modified crude fiber	$Y = 30.7 - 9.5416X$	1.89	-.86**
Protein	$Y = 0.9155X - 3.1$	0.63	0.99**

[a] Digestion trials conducted on 43 different samples of alfalfa hay.

[b] Y equals total digestible nutrients or digestible protein, as the case may be; X equals lignin, crude fiber, modified crude fiber or protein, as the case may be. All results are reported on an oven-dry basis. **Significant at the 1% level. (Adapted from Meyer and Lofgreen, 1959)

The relationships between lignin and digestibility of 5 forage fractions was examined by Van Soest and Moore (1965). Correlations were computed expressing lignin content in different ways: as a percentage of the dry matter, of NDF, and of ADF, and as the logarithm of lignin concentration of ADF. The correlations of all forms of lignin expression with digestibility of fibrous portions were highly significant. However, in case of the non-fibrous fractions, significance was attained only when lignin was expressed as a percentage of dry matter. In the case of nitrogen, the decline in nitrogen with increase in lignin concentrations would account for the correlation. For the purpose of predicting availability of fiber fractions, expression of lignin on the basis of ADF rather than NDF was preferred because this was the preparatory step in the isolation of lignin. This mode of expression appeared to involve less error and was termed lignification (L).

The high correlation between NDF digestibility and logarithm of L was of importance. The NDF included the entire fibrous fraction of the forages, which lacked uniformity in respect to nutritive value. Lignification accounted for the lack of uniformity and the variation in digestibility. Moreover, the change of the undigested plant residue (F) with respect to lignin was proportional to the lignin content in the fibrous fraction: df/dl = KL, where K was the slope of the regression of the fiber indigestibility on natural logarithm of L (Van Soest and Moore, 1965).

Since the lignification (L) was negatively related to digestibility and the ND solubles (S) were positively related to digestibility, it was possible then to express these two factors as ratio. This ratio could be written L/s, which was an estimate of indigestibility. The ratio was found to regress linearly with digestibility. Hence, an index of availability (A) was expressed as: A = 100 - 100(L/s).

Digestibility has been determined by total collection from 39 feeds including forages of different forage species (Grasses and legumes, mixture of forages, and mixed feeds with concentrates. On a group of 29 feeds crude fiber correlated -0.77 while (A) yielded = .95 with digestible energy (Table 12).

TABLE 12 Prediction Equations for the Estimation of Nutritive Value from Index of Availability

Evaluation		Equation	Correlation	N of Feeds
Digestible dry matter (%)	=	0.782A + 12.7	+0.94	39
Digestible energy (%)	=	0.732A + 13.7	+0.96	39
TDN (%)	=	0.653A + 16.7	+0.95	29
Estimated net energy (therms)	=	0.905A - 11.2	+0.95	29

(Adapted from Van Soest and Moore, 1965)

The utilization of forages by ruminants was limited by feed intake which was generally a more limiting factor than digestibility, relative to animal productive yields (Van Soest, 1978b).

Survey and correlation data indicate that while intake and digestibility are interrelated, the intake factor had a great degree of independence and seems to be influenced by certain factors (hemicelluloses that have little association with digestibility). Lignin was a major factor limiting digestibility, and had a consistent effect on intake (Van Soest, 1965a).

However, Cook and Child (1977) found out that no chemical constituent included in the proximate analysis of diets of range animals appeared to account for any statistical amount of variation in daily consumption. Regression equations were developed to determine intake of range forages by sheep during different seasons from the nutrient content of forages. There was no significant correlation. Protein, lignin, and gross energy were perhaps the most influential but even these constituents varied widely among seasons.

It was now known yet why animals eat the species they did during various seasons or on certain sites. Feed volume and the content of cell wall were factors associated with low feed intake. The association of lignin with intake could be considered a secondary association that appeared in date-of-cutting studies, where lignin and cell wall increased with plant maturity while intake and digestibility declined (Van Soest, 1965a).

Lignin rate of passage had a very high correlation (+.90) with cell wall intake (Van Soest, 1965a). Cell wall might be correlated better with forage intake than forage volume because it was better associated with the relief factors of communication and passage (Van Soest, 1978b).

In range plants, Cook (1966) and Cook and Harris (1950) found that digestible dry matter and crude protein were inversely related to lignin content of range forages.

However, the problems associated with the use of lignin concentration as an estimate of the nutrient digestibility might be summarized as: (1) the complex and incompletely unknown structure of lignin, (2) the lack of efficient and reliable standardized procedure, and (3) the inherent variability in lignin content among forage species (Barnes, 1977).

Cellulose was the principal constituent of crude fiber and the "true" cellulose was determined by the method of Crampton and Maynard (1938) usually. This procedure was more rapid than crude fiber but provided no advantage for the estimation of digestibility ($R = -0.46$ for cellulose and -0.49 for crude fiber) that was reported by Sullivan (1964).

Gaillard (1966) observed that hemicellulose was composed of a mixture of different polymers, which could have different digestibilities. The less digestible hemicellulose was found to contain high amounts of anhydro-uronic acid. Values of anhydro-uronic acid determined from neutral detergent fiber were used to predict organic matter digestibility. The correlation of cell wall content and anhydro-uronic acid with organic matter digestibility was 0.59 ($Sy.x = 7.8$) (Gaillard and Nijkamp, 1968). The inclusion of lignin resulted in a correlation of $R = 0.95$ with organic matter digestibility.

The relationship between digestible amounts of hemicellulose (Y) and the content in the dry matter (X) was:

$Y = 9.4 + 0.37X$ ($R = 0.50$) for grasses

$Y = 2.4 + 0.36X$ ($R = 0.80$) for legumes

$Y = 0.79\ x - 2.3$ ($R = 0.94$) for total grasses and legumes.

Schneider et al. (1951) used the proximate nutrients as predictors in equations which allowed the adjustment of digestibilities of almost all feeds fed to cattle and sheep. The feed involved was also taken into account. It was assumed that the digestion coefficients of the various nutrients and the content of TDN could be expressed as function of proximate compositions as in the following equation:

$Y = \bar{y} + b_1(X_1 - \bar{X}_1) + b_2(X_2 - \bar{X}_2) + b_3(X_3 - \bar{X}_3) + b_4(X_4 - \bar{X}_4)$ where Y was the digestion coefficient for a given nutrient (or the content of TDN) in a particular sample of feed; $\bar{y}$ was the average value of the digestion coefficient (or content of TDN) for the feed which the sample represents; b_1, b_2, b_3, and b_4 were the partial regression coefficients; X_1, X_2, X_3, and X_4 were the percentages of the crude protein, crude fiber, NFE, and ether extract in the sample; and $\bar{X}_1$, $\bar{X}_2$, $\bar{X}_3$, and $\bar{X}_4$ were the average percentages of crude protein, crude fiber, NFE, and ether extract for the feed. The partial regression coefficients for adjusting digestion coefficients and TDN to proximate composition for cattle and sheep were computed for five different classes of feeds.

Christiansen (1979) estimated nutrient digestible amounts from nutrient percent content by two ways. First, by simple regression equations of the form $Y = b_o + b_1X_1$ where Y was the nutrient digestible amount and X was the nutrient percent content. This statistical model was used by Lucas et al. (1961) in estimating the true digestibility (b_1) of a given chemical component of animal feeds. The regression constant (b_o) estimated the nutrient endogenous excretions and the standard deviation of the regression coefficient (S_b) together with the coefficient of determination (R^2) estimates how uniformily the nutrient was digested (true digestibility) over the diets analyzed.

Crude protein and available carbohydrates were shown to be highly uniform in true digestibility across all diet treatment ($R^2 = .97$, $S_b = 2.3\%$; $R^2 = .98$, $S_b = 2.1\%$ respectively, for crude protein and available carbohydrates).

Second, Christiansen (1979) used complex regression equations to estimate nutrient digestible amount from nutrient percent content. Two types of multi-variant equations were generated by using indicator or dummy variables (A quantitative indicator used in a regression model to identify the classes of a qualitative variable (Neter and Wasserman, 1974) in addition to the nutrient percent content to predict the digestible amount of the nutrient. The indicator variables were added to the model to adjust for variability due to the treatment main effects and interaction effects. While the analysis of variance was used as a guide in picking the treatment factors that showed a substantial effect upon digestibility of a given feed constituent.

All type one equations showed a significant improvement over the simple equations in estimating the digestible amount of each nutrient. All type one equations also showed higher coefficients of determination (R^2) than those shown by the simple equations (crude protein, .98 vs .97; available carbohydrates, .99 vs .98; total lipids, .55 vs .19; hemicellulose, .94 vs .89; cellulose, .94 vs .79; cell walls, .95 vs .81; neutral detergent fiber, .96 vs .84; acid detergent fiber, .93 vs .69; and crude fiber, .94 vs .76).

Type two equations for hemicellulose, cellulose, cell walls, neutral detergent fiber, acid detergent fiber, and crude fiber showed only a slight improvement in the R^2 value over that shown by the type one equations.

Dry matter digestibility was computed from crude protein of 165 herbage samples of different sources (Sullivan, 1964). The correlation coefficient was as low as 0.24 with a standard error of the estimate $Sy.x = \pm 7.1$. Crude protein was not likely to be a very reliable predictor of dry matter digestibility because it was much affected by nitrogen fertilization and relative differences in content among legume and grass species (Van Soest, 1967). Besides, the use of crude protein to estimate digestibility of dry matter was based on the hope that the decrease in protein content was uniformly associated with the decline in digestibility and maturity of forage. Hence, it was not sound to expect the amount of the available components such as protein to form a fixed relationship with the digestibility of the cell wall or any fiber constituent whose availability was affected by different factors. The use of crude fiber to estimate digestibility of protein or cellular contents was invalid (Van Soest, 1967).

However, Sullivan (1964) showed that digestible crude protein could be predicted for crude protein content of feedstuffs ($R = 0.99$; $Sy.x = 0.5$).

Under range conditions, Cook and Child (1977) found that digestible protein was the most important nutrient determination because it was associated with energy, phosphorous, and carotene content of the forage and could be determined rather accurately from total protein and lignin when predicted values fell within ranges of 2 to 10 percent.

However, in range forages the digestibility of crude protein varies from as high as 80 percent in the early growth to as low as 20 percent in mature dormant plants (Cook and Child, 1977). Regression equations were of practical value in estimating digestible protein from total protein. The following regression equations were suggested for estimating digestible protein (DP) of hays from total protein (TP):

$DP = -3.48 + 0.93\ TP$ (Holter and Reid, 1959).

$DP = -2.86 + 0.93\ TP$.

$DP = -3.51 + 92\ TP$ (Stallcup et al. 1976)

Cook and Child (1977) tabulated linear regression equations developed by various workers to predict digestible coefficients and quantity of digestible material in forages with varying degrees of success as measured by the magnitude of R^2 values.

However, in the short grass plains of Colorado, prediction formulae for digestible protein showed that total protein alone gave R^2 values of 0.92 (Cook and Child, 1977). By using total protein (TP) and digestible energy (DE) as predictors as much as 0.96 of variability in digestible protein in diets of steers could be counted for as shown in R^2 values (Table 13).

In a study of animal response, Cook et al. (1977) found out that the analysis of 14 independent factors determined that only a relatively few nutrients, such as digestible protein and digestible energy were even moderately associated with animal gains on rangelands. Digestible protein alone was reported to be the best factor available to evaluate the nutritive quality of range forages.

In all cases studied, it was found that digestible protein (DP) was more closely related to animal response than digestible energy (DE). In most cases, the accounted animal variation in animal gain was increased only slightly (R^2 = 0.77 to 0.83) when the influence of digestible energy was added to digestible protein. Digestible protein content of the forage reflected increased forage growth after summer precipitation and the decrease of nutrients associated with phenological advancement of forage plants. However, digestible energy, which was also moderately associated with animal gain, did not show a marked response to either precipitation or to the advancing growth stages of plants. The lines of predictive formula indicate that predicted gain

TABLE 13 Nutrients Shown in a Predictive Linear Equation for Determining Digestible Protein in Range Plants for Three Seasonal Range Types for Sheep and Cattle

Predictive factors (b's)	R^2 x 100
Sheep, Spring (seeded foothills)	
- 4.10 + 0.97 (TP%)	92.9
19.49 - 1.97 (Lig%)	61.9
84.80 - 0.64 (Lig^2%)	72.0
0.77 + 0.82 (TP%) - 0.51 (Lig%)	94.9
108.60 - 0.50 (Lig^2%) - 0.03 (Cellu. % x CHO %)	82.0
Cattle, Spring (seeded foothills)	
- 2.79 + 0.84 (TP%)	90.0
21.63 - 2.11 (Lig%)	44.7
- 3.45 + 0.85 (TP%) + 0.08 (Lig%)	90.4
- 10.42 + 10.17 (TP%) - 0.35 (TP^2%)	90.9
81.07 + 13.19 (TP%) + 1.52 (Cell. %) - 0.43 (TP^2)	93.4
Sheep, Summer (mt. range)	
- 3.32 + 0.69 (TP%)	60.3
10.56 - 0.50 (Lig%)	31.6
1.27 + 0.60 (TP%) - 0.32 (Lig%)	72.0
Cattle, Summer (mt. range)	
- 0.77 + 0.48 (TP%)	34.1
6.56 - 0.27 (Lig%)	25.5
1.93 + 0.40 (TP% - 0.20 (Lig%)	48.0
Sheep, Winter (desert range)	
- 3.02 + 0.84 (TP%)	84.0
3.64 - 0.01 (Lig%)	00.7
- 1.59 + 0.87 (TP%) - 0.14 (Lig%)	87.6
Cattle, Spring-Summer (mixed grass)	
- 1.98 + 0.86 (TP%)	88.3
- 7.32 + 0.21 (DDM%)	52.7
9.61 - 0.002 (GE kcal/lb)	0.4
- 7.38 + 0.011 (DE kcal/lb)	54.6
- 6.27 + 0.710 (TP%) - 0.094 (DDM%)	95.6
Cattle, Spring-Summer (short grass)	
- 2.01 + 0.91 (TP%)	91.9
16.84 - 0.006 (GE kcal/lb)	3.4
- 3.54 + 0.16 (DDM%)	24.5
4.99 + 0.009 (DE kcal/lb)	43.7
- 4.55 + 0.80 (TP%) - 0.003 (DE kcal/lb)	94.9
.13 + 0.76 (TP%) - 0.003 (GE kcal/lb) + 0.004 (DE kcal/lb)	95.5

(Adapted from Cook and Child, 1977)

followed actual gain more closely from the percentage of digestible protein in the ration than from digestible energy (Cook et al. 1977). These results were in agreement with those of Cook and Harris (1968a) who found that animal response appeared to follow digestible protein content of the forage more closely than any other nutrient combination of nutrients.

Cook and Child (1977) pointed out that the diets used in calculations consisted of changes in the proportion of the plants eaten and changes in species of plants and forage classes consumed as well. The nutrient content of the grazing animal's diet was also influenced by maturity changes and weathering of mature plants. Thus, any predictive equation that accounted for 70 to 75 percent of the variation in the dependent variable was of practical significance in range livestock nutrition.

Summative Equations. The digestibility of organic matter of feedstuffs could be predicted by the approach used by Lucas and Smart (1959) as expressed in terms of the following summative equation:
DOM = Dcc + Dcw - MFOM where Dcc = digestible organic cell contents, Dcw = digestible organic cell walls, and MFOM = metabolic fecal organic matter excretion. The values were expressed as percentage of dry matter.

Van Soest (1963a) proposed his approach of the division of forage dry matter into cell walls and cell contents. A neutral detergent fiber (NDF) fraction (referred as cell wall constituents), an acid detergent fiber (ADF) fraction, and an acid detergent lignin (ADL) fraction resulted from this approach of analysis. ADF and ADL are usually used in the prediction of digestibility. NDF was best related to intake (Van Soest, 1965a; Van Soest and Mertens, 1977). Rohweder et al. (1978) suggested the use of ADF and NDF system in a proposed hay grading system.

The cellular contents were 98 percent digestible and not affected by lignification (Van Soest and Moore, 1965). The cell wall constituents were insoluble in neutral detergent and were partially available. Summative equations had been proposed for calculating digestibility of mixed forages considering all contents and cell walls were separate digestive entities (Georging and Van Soest, 1970; Sullivan, 1964; Van Soest, 1967).

Van Soest (1967) developed a summative equation to estimate the true digestibility of the nutrients in feedstuffs using the cell wall and cell content partitioning of feed dry matter. Lucas test was also applied in this method. In the Lucas test, the digestible amount of the component to be tested (Y) was regressed or percent of that component (X) in the dry matter of forage. The regression constant was an estimate of endogenous excretion of the component (which was assumed to be constant (a) for the tested forage, while the slope of regression (b) estimated the average true digestibility. Hence, $Y = a + bX \pm Sy.x$. When the digestible amount of cellular contents (Y) was regressed against the total amount in the dry matter (X) (measured as dry matter soluble in neutral detergent) the following relationship was given for grasses and legumes (Van Soest, 1967): $Y = 0.98X - 12.9$ ($R = 0.99$). The relationship between the digestible amount of cell walls (Y) and the total content in the dry matter was (Van Soest, 1967):

$Y = 12.9 + 9.46X$ ($R = 0.46$) for grasses

$Y = -6.1 + 0.60X$ ($R = 0.60$) for legumes

$Y = -1.3 + 0.62X$ ($R = 0.73$) for total grasses and legumes.

The true digestibility of dry matter (Y) of forages was calculated from cell contents (CC), cell wall (W) and log of percent lignin in acid detergent fiber (X) (Van Soest, 1967):

$$Y = 0.98\ CC\% + W(147.3 - 78.9X)$$

This summative equation was an attempt to present a calculation procedure that recognized cause and effect relationships between chemical components and availability. If the endogenous and bacterial excretion as well as the true digesibilities of the cellular contents, cell wall and dry matter were all determined experimentally in a total collection digestion trial (Van Soest, 1966a), it was possible to arrive at a portion of the apparent digestion coefficient into the portions arising from different sources. Such a partition might be related to animal kind and conditions of feeding (Van Soest, 1967).

The summative equation concept should serve as the basic concept for rational prediction of the digestibility of organic matter values of hay. However, a limitation to the routine use of summative equation was the lack of reliable and fast procedure of estimating the digestible cell walls (Barnes, 1975). Moreover, this method might work well with forage crop such as alfalfa but not with range shrubs.

The correlations of acid detergent fiber, cell wall content, and acid detergent lignin with digestibility or intake were not much improvement over other chemical methods, however, (Oh et al. 1966; Sullivan, 1964; Van Soest, 1965a). A higher correlation was obtained between dry matter digestibility and proposed availability index based on estimating the degree of lignification (Van Soest and Moore, 1965).

The dry matter disappearance of forages by purified enzymes and aqueous solutions was found to be highly correlated with digestibility and nutritive value index (NVI) (Donefer et al. 1963). The use of cellulase enzymes for the estimation of herbage quality was practical. High correlations were obtained with in vivo digestibility in published TDN values (R = 0.92) (Guggolz et al. 1971) and NVI (R = 0.92) (Donefer et al. 1963).

Enzymatic hydrolysis of the carbohydrates of cell wall had been suggested for estimation of both the extent and rate of hydrolysis of total cell wall (Bailey et al. 1978). This procedure did not develop because of the variation in cellulase activity among sources and batches of cellulase enzymes. However, as quality control manufacturing methods were developed for the production of cellulase powders with uniform cellulase activity, the use of this technique might increase (Barnes, 1973).

Plant species was reported to affect correlation coefficients (Hartley et al. 1974). Grasses gave highly significant correlations (R = 0.96) between dry matter digestibility and percentage of cell wall digested by cellulose enzyme, while legumes gave lower correlation coefficients.

Another method was described for the prediction of the in vivo digestibility of dry matter and cell wall of grasses. The method involved incubating grass cell walls with a commercial cellulase for 16 hours and measuring the optical density (OD) of the filtrate at 324 μm OD (Hartley et al. 1974). The prediction equation was based on a highly significant correlation (R = 0.978) between OD and dry matter digestibility using a total of 27 samples of three species of grass with dry matter digestibility ranging between 60 and 83.

Cell wall digestibility = 39.84 + 48.91 OD R = 0.979, SD = 0.19,

Dry matter digestibility = 48.30 + 35.57 OD R = 0.978, SD = 1.65.

The method could not be used for the prediction of dry matter digestibility of red clover and sainfoin due to their filtrates having low optical density values.

Modified fungal enzyme procedures (including predigestion with acid pepsin or neutral detergent) could be used to predict relative differences in digestibility of most grasses and legumes (Jones and Hayward, 1975; Roughan and Holland, 1977).

The problem of estimating digestibility from chemical composition remains because there was no chemical method that would partition the carbohydrates of the cell wall of plants into available and non-available fractions (Van Soest, 1967). Regression equations utilizing summative calculations had disclosed a variety of factors that influence digestibility. The difficulty was that while such equations might estimate digestibility very satisfactorily provided the right measurements were made, the number of determinations and the laboratory work was large and expensive.

The Energy Systems and Mathematical Models to Predict Energy Utilization of Feedstuffs

Crampton and Harris (1969), Harris et al. (1972) and Kromann (1971) reviewed the systems that described the energy values of feedstuffs as follows:

The Total Digestible Nutrients (The TDN System). One of the most common methods employed to assess the nutritive value of feeds was to determine their contents of the digestible nutrients (Morrison, 1956). Hence, the total digestible nutrients (TDN) system had been used for over 100 years in many parts of the world (Australia, Latin America, the Middle East, and the USA) as a measure of the energy content of feeds (Harris et al. 1972).

The TDN is the sum of all digestible organic nutrients - protein, fiber, nitrogen free extract (NFE) and ether extract (EE) and fat (the latter being multiplied by 2.25 because its energy value of animals was approximately 2.25 times that of protein or carbohydrates) (Morrison, 1956). The percents of TDN represent the approximate heat or energy value of the feed. The digestible protein was included in this total since protein serves as a source of heat and energy when more was provided than was required to meet the protein needs of the body. The TDN system was based on the determination of the amounts of digestible nutrients which was deducted in the loss that occurs in the undigested materials in the feces. It was assumed that the remainder (the digested nutrients) was all assimilated and used in the body. However, this was not strictly true. Energy losses of three other types occur in digestion and utilization of foods.

The TDN system did not give good measurements of nutritive energy because it did not agree with basic scientific concepts and nutrition theory when compared with other measures of nutritive energy (Harris et al. 1972).

Ensminger and Olentine (1978) and Harris et al. (1972) described certain weaknesses of the TDN system:

First, TDN was based on the proximate analysis of plant cell constituents which lacked uniformity. The nitrogen free extract (which was supposed to be highly digestible) contained the sugars, starch, and part of hemicellulose and lignin. While the crude fiber (supposed to be the least digestible) contained all the original cellulose, variable portion of hemicellulose, and a small (but variable) portion of lignin. For some feeds, crude fiber was as digestible as NFE.

Second, the TDN system overevaluated high fiber feeds in relation to low fiber feeds. The reason for this overevaluation was the higher heat loss per pound of TDN in the case of the high fiber feeds. A comparison was made between a high and low fiber ration feed to growing cattle in amounts to produce the same daily gain (Lofgreen, 1965a). In this case, the heat lost from a pound of TDN from the high fibrous feed was 24 percent greater than that lost from a pound of TDN from the low fiber feed. Therefore, a pound of TDN from hay was not as nutritive as a pound of TDN from concentrates because of the heat loss.

Third, crude protein was calculated by multiplying the nitrogen percent by 6.25 assuming that all proteins contain the same amount of nitrogen. Besides, it assumed that all nitrogen was of proteinous origin.

Fourth, the TDN system was based on physiological fuel values for humans and dogs. These values did not apply well to ruminants. Hence, the factor of 2.25 to convert fat content to energy was not always a constant. In addition, the ether extract of certain range forages were high in non-nutritive fats such as waxes, resins and essential oils (Cook and Harris, 1968b) which overestimated the energy value of the ether extract fraction.

Fifth, it did not measure energy in energy units (it is expressed as a percent or in pound or kilogram while energy was expressed in calories).

Sixth, the nitrogen free extract (NFE) fraction was calculated by difference, and hence, it was a pool of errors of other methods.

Seventh, it did not consider important losses such as energy lost in urine, gasses and heat increment.

In summary, the TDN system attempted to measure what feeds contain rather than what they accomplish or produce. However, the main advantage of the TDN system was that it was simple, easy to understand and easy to apply to feeding practices.

Harris et al. (1972) developed a series of multiple regression equations to calculate TDN directly from proximate analysis of five classes of feedstuffs for cattle, horses, sheep, and swine. Data for these equations were selected from data files.

Van Soest (1971) estimated values of TDN from digestible dry matter (DDM) by the following equation:

$$\text{TDN} = \text{DDM} - \text{total ash} + \text{silica} + 1.25 \text{ ether extract} + 1.9.$$

The Calorie System. All animal functions and biochemical processes required a source of energy to derive the various processes to completion. This applies to all life processes and animal activities such as chewing, digestion, maintenance of body temperature, and production (Church and Pond, 1976).

Harris (1966), Harris et al. (1968a); Harris et al (1972) and Crampton and Harris (1964) gave a complete glossary of energy terms and outline the conventional system of energy terminology (Figures 5,6).

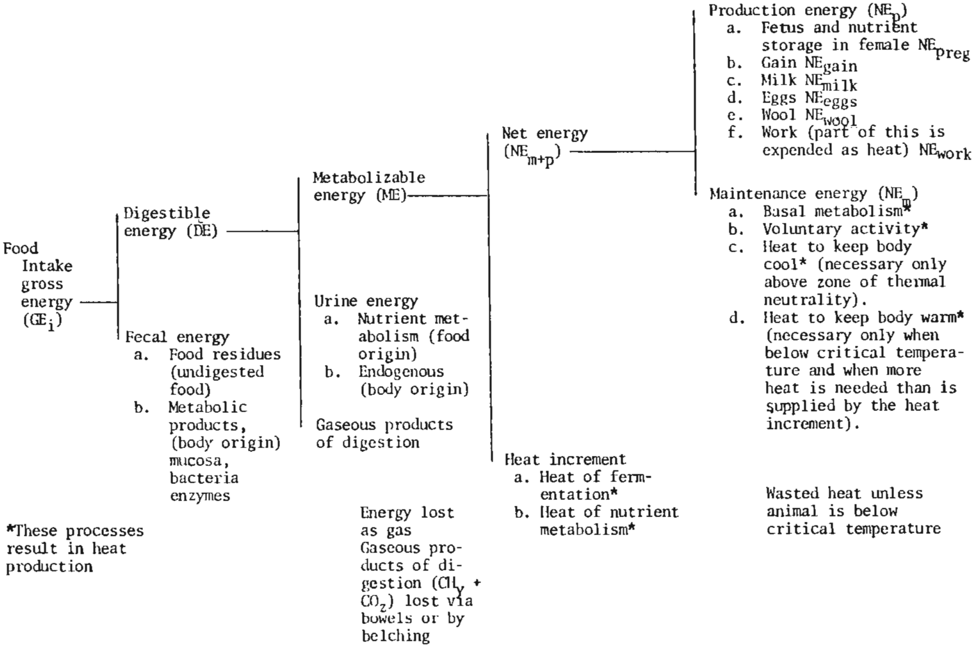

FIGURE 5 Conventional biological partition of feed energy. (Adapted from Harris et al. 1972)

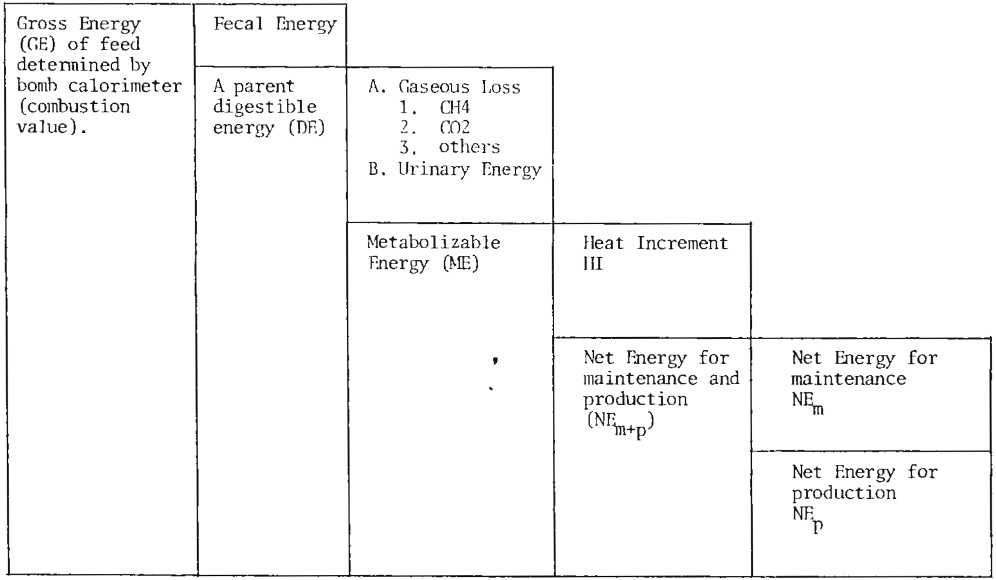

FIGURE 6 A conventional scheme of feedstuff energy utilization

Gross Energy. Gross energy was defined as the amount of heat, measured in calories, that is released when a substance is completely oxidized in a bomb calorimeter containing 25 to 30 atmospheres of Oxygen. It was referred also as "the heat of combustion" (Harris, 1966). The determination of energy values by the bomb calorimeter was one of the most accurate analyses carried in the laboratory and seems that a valuable and direct evaluation of the digestibility of feedstuffs has been overlooked (Swift, 1957). The food-intake gross energy (GEi) was however, the gross energy of the feed consumed:

GE_i = dry weight of food consumed X GE of food per unit dry weight (Harris, 1966).

Energy values of different feedstuffs or nutrients varied, but typical values are 4.10 (kcal/g), 5.65 (kcal/g), and 9.45 (kcal/g) for carbohydrates, proteins, and fats, respectively. The differences reflected mainly the state of oxidation of the initial compound. A typical monosaccharide such as glucose had an empirical formula of $C_6H_{12}O_6$, or one atom of oxygen per one atom of carbon. In a fat molecule, such as tristearin, there are 6 atoms of oxygen and 57 atoms of carbon. This fat required more oxygen for oxidation and gave off more heat in the process (Church and Pond, 1976).

The gross energy values of feedstuffs were of little practical value in evaluating feeds for animal usage. A poor quality feed such as oat straw had the same GE value as corn grain (4.4 kcal/g).

A gross energy (GE determination on a feed had no relationship to its nutritive value because a large part of it cannot be digested, absorbed or metabolized by animals (Fonnesbeck et al. 1975). Gross energy represented chemical composition of feedstuffs and did not provide direct prediction of utilization and effect in animal production (Nehring and Haenlein, 1973). Moreover, the gross energy value did not give a clear cut idea about the energy utilization in the body. Hence, the digestible energy (DE) was used.

Digestible Energy. The apparent digestible energy of feeds could be defined as the food intake gross energy minus fecal energy. Other terms were apparent absorbed energy or energy of apparently digested food.
DE = (GE of food per unit dry weight X dry weight of food) - fecal energy.
Fecal energy (FE - GE of feces per unit dry weight X dry weight of feces.

The final evaluation of feeds by this method would be closely comparable to TDN but would be a direct result of only one accurate analysis of the feed and one of the feces (Swift, 1959). DE is simple and easy to understand and to be determined. One pound of TDN is equal to 2,000 kilocalories of DE. However, DE had the same characteristic of TDN of over-evaluation of high fibrous feeds (Lofgreen, 1965a). Moreover, digestible energy does not account for the gaseous loss of energy (Crampton and Harris, 1969).

True digestible energy was determined by measuring the energy in fecal excretions (metabolic fecal energy) or an animal that was fasting or being fed a diet that was supposed to be completely digested (milk or eggs). This amount was then subtracted from total fecal excretion of the animal. This method was not feasible with most herbivores and is rarely practiced (Church and Pond, 1976).

Direct determination of digestible energy (DE) through digestion trials was costly and time consuming. Moreover, feed composition tables gave average DE values for similar feedstuffs but the chemical composition of a specific lot of feed might not compare closely to those described in the table or it might be a mixed ration of unknown composition (Fonnesbeck et al. 1975).

Chemical analysis that separate organic matter as it was selectively digested by animals could become a basis for calculating digestible energy. The application of a stepwise regression equation enabled Fonnesbeck et al. (1975) to estimate DE from the chemical analyses of feedstuffs for different kinds of animals. Sheep, swine, rabbits, and rats were fed diets formulated to contain 1 percent to 55 percent cell walls in digestion trials. The diets consisted of barley grain, soybean meal, wheat flour, soyflour, alfalfa hay, and barley straw. DE was highly correlated to cell wall (CW), cell content (CC), soluble carbohydrates (SC) cell wall carbohydrates (CWC), lignin, crude protein (CP), and non-nutritive matter (NNM) content of diets. CC, SC, and CW were the most highly correlated to DE in simple regression equations and accounted for over 90 percent of the variation in DE. In multiple regression equations lignin and crude protein were selected to account for some additional variation (Table 14). However these equations should only be applied by species of animals over the range of nutrient content used in the experimental diets and could not be used with cell wall analysis by other methods (Fonnesbeck et al. 1975).

Christiansen (1979) developed models to predict digestible energy (DE) of sheep diets from estimated values of digestible amounts of crude protein (Y_{cp}), available carbohydrates (Y_{ac}), total lipids (Y_{tl}), cellulose (Y_{cl}), and hemicellulose (Y_{hc}):

TABLE 14 Regression Equations for Calculating Digestible Energy from Various Chemical Components of the Diet for Various Species of Animals[a]

Item	b_o	b_1	X_1	b_2	X_2	b_3	X_3	R^2	Sy.x
In general:									
DE =	4.23	-.0444	CW%	--	--	--	--	.919	.207
DE =	5.25	-.0496	CW%	-.0551	CP%	--	--	.964	.138
DE =	-.077	+.0427	CC%	--	--	--	--	.964	.138
DE =	.709	+.050	SC%	--	--	--	--	.956	.152
DE =	.869	+.047	SC%	-.0098	lignin%	--	--	.964	.139
DE =	.693	+.041	SC%	-.0228	lignin%	+.0306	CP%	.966	.135
For sheep:									
DE =	4.46	-.0466	CW%	--	--	--	--	.936	.119
DE =	.646	+.0548	SC%	--	--	--	--	.938	.117
DE =	-.716	+.0748	SC%	+.134	lignin%	--	--	.944	.113
DE =	4.55	-.0584	CWC%	--	--	--	--	.938	.117
DE =	4.91	-.111	CWC%	+.214	NNM%	--	--	.946	.111
For rabbits:									
DE =	4.34	-.0491	CW%	--	--	--	--	.696	.318
DE =	5.17	-.0478	CW%	-.0565	CP%	--	--	.971	.100
DE =	4.04	-.251	NNM%	--	--	--	--	.796	.261
DE =	3.52	-.315	NNM%	+.029	CWC%	--	--	.970	.102
DE =	4.60	-.213	NNM%	-.0456	CP%	--	--	.971	.101
DE =	2.59	-.0314	lignin%	--	--	--	--	.635	.349
DE =	1.15	-.0459	lignin%	+.0294	OCC%	--	--	.971	.101
For swine:									
DE =	4.30	-.050	CWC%	--	--	--	--	.972	.090
DE =	4.43	-.0466	CWC%	-.0273	ash%	--	--	.978	.083

TABLE 14 (CONTINUED)

Item	b_o	b_1	X_1	b_2	X_2	b_3	X_3	R^2	Sy.x
For swine:									
DE =	.59	+.0391	OCC%	--	--	--	--	.978	.080
DE =	1.89	+.0254	OCC%	-.0177	CWC%	--	--	.980	.079
DE =	1.135	+.0448	SC%	--	--	--	--	.970	.093
DE =	.166	+.0391	SC%	+.0724	CP%	--	--	.982	.075
DE =	-4.54	+.0755	SC%	+.183	CP%	+.0443	CW%	.985	.073
DE =	2.22	+.0292	SC%	-.129	lignin%	--	--	.983	.073
For rats:									
DE =	4.25	-.0495	CW%	--	--	--	--	.965	.105
DE =	2.54	-.0272	CW%	+.0241	SC%	--	--	.973	.094
DE =	-.34	+.045	OCC%	--	--	--	--	.971	.095
DE =	.52	+.0522	SC%	--	--	--	--	.962	.110

[a] Digestible energy is calcualted in kcal/g or Mcal/kg. Abbreviations for chemical components of the diet are as shown in Table 3. The regression equations are of the form $Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3$ .... R^2 is the multiple correlation coefficient; Sy.x is the standard error of estimate. (Adapted from Fonnesbeck et al. 1975).

DE = 4(Y_{cp} + Y_{ac} + Y_{cl} + Y_{hc}) + 9(Y_{tl}) where the 4 and 9 were assigned physiological feul values (megacalories per kilogram) for feed carbohydrates and lipids respectively.

Christiansen (1979) also estimated DE from nutrient percent content of sheep diets. He used simple equations ($Y = b_o + b_1X_1$), where Y equalled estimated DE and X_1 equalled the diet percent content of available carbohydrates, cellulose, cell walls, neutral detergent fiber, acid detergent fiber or crude fiber. The precision of the simple model was shown to be average to poor in estimating DE. R^2 values ranged between 0.50 to 0.71 with residual standard deviations ranging from 0.20 Mcal/kg to 0.27 Mcal/kg.

Cellulose, cell walls, neutral detergent fiber and acid detergent fiber appeared to be comparable as DE predictants, though the chemical composition between these separate fractions was different. Neutral detergent fiber was shown to be the most accurate as a predictant. Available carbohydrates, crude fiber, and A models were markedly lower in precision for estimating DE than cellulose, cell wall, neutral detergent fiber, and acid detergent fiber models.

The use of complex equation (multivariant models) for estimating DE directly using the diet percent content of cellulose, cell walls, neutral detergent fiber, acid detergent fiber, or crude fiber as the only quantitative independent variable in the equation, significantly improved the DE predictability than corresponding simple modes (Christiansen, 1979). This was shown by a distinct increase in R^2 values (cellulose, 0.88 vs 0.69; cell walls, 0.88 vs 0.70; neutral detergent fiber, 0.90 vs 0.71; acid detergent fiber, 0.88 vs 0.68; and crude fiber, 0.90 vs 0.56) and a decrease in the residual standard deviation of regression. Moreover, the complex models significantly reduced the unexplained variation (SSE). The complex models estimated closer DE to observed DE values than in the case of simple models.

Single predictive chemical constituents in range plants suitable for estimating digestible energy were identified by the computer as being lignin, gross energy, and crude protein (Cook and Child, 1977). Lignin alone accounted for 60 to 77 percent variation occurring in DE determinations of seeded foothill range (cattle and sheep) and on mountain summer range (cattle). Other range types showed lower R^2 values.

Digestible dry matter in diets of steers or mixed grass ranges during spring and summer could be used to predict DE with a relatively high degree of accuracy ($R^2/100 = 79.8$ percent). Using both digestible dry matter and gross energy, Cook and Child (1977) reported R^2 of 0.85 (Table 15).

On short grass ranges during spring and summer, however, DE was not predictable to any high degree of accuracy by using a single chemical constituent as a predictor. When digestible dry matter, digestible protein and gross energy were used, R^2 values were about 0.70 (Cook and Child, 1977). In the case of swine Drennan and Maguire (1970) examined the relationship between crude fiber and DE and ADF and DE values for 16 diets (contained 3 to 14 percent CF; 2 to 5 percent fat, and 15 to 21 percent crude protein) and found that crude fiber (CF) and acid detergent fiber (ADF) were closely related to DE:

DE (kcal/kg DM) = 4068.7 - (103.4 X %CF); R = -.89

DE (kcal/kg DM) = 4102.9 - (85.0 X %ADF); R = .92

However, Morgan (1976) reported that when application was limited to

TABLE 15 Linear Equations and Predictive Factors from Proximate Analysis for Percent Digestible Energy for Sheep and Cattle on Various Seasonal Range Types

Predictive Factors (b's)	R^2 x 100
Sheep, Spring (seeded foothills)	
1584 - 72.6 (Lig%)	45.3
- 39 + 0.62 (GE kcal/lb)	24.1
152 - 84.6 (Lig%) + 0.79 (GE kcal/lb)	83.7
1210 = 2.59 (Cell%)	00.8
1379 = 100 (Lig%) + 13.26 (Cell%)	58.9
1298 - 71 (Lig%) + 7(OCH%)	47.4
Cattle, Spring (seeded foothills)	
1557 - 62.7 (Lig%)	40.6
-616 + 0.84 (GE kcal/lb)	15.3
1682 - 19 (Cell%)	66.7
155 - 59.18 (Lig%) + 0.69 (GE kcal/lb)	71.4
1734 - 17 (Lig%) - 16 (Cell%)	68.5
1576 - 63 (Lig%) - 0.48 (OCH%)	40.6
Sheep, Summer (mt. range)	
1119 - 45 (Lig%)	29.9
1893 - 0.52 (GE kcal/lb)	27.3
2298 - 44 (Lig%) - 0.49 (GE kcal/lb)	34.1
779 + 3.47 (Cell%)	00.2
1685 - 50 (Lig%) - 14 (Cell%)	33.1
642 - 41.8 (Lig%) + 16.1 (OC%)	35.1
Cattle, Summer (mt. range)	
1541 - 63.0 (Lig%)	72.2
-540 + 0.76 (GE kcal/lb)	5.5
-280 - 64.4 (Lig%) + 0.93 (GE kcal/lb)	80.6
288 + 23 (Cell%)	12.6
1668 - 65.0 (Lig%) - 3.7 (Cell%)	72.5
1043 - 60.3 (Lig%) + 12.8 (OCH %)	75.3
Sheep, Winter (desert range)	
1054 - 41.08 (Lig%)	24.9
98 + 0.26 (GE kcal/lb)	4.7
50 - 63.87 (Lig%) + 0.69 (GE kcal/lb)	51.5
257 + 13 (Cell%)	16.3
763 - 33 (Lig%) + 8.5 (Cell%)	30.6
1080 - 41 (Lig%) - 0.64 (OCH%)	24.9
Cattle, Spring-Summer (mixed grass)	
111.41 + 17.47 (DDM%)	79.8
891.09 + 49.133 (DP%)	54.7
994.73 + 0.088 (GE kcal/lb)	0.2
853.18 + 35.72 (TP%)	34.1

TABLE 15 (CONTINUED)

Predictive Factors (b's)	R^2 x 100
-949.44 + 18.4 (DDM%) + 0.52 (GE kcal/lb)	85.0
-813.39 + 16.22 (DDM%) + 10.05 (DP%) + 0.49 (GE kcal/lb)	86.11
Cattle, Spring-Summer (short grass)	
253.99 + 14.83 (DDM%)	45.0
838.07 + 34.35 (TP%)	28.9
871.69 + 44.64 (DP%)	43.7
113.25 + 0.55 (GE kcal/lb)	7.1
358.07 + 10.06 (DDM%) + 29.42 (DP%)	59.3
-912.68 + 8.52 (DDM%) + 35.99 (DP%) + 0.71 (GE kcal/lb)	70.2
-646.53 + 6.81 (DDM%) + 52.7 (TP%) + 91.34 (DP%) +0.69 (GE kcal/lb)	75.0

In the case of sheep on winter range the predictive factor is metabolizable energy instead of digestibile energy as above. (Adapted from Cook and Child, 1977) cereals and cereal-based diets both measures of fiber gave the following reasonable predictions of energy value:

DE (kcal/kg DM) = 4228 - (140 X %CF); R = -.97

DE (kcal/kg DM) = 4179 - (86 X %ADF); R = -.96

Henry (1976) reported similar results. The apparent digestibility of energy (ADE) was also related to the different measures of dietary fiber (CF, ADF, AND NDF) by taking into account the source of fiber used (wheat brain and dehydrated alfalfa meal). In case of CF, the equations were as follows:

Wheat bran: ADE = 96.29 = 3.04 (± .25) CF% DM; R = -.938.

Alfalfa meal: ADE = 93.02 - 2.09 (± .32) CF% DM; R = -.988.

The equations for ADF were:

Wheat bran: ADE = 95.35 - 2.23 (± .25) ADF% DM; R = -.941.

Alfalfa meal: ADE = 93.83 - 1.75 (± .23) ADF% DM; R = -.983.

When ADE coefficients were related to total cell wall content (NDF) the following equations were reported:

Wheat brain: ADE = 96.34 - .865 (± .081) NDF% DM; R = -.958.

Alfalfa meal: ADE = 100.77 - 1.19 (± .26) NDF% DM; R = -.955.

When data for both feeds were combined, the equation relating ADE to NDF was:

ADE = 96.71 - .886 (± .070) NDF% DM; R = -.959.

A value of 2.1 of the rate of decrease of ADE for one percent increase in CF was observed with dehydrated alfalfa meal compared to 3.0 with wheat bran (Henry, 1976). This difference was due to a lower percentage of hemicellulose in the cell wall constituents, which was reflected in a higher ADF/NDF ratio.

When the various classes of feedstuffs were considered, the rates of decrease in apparent digestibility of energy with increasing levels of crude fiber was determined. The correction factors for crude fiber were closely related to the composition of cell wall constituents (the ratio of cellulose to hemicellulose, which was itself in relation with the ADF/NDF ratio: the higher the ADF/NDF ratio, the lower the depressive effect of crude fiber on ADE). The greatest decrease in ADE was induced by wheat bran, and more generally by milling by-products, which contain a high hemicellulose content (corresponding to a low ADF/NDF ratio) (Henry, 1976).

Metabolizable Energy. Apparent DE was not a correct measure of the digestibility of a given ration or nutrient because the gastro-intestinal tract was considered to be an active site for excretion for various products that ended up in feces, and because there might be considerable sloughing of cellular debris from cells lining the gastrointestinal tract. Undigested microbes and their by-products might account for a large portion of the feces of certain species (Church and Pond, 1976). Much of the microbial growth occurred in the cecum and large intestine and pass with feces. Fibrous plant components such as cellulose and xylan, which were foreign to the animal body, had true digestible energy values.

However, true digestible energy could be determined by measuring the metabolic fecal energy of an animal that was fasting or fed a diet that was completely digested such as milk or eggs.

Feed energy was further partitioned into metabolizable energy (ME, which was defined as the food intake gross energy minus fecal energy, minus energy in the gaseous prducts of digestion, minus urinary energy (Harris, 1966). $ME = GE_i - FE - GPD - UE$ where FE = fecal energy and UE = urinary energy.

Metabolizable energy of a feedstuff was influenced by the same factors affecting the digestibility of that feed. These factors were feed composition, processing and treatments, species of animal, level of feeding, and associative effects (McDonald et al. 1973). GPD was the gaseous products of digestion and that included the combustible gases produced in the digestive tract incident to the fermentation of the ration. The energy of these gases was measured by determining the gross energy content. Methane made up the major proportion of the combustible gases produced. Carbon dioxide (Co_2), carbon monoxide, acetone, ethane, and hydrogen sulfide were also produced (Harris, 1966).

A small amount of energy was lost in the combustible gases (especially methane) which were produced in the fermentation of cellulose, pentosans, and other carbohydrates in the digestive tract, particularly in the rumen of ruminants.

Methane was derived from the reduction of carbon dioxide by hydrogen. Both gases were produced as a result of acetic acid formation. The production of propionic acid did not result in the formation of waste gases. A portion of the energy loss from the rumen was represented by gaseous carbon dioxide. The remaining portion was as methane.

Methane usually ranged from 3 to 10 percent of gross energy in ruminants. The amount produced depended on the nature of the diet and level of feed intake. Low quality diets resulted in larger proportions of methane and the percentage of GE loss as methane declined as feed intake increased (Church and Pond, 1976). Methane losses were estimated by Blaxter (1961) as follows:

$CH_4 = 4.28 + 0.059A$ for roughages,

$CH_4 = 6.05 + 0.020A$ for pelleted rations, where CH_4 = kilocalories methane per hundred kilocalories of food GE, and A = the apparent digestiblity of GE at maintenance.

Blaxter and Clapperton (1965) estimated gaseous energy loss by the following formula:

Methane = 1.30 + 0.112 D-L (2.37 - 0.050 D) where methane was expressed as kcal per 100 kcal of GE of feed, D = digestibility of energy at maintenance level of feeding, and L = the level of feeding as a multiple of maintenance.

Methane losses varied more than urinary losses with nutritional level. Armstrong (1964) summarized the combined effect of digestibility, methane, and urinary losses in the following equation:

dQ = 9.5 - 0.11 QM where dQ = depression of ME of feed (kcal per 100 kcal GE) on increased feed intake from maintenance to twice maintenance, and QM = ME of feed as a percent of its GE (determined at the maintenance level of feeding). Swift et al. (1948) estimated methane by the use of the following equation:

Methane = 2.41X + 9.80, where methane was in grams and X represented hundreds of grams of carbohydrate digested. In general, methane production was about 8 percent of GE at maintenance and it falls to 6-7 percent at higher levels of feeding.

The availability of hydrogen limited the amount of carbon dioxide converted to methane. The formation of acetic acid gave rise to the greatest relative production of methane due to the simultaneous production of hydrogen. The formation of butyric acid utilizes hydrogen to reduce acetoatate and, therefore, limited the amount of carbon dioxide converted to methane. The formation of propionic acid also utilized hydrogen and, therefore, acted to limit the amount of carbon dioxide to methane.

The ruminant animals meet their energy needs primarily by absorbing VFAs and simple sugars from the digestive tract. Approximately 70 percent of the animal's energy needs were obtained from VFAs. Of the remaining 30 percent, 10 percent was derived from more fermented dietary ingredients digested in abomasum and small intestine and 20 percent was derived from digestion of microbial cells which were passed to the abomasum and small intestine from the rumen reticulum.

Urinary energy (UE) was defined as the gross energy of urine. It included the energy content of nonutilized portions of the absorbed nutrients and the energy contained in the enodenous fraction of urine (Harris, 1966).

Energy was lost in urea and other nitrogenous waste products that are excreted in the urine. These compounds had energy which was lost to the animal. This loss was small with feeds which were low in protein, and was not very great even with feeds rich in protein. The energy lost by ruminants in urine should be considered in evaluating the metabolizable energy values of feeds for such animals (Harris, 1963). Measurements of such losses were usually made by drying urine samples and determining its heat of combustion in a suitable carolimeter. However, Street et al. (1964) assumed that the heat of combustion of urine bears a direct relationship to the nitrogenous compounds present, chiefly urea. Hence, urine energy values could be estimated from urine nitrogen. The correlation between urine nitrogen (UN) and urine energy (UE) values yielded an R^2 of 0.92. Equations for the estimate of UE were found as follows:

UE (kcal/gm) = 0.022 + 0.118 (UN%) for cattle;
UE (kcal/gm) - 0.027 + 0.119 (UN%) for sheep; and
UE (kcal/gm) + 0.026 + 0.117 (UN%) for both kinds of animals.

Above maintenance, there was no relationship between UE and UN (Blaxter et al. 1967). The UE increased with urinary carbon (C = grams per 24 hours) according to the following equation: UE = 9.66 C - 3.0.

The overall equation developed by Street et al. (1964) could be a useful method for estimating urine energy, and that it facilitates greater usage of the concept of metabolizable energy in research and practical feeding of cattle and sheep.

At maintenance, Blaxter et al. (1966) found that heat of combustion of urine (UE = kcal/100 kcal of diet) was related to the crude protein (CP) percentage of the diet by the equation: UE = 1.6 + 0.25 CP. Actual urinary losses were in the range of 3 to 5 percent of GE in ruminants, or 12 to 35 kcal per gram of nitrogen excreted (Church and Pond, 1976). As level of feed intake doubled, the urinary energy losses increased from 0.6 to 0.8 kcal GE. Blaxter (1961) reported increased UE as level of dietary increased for cattle fed various levels of roughages. The increase of UE was not uniformly influenced over all levels at dietary roughage for the caloric value was greater for steers fed higher than 100 roughage diets.

The concept of urinary nitrogen used to determine the nitrogen balance that was in turn used to determine the nitrogen corrected metabolizable energy (ME_n) to account for the nitrogen retained or lost from the body tissue (Harris, 1966).

Nitrogen balance (NB) or nitrogen retention was the nitrogen in the food intake minus the nitrogen in the feces (FN), minus the nitrogen in urine (UN).

NB = NI - FN - UN.

$ME_n = GE_i$ - FE - GPD - UE ± (NB X 7.45 kcal).

Nitrogen-corrected metabolizable energy was defined as the food intake gross energy minus fecal energy, minus energy in gaseous products of digestion, minus urinary gaseous products of digestion, minus urinary energy. The total was then corrected for nitrogen retained or lost from the body. There was no need to consider the GPD for birds and monogastric mammals.

The correction was made as follows for mammals for each gram of nitrogen lost from the body (equal to negative nitrogen balance) 7.45 kcal were added to the metabolizable energy; and for each gram of nitrogen retained in the body (equal to positive nitrogen balance) 7.45 Kcal were subtracted from the metabolizable energy. However, this value was obtained with dogs, and it might not be entirely correct for other animals. In case of producing animals (milk, eggs, etc.), no correction was made for nitrogen in their products (Crampton and Harris, 1969; Harris, 1966). The correction factor for poultry was 8.22 kilocalories because it represented the energy equivalent or uric acid per gram of nitrogen. The factor 8.7 kilocalories was sometimes used because it gave approximately the average energy content of urine per unit of nitrogen (Harris, 1966).

The concept of metabolizable energy had the advantage of considering two energy losses which digestible energy did not. In most cases, however, these losses were small in comparison to the fecal lost (Church and Pond, 1976; Lofgreen, 1965a). Little was gained by the use of ME over DE or TDN. However, in cases of certain feedstuffs containing large amounts of essential oils, ME had a great advantage since these oils or detoxification products such as hippuric acid were absorbed but were excreted in the urine (Crampton and Harris, 1969; Church and Pond, 1976). The TDN and DE of such feeds would be a more accurate measure since high urinary loss would be subtracted and the evaluation is more realistic (Lofgreen, 1965a). However, ME had the same disadvantage as DE and TDN in the case of heat loss per unit of intake. Thus, ME did not seem to be better than DE or TDN for most purposes. Crampton and Harris (1969) added the term heat of fermentation corrected metabolizable energy (ME_{hf}). ME_{hf} was defined as the gross energy food intake minus fecal energy, gaseous products of digestion, heat of fermentation (HF), and urinary energy: $ME_{hf} = GE_i - FE - GPD - HF - UE$.

The efficiency of utilization of ME for maintenance was about 74 percent (ARC, 1965). However, there were variations among feedstuffs depending on the ME value of dry matter. The ARC (1965) used the metabolizable energy systems to replace the starch system. The ME was divided into:

a. ME for maintenance. The end products of the digestion process in ruminants were used for maintenance with an efficiency ranging between 80 to 85 percent (mean - 82.7 percent) irrespective to type of diet given and the fermentation the diet provoked in the digestive tract of the animal. A wide variety of feedstuffs including pelleted hays, artificially dried herbages, mixtures of roughages and cereals, and cereals given alone was used and analysis of variance showed that there were no statistically significant differences between the results for the different feeds.

The mean values for efficiency of utilization of ME for maintenance (k_m) were very close to the value 74 percent. The errors attached to these means were standard deviations between feeds. The value k_m tended to increase with the percentage of the gross energy metabolized(Q_m): $k_m = 54.6 + 0.30\ Q_m$. More metabolizable energy was required for the maintenance when diets were of poor quality roughages than when they were of high quailty. That might be partially because methane losses and fermentation losses of heat were not a constant fraction of the metabolizable energy.

b. Metabolizable energy for work.

c. Metabolizable energy for fattening mature animals. The efficiency with which ME was converted to fat (k_f) could be calculated as follows: $k_f = 65.6 - 0.70F$, where k_f was the number of kilocalories of body fat retained for every 100 kilocalories ME ingested above maintenance, and F was the percentage of crude fiber in the diet. The efficiency with which ME above maintenance was used for inducing fattening varied over a range of 15 to 70 percent. This variation appeared to be associated with the variation in the chemical form in which energy as nutrients reached the tissues.

d. Metabolizable energy for growth of young animals. The efficiency with which ME was used for growth in young ruminants was probably higher than that for fattening, but a convergence occurred at weight in cattle of about 300 kilograms. In calves, feed efficiency was 80 to 85 percent when milk was fed as a sole feed.

e. Metabolizable energy for pregnancy. It was more simple to assume that the maternal maintenance cost which changed and that the energetic efficiency of the gains was the same as in normal growth.

f. Metabolizable energy for lactation. The efficiency with which ME was used for lactation when body gain of energy was zero was difficult to measure, but varied relatively little from 70 percent, decreasing slightly for diets high in fiber or starch.

In swine nutrition, ME was related to the crude fiber (CF) and acid detergent fiber (ADF) contents of cereal and cereal-based diets (Morgan, 1976:

$\text{ME (kcal/kg DM)} = 4096 - (135 \times \%\text{CF}); \quad R = -.47$

$\text{ME (kcal/kg DM)} = 4049 - (83 \times \%\text{ADF}); \quad R = -.95$

Moreover, Morgan (1976) found that a combination of crude protein, acid ether extract and nitrogen free extract gave the best prediction of DE and ME, based on energy values and chemical analysis of a total of 37 feeds and mixed rations:

$\text{DE (kcal/kg DM)} = (109.9 \times \%\text{crude protein}) + (149.3 \times \%\text{acid ether extract})$
$+ (90.1 \times \%\text{NFE}) - 4030; \quad R - .95.$

$\text{ME (kcal/kg DM)} = (99.5 \times \%\text{crude protein}) + (144.7 \times \%\text{acid ether extract})$
$+ (87.8 \times \%\text{NFE}) - 4795; \quad R = .94.$

The usefulness of these equations was tested by comparing ME values of 16 diets (determined experimentally) with values summated from determined ingredient energy value and with predicted values (Morgan, 1976). In general, summated values were more similar to the determined values than were the predicted values. Hence, for diets or feedstuffs

that were widely varying in composition, dietary analysis alone did not give an accurate estimate of energy values. When digestibility coefficients were included, greater accuracy was obtained:
ME (kcal/kg DM) = (46.2 X %digestible crude protein) + (100.7 X %digestible ether extract) + (44.2 X %digestible crude fiber) + (40.7 X %digestible NFE); R = .99 (Nehring, 1969).

It would be necessary to use tabulated values for digestibility coefficients of the nutrients when applying such equations. Using tabulated coefficients would decrease the accuracy of predicted values derived from these equations. However, there was no real alternative that existed to use with such equations in cases where a rapid estimate of the energy value of a diet of unknown composition was required, or when considering a feedstuff for which no experimental determination of energy value had been made (Morgan, 1976).

In the case of poultry, the gaseous products were usually negligible and ME was the feed intake gross energy minus the excreta gross energy. A correction for nitrogen retained in the body was frequently applied to yield an ME_n value. This was the most common measure of available energy in poultry nutrition (NRC, 1977). True metabolizable energy (TME) for birds was the feed intake gross energy minus the excretal energy of feed origin:

$TME = \text{feed energy} - [\text{excreta energy} - (FE_m + UE_e)]$ or

$TME = AME + FE_m + UE_e$ (Sibbald and Price, 1977).

A correction for nitrogen retention could be applied to give TME_n. Sibbald (1976) developed a new method for estimating TME values of feedstuffs for poultry. These TME values were higher than ME values, but they have an apparent advantage of being unaffected by variations of feed intake.

ME for poultry was calculated as follows (Titus, 1961):
ME (kcal/g) = digestibility % X energy equivalents (kcal/g).
Titus (1961) also suggested the following: The energy equivalents for poultry: 3.84 for protein, ether extract (9.49 for meat and fish meals, 9.33 for grain seeds, and 9.21 for milk products), carbohydrates or NFE (4.2 for grains, 4.0 for legume seeds, 3.8 for legume leaves and stems and 3.7 for milk products), and 2.1 for crude fiber.

Carpenter and Clegg (1956) predicted ME of poultry feedstuffs from their chemical composition:
ME (kcal/kg) ± 53 + 38 (% CP + 2.25 EE + 1.1 X % starch + % sugar).
This formula gave predicted figures for the ME of feeds tested with a standard deviation of the ± 190 kcal/kg from the determined figures.

The relations between the ME and two functions of the analytical results were studies. Function A (% CP + 2.25 X % EE + % NFE) was based on the results from standard proximate analysis with the EE multiplied by 2.25: Y = 120 A = 7390 (with residual standard deviation ± 340 kcal/kg), where Y = ME. In function B (% CP + 2.25 % EE + 1.1 X % starch + % sugar), NFE was replaced by starch + sugar with 1.1 correction of the starch to allow for difference in the gross energy of starch and glucose.
Y = 38 B + 53 (with a residual standard deviation ± 190 kcal/kg).
Furthermore, Carpenter and Clegg (1956) showed closer relationships between chemical and biological results of ME (Y), as in the following equations:

$Y = 40\ X\ (\%\ \text{starch}) + 25\ X\ (\%\ \text{CP}) + 70\ X\ (\%\ \text{EE} + 470)$; (SD ± 140 kcal/kg)

$Y = 34\ X\ (\%\ \text{starch}) + 1250$; (SD ± 180 kcal/kg)

Sibbald et al. (1963) used function B (1.1 X starch + sugar + protein + 2.25 X EE) from the study of Carpenter and Clegg (1956). Function B was divided by dry matter and used as the independent variable (X). The biologically derived ME (Cal/gDM) was employed as the dependent variable (Y):

$Y = 0.828 \pm 2.677\ X$ (residual SD ± 0.285 Cal/g). This equation was different from that of Carpenter and Clegg (1956). It also resulted in variation of biologically determined ME values. Hence, the following equation is derived:

$\text{ME (Cal/g DM)} = 4.1\ X\ \text{starch} + 3.55\ X\ \text{sugar} + 3.52\ X\ \text{CP} + 7.85\ X\ \text{EE})/\text{DM}$; which was capable of predicting classical ME values for most feedstuffs with sufficient precision for practical purposes where starch, sugar, crude protein, ether extract, and dry matter were expressed as gram per gram feedstuffs (Sibbald et al. 1963). Other combinations of variables including crude fiber, nitrogen free extract, gross energy, and ash failed to give better prediction equations (Table 16).

More regression equations to predict ME of poultry feedstuffs were developed by Sibbald and Price (1976a,b). These regression equations were not found to perform significantly better than equations found in the literature. Whether any of the prediction equations were suitable for practical application would depend on the magnitude of error that could be tolerated.

Since true metabolizable energy was not affected by variations of feed intake (Sibbald, 1976), the difference TME-AME (within grains) increased with increasing AME values. There was evidence that this

TABLE 16 The R^2 Values Obtained from Regression Analyses of Various Combinations of Independent Variables (N = 103)

	Independent variables[a]									
Line	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	Y_1	Y_2
1	+	+	+	+			+		0.724	0.788
2	+	+	+	+		+			0.722	0.723
3	+	+	+	+					0.722	0.732
4	+	+	+			+	+		0.718	0.724
5	+	+	+		+		+		0.719	0.729
6	+	+	+		+	+			0.728	0.740
7	+	+	+			+			0.718	0.728
8	+	+			+	+	+		0.712	0.728
9	+	+		+		+	+		0.673	0.679
10			+	+		+	+	+	0.593	0.584
11			+		+	+	+	+	0.597	0.588

*X_1 starch, X_2 sugar, X_3 gross nitrogen, X_4 ether extract, X_5 gross energy (Cal./gm), X_6 nitrogen free extract, X_7 crude fiber and X_8 ash, all except X_5 being expressed as gm./gm. dry matter.

**Y_1 and Y_2 are classical and corrected ME respectively, expressed as Cal./gm. dry matter. (Adapted from Sibbald et al. 1963) trend was associated with voluntary intake of AME assay diets containing low energy grains.

TME was predicted from AME as follows (Sibbald and Price, 1977): TME = 2.864 + 0.303 AME or TME = AME = 2.864 = 0.697 AME, for wheat, and TME = 2.020 + 0.538 AME or TME - AME = 2.020 - 9.462 AME, for oats.

The bulk density of barley (kilogram per bushel) was highly correlated with TME (kcal/gDM) (Sibbald and Price, 1976b): TME (kcal/g air dry barley) = 2.169 + 0.0145 bulk density (kg/bushel); R = 0.911. This equation might be used to predict the TME values of barleys within the range of 40.0 = 70.2 kg/bushel.

Harris et al. (1972) listed methods by which metabolizable energy was calculated for different kinds of animals:

a. For cattle, horses, sheep and swine, ME was calculated from average metabolizable energy (ME) expressed in Megacalories per kilogram.

b. For poultry, calculated from the average nitrogen equilibrium metabolizable energy (ME_n) for chickens and turkeys. Value was expressed in kilocalories per kilogram.

c. For sheep, horses, and finishing cattle, calculated from DE as follows: ME(mcal/kg) = DE (Mcal/kg) X 0.82. However, this value was only an approximation as the ME/DE ratio might vary considerably being affected by the nature of diet and level of feeding (Moe and Flatt, 1969).

Harris and Asplund (1968) developed a regression equation for converting digestible energy to metabolizable energy for sheep fed various amounts of beet pulp and alfalfa hay: ME = 104DE - 674.

d. For lactating cattle, calculated from DE as follows (Moe and Flatt, 1969): ME(Mcal/kg) = 0.93 DE(Mcal/kg) = 0.30.

e. For swine, calculated from DE as follows (Harris and Asplund, 1968): ME (Kcal/kg) = DE (Kcal/kg) X 96 - (0.202 X crude protein %)/100.

Net energy. Since little was gained by changing from TDN to DE or ME, it was proposed that an effort be made to adopt the net energy (NE) system of expressing energy values of feeds and energy requirements of animals.

Harris (1963, 1966) defined net energy (NE) as the difference between metabolizable energy (NE) and heat increment (HI), and included the amount of energy used either for maintenance only or for maintenance and production. Net energy might also be expressed as the gross energy of the gain in tissue or of the products synthesized plus the energy requirement for maintenance.

Heat increment (HI) was defined as the increase in heat production following consumption of food when the animal is in a thermoneutral environment. It consisted of increased heats of fermentation and of nutrient metabolism. There was also a slight heat expenditure in musticating and digesting of food. This heat was wasted except when the environmental temperature was below critical temperature, and this heat was then used to keep the body warm. Hence, when heat was used in this manner, it was considered a part of the net energy requirement for maintenance (Harris, 1966). Heat increment was calculated as follows: HI of feed fed = heat production from animal on feed - heat production of animal while fasting. The heat increment of a specific nutrient could be determined. It was referred to as the specific dynamic effect, then.

Other energy losses (included in heat increment) were the heat of fermentation (which is the heat produced in the digestive tract as a result of microbial action), and heat of nutrient metabolism (which is the heat produced as a result of the utilization of absorbed nutrients).

The resulting heat was produced by oxidative reactions which were (a) not coupled with energy transfer mechanisms or (b) the result of incomplete transfer of energy; (c) partly due to heat production as a result of work of excretion by the kidney, and (d) increased muscular activity of the gastrointestinal tract, respiratory, and circulatory systems resulting from nutrient metabolism (Church and Pond, 1976). 80 percent of the heat increment might originate in the viscera (Brody, 1945).

Heat increment was not a constant for a given animal and a given feedstuff, but depended on how the nutrient was utilized. Armstrong and Blaxter (1957) gave values of heat increment of feeding different nutrients and diets to different kinds of animals (Table 17). Rumen fermentation of fiber resulted in high production of acetic acid which was used less efficiently than other volatile fatty acids, resulting in a higher HI (Church and Pond, 1976). The HI was estimated to be 5

TABLE 17 Heat Increment of Feeding (Kcal/100 Kcal ME at Maintenance)

	Species			
Nutrient	Rat	Swine	Sheep	Cattle
Fat	17	9	29	35
Carbohydrate	23	17	32	37
Protein	31	26	54	52
Mixed rations	31	10-40	35-70	35-70

(Adapted from Armstrong and Blaxter, 1957) to 10 percent of gross energy of feedstuffs in ruminant animals (Blaxter, 1962). In monogastric animals, some heat of fermentation originated from fermentation in the lower portion of the small intestine, cecum, and large intestine.

Total heat production (HP) of an animal consuming feed in a thermoneutral environment is composed of the heat increment (heat of fermentation and heat of nutrient metabolism) plus heat used for maintenance (basal metabolism and heat of voluntary activity) (BM + VA) HP = HI + BM + VA, where basal metabolism was defined as the chemical change that occurs in the cells of an animal in fasting and a resting state when it uses just enough energy to maintain vital cellular activity, respiration, and circulation as measured by the basal metabolic rate. Sex might have an effect on energy expenditure. In man, basal metabolism of the male was about 6 to 7 percent higher than the female, a difference which showed up at 2 to 3 years of age. In domestic animals, castration resulted in a 5 to 10 percent depression in basal metabolism. Thyroid activity had a marked effect as hypothyroid individuals might have a very low basal metabolism. Nervous, hyperactive animals had a high heat production (Church and Pond, 1976).

Moreover, species and breeds might differ in energy expenditure, too. Sheep tended to be about 15 percent below and cattle tended to be about 15 percent above the average basal metabolism value of metabolic body weight ($BW^{0.73}$). The average metabolism value was 70 kilocalories $BW^{0.73}$. These differences between cattle and sheep could be due to the fact that cattle originated and evolved in cold northern climates where heat production was a critical factor for survival, while sheep originated in subtropical areas where low heat production had survival value (Blaxter, 1962). Ayrshire steers were about 100 kilocalories $BW^{0.73}$ and compared to 81 kilocalories for Angus steers. Similar differences have also been observed between breeds of sheep and dairy cows (Blaxter and Wainman, 1966).

The energy of voluntary activity (VA) was defined as the amount of energy needed to an animal to provide the energy required in getting up, standing, moving about to obtain feed, grazing, drinking, and laying down (Harris, 1966). Heat production was measured directly by an animal calorimeter, or indirectly by the following formula: HP (kcal) = 3.866 (liters 0_2) + 1.200 (liters CO_2) - 0.229 (gram urinary nitrogen X 6.25) = 0.518 (liters methane). This formula might be applied to ruminants, nonruminants, and birds (Harris, 1966). Since in nonruminants and birds methane was produced in a very little amount, the methane component could be left out of the equation.

Heat production was also determined by the comparative slaughter technique as follows (Lofgreen, 1965b): $HE = ME - NE_p$. The portion of the total heat production for maintenance (NE_m) might be estimated by feeding two or more levels and extraplating the data to zero energy intake. Carbon and nitrogen balance studies could also be used to estimate HI (Harris, 1966).

Under pasture and range conditions, the energy expenditure was different from that measured under confinement conditions at maintenance levels. Blaxter (1962) reported that activity by grazing sheep and cattle at maintenance and in a thermoneutral environment would increase their total energy expenditure by 11 (sheep) and 16 (cattle) percent more than indoor conditions.

Such high maintenance requirements for sheep at pasture might be due to increased costs of body movement at pasture, the effect of outdoor environment, or errors due to the measurement of organic matter intake (Blaxter, 1962). This extra increased expenditure could be also due to increased overall costs associated with grazing, especially that of walking and harvesting the herbage, which depended on the availability of pasture and environmental stresses. The work of eating and the work of digestion done by the gut in handling bulky pasture materials might also account for the extra cost of energy expenditure under pasture conditions and could increase (with other factors) the maintenance energy requirements of animals on range by 25 to 50 percent (Osuji, 1974).

Under the "conventional scheme" fecal metabolic energy and endogenous urine energy were considered part of the losses in digestion and metabolism. However, these fractions were considered part of the maintenance energy requirements (Harris, 1963, 1966).

Fecal metabolic energy (fecal energy, metabolic = FE_m) was defined as the amount of energy contained in the metabolic (body) fraction of feces that is not obtained from nonabsorbed ration residues (Harris, 1963, 1966). Under production conditions, animals consumed more feed and FE_m fraction was larger, providing the digestibility of the rations was the same (Harris, 1966).

Urinary endogenous energy (Urinary energy, endogenous = UE_e) was also defined by Harris (1963, 1966) as the amount of energy contained in the endogenous (body) fraction of the total urine. If hormonal control increased the basal metabolism in producing animals, this fraction might increase for those animals (Harris, 1966).

Hence, true digestible energy (TDE), true metabolizable energy (TME), N-corrected true metabolizable energy (TME_n), and true net energy (TNE) could be calculated as follows:

$TDE = GE_i - (FE - FE_m) - GPD - HF$

$TME = GE_i - (FE - FE_m) - GPD - HF - (UE - UE_e)$

$TME_n = GE_i - (FE - FE_m) - GPD - HF - (UE - UE_e) \pm (NB \times 7.45 \text{ calories})$,

and $TNE = GE_i - (FE - FE_m) - GPD - HF - (UE - UE_e) - HNM$, where HNM was the heat of nutrient metabolism. The true net energy for maintenance (TNE_m) was calculated as follows (Harris, 1966): $TNE_m = BM + VA + FE_m + UE_e$.

The net energy value of a feed might become a minus quantity if the metabolizable energy it supplies was less than the expenditure involved in its utilization. Straw had very little value for ruminants, and for horses it was worse than useless, since the horse expended more energy in eating and digesting it than the straw yielded in metabolizable form (Cuthbertson, 1969).

Therefore, net energy of feedstuffs represented that portion of the feed which was available to the animal for maintenance and production purposes after accounting for losses in the feces, urine, digestive gases, and heat increment. Hence, the disadvantage of TDN, DE, and ME relative to over evaluating high fibrous feeds was overcome (Lofgreen, 1965a).

Harris (1966) insisted that it should be clearly stated which functions were included when reporting net energy values. There might be values for net energy for maintenance and production (NE_{m+p}), net energy for maintenance alone (NE_m), or net energy for production alone

(NE_p). Hence, the concept of net energy could be fractionated into two fractions. First was the net energy for maintenance (NE_m) which is the portion of net energy expended to keep the animal in energy equilibrium (stable body weight). The NE_m for a producing animal might be different from a non-producing animal of the same species and weight. This difference occured due to change in amount of hormones produced and to differences in voluntary activity. The NE_m is a tax that an animal pays whether it produces or not. The increased NE_m due to production states could be related to maintenance. However, in practice this increase was related to the production requirement.

The second fraction of the NE was that for production (NE_p) which is the fraction of net energy required in addition to that needed for body maintenance that is used for work or tissue gain (growth and/or fat production), or for the synthesis of a fetus, milk, eggs, wool, fur, or feathers.

Most nutritionists agreed that in theory, the net energy system was superior to other systems since all losses were considered in its measurement. The NE system had not been widely adopted, however. That might be due to two main reasons. First, NE values varied with variations in balance in other nutrients, level of feeding, and the production function involved. Second, NE values had been exceedingly difficult, slow, and expensive to determine because of equipment and facilities required (Lofgreen, 1965a).

There were two systems of net energy in use in the United States (Harris et al. 1972). First, the California system for finishing beef cattle. This system expressed the requirements for certain physiological functions in terms of net energy (net energy for maintenance = NE_m; net energy for gain = NE_g). Net energy values for some cattle feeds including NE_m and NE_g might be computed from the following formulae (Lofgreen and Garrett, 1968): Log F = 2.2577, $NE_m = 77/F$, $NE_g = 2.54 - 0.0314F$, where F was the grams of dry matter per unit of metabolic body weight ($W^{0.75}$) required to maintain energy equilibrium.

The theoretical basis of the California net energy system was examined in the context of the following assumptions (Knox and Handley, 1973):

1. The net energy for maintenance (NE_m) was equal to fasting heat production, and could be estimated from heat production data obtained at or above maintenance. Fasting heat production was estimated by plotting the logarithm of heat produced versus the ME intake and extrapolating the zero ME intake (Lofgreen and Garrett, 1968). The equation derived was $\text{LogH} = 1.8851 + 0.00166\ \text{ME}$, where H and ME were in kcal/kg$^{0.75}$, with no significant difference between steers and heifers.

The use of the logarithm of H to obtain linearity was questioned (Reid and Robb, 1971). The linear plot of the data of Lofgreen and Garrett (1968) indicated a fasting heat production of 38 kcal/kg $^{0.75}$. This value was about 50 percent of fasting heat production rates in steers as reported by other workers (Knox and Handley, 1973).

2. Net energy for maintenance was constant irrespective of the level of production. Maintenance energy requirements might vary when animals have great variation in energy deposition. Maintenance requirements (ME/kg$^{0.75}$) varied with the physiological processes occuring in dairy cows (Moe et al. 1971).

3. There was a linear relationship between ME intake and energy for production (P), provided all measurements were made above energy

for production (P), provided all measurements were made above energy equilibrium.

4. The caloric content of body weight gain (NE_g) could be estimated by specific gravity techniques.

5. The ME content of a ration was constant and could be used to predict NE_m and NE_g. Hence, the California net energy system did not account for the factors that may affect the ME values of feedstuffs.

6. It was possible to predict daily gain by knowing the NE_m and NE_g of a ration and the caloric value of the new tissue deposited. Conversely, that it was possible to estimate the amount of a given diet required for a specific rate of gain.

Moreover, the California system tended to over predict final weights in lighter animals, but was precise with heavier animals (Knox and Handley, 1973).

The system's largest handicap, however, was that most of the net energy values for feedstuffs had been estimated from TDN values rather than accurately measured in controlled feeding trials (Shirley, 1980).

Second, the net energy system for dairy cattle that was developed by Moe and Flatt (1969). This system adjusted the requirements of net energy for various physiological functions in terms of the utilization of net energy for production. It was concluded that cost of energy for milk production was independent of level of milk production. Decrease in digestibility because of high feed intake was compensated by decrease of methane production.

Net energy for lactation (NE_{milk}) was defined as the caloric content of the total milk produced by the lactating dairy cow (Moe and Flatt, 1969). The total NE_{milk} requirement was the caloric content of the milk plus the net energy required for maintenance. Net energy for milk was computed as follows:

NE_{milk} (mcal/kg dry matter) = $-0.44 + 0.84 \pm 0.2$ ME (Mcal/kg DM)

$NE_{milk} = -0.77 + 0.84 \pm 0.2$ DE (Mcal/kg DM)

$NE_{milk} = -0.46 + 0.0369 \pm .0009$ % ME

$NE_{milk} = -0.80 + 0.0373 \pm 0.0010$ % DE

$NE_{milk} = -0.62 + 0.0352 \pm 0.0010$ % TDN

$NE_{milk} = +0.25 + 1.15 \pm 0.03$ ENE (Mcal/kg DM), where ENE was the estimated net energy (Moe and Flatt, 1969).

The amount of energy required for maintenance of nonpregnant, lactating cows in body energy equilibrium and ingesting a diet of optimum protein content under conditions of limited physical activity was 73 kilocalories NE_{milk} per $kg^{0.75}$ body weight. The amount of net energy required for milk production was 0.74 Mcal NE_{milk} per kilogram 4 percent corrected milk (Moe et al. 1972). Moreover, the NE_{milk} of individual diets was related to the concentration of digestible energy in the diet: NE_{milk} (Mcal per kg DM) = 0.68 DE (mcal per kg DM) = 0.36.

Moe and Tyrrell (1976) introduced more prediction equations to estimate NE_{milk} when the digestibility of the total diet was known:

NE_{milk}(Mcal/kg DM) = $-0.36 + 0.677$ DE (Mcal/kg DM),

NE_{milk} (Mcal/kg DM) = $-0.12 + 0.0266$% TDN or

NE_{milk} (Mcal/kg DM) = $-0.19 + 0.703$ ME (Mcal/kg DM).

When using the first and the third equations, it should be pointed out that the DE and ME value which was appropriate for the producing animal and not a value measured at the maintenance level or with a different species of animal. If only maintenance values were available,

NE_{milk} value at an average production level could be estimated from the following equations (Moe and Tyrrell, 1976):

NE_{milk} (Mcal/kg DM) = -0.36 + 0.623 DE (Mcal/kg DM)

NE_{milk} (Mcal/kg DM) = -0.12 + .0245 TDN (% of DM)

Harris et al. (1972) compared the terminology for the two systems of net energy and TDN (Figure 7). The term $NE_{lactating}$ cows was used to represent NE required for maintenance, pregnancy, and milk production in the Moe and Flatt system.

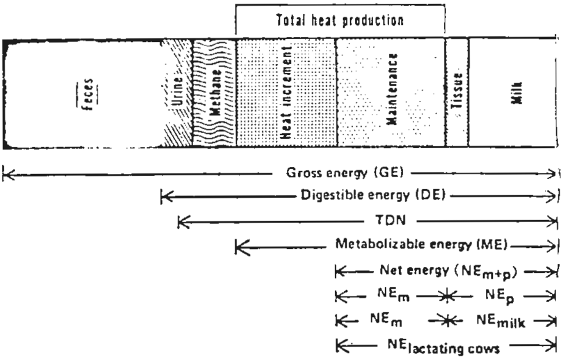

FIGURE 7 Comparison of terminology for TDN, the Lofgreen system and the Moe and Flatt system. a. NE lactating cows is designated instead of NE_{milk} since the latter term could be used for maintenance, pregnancy and milk production. (Adapted from Harris et al. 1972)

In Lofgreen's system, the metabolizable energy for gain or the heifer was not utilized as efficiently as that for maintenance (Figure 10). The lactating cow, however, was utilizing ME for maintenance has been adjusted to the same utilization as that for milk production (Figure 8)(Moe and Flatt, 1969).

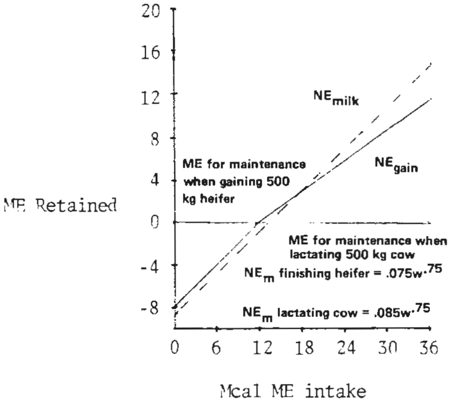

FIGURE 8. A comparison of two methods of expressing energy requirements. The solid line represents the system of Lofgreen (Lofgreen and Garrett, 1968) and the dotted line represents the system of Moe and Flatt (1969). (Adapted from Harris et al. 1972)

The NE$_{milk}$ values were used for both body tissue storage and the estimation of maintenance for dairy cattle. The California system recognized the differences for maintenance and gain. The Moe and Flatt (1969) system did nor ignore this difference but expressed the values of maintenance and gain in units of NE$_{milk}$. Hence, it was simpler and less confusing (Kromann, 1973; Moe et al. 1972). Besides, the efficiency of milk production was greater than that of tissue deposition. Consequently, the values of NE$_{milk}$ were greater than that of Morrison ENE (Van Soest, 1973b).

Inter-Conversion Among Systems. The USA National Research Council, Committee of Animal Nutrition passed a resolution to start using the calorie system along with the TDN system to describe the energy values of feeds, rations, and nutrient requirements of the animals (Crampton and Harris, 1969). Hence, there was a need to shift from the TDN system to a more accurate one such as the energy system. However, the great amount of compiled TDN data were available and could not be simply thrown away. Instead, the conversion of one system to another was practiced.

Mathematical models were developed to convert from one system of describing energy utilization of another. Swift (1957) obtained a total of 312 TDN and digestible energy (DE) values of mixed and roughage rations for cattle and roughage rations for sheep. The average or mean value of the 312 determinations was 1999.4 calories per pound of TDN (or 4.41 calories per gram TDN). The caloric values of one pound of TDN were, 1996, 1982, and 2007 for the roughage rations for cattle, mixed rations for cattle, and roughage rations for sheep, respectively. The difference between any two of the three means did not show significance. For practical purposes, to convert TDN to DE one might simply multiply the weight of TDN in pound by the factor 2000 to obtain its equivalent in calories (Swift, 1957). The results were in close agreement with these conversion factors obtained by Crampton et al. (1957).

Errors existed in the use of 4 calories per gram of TDN as caloric value of digested protein, of 9 calories per gram for digested ether extract, and 4 calories per gram for digested carbohydrated (Crampton et al. 1957). Since these errors were systematic, they could be statistically corrected.

Barth et al. (1959) determined the caloric value of TDN from the digestible protein content of roughage. Calories per gram TDN = 4.343 + 0.0199 X % digestible protein. All the appropriate TDN and DE data from forages in which both determinations were calculated from one and the same conventional digestion trial with cattle and sheep assembled and separated into hay and silage values, and the ratio of TDN and DE (calories per gram of TDN) was calculated for each individual pair of observations. Because no essential difference in the TDN-DE ratio of a specific protein content was observed between hays and silages, they were grouped together. The correlation coefficient of caloric value of TDN and digestible protein in the roughages was 9.64. The inclusion of digestible protein in the prediction of DE values seemed to eliminate much of the variability remaining from an average TDN-DE conversion factor which considers TDN only (Barth et al. 1959).

The Animal Nutrition National Research Council, Feed Composition Committee had adopted the following conversion factors on the basis of the work of Crampton et al. (1957) and Swift (1957):

$$\text{DE (kcal/kg)} = \frac{\text{TDN\%}}{100} \text{ X } 4409, \text{ or DE} = 44.09 \text{ TDN\%}.$$

$$\text{ME (kcal/kg)} = 82\% \text{ DE, or ME} = .82 \text{ DE}.$$

These values had proven useful and permitted the estimation of caloric values from TDN data (Harris and Asplund, 1968).

Factors affecting relationships between digestible energy (DE), metabolizable energy (ME) and total digestible nutrients (TDN) were studies by Harris and Asplund (1968). Thirty-five mature wether sheep were used to determine DE and TDN by the conventional methods. Metabolizable energy was also calculated for rations varying in DE from 2342 to 3487 kilocalories per kilogram and at energy intakes from 9.9 to 18.3 kilocalories of ME per kilogram metabolic body weight ($W_{kg}^{0.75}$). There were highly significant correlations between ME, DE, and TDN (R^2 = .98 or higher). The following regression equations were derived:

DE = 36.13 TDN% + 518

TDN% = 0.027 DE - 12.4

ME = 1.04 DE - 674

DE = 0.96 ME + 653

ME = 37.5 TDN% - 130

TDN% = 0.026 ME + 5.0

The mean values of DE/TDN was 44.20. Standard errors of the mean was ± 0.27. Highly significant negative coefficients of correlation between DE/TDN and DE (-0.829) and TDN (-0.881) were observed while ME/DE was highly significantly positively correlated with DE (0.940) and TDN (0.943). There was no significant correlation between DE/TDN and energy intake and ME/DE. Level of energy intake was found to have little influence on the conversion factors (Harris and Asplund, 1968). The regression equations presented above were not intended to be definitive, since the experiment involved only a very restricted variety of feedstuffs.

In swine, the effect of crude protein content on ME/DE ratio was highly significant (Morgan, 1976):

(ME/DE) X 100 = 99.7 - (.189 X % crude protein); R = 0.94.

The decrease in ME/DE ratio with increasing crude protein percent in the feeds was due to increased excretion of nitrogenous compounds (principally urea) by urine. These products represented additional losses of energy to the animal since they did not represent the complete oxidation of dietary proteins. At a constant level of dietary protein ME to DE ratio would be influenced by the biological value of the protein. A poorer quality protein induced more urea excretion. Hence, the use of DE to describe energy values tended to exaggerate the value of protein-rich feeds compared with cereals (since DE does not consider urinary energy losses) (Morgan, 1976).

Van Soest (1973b) pointed out that the basic difference between the TDN and the NE systems was that NE placed a lower value on less digestible and high fiber feeds. Net energy trials are expensive and technically tedious to perform. Consequently, measurements of NE would be behind those of ordinary digestion trials, and NE will have to be estimated for many feedstuffs. The problem then was to improve the methods of TDN-NE conversion. Digestibility and fiber fractions should be considered. Moreover, the reliability of the original TDN figures should be examined.

Van Soest (1973b) summarized various equations for TDN-NE conversion (Table 18). Three different net energy systems were considered in this summary. The Morrison system was giving way to the use of gain and maintenance values for beef cattle and lactation values (milk production) for dairy cattle. Furthermore, Van Soest (1973b) summarized the interconversion between the various energy systems as it is shown in Table 19.

In swine, the relationships between TDN, DE, and ME were reported by Morgan (1976) to be as follows:

$DE\ (kcal/kg\ DM) = (45 \times TDN) + 156;\quad R = .92$

$ME\ (kcal/kg\ DM) = (43 \times TDN) + 71;\ R = .98$

$ME_n\ (kcal/kgDM) = (42 \times TDN) - 27;\quad R = .99$

TDN was closely related to ME especially when ME was correlated to zero nitrogen retention. The relationship between ME and DE was:

$ME\ (kcal/kg\ DM) = .876\ DE\ (kcal/kg\ DM) + 217.6;\quad R = .97$

The problem of converting TDN to NE was being complicated by the inconsistancy of the TDN value of feedstuff (Van Soest, 1973b). Variation in TDN value arised from two sources: The first was the variation in

TABLE 18 Equations for Conversion of TDN to Net Energy[a]

Equation	Source
$NE = 0.0306\ TDN - 0.76$	Moe et al. (1953)
$NE_{milk}{}^{b} = 0.037\ TDN - 0.77$	Moe and Flatt (1969)
$NE_{maintenance} = 0.029\ TDN - 0.29$	Van Soest (1971)[c]
$NE\ gain = 0.029\ TDN - 1.01$	Van Soest (1971)[c]
$NE\ milk = -0.01\ TDN\ (2.86 - 35.5/s)$	Van Soest (1971)[d]

[a] All NE values were adjusted to metric system Mcal/kg. TDN was expressed as units 100 lb.

[b] NE_{milk} was identical with NE lactating cows as used in NRC publications (1971).

[c] These equations were based on linear conversions of Van Soest (1971). The logametric equations of Lofgreen and Farrett (1968) were omitted and were cumbersome and do not increase accuracy of estimation.

[d] The value of s was the non-cell wall (100 - % NDF). (Adapted from Van Soest, 1973 b).

TABLE 19 Interconversion of Net Energy Values

Equation	Source
$NE_{milk} = 1.21\ ENE^{a}$	Moe and Tyrrell (1972)
$NE_{maintenance} = 0.78\ NE_{lactation} + 0.31$	Van Soest (1971)
$NE_{gain} = 0.78\ NE_{lactation} - 0.41$	Van Soest (1971)
$NE_{maintenance} = 0.99\ NE_{gain} + 0.69$	Van Soest (1971)
$NE_{maintenance} = 0.79\ NE_{lactation}$	Van Soest (1971)

[a] ENE = Estimated Net Energy. (Adapted from Van Soest, 1973b).

quality of the feedstuff according to source. The second was the decline in digestibility with increasing levels of intake.

European Systems. Other systems of energy evaluation of feedstuffs were being used in other parts of the world. Van Es et al. (1978) introduced three new systems for energy evaluation in the Netherlands, France, and Switzerland.

a. The energy systems in the Netherlands (Van Es, 1978) for dairy and beef cattle: The relationship between metabolizable energy (ME) content and digestible nutrients in sheep and cattle fed at, or slightly above the maintenance level was studied. Non-lactating cows fed at 0.5 to 1.7 times maintenance the following equation for ME was given: $ME/T = 3.86\ D\ X\ P/T + 11.03\ D\ X\ L/T + 3.26\ D\ X\ F/T + 3.42\ D\ X\ X/T$ (1), where T = dry matter (kg); $D\ X\ P$ = digestible crude protein; $D\ X\ L$ = digestible crude fat; $D\ X\ F$ = digestible crude fiber; and $D\ X\ X$ = digestible nitrogen-free extract.

When only the contents of digestible organic matter (DO/T, g/kg) and of digestible crude protein (D X P/T) were available, ME for cattle could be predicted from the following equation:

$$ME/T = 3.35\ DO/T + 1.76\ D\ X\ P/T \qquad (2)$$

For forages with a low protein content ($DO/DXP > 7$), ME/T could be predicted by the following equation:

$$ME/T = 3.6\ DO/T \qquad (3)$$

However, for forages with a low protein content but higher fat content (corn silage), equation (3) gave low results. Hence, for corn silage, ME/T could be predicted from equation (4):

$$ME/T = 3.7\ DO/T \qquad (4)$$

For feedstuffs with DO/DXP ratio below 7, the following equation (5) was used. The lower value of the coefficient of DXP was to be used again when values of ME/T for cattle were to be predicted from DO/T and DXP/T values obtained with sheep:

$$ME/T = 3.4\ DO/T + 1.7\ (\text{or } 1.4)\ DXP/T \qquad (5)$$

When the sugar content of feedstuffs ("sugar"/T) was included; ME/T could be predicted from equation (6):

$$ME/T = 4.1\ (\text{or } 3.8)\ DXP/T + 9.0\ DXL/T + 3.3\ DXF/T + 3.5\ DXX/T + (-0.15\ \text{'sugar'}/T) \qquad (6)$$

The regression coefficient of DXP/T was reduced to 3.8 if ME/T for cattle was to be predicted from sheep digestion data because the digestibility coefficient of crude protein was found to be about 7 percent higher than that with cattle. Forages used were green fodders, conserved green fodders, but not roots, tubers, straw, or chaff.

For concentrate feedstuffs Van Es (1978) adapted the following equation to predict gross energy (GE):

$$GE/T = 5.77 \times P/T + 8.74 \times 1/T + 5.00 \times F/T + 4.06\ XX/T + (-0.15\ \text{'sugar'}/T) \qquad (7)$$

The 'sugar' correction was to be included for feedstuffs that contain more than 8 percent 'sugar'. GE/T for forages was calculated from equation (8):

$$GE/T = 4400 \qquad (8)$$

since most forages had a GE/T content close to 4400. Higher values were rarely found. Lower values were found especially after contamination with soil particles. Hence, ME as a percentage of GE (g) could be predicted for all feedstuffs from the following equation:

$$g = 100\ (ME/T)\ /\ (GE/T) \qquad (9)$$

The prediction of the ME content of feeding levels above maintenance was done by decreasing the ME content by 1.8 percent per multiple of the maintenance feeding level.

The net energy content for lactation (NE_1) was predicted by the following equation:

$$NE_1/T \text{ (kcal/kg T)} = 0.60 \left[1 + 0.004 \ (q - 57)\right] \ ME/T \qquad (10)$$

Because the feeding level had an influence on the ME content, the NE_1/T values would vary with the feeding level. Hence, it was proposed to have only one net energy-lactation value for each feedstuffs. This value should apply to the average feeding level of lactating cows in the Netherlands. This level was 2.38 times maintenance (maintenance at 550 kg + a production of 15 kg 4%-fat-corrected milk). Therefore, the result of equation (1) had to be multiplied by 1-(2.38-1) 0.018 = 0.9752, if the values of ME/T used in equation (1) applied to the maintenance feeding level.

For practical purposes, it was proposed to work with a feed unit rather than with net energy calories or Joules. An arbitrary feed-unit-lactation was chosen. One feed-unit-lactation (VEM) containing 1.650 kcal net energy lactation value of one gram barley. The VEM could be predicted from equation (11):

$$VEM/T = 0.6 \left[1 + 0.004 \ (g - 57)\right] \ 0.9752 \ \frac{1}{1.650} \ ME/T. \qquad (11)$$

The resulting value applies to a feeding level of 2.38 (maintenance + 15 kg 4% fat-corrected milk).

In case of beef cattle the feed unit for growth (VEVI) was derived from the ME content and the value of (q) of feedstuffs and rations predicted in the same way as in the system for dairy cattle. A correction for feeding level was not applied to the ME value because in growing cattle the feeding level seldom exceeded twice maintenance.

The efficiency of the utilization of ME for maintenance (km) and for growth (kg) differ. Moreover, the influence of g on kg was greater than on km. Equation (12) predicts km using the average value for km of 0.717 by ARC (1965), and the knowledge of 90.4 percent increase of km for each unit increase of g used also for the VEM system:

The daily energy gain (RE) was estimated by the following equation (for Friesian bulls):

$\text{RE (kcal)} = (500 + 6W) \times \Delta W/(c - 0.3\,\Delta W)$ (13) where W was body weight (kg), and ΔW was daily live weight gain. Both W and ΔW were related to energy retention in equation (13). kf was predicted by the equation of Blaxter (1974):

$\text{kg} = 0.0078g + 0.006$ (14)

Thus, total net energy used for maintenance and growth = $78.87\ W^{3/4} + \text{RE}$ (15). Therefore, the concept of animal production level (APL) which was equal to the ratio of total net energy to net energy for maintenance could be estimated as follows:

$$\text{APL} = (78.87\ W^{3/4} + \text{RE}) / (78.87\ W^{3/4}) \qquad (16)$$

It was possible, then, to compute $k_{m,f}$ as follows:

$$k_{m,f} = (78.87\ W^{3/4} \times \text{APL}) / \text{ME}_m + \text{ME}_f)$$

$$= 78.87\ W^{3/4} \times \text{APL} / (78.87\ W^{3/4}) / k_m + 78.87^{3/4}\ (\text{APL} - 1) / \text{kf}$$

$$= \frac{\dfrac{0.0078\ g + 0.006}{-0.548 + 0.00493\ g}}{(0.554 + 0.00287\ g)\ \text{APL}} + 1 \qquad (17)$$

The total net energy content of feedstuffs (separate or mixed in rations) was equal to: $k_{m,f} \times \text{ME}$. For practical purposes, a growth net energy quantity of 1.650 was chosen as the unit of the system (about that contained by one gram of barley). Hence,

$$VEV = \frac{\frac{0.0078 + 0.006}{-0.548 + 0.00493\ g} X \frac{ME}{1,640}}{(0.554 + 0.00287\ g)\ APL} + 1 \qquad (18)$$

This meant that a feedstuff had several feeding values depending on the APL of the animal consuming it. However, to make uniform and easy to apply, only VEV values for an APL of 1.5 as feed units for intensive growth (VEVI) were tabulated:

VEVI - VEV with APL equal to 1.5 (19)

Van Es (1978) pointed out several weaknesses in the system for growing cattle. The equation to predict energy retained in the body (RE = kcal/day) from live weight and daily gain was based on a limited number of data. The equation used to calculated efficiency of the utilization of ME for growth and fattening (kf) had a fairly high error of prediction. More information on these points were needed to improve the system by changing some coefficients.

The values of feed unit lactation (VEM) and feed unit growth (VEVI) of the various feedstuffs did not differ much on average. In the VEVI system 2/3 of the net energy of the ration was used for maintenance, with an average km (efficiency of utilization of ME for maintenance) near 0.70, the other third for production with an average k_f near 0.50. Therefore, the $k_{m,f}$ values averaged 0.63, a value close to the k value of 0.60 for maintenance and milk production in the VEM system. The variation of the VEVI values of the various feedstuffs was greater than of VEM values, because the influence of g (ME as a percentage of GE) was greater than on k_1 and k_m.

Tables were given to calculate the requirements for maintenance, at different milk production levels, for young cattle to become dairy cows, and for beef cattle (Van Es, 1978).

b. The French energy systems for ruminants (cattle, sheep and goats) was introduced by Vermorel (1978): The feed unit system was the basic system that expressed the energy value of feedstuffs in France. One feed unit (FU) was the net energy value of one kilogram of barley for maintenance or production. In the new system, proposed by Vermorel (1978), the net energy values of feedstuffs were estimated from their ME content and from partial efficiencies of ME for maintenance, fattening, or lactation (Table 20). This system was different from the other energy systems by three points:

i. ME content of a feedstuff was estimated from its gross energy content (GE, the apparent digestibility of energy (DE), and the ratio of ME and DE (ME = GE X DE X ME/DE).

ii. The net energy value of feedstuffs was expressed in feed units (FU) (UFL for lactation and UFV for maintenance and meat production with an animal production level of 1.5).

iii. Energy allowances for slowly and rapidly growing animals had been determined using the results of feeding trials, due to lack of information on both maintenance requirement and energy retention of animals of the different breeds in France, and on the efficiency of ME utilization for growth.

A relationship was established between DE and ME, according to the chemical composition of the diet and the level of feeding. The ratio between ME and DE (ME/DE) depended upon the levels of crude fiber

TABLE 20 Scheme Showing the Different Steps for the Estimation of Energy Value for Feedstuffs in the UFL and UFV Systems

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$NE = GE \times dE \times ME/DE \times k$

Gross energy: GE
- Green forages, grass silages and hays: a function of the crude protein level
- Other forages: mean values (kcal/kg OM) depending on variety and stage of growth
- Concentrates: a function of the chemical composition + corrections

Digestible energy: $DE = GE \times dE$
- Energy digestibility (De): a function of OM digestibility (dO)
- dO: - forages: a function of crude protein and crude fiber contents
  - concentrates: values as in feeding tables

Metabolizable energy
- Forages and concentrates: $ME = DE \times ME/DE$
- ME/DE: a function of crude protein and crude fiber contents and of level of feeding
- Mixed concentrates: directly estimated from chemical composition

---

Net energy for lacatation (UFL)	(Net energy for meat production(UFV)
$NE_1 = ME \times k_1$	$NE = ME \times k_{mf}$
$k_1 = 0.60 + 0.24\ (q - 0.57)$	$k_m = 0.287\ q + 0.554$
(where $q = ME/GE$)	$k_f = 0.78\ q + 0.006$
	$k_{mf} = \frac{k_m \times k_f \times 1.5}{k_f + (k_m \times 0.5)}$
Energy value (UFL) $= \frac{ME \times k_1}{1.730}$	Energy value $= \frac{ME \times k_{mf}}{1.855}$

(Adapted from Vermorel, 1978)

(XF, g/kg, DM), crude protein (Xp, g/kg DM) and the level of feeding (i = 1 for maintenance). The relationship for sheep was:

$ME/DE = 0.826 - 8.77 \times 10^{-5} XF - 1.74 \times 10^{-4} XP + 0.0243i$ ($\pm$ 0.0093):

R = 0.90

For dairy cows, the relationship differed in the constant being 0.8240 instead of 0.8286.

ME values of commercial concentrates were directly estimated from their chemical composition:

ME (kcal/kg OM) - 3260 + 0.455 XP + 3.517 XL = 4.037 XF; (R = 0.942)

where OM = organic matter; XP, XL, and XF = crude protein, crude fat, and crude fiber, respectively.

The next energy value for lactation was expressed in feed units 'milk' (unité Fourragère Lait' = UFL). One UFL was equivalent to the energy value of one kilogram of standard barley (86% DM, 3.800 McalKGE/kg, organic matter digestibility = do = 0.86, energy digestibility = DE = 0.847, ME/DE = 0.845 and ME utilization for lacation = kl = 0.636).

1 UFl = 3.800 X 0.847 X 0.845 X 0.636 = 1.730 $McalNE_1$

Energy value (UFl) of feedstuffs = $\frac{ME \times 0.60\ [1 + 0.4\ (q - 0.57)]}{1.730}$ where

q = Metabolizable energy as a percentage of gross energy.

The maintenance requirement for housed dairy cows could be estimated from the following equation:

Maintenance requirement (UFL) = 1.4 + 0.6 W/100 where W = body weight.

The net energy required for milk production corresponded to the energy content of the milk produced: 0.750 Mcak/kg fat = corrected (4%) milk (FLM). The relationship between FCM production and NE1 requirement was constant and amounts to 0.750 $McalNE_1$ or 0.43 UF_1 per kg FCM.

The net energy for lactation (UFL) was used for dairy females (cows, goats, ewes) during lactation, pregnancy or dry; for dairy heifers, ewes, lambs, kids, and for wintering animals or slowly-growing animals when the animal production level (APL) lied between 1.0 and 1.35 and for breeding animals where APL was about 1.

The energy value of a feedstuff for meat production corresponded to its net energy for maintenance and production for an APL of 1.5. Its expressed in UFV (feed units 'meat' = unités Fourragères 'viande'). One UFU was defined as the net energy value of one kilogram of standard barley. Net energy value of barley:

$q = 0.716$; $km = 0.760$; $k_f = 0.565$; $k_{mf} = 0.681$

$NE = 3.800 \times 0.847 \times 0.845 \times 0.681 = 1.855$ Mcal.

Energy value (UFU) of a feedstuff $= \frac{ME \times k_{mf}}{1.855}$

UFU was used for all rapidly-growing animals for slaughter (steers, bulls, beef heifers, and fattening lambs) when APL was above 1.35).

There were certain weaknesses in the new French system (UFL and UFU) for energy values of feedstuffs (Vermorel, 1978). The assumption in the NE system for lactation was made that the relationship between q and k_1 established for good quality diets was also applicable to poor or medium quality hays when given to suckling cows or ewes. The UFU system for rapidly growing animals used the k_f determined on mature fattening ruminants due to lack of information on efficiency of ME utilization for growth. There were also weak points in the systems in the corrections both for associative effects and influence of feeding level. However, the system was flexible enough to allow incorporation of new information for improvement.

c. The energy system in Switzerland proposed by Bickel and Landis (1978): This system was similar to that of the energy system of the Netherlands proposed by Van Es (1978) except that the energy unit megajoules was used instead of feed units in determining energy values of feeds and energy requirements of animals.

ME was calculated from the content of digestible nutrients which in turn were determined on adult sheep at the maintenance level of feeding. ME/T was determined for different classes of feeds by the same way that Van Es (1978) used. Equations were expressed in MJ instead of calories:

$ME/T = 15.9\ DXP/T + 37.7\ DXL/T + 13.8\ DXF/T + 14.7\ XX/T\ (-0.63\ sugar/T)$ for concentrates.

Sugar correction was applied when they exceeded 8 percent of dry matter. For forages (except maize silage):

$ME/T = 15.1\ DO/T$ if $DO/DXP > 7$

$ME/T = 14.2\ DO/T + 5.9\ DXP/T$ if $DO/DXP < 7$.

For maize silage:

$ME/T = 15.5\ DO/T$.

For the estimation of net energy values of feedstuffs the Swiss system applied the same formula used by Van Es (1978):

$NEL/T = 0.09752 \times ME/T\ (0.463 + 0.24q)$ or $NEW/T = ME/T \times k_{m,f}$, where

$k_{m,f} = \frac{k_m \times k_f \times APL}{k_m\ (APL - 1) + k_f}$ and $k_f = 0.006 + 0.78q$ and $k_m = 0.554 + 0.278q$.

NEL refered to the energy value of feed for dairy cows (MJ), and NEW referred to the energy value of feed for beef cattle (MJ). The NEL values referred to a feeding level of i = 2.38 and the NEW values referred to an APL = 1.5. Both values were used by Van Es (1978).

The energy requirements for dairy cows were estimated by the following equation:

$NEL/day = 9.293\ W^{3/4} + 3.14\ FCM/day$

The factor 3.14 was different from that 3.06 proposed by Van Es (1978). The same equation could be rearranged as follows:

$NEL/day = W/20 + 5 + 3.14\ FCM/day$

The NEL requirement for pregnancy $3RE_p$; assuming that three units NEL were needed to produce one unit NE_p (that was due to the lower value of k_p compared to k_f). RE_p stood for the energy retained in the body for pregnancy (MJ).

The estimation of the energy needs for growing cattle depended on the accuracy of estimating the energy value of body gain. The daily requirements of beef cattle, fattened at APL = 1.5 could be calculated from the following equation:

$NEW/day = NEW_m + RE_f/day$, where RE_f = the energy retained in the body for fattening (MJ). For different daily body gains and body weights (different APL), the total requirement could be calculated as follows: $NEW/day = 1.5\ NEW_m + \frac{k_{m,f}}{k_f}(RE_f/day - 0.5\ NEW_m)$, where the actual RE_f/day was converted into NEW/day. If $q = 0.57$ and $NEW_m = 0.330 \times W^{3/4}$, the above equation could be rewritten: $NEW/day = 0.495\ W^{3/4} + 1.33\ (RE_f/day - 0.165\ W^{3/4})$.

The energy requirements of replacement heifers were expressed in NEL instead of NEW for practical reasons:

$$NEL/day = \frac{NEW/day}{k_{n,f}} \times 0.9725 k_1$$

In Switzerland, heifers were usually reared on a feed with mean g = 0.53 (DO - 0.7). Hence, NEL/day was nearly equal to NEW/day. The requirement of dairy heifers could be calculated as follows, then:

$NEL/day = NEL_m + RE_f/day$

Energy values of feedstuffs and animal requirements were interconvertable among the new European (The Netherlands, French and Swiss) energy systems since they were based on the same scientific principles (Vermorel, 1978).

	France	Netherlands	Switzerland
For lactation and slow growth	1 UFL	1000 UEM	6.9 NEL
For rapid growth	1 UFV	1060 VEVI	7.3 NEW

However, small variations might persist for some feedstuffs due to different methods of predicting ME in France and for forages, and due to differences in composition and digestibility resulting from climatic differences (Vermorel, 1978).

Nehring and Haenlein (1973) introduced a system for feed evaluation and ration calculation based on net energy for fattening. Contents of the net energy (NEF = the efficiency of utilization of feed nutrients for fat deposition) in purified nutrients and feeds from different classes had been determined in several hundred respiration brials by different methods. Results showed that NEF could be estimated from contents of digestible nutrients with the same degree of accuracy as by direct determination in respiration experiments. The regression equations could be used without restrictions in monogastric animals. For ruminants, however, due to interactions between the basal ration and supplements in rumen, the difference method was replaced by an evaluation of whole rations (92 rations with cattle and 81 with sheep).

Regression equations were developed to predict gross energy (Y_3) from crude protein (Z_1), crude fat (Z_2), crude fiber (Z_3), and nitrogen-free extract (Z_4) as follows:

$$Y_3 = 5.72Z_1 + 9.50\ Z_2 + 4.79\ Z_3 + 4.03Z_4 \pm 9.90\%$$

The digestible energy (Y_2) and metabolizable energy (Y_4) were also predicted from the nutrient components of feedstuffs for different kinds of animals as shown in Table 21.

Moreover, regression equations were developed to estimate NEF in concentrates for different kinds of animals as shown in Table 22. The small standard deviations of the regression equations indicated that for different kinds of animals generally valid and reliable estimates of NEF values could be estimated from the contents of digestible nutrients.

Final regression equations for NEF values of all feedstuffs and all farm animals were given in Table 22 for the determination of NE_f as a feeding system.

However, the application of such a system seemed to be complicated for practical feeding. An alternative concept was developed to proceed from the common production of all nutrients, at which they can be replaced according to their energy potential (fat production in adult animals).

The new energy feed unit (NE_f = net $energy_{fat}$) equals the energy value of one kilo calorie net energy produced in adult animals under standardized conditions. NE_f units were subdivided into NEF_r for cattle (Rind), NEF_s for pigs (Schwein) and NEF_h for poultry (Huhn). For practical calculations, the energy feed unit (EF) was introduced. EF was a multiple of 1 kcal NEF. The EF_r for cattle = 2.5 kcal NEF; the EF_s and EF_u, for swine and poultry, respectively equals 3.5 kcal NEF.

TABLE 21 Regression Equations for the Calculation of Contents of Digestible Energy[a] and Metabolizable Energy[a]

Y_2 =

cattle = $5.79X_1 + 8.15X_2 + 4.42X_3 + 4.06X_4 \pm 1.0\%$ (ration trials)
sheep = $5.72X_1 + 9.05X_2 + 4.38X_3 + 4.06X_4 \pm 0.9\%$ (ration trials)
pig = $5.78X_1 + 9.42X_2 + 4.40X_3 + 4.07X_4 \pm 1.0\%$ (ration trials)
rat = $5.51X_1 + 9.37X_2 + 4.05X_3 + 4.05X_4 \pm 2.1\%$ (difference method)

Y_1 =

cattle = $4.32X_1 + 7.73X_2 + 3.59X_3 + 3.63X_4 \pm 1.3\%$ (ration trials)
sheep = $4.49X_1 + 9.05X_2 + 3.61X_3 + 3.66X_4 \pm 1.8\%$ (ration trials)
pig = $5.01X_1 + 8.93X_2 + 3.44X_3 + 4.08X_4 \pm 1.3\%$ (ration trials)
rat = $4.73X_1 + 9.45X_2 + 4.13X_3 + 4.13X_4 \pm 2.6\%$ (difference method)
chicken = $4.26X_1 + 9.50X_2 + 4.23X_3 + 4.23X_4 \pm 3.21\%$ (difference method)

[a] Y_2 = digestible energy; Y_1 metabolizable energy; X_1 - X_4 = digestible protein, digestible fat, digestible fiber and digestible nitrogen-free extract, respectively = figures are standard deviations. (Adapted from Nehring and Haenlein, 1973)

TABLE 22 Equations for the Calculations of NEF* in Concentrates

Species	Digestible Crude Protein (X_1)	Digestible Crude Fat (X_2)	Digestible Crude Fiber (X_3)	Digestible Nitrogen-Free Extract (X_4)	Standard Deviation
Cattle	$Y = 1.78X_1$	$+ 7.04X_2$	$+ 2.37X_3$	$+ 2.13X_4$	± 68(±3.7%)
Sheep	$Y = 1.85X_1$	$+ 8.09X_2$	$+ 0.09X_3$	$+ 2.39X_4$	± 81(±4.4%)
Rabbit	$Y = 2.31X_1$	$+ 7.94X_2$	$+ 3.16X_3$	$+ 2.62X_4$	± 63(±2.7%)
Pig	$Y = 2.40X_1$	$+ 7.71X_2$	$+ (0.01X_3)$	$+ 3.27X_4$	± 127(±5.8%)
Rat	$Y = 2.52X_1$	$+ 8.82X_2$	$+ (1.88X_3)$	$+ 3.26X_4$	± 87(±3.3%)

[a] Y = kcal NEF. (Adapted from Nehring and Haenlein, 1973)

The term "protein-energy quotient" (PEQ) was introduced to characterize relationships between energy feed values and contents at digestible crude protein. $\mathrm{PEQ} = \frac{\text{digestible crude protein}}{\text{EF}} \times 100$ = gram digestible crude protein in 1,000 EF (or 1 kEF).

It was shown that not all feedstuffs (separate or mixed) needed to be determined directly in respiration trials. NEF values of such feedstuffs or mixtures could be determined from content of digestible nutrients with high degrees of accuracy (Table 23).

TABLE 23 Final Regression Equations for the Calculation of NEF

Basis: Ration Evaluation
$Y_{cattle}NEFr = 1.71X_1 + 7.52X_2 + 2.01\ (X_3 + X_4) - 59.3W \pm 3.5\%^b$
$Y_{sheep}NEFr = 1.82X_1 + 8.39X_2 + 1.90\ (X_3 + X_4) - 40.8W \pm 5.1\%^b$
$Y_{pig}NEFs = 2.56X_1 + 8.54X_2 + 2.96\ (X_3 + X_4) - 66.7W \pm 3.9\%^c$
Basis: Difference Method
$Y_{chicken}NEFh = 2.58X_1 + 7.99X_2 + 3.19\ (X_3 + X_4) \pm 5.2\%^c$
$Y_{rat}\ NEFs = 2.51X_1 + 8.59X_2 + 3.04\ (X_3 + X_4) \pm 5.8\%^c$

[a] Y = kcal NEF; X_1, X_2, X_3 and X_4 are digestible crude protein, digestible crude fat, digestible nitrogen free extract and digestible crude fiber and W = (body weight)$^{.75}$.

[b] For green forages, silages from green forages and artificially dried green forages a deduction of 10% from the NEF values.

[c] In the monograstric animals, pigs and poultry, the following corrections are necessary for feeds high in sugar, or for milk and milk products.
1 g disaccaride : - .15 kcal
1 g monosaccaride : - .30 kcal
1 g milk protein : +1.0 kcal
1 g milk fat : -1.0 kcal
(Adapted from Nehring and Haenlein, 1973).

Net energy systems (NE) were not the ultimate in feed evaluation (Moe and Tyrrell, 1973). However, they were ideal systems of practical expressing the energy value of feedstuffs, the energy requirement of an animal for a specific physiological function (Kromann, 1973), feed selection, ration balancing and performance prediction (Moe and Tyrrell, 1973).

The difference among the several net energy systems were largely differences in interpretation rather than differences in scientific validity (Moe and Tyrrell, 1973). Because these systems were developed by independent laboratories, there was a question whether individual values used in each system were comparable. Different assumptions and different terminology in developing the net energy systems led to a kind of confusion (Moe and Tyrrell, 1973).

The California, Germany, and British systems of determining NE were evaluated on the basis of the number of metabolic factors which they consider as variables in NE estimation. The European NE systems considered more variables than the California system, which regarded all of the factors to be constant under different environmental conditions (Kromann, 1973).

Moe and Tyrrell (1973) considered that there were two schools of thought concerning maintenance. The first (California, British) assumed that the appropriate expression of the net energy requirement of maintenance was equal to fasting metabolism and that variation in efficiency of energy used for maintenance was less than for production. The second (Beltsvill, German) described maintenance in terms of the energy value for production. "The difference was one of application rather than principle."

The differences among energy systems were illustrated graphically in Figure 9 by Moe and Tyrrell (1973). In each diagram, the portion of the figure below energy balance indicated the use of energy for maintenance. The portion above energy balance showed the use of energy for production. In part A, a single line represented the relationship between ME intake and energy balance below maintenance and another line represents the energy use above maintenance. Thus, it was concluded that the use of ME for either maintenance or production was constant and was independent of the nature of the diet. This was the assumption made in TDN, DE, or ME systems.

In part B, the efficiency of energy used for maintenance was constant, but the productive efficiency was not. The total amount of variation in the amount of ME required to achieve a certain level of production was related to variation in efficiency of production rather than maintenance.

In part C, both maintenance and production efficiency vary but one was a function of the other. The California and the British systems were of this type.

In part D, maintenance was shown to be a function of NE_p. The amount of energy needed for maintenance was expressed in terms of production units. The Beltsvill NE_{milk}, German, the starch equivalent, and the Scandinavian feed unit systems are of this type.

At ad libitum level of intake, the differences among all systems in C and D were minimal.

Energy metabolism was affected by many factors. Kromann (1973) discussed these factors as follows:

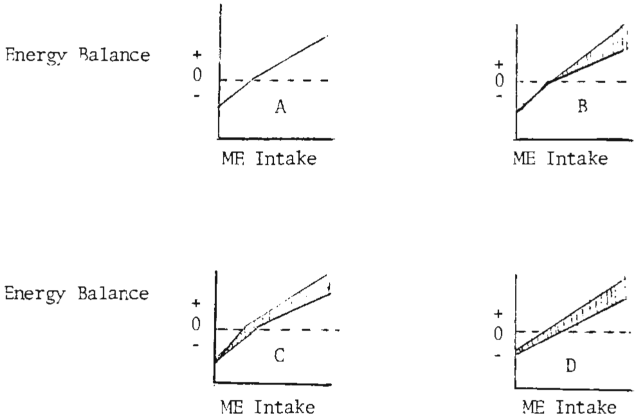


FIGURE 9 Four methods of describing variation in energy use. In A, B and C the net energy required for maintenance is set equal to the fasting metabolism. In D, it is computed by regression. Nearly all net energy systems are described by C or D. Above maintenance and particularly ad libitum intake the differences between these two systems are minimal. (Adapted from Moe and Tyrrell, 1973)

a. Chemical composition of diet: Fecal energy loss was considered to be the greatest loss of energy (20 to 60 percent of gross energy intake) and was a function of digestibility. Digestibility was affected by chemical composition of feedstuffs. Lignin exerted a great effect on digestibility of feeds, for example (Van Soest, 1970). Assuming that an adequate supply of all nutrients, the chemical composition of a diet was the main factor influencing digestibility.

b. Associative effects: The influence of cell wall was related to the chemical composition of the ration consumed and not of its individual ingredients (Van Soest, 1973b). The cell wall was partly responsible for interactions among feedstuffs. This interaction (or associative effect) was small for high quality feeds but increases in case of low-quality feeds. Fiber size also had an effect. These interactions of efficiency as a result of fiber were the primary reasons for the shift to net energy systems rather than systems based on metabolizable energy (Van Soest, 1973b).

Vermorel (1978) found that ME was influenced by the associative effect between roughages and concentrates. Hence, corrections for ME contents of rations were introduced for the interaction effects and for the feeding level (Table 24). The corrections were important for dairy cows (Table 25). For growing and fattening ruminants average corrections were directly introduced in the recommended allowances.

Kromann (1973) considered the associative effects of feeds to be a "two-way" dependency when there were two ingredients in a ration, and an "N-way" dependency if there were 'n' ingredients. The digestibility of the mixed ingredients might not be addictive. Hence, the net digestibility might not be the sum of the digestibilities of the

TABLE 24 Reduction (%) of ME Content of Rations Due to Associative Effects and Level of Feeding

Forage Quality	% Concentrate 20	 40	 60
Associative effects:			
good quality forages	1.0	2.5	4.0
poor quality forages	2.0	4.0	6.0
Effect for one unit increase in feeding level (for all forages)	0.5	1.0	1.5

(Adapted from Vermorel, 1978)

TABLE 25 Reduction in the Net Energy (UFL) Content of Rations for Dairy Cows Due to Associative Effects and Increases in the Level of Feeding (Influence of Forage Quality, Concentrate Level and Milk Production)

Forage Quality	Good Quality Forage[a]			Poor Quality Forage		
% Concentrate	20	40	60	20	40	60
Milk production (kg FCM/day)						
10	0.1	0.3	0.4	0.2	0.4	0.6
15	0.1	0.4	0.6	0.3	0.5	0.8
20	0.2	0.5	0.8	0.3	0.7	1.0
25	0.3	0.6	1.0	0.4	0.9	1.3
30	0.3	0.8	1.2	0.5	1.1	1.6
35	0.4	1.0	1.5	0.6	1.3	1.9
40	0.5	1.2	1.8	0.7	1.5	2.2

[a] Good quality forages: green forages, grass silages and maize silages when dO >0.70 and hays when dO >0.65. (Adapted from Vermorel, 1978)

individual ingredients at all levels. In a ration with associative effects, the digestibility of each ingredient could be determined by equations for 'n' constituents varied in 'n' different rations as follows (Kromann, 1967):

$a11\ X\ 1 + a12\ X\ 2 + \ldots\ a1n\ X\ n = k_1$

${}_a21\ X\ 1 + a22\ X\ 2 + \ldots\ a2n\ X\ n = k_2$

$an1\ X\ 1 + an2\ X\ 2 + \ldots + 2_{nn}\ X_n = k_n$ where

ai_j = fraction of each ingredient in the ration;

x_j = digestibility of the ingredient in the ration, and

k_j = digestibility of the total ration j.

These equations could be solved for k_j simultaneously by determinates.

This method could be used to determine the "international" NE_{m+p}, ME, and DE values of ration ingredients (Kromann, 1973). First, the NE_{m+p}, ME, and DE of rations should be determined experimentally by the conventional methods. Then, NE_{m+p}, ME, and DE values of the ingredients were determined by these simultaneous equations.

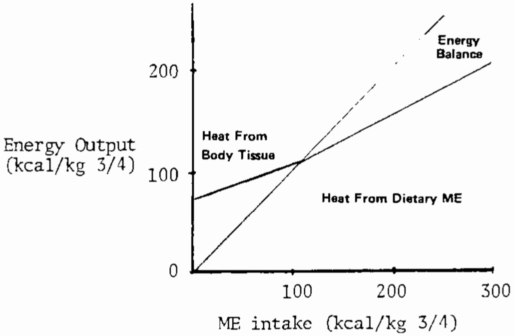
Because of the interaction between variation in efficiency due to diet and variation due to physiological function, it was not clear how to best describe the energy value of feedstuffs for producing animals (Moe and Tyrrell, 1973).

c. Level of intake: Moe and Tyrrell (1972) and Moe et al. (1965) reported that the greatest error in net energy estimation was the decline in digestibility with level of intake. Since most TDN values were based on digestion trials conducted at near maintenance levels, the application of such results to a higher level of feeding at which NE values must be applied resulted in an error to the extent that TDN value had declined. Hence, predicted NE values could be higher than normal especially in the case of dairy cattle which consume large amounts of feedstuffs.

Furthermore, Moe and Tyrrell (1973, 1976) recognized that the gross efficiency in energy utilization was influenced by level of production and body size. These two criteria have the greatest effect on gross energetic efficiency. At zero production, the gross efficiency was zero. Hence, total requirement of animals was divided into needs for maintenance and for production. Moreover, the dietary energy was not utilized with equal efficiency for all physiological functions. The proximate ranges for the efficiency of use of ME were as follows (Moe and Tyrrell, 1973):

cold stress	100%
maintenance	70 to 80%
lactation	60 to 70%
growth	40 to 60%
pregnancy	10 to 40%

The relationship between energy output and ME intake as ME was increased from zero to ad libitum was studied (Moe and Tyrrell, 1973). Figure 10 shows that at zero ME intake (fasting), body tissue was mobilized to meet the energy requirements of maintenance. Therefore, the fasting metabolism for fasting heat production was sometimes used as an expression of the net energy requirement of maintenance (NE_m). When feed intake increased, heat production also increases until at maintenance the total heat production equalled ME intake. The change in heat production between fasting and maintenance was a measure of the relative value of body tissue and dietary energy in meeting the energy requirements for maintenance.



Source of Heat Production

FIGURE 10 Relationship between ME intake and heat output showing a greater change in heat production per unit increase in ME intake above maintenance. The point where the lines cross is maintenance. (Adapted from Moe and Tyrrell, 1973)

Increasing ME intake above maintenance resulted in a positive energy balance and heat production increased (heat increment). The change in energy balance above maintenance was called net energy for production (NE_p). When a net energy value was calculated as the difference between fasting and energy balance at greater intakes than maintenance, the term NE_{m+p} was used to mean net energy for maintenance and production. If the measurement of NE_{m+p} value was made at successively lower and lower levels of intake, the resulting value would approach the NE_m value (Figure 11). Therefore, NE_{m+p} was affected by the level of intake. Hence, the use of separate terms for maintenance was weakness in the California and the British systems of energy (Moe and Tyrrell, 1973).

Adjustments were suggested for feeds fed in energy balance trials (Moe and Tyrrell, 1973). The TDN value obtained at the production level of feeding was applied to the net energy estimation. Rations that mainly contained corn silage and corn grain declined about four units TDN per unit of maintenance intake (Moe et al. 1965). Moe and Tyrrell (1973) suggested a revision of the corn value (NE_{milk}) downward for 2.42 to 1.98 for a dairy cow consuming three times maintenance. Balance studies indicated a TDN of 87 for corn equivalent to an NE_{milk} of 2.13 to 2.27. The average drop for 8 feeds observed in TDN per maintenance unit was 4.6 percent as compared with decline of 5.4 percent for NE_{milk}. This decline in NE was mainly due to the drop in digestibility of TDN.

The energy systems had certain limitations (Moe and Tyrrell, 1973). First, a net energy system was a compromise if a fixed energy value was assigned to a particular feedstuff or ration. There was no single net energy value for a particular feed since there was variation in

Net Energy Terminology

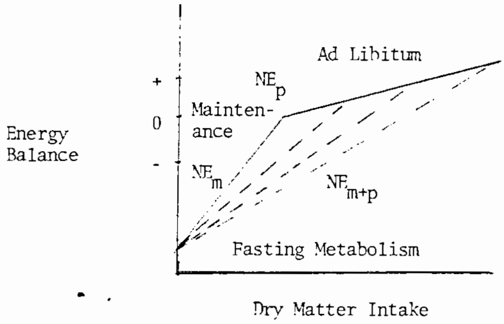


FIGURE 11 Relationship between energy balance and net energy terminology. As dry matter intake is reduced from ad libitum to maintenance NE$_{m+p}$ approaches NE$_m$. It is, therefore, of limited use as an expression of the energy value of feedstuffs. (Adapted from Moe and Tyrrell, 1973)

chemical and physical properties of individual feedstuff. Corn grain, for example did not have a single NE_g value (which was more correct than other values). There was variation in corn grain of different varieties grown in different areas under different environments and processed differently. Hence, there were specific characteristics of corn grain which determine its NE_g value through the nature of the fermentation process and digestion which it undergoes. There was a relationship between the physiology of the animal and the nature of digested end products (VFAs, glucose, amino acids, etc.). The absolute amount of each of these metabolites absorbed determined the actual energy values of any feedstuff or a mixture of feedstuffs.

Second, limitation of energy systems was that the composition of product formed was not described. The NE_{milk} did not consider the variation in the ratio of milk fat to protein resulting from decline in milk fat percentage, for example. The NE_g did not distinguish between fat and protein gain either. Hence, if the partial efficiency of energy use for fat and protein synthesis was different, this presents a limitation in the use of both the net energy concepts. Tyrrell et al. (1971) found that the ratio of fat and protein gain changed markedly as level of feed intake was changed. As feed level increased from maintenance towards ad libitum, there was a little change in the total protein deposited. Most of the increased energy retained at the ad libitum level was in the form of fat deposition.

Third limitation of most feeding systems was the decreased availability of nutrients at higher levels of intake. Many of the net energy systems generate NE values for feeds from digestibility data taken from tables of feed composition. Many of these values were determined at maintenance level of feeding. If a diet decreased in the nutritive value at higher intakes, then the NE value as well as the DE or TDN value will be overestimated.

Mathematical models could also be used in many other areas of animal nutrition. Kearl et al. (1976) described the use of models that incorporated various factors such as utilization of nutrients by the animal at different levels of intake, specific animal requirements for different levels of production, environmental influences, inherent variations in nutrient composition of a feed and its utilization by animals, differences in animal response to feeding regimes, prices paid for feeds, availability of feeds, non-feed expenses, the prices for the animals and returns from marketed products.

Other Systems Used to Describe the Energy Value of Feedstuffs

The starch equivalent (SE): This system was widely used in Europe to denote energy values (Harris et al. 1972). The starch equivalent was defined as the amount of pure starch, perfectly digested, which had the same fat-producing power as 100 pounds of the feedstuffs (Cuthbertson, 1969). Kellner (1905) established a series of factors for the fat-producing powers in bullocks of the energy-producing nutrients. One kilogram of starch was calculated to produce 0.250 kilogram fat in the animal body and this was equivalent to 2380 kilocalories of chemical energy. Furthermore, Kellner (1905) calculated the theoretical fat-producing powers of feed stuffs from their content of digestible nutrients and then determined the actual fat-producing power experimentally. There was good agreement in both calculations except where the feedstuffs were high in crude fiber.

Starch equivalent could be converted to net energy by multiplying by 1071/100. The net energy value of starch being 1071 kilocalories per pound. The division by 100 takes into account that starch equivalent was expressed per 100 kilograms (pounds) of feeds, while net energy values were expressed per kilogram (or pound).

Russian oat unit (OU) which was based on the amount of oats required to produce as much as 100 kilograms of feed being used.

Scandinavian feed unit (FE, from the term Foderenhet). This system used barley as the reference feed and referred to milk production instead of fattening.

Modified feed unit or French feed unit (FE_c or UF).

These systems used true protein value, while the TDN system used crude protein (Ensminger and Olentine, 1978). Table 26 shows how these energy systems relate to the TDN system.

The term Joule was suggested to replace the term calorie to express energy terms. A calorie was defined as the amount of heat required to increase the temperature of one gram of water from 14.5^o to 15.5^o C, the specific heat of water at 15^o C at constant pressure being defined as unity. A calorie could more precisely be defined as the thermochemical calorie since the standard used in calorimetric work in nutrition was the heat combustion of benzoic acid. This was mainly expressed as Jules per gram mole and secondarily as thermochemical calories per mole (Harris et al. 1972). The joule was defined as the work done when the point of application of a force of one newton (N) was displaced through a distance of one meter (M) in the direction of the force. One calorie 4.184 joules.

TABLE 26 Determination of Energy Units

Energy Units[1]	Unit of the Digestible Nutrient	Digestible				Further Procedure
		Protein	Ether Extract	Crude Fiber	N-Free Extract	
		Multiply by				
TDN	%	1 (crude protein)	2.25	1	1	Sum up
SE....	Weight units or %	0.94 (true protein)	2.41 2.12 or 1.91[2]	1	1	Sum up and multiply by the "availability"
FE_c....	g/kg	0.94 (true protein)	2.41 2.12 or 1.91[2]	1	1	Sum up, multiply by the "availability," and divide by 700
OU....	k/kg	0.94 (true protein)	2.41 2.12 or 1.91[2]	1	1	Sum up, multiply by the "availability," and divide by 600
FE....	k/kg	1.43 (true) protein)	2.41 2.12 or 1.91[2]	1	1	Sum up, multiply by the "availability," and divide by 750

---

[a] TDN = total digestible nutrients; SE = starch equivalent; FE_c = modified or French feed unit; OU = Russian oat unit; FE = Scandinavian feed unit.

[b] Digestible ether extract of oily seeds, cakes, and feeds of animals origin should be multiplied by 2.41; that of leguminous seeds, cereal grains, and their by-products by 2.12; and that of hays, straws, chaffs, green fodders, silages, roots, and tubers by 1.91. (Adapted from Ensminger and Olentine, 1978).

Protein Utilization

The concept of "net nutrient" was first proposed to be applied to nitrogen nutrition and other nutrients (Harris and Asplund, 1968). The concept of "net nitrogen" could be of great importance in studying the nitrogen contribution to a certain ration (Figures 12 and 13).

The first step in applying the concept of net nitrogen was to determine the digestible protein of the diet. Regression equations for each class of feed and animal kind were developed (Knight and Harris, 1966) may be used (Tables 27 and 28). The regression equation: Y(Digestible protein) = .866 X (crude protein) - 3.06 (developed by Knight and Harris, 1966) was used by the NRC (1971). It was similar to that of Holter and Reid (1959) that worked on Morrison's (1956) data: $Y = 0.883 X - 3.07$. However, it was different from the equation resulted from Cornell data ($Y = 0.929 X - 4.48$) (Holter and Reid, 1959). Similar equations for predicting digestible true protein were needed (Harris et al. 1968a). The second step was to predict true digestible nitrogen or true absorbed nitrogen (TAN) which could be computed from the nitrogen content of forages (Harris et al. 1972). In classical methods of estimating true digestible nitrogen it was necessary to have an estimate of the metabolic nitrogen. Mitchell (1924) determined the value of metabolic nitrogen by feeding a nitrogen-low or nitrogen-free diet. It was practically difficult to apply the method of Mitchell (1924) because animals might refuse to eat diets low in nitrogen. Hence, Harris et al. (1972) proposed that metabolic nitrogen values might be obtained from metabolism data from animals fed nitrogen levels both

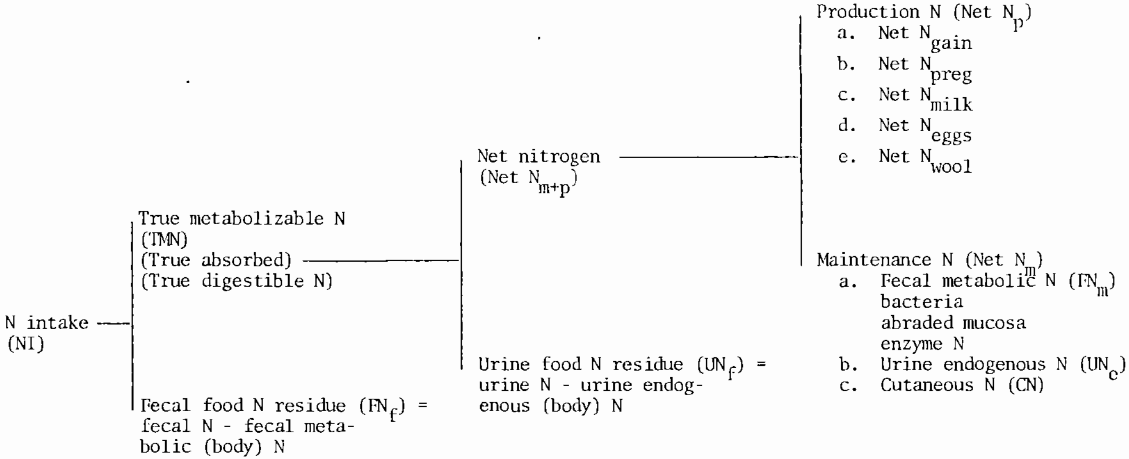


FIGURE 12 Biological partition of dietyary nitrogen (N). (Adapted from Harris et al, 1972)

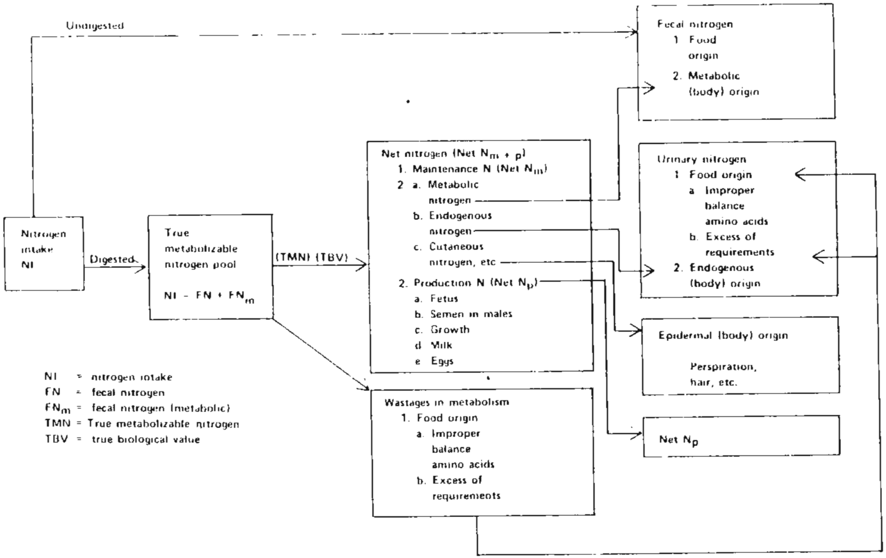


FIGURE 13 Flow chart illustrating nitrogen and protein metabolism. (Adapted from Harris et al. 1968b)

TABLE 27 Equations Used to Estimate Digestible Protein (Y) from Crude Protein (X) for Five Animal Kinds and Four Feed Classes

Animal Kind	Feed Class	Sample Size	Correlation Coefficient	Regression Equation	Standard Deviation From Regression
C[a]	D[b]	210	.970	$Y = 0.866X - 3.06$	0.75
S	D	521	.971	$Y = 0.897X - 3.43$	0.77
C	P	84	.976	$Y = 0.850X - 2.11$	0.61
S	P	251	.979	$Y = 0.932X - 3.01$	0.69
C	E	85	.972	$Y = 0.918X - 3.98$	0.89
CSHG	S	235	.969	$Y = 0.908X - 3.77$	0.58
G	DP	20	.986	$Y = 0.933X - 3.44$	0.50
H	DP	33	.967	$Y = 0.849X - 2.47$	0.87
GHS	E	237	.975	$Y = 0.916X - 2.76$	0.51
R	DP	35	.951	$Y = 0.772X - 1.33$	0.82

[a] Animal kind symbols are as follows: C = cattle, G = goats, H = horses, R = rabbits, S = sheep.

[b] Feed class symbols are as follows: D = dry roughages, P = pasture and range plants, S = silages, E = energy feeds. (Adapted from Knight and Harris, 1966)

TABLE 28 The Relationship Between the Percentages of Crude Protein (X) and Digestible Protein (Y) in Dry Forages, Pasture and Green Soiling Crops, Silages, and Energy Feeds by Swine

Feed Class	Sample Size	Correlation Coefficient	Regression Equation	Standard Deviation From Regression
DP[a]	12	.995	$Y = 0.846X - 4.50$	1.50
S	6	.963	$Y = 0.954X - 2.76$	1.40
E	109	.967	$Y = 0.909X - 2.31$	2.42

[a] Feed class symbols are as follows: D = dry roughages, P = pasture and green soiling crops, S = silages, and E = energy feeds. (Adapted from Knight and Harris, 1966)

below and above the maintenance requirement and calculating the intercept of the following regression equation (R = .79):

Apparent digestible nitrogen (%) = -0.40 + 0.74N, where N = the nitrogen content of forages.

For the calculation of the biological value for maintenance and production (BV_{m+p}) the urinary nitrogen needed to be used as in the following equation (Mitchell, 1924):

$$BV_{m+p} = \frac{NI - (FN - FN_m) - UN - UN_e}{NI - (FN - FN_m)} \times 100, \text{ where}$$

NI = nitrogen intake, FN = fecal nitrogen, FN_m = metabolic fecal nitrogen, UN = urinary nitrogen, and UN_e = endogenous urinary nitrogen.

This formula could be rearranged as follows (Harris et al. 1972):

$$BV_{m+p} = \frac{(NI - FN - UN) + FN_m + UN_e}{NI - FN + FN_m} \times 100 \ .$$

The term (NI - FN - UN) was nitrogen balance or production nitrogen. The term ($FN_m + UN_e$) was the amount of nitrogen needed for maintenance. The term $NI - FN + FN_m$ was true absorbed nitrogen. Thus, the formula could be written:

$$BV_{m+p} = \frac{\text{maintenance N + production N}}{\text{true absorbed nitrogen}} \times 100.$$

Therefore, the biological value for maintenance (BV_m) was the percentage of true absorbed nitrogen that was utilized for maintenance:

$$BV_m = \frac{FN_m + UN_e}{NI - FN + FN_m} \times 100$$ and, the biological value for production (BV_p) was percentage of the true absorbed nitrogen that was utilized for production:

$$BV_p = \frac{NI - FN - UN}{NI - FN + FN_m} X\ 100$$

The value of UN_e was estimated from the intercept of the regression equation: urine nitrogen = 0.102 g + 0.91 apparent absorbed nitrogen (R = 0.87). The average weight of horses (423 kilograms) UN_e (milligram per kilogram body weight) was 9.4 grams per day (Harris et al. 1972).

Net nitrogen (Net N_{m+p}) was the percentage of the intake nitrogen that was utilized for maintenance and production:

$$\text{Net } N_{m+p} = \frac{FN_m + UN_e + (NI - FN - UN)}{NI} X\ 100 \quad \text{or}$$

$$\text{Net } N_{m+p} = \frac{\text{Net } N_m + \text{Net } N_p}{NI} X\ 100 \quad \text{or}$$

Net N_{m+p} was the product of BV_{m+p} times the ture digestibility coefficient: Net N_{m+p} = TAN % X BV_{m+p}. The results obtained with regression equations, from horses fed on alfalfa and oats diet, were similar to those obtained from the conventional methods (Harris et al. 1972).

However, the concentration of crude protein in a feedstuff influenced its digestibility. Mitchell (1942) used data tabulated by Morrison (1936) found that the following equation expressed curvilinear relationship between the apparent digestibility (Y) of protein and the protein percent (X) in the forages:

$Y = 42.64\ (X - 5)^{0.215}$, for cattle and sheep.

Forbes (1950) used the same method on data from Schneider (1947) and got the following equations:

$Y = 40.31\ (X - 5)^{0.218}$; for cattle and sheep

$Y = 35.31\ (X - 5)^{0.272}$; for cattle (R = .99)

$Y - 42.13\ (X - 5)^{0.200}$; for sheep (R = .90) .

It was concluded that the protein in low protein forages was more efficiently digested by sheep than by cattle. This was in agreement with results of Holter and Reid (1959) who concluded that under the usual conditions of digestion trials, sheep might consume less feed (especially of low-protein, high fiber feeds) per unit of body weight and, therefore, excrete less metabolic nitrogen than cattle. The effect of a lower metabolic excretion of nitrogen in contributing to a higher apparent digestibility of protein would be pronounced at low levels of protein intake because under this condition metabolic nitrogen constitutes most of the total nitrogen in feces.

Holter and Reid (1959) employed data from two sources (Cornell data and Morrison's 1956 data). The intra-forage (inter-animal) coefficient of variation in digestibility of protein for the Cornell data was 2.4 percent. The apparent digesibility of protein was found to be highly significantly correlated with the concentration of crude protein of forages. The relationships between the two variables for green and dry forages were found to deviate highly significantly from linearity. However, the regression for silages was essentially linear. For green and dry forages, the curvilinearity of the relationship was the result of the decrease as in the relative contribution of metabolic nitrogen to the total fecal nitrogen as the crude protein concentration of forages increases.

The following regression equation resulted from fitting the method of Mitchell (1942) to the data of the Cornell green forages fed to cattle:

$Y = 34.90\ (X - 5)^{0.297}$

MATERIALS AND METHODS

Source of Data

Data used in this study were obtained from the International Databank System (International Feedstuffs Institute, Utah State University). This system is an international system for collection, calculation, and retrieval of data on the composition of animal feeds (Harris et al. 1968a).

Data had been collected from three major sources. First source was the collaborating laboratories, second was published data in literature and third was data from the centers related to the International Network of Feed Information Centers (INFIC). INFIC has been organized to standardize the naming of feed methods for analyzing and reporting feed composition data throughout much of the world. However, included in this study were the data of Canada and the U.S.A.

INFIC developed an "International System" to name feeds, record chemical and biological data about feeds, and to make it possible to code the data so it can be summarized, retrieved, and printed in flexible formats. On-line data are available for using a remote terminal for calculating diets to obtain maximum profit (INFIC, 1978).

The "International Feed Vocabulary" system had also been devised to make it possible to know the contents and other characteristics of a feed from its name (INFIC, 1978; Harris et al. 1965).

An "International Feed Name" was made up by combining descriptors of six facets:

1. Origin including scientific name (genus, species, variety), common name (generic, breed or kind, strain) and chemical formula.
2. Part fed to animal and as affected by processes.
3. Proccess(es) and treatment(s) to which the part eaten was subjected prior to feeding.
4. Stage of maturity or development (applicable to forages and animals).
5. Cutting (primarily applicable to forages).
6. Grade.

These six facets give qualitative description of the feed.

The International Feed Vocabulary is a system used in naming feedstuffs. This system is a modification of the international system proposed by Harris (1963) and Harris et al. (1968a). Thousands of feedstuffs were recorded and given "International Names" in English, German and French (INFIC, 1978), and in Arabic and Turkish (Kearl et al. 1979). The Portuguese and Spanish versions are being prepared. These International Names are in wide use throughout the world.

The International Feed Vocabulary is designed to give a comprehensive name of each feed as concisely as possible. Each feed is coined by using descriptors within one or more of the six mentioned facets.

Classification of Feedstuffs

Feedstuffs were divided into the following eight classes:

1. Dry forages and roughages. This class included all forages and roughages that are cut and cured. Forages and roughages are low in net energy per unit weight, usually because of their high fiber content though sometimes because of their high water content. When products contain more than 18 percent crude fiber on dry matter basis, they are classified forages (legumes, grasses) or roughages (straw, fodder, stover, hulls, shells).

2. Pasture, range plants and forages fed green. Included in this class are all forage feeds not cut or cured. They may be dry or weathered (subjected to weather conditions such as rain, frost, stem dry or grazed after the growing season) when consumed.

3. Silages. Silages are defined as fermented forage plants by ensiling. Ensiling is a method to preserve feedstuffs. It is a process that includes the changes which takes place when forage or feed with sufficient moisture to cause fermentation is started in a silo in the absence of air (Ensminger and Olentine, 1978).

4. Energy feeds. These were products that have less than 20 percent crude protein and less than 18 percent crude fiber. Examples were: cereal grains, mill by-products, roots, fruits, and nuts. However, certain roots, fruits, nuts and their by-products are classified as roughages.

5. Protein supplements. They were products which contain 20 percent or more crude protein (Nitrogen x 6.25). These supplements could be from animal origins (livestock, fish, marine, milk and poultry) or plant origin (seeds and seed meals).

6. Mineral supplements.

7. Vitamin supplements.

8. Additives (antibiotics, coloring material, flavores, hormones, medicants).

However, only the first five classes were included in this study.

The six-digit international feed number (IFN) given after each name is used for control purposes to identify each feed for summarization and retrieval of data. This number may be also used as the "numerical name" of a feed when using a computer to calculate diets to obtain maximum profit. The first digit of the IFN is always its class designation (INFIC, 1978).

IFN could be long or short. A complete international long name consists of all descriptors applicable to that feed (INFIC, 1978). The long international feed name would be used for comprehensive feed tables such as an atlas of feed composition data (NRC, 1972). The international short feed name (Harris , 1976) are coined by leaving out certain descriptors which are understood (aerial parts for forage) or by using descriptors which are used in commerce (meal is used in place of dehydrated ground for those feeds which are processed).

It was proposed that international short feed names for a given language be used as a legal name in a country for feed control purposes, commerce, and for feed composition tables for every day use (INFIC, 1978). Short names have been used by the NRC (1977).

The Systematic Collection and Recording of Data on Feed Composition. Harris et al. (1968a) and Harris (1970) devised an international source form for recording data. This form had been revised so that data on additional attributes such as toxic constituents, fertilizer, and pollution could be recorded (INFIC, 1978). This form was divided into cards, and a description of information to be filled in for each area of the source follows. These cards were:

1. Card 10: Describes origin of data, origin of sample and description of feed.
2. Card 21: Describes quality of feed, soil and fertilization.
3. Card 22: Describes storage of silage.
4. Card 24: Describes pollution and plant protection.
5. Card 30: Describes digestibility trial data when a digestibility trial has been conducted on the feed sample.
6. Card 40: Describes chemical and biological data on the feed sample.

The source forms are designed so information may be punched directly into 80-column computer cards or onto magnetic tape (INFIC, 1978).

Classification of Animal Kinds

Biological data were sorted by kind of animals within each class of feedstuffs because different species of animals may greatly differ in feed utilization. Moreover, animal species have different nutrient requirements. Hence, animals were divided into the following kinds.

1. Cattle
2. Horses
3. Rabbits
4. Sheep
5. Swine
6. Poultry

In vitro results were also included in this study whenever data were available.

Mathematical Models

A significant regression or change of one variable in relation to another indicated a strong possibility of predicting an unknown value from one that was known (Harris et al. 1972).

By usual statistical convention the dependent variable was designated as Y, and the independent variables were designated as X's. Each independent variable (X) included in the equation will fluctuate with Y in its own way.

Linear regression equations might be written as follows: $Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3$. . . etc. where b_0 is the Y intercept when $X = 0$ (regression constant) and b_1, b_2, b_3. . . etc. are the respective changes in Y per unit change (regression coefficient) of independent variables X_1, X_2, X_3 . . . etc. With only one independent variable (X_1) it is called simple linear regression and with more than one (X_1, X_2, X_3. . . etc.) multiple linear regression. Usually multiply linear regression methods give more accurate estimates of the dependent variables.

<u>TDN Studies</u>. Simple linear regression models were developed for TDN: $Y = b_0 + b_1X_1$ where $Y = \text{TDN}\%$, b_0 = constant (intercept of Y when $X = 0$), b_1 = regression coefficient (slope of line that indicates the rate of change in Y), and X_1 = the percentage of any of the proximate analysis components (crude fiber, ether extract, nitrogen-free extract, or crude protein). Meyer and Lofgreen (1956) used the same approach

to predict TDN from crude fiber, lignin or nitrogen content of alfalfa.

However, since TDN value was a result of the digestibility of more than one entity, multiple regression equations were used as follows:

TDN% (Y) = $b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$ where

b_0 is a constant (the intercept of Y when X = 0).

b_1, b_2, b_3, b_4 are the regression coefficients of X's, and X_1, X_2, X_3, and X_4 are the percentages of digestible or proximate crude fiber, ether extract, nitrogen-free extract and crude protein, respectively for a certain feedstuff.

In order to show the interactions among the nutrient components of feeds, the following model (developed by Harris et al. 1972) was used:

TDN% = $b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_2^2 + b_6X_3^2 + b_7X_1X_2 + b_8X_1X_3 +$

$b_9X_2X_3$, where b_0 was a constant (the intercept of Y where X=0), b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8 and b_9 were the regression coefficients of the X's and X_1, X_2, X_3 and X_4 were the percentages of crude fiber, ether extract, nitrogen free extract and crude protein, respectively for a certain feedstuff.

Another approach was followed to estimate TDN. This approach consisted of: first predicting the digestible nutrients (digestible crude fiber, digestible ether extract, digestible nitrogen-free extract and digestible crude protein) from the actual percentages of nutrients in a feed. Two models were used to predict the digestibility of nutrients from their actual percentages: the simple regression model: $Y = b_0 + b_1X_1$ where Y was the digestible nutrient, b_0 is the intercept of Y when X=0, and X was the percentage of the nutrient in the feed.

The following multiple regression was also used to predict the digestibility of a certain nutrient:

$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$ where Y was the digestible nutrient, b_0 was a constant; b_1, b_2, b_3 and b_4 were regression coefficients of the X's and X_1, X_2, X_3 and X_4 were the percentages of crude fiber, ether extract, nitrogen-free extract and crude protein, respectively.

The second step was to calculate TDN from the digestible nutrients according to the conventional way of calculating TDN:

TDN = digestible crude fiber X_1 + digestible ether extract X 2.5 + digestible nitrogen-free extract X_1 + digestible crude protein X_1.

Classes of feedstuffs were subdivided into more related subdivisions, as follows:

Subclass	Class 1	Class 2	Class 3	Class 4	Class 5
Legumes	11	21	31	--	--
Grasses	12	22	32	--	--
Legumeous roughages	13	23	33	--	--
Non-legumeous roughages	14	24	34	--	--
Mixture (legumes & grasses)	15	25	35	--	--
Animal origin	--	--	--	41	51
Avian origin	--	--	--	--	52
Marine origin	--	--	--	--	53
Milk origin	--	--	--	--	54
Plant origin	--	--	--	42	55

Then data from classes 1, 2, and 3 were pooled together and subgrouped into 5 subgroups while data from each of classes 4 and 5 were subgrouped into 2 subgroups as follows:

Subgroups	Class 1 + Class 2 + Class 3	Class 4	Class 5
Legumes	11	--	--
Grasses	12	--	--
Legumeous roughages	13	--	--
Non-legumeous roughages	14	--	--
Mixture (legumes & grasses)	15	--	--
Plant origin	--	41	--
Animal origin	--	42	--
Animal origin	--	--	51
Plant origin	--	--	52

Subgroups of classes of feedstuffs.

TDN was calculated for each animal kind within each subclass and subgroup of feedstuffs.

A third approach was used to predict TDN values using the qualitative factors that may affect the value of TDN, besides the chemical composition (Christiansen, 1979; Fonnesbeck et al. 1981 a,b).

Data was classified as follows:

a. Classes of feedstuffs were subdivided into groups of feeds that were from the same family:

Class Code						
1	2	3	4	5	Subclass	Sub-subclass
11	21	31	--	--	legumes	
12	22	32	--	--	grasses	
13	23	33	--	--	legumous roughages	
14	24	34	--	--	non-legumous roughages	
15	25	35	--	--	mixture (legumes + grasses)	
			41	--	plant origin	
			13			fruits
			15			cereal grains
			20			mill by-product nad residue, bakery by-products
			21			carbohydrate supplements (molasses, starches, sugars, flours,...)
			22			nuts
			24			oils
			27			roots and tubers
			42		animal origin	
			11			fats (fat, tallow, lard, grease, . . .)
			37			whey and whey by-products
				51	animal origin	
				04		carcasses (carcass meat trims, carcass residues, meat and bones)
				19		meats
				35		tankage
				37		viscera
				52	avian origin	
				04		carcasses (carcass residues)
				10		egg contents (yolk, white...)
				14		gizzard
				16		hatchary by-products
				36		viscera
				40		litter and wastes
				53	marine origin	
				54	milk origin	
				05		casein and milk by-products (cheeses...)
				55	plant origin	
				29		seeds

b. Stages of maturity were divided as follows:

Code	Stage
0	unknown
1	early and late vegetative + regrowth early vegetative
2	early bloom + mid-bloom
3	full bloom + late bloom
4	milk stage + doughstage
5	mature
6	postripe + stem cured

c. Parts-eaten:

Code	Part
01	aerial parts
02	brain
03	browse
04	carcasses (carcass meat trim, carcass residues, meat and bones...)
05	casein and milk by-products (cheeses...)
06	chaff
07	cobs
08	cones
09	ears
10	egg contents (yolk and white)
11	fat (grease, lard, tallow...)
12	fodder
13	fruits
14	gizzard
15	grains (cereal grains)
16	hatchary by-products
17	hulls
18	leaves
19	meat (plant nuts)
20	mill residues, mill by-products, bakery by-products...
21	carbohydrate supplements (molasses, starches, sugars...)
22	nuts
23	nuts with shells
24	oils
25	pods
26	pulp
27	roots and tubers
28	screenings and mixed screenings
29	seeds
30	shells
31	stems and twigs
32	stillage
33	stover
34	straw
35	tankage

Code	Part
36	viscera
37	whey and whey by-products
38	whole plants and mixed plants

TDN was predicted, then the estimated values were compared with the actual TDN values using the MDCF computer program (Hurst, 1979).

Digestible Energy Studies. Simple linear regression models were developed to predict digestible energy of feedstuffs from their proximate analysis (Cook and Child, 1977; Christiansen, 1979).

$Y = b_0 + b_1X_1$ where Y = De in Mega calories (in kilocalories for swine), b_0 = constant (intercept of Y when X = 0), b_1 = regression coefficient (the slope of line that indicates the rate of change in Y), and X_1 = the percentage of any of the proximate analysis components (crude fiber, ether extract, nitrogen-free extract or crude protein). DE was calculated from predicted digestible nutrient values.

Multiple linear regression equations were also used to predict DE of feedstuffs from their proximate analysis as follows (Nehring and Haenlein, 1973); $Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$ where Y = DE in Mega calories (in kilocalories for swine), b_0 = constant (the intercept of Y when X = 0), b_1, b_2, b_3 and b_4 were regression coefficients of the X's, and X_1, X_2, X_3 and X_4 were the digestible or proximate content of crude fiber, ether extract, nitrogen-free extract and crude protein of a particular feedstuff, respectively.

Digestible energy was also predicted from TDN% by a simple linear regression equation (Crampton et al. 1957; Harris and Asplund, 1968; Swift, 1957; Van Soest, 1971). (Y) DE (Mega calories) = $b_0 + b_1$ TDN%, where b_0 was a constant (the intercept of Y when X = 0), and b_1 was the regression coefficient (the slope of the line that indicated the rate of change in DE (Y) value).

Feedstuffs were classified into five classes (dry forages and roughages, pasture, range plants, and forages fed green, silages, energy feeds and protein supplements).

Animal kinds were also considered as in the case of TDN studies. Hence, DE was predicted for each kind of animal within each class of feedstuffs (whenever data were available).

Metabolizable Energy Studies. The same approach of predicting DE from proximate analysis was used to predict metabolizable energy (ME) for each kind of animals within each class of feedstuffs (whenever data were available): $Y = b_0 + b_1X_1$ where, Y = ME in Megacalories (kilocalories for swine), b_0 = the intercept of Y when X = 0 (a constant), b_1 = the regression coefficient of X (the rate of change in Y), and X_1 = any of the four components of proximate analysis (crude fiber, ether extract, nitrogen-free extract or crude protein).

A multiple regression equation was also used to predict ME from proximate analysis as followed: $Y - b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$ where Y = ME in Megacalories (in kilocalories for swine), b_0 = constant, b_1, b_2, b_3 and b_4 were regression coefficients of the X's, and X_1, X_2, X_3 and X_4 were the percentages of digestible or proximate nutrients (crude fiber, ether extract, nitrogen-free extract and crude protein).

This approach was used by many researchers (Bickel and Landis, 1978; Nehring and Haenlein, 1973; Van Es, 1978; Vermorel, 1978).

ME was also predicted from TDN value: $Y = b_0 + b_1$ (TDN%) where Y = ME in Megacalories (in kilocalories for swine), b_0 = constant, and b_1 = regression coefficient.

Moreover, ME was predicted from the DE values of feedstuffs as follows: $Y = b_0 + b_1$ (DE) where Y = ME in Megacalories (kilocalories for swine), b_0 = constant, and b_1 = regression coefficient.

A similar method was used for sheep by Harris and Asplund (1968) and for swine by Morgan (1976).

ME was also predicted from TDN values for each kind of animal within each class of feedstuffs as follows: $Y = b_0 + b_1$ (TDN%) where Y = ME in Megacalories (kilocalories for swine), b_0 = constant and b_1 = regression coefficient of X (TDN%).

Harris and Asplund (1968) and Morgan (1976) used the same approach for sheep and swine, respectively.

Protein Utilization. Knight and Harris (1966) found out a linear relationships between digestible protein and the protein concentration in feedstuffs.

Simple regression equations were developed to predict digestible crude protein (DCP) from crude protein (CP) concentration for each kind of animal within each class of feedstuffs mentioned: Y (DCP%) $= b_0 + b_1X_1$ where b_0 was a constant, b_1 was the regression coefficient of X_1, and X_1 was the crude protein percentage of the feed.

However, the digestibility of a certain nutrient could be affected by the presence of other nutrients. Hence, a multiple regression equation was developed to predict DCP from the proximate analysis, as follows: DCP% $= b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$ where b_0 was a constant,

b_1, b_2, b_3 and b_4 were the regression coefficients of the X's, and X_1, X_2, X_3 and X_4 were the percentages of crude protein, crude fiber, ether extract and nitrogen-free extract, respectively.

Nitrogen-Corrected Metabolizable Energy (ME_n) for Poultry. ME_n was estimated from each proximate nutrient contents of different classes of feedstuffs by the use of simple regression as follows:
$Y(ME_n) = b_0 + b_1X_1$ when b_0 was the intercept of Y when $X = 0$ (a constant), b_1 = the regression coefficient of X (the rate of change in Y), and X_1 = any of the four components of proximate analysis (crude fiber, ether extract, nitrogen free extract or crude protein).

Multiple regression was also employed to estimate ME_n:
$Y(ME_n) = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$, where b_o = constant, b_1, b_2, b_3 and b_4 were the regression coefficients of the X's, and X_1, X_2, X_3, and X_4 were the percentages of crude fiber, ether extract, nitrogen free extract and crude protein, respectively.

Net Energy for Production (NE_p) for Poultry. NE_p was estimated by the use of the simple and multiple regression equations, as it was the case in predicting ME_n. Moreover, NE_p was estimated from NE_n by simple regression: $Y(NE_p) = b_o + b_1 (ME_n)$, where b_0 = constant and b_1 = the rate of change in Y.

Computer Programs

(SPSS) Statistical Package for the Social Sciences (Nie et al. 1975) was used. SPSS is an integrated system of computer programs designed for the analysis of social science data. The system provided a unified and comprehensive package that enables the user to perform many different types of data analysis in a simple convenient manner. SPSS allowed a great deal of flexibility in the format of data. It provided the user with a comprehensive set of procedures for data transformation and file manipulation, and it offered the research a large number of statistical routines.

In addition to the usual descriptive statistics, simple frequency distributions, and cross-tabulation SPSS contained procedures for simple correlation, partial correlation, means of variances for stratified subpopulations, one-way and N-way analysis of variances, multiple regression, discriminant analysis, scatter diagrams, factor analysis, canonical correlations, and Guttman scaling. The data-management facilities could be used to modify a file of data permanently and can also be used in conjunction with any of the statistical procedures. These facilities enabled the user to generate new variables which are mathematical and/or logical combinations of existing variables, to record variables, and to sample, select, or weight specified cases.

This program was used in all mathematical models developed to predict TDN, digestible energy, metabolizable energy, and digestible protein.

MDCR (Multivariate Data Collection Regression). This program performs a wide variety of transformations, generates dummy variables for a wide variety of factorial type and nested experimental designs, and computes means, standard deviations, a complete correlation matrix and the corrected sums of squares and products matrix. It stores arrays on disks which are used as input together programs in the series (Hurst, 1979).

SMRU (Stepwise Multiple Regression Upward). Is a stepwise addition program which has the capability of making groups of variables act as single variable (Hurst, 1979) variables may be added singly or groups of variables may be defined as subsets wherein a group of variables are evaluated and added as a single unit.

The last two programs (MDCR and SMRU) were used to predict TDN from proximate analysis of feedstuffs and other qualitative factors.

RESULTS AND DISCUSSION

Predicting Digestible Nutrients

Predicting Digestible Crude Protein (DCP)

Digestible Crude Protein from Crude Protein (CP). Digestible crude protein was found to be highly correlated (R^2 = .78 to .97) with CP contents (Appendix Figures 14 to 32) of all classes of feedstuffs for all kinds of animals (Table 29). These results were in agreement with those of Knight and Harris (1966).

DCP was found to be linearly related to the concentration of crude protein in all classes of feeds. Holter and Reid (1959) reported similar relationships for dry and green forages fed to sheep and cattle.

Classes of feedstuffs were subdivided into more related subclasses in an attempt to find out if the subdivision of classes of feeds could have an effect on predictability of nutrients from their crude concentrations in the feeds. Table 30 shows the results of predicting DCP from CP of the subdivided classes of feeds for various kinds of animals. In general, the correlation between DCP and CP was high (R^2 = .74 to .99) except in the case of the non-legumeous roughages in dry forages and roughage for horses.

Crude protein content of the non-legumeous roughages is very low that the digestibility of protein could be negative due to more metabolic nitrogen excretion than the feed could furnish to the body. However, animals differ in utilization of crude proteins from such feeds.

TABLE 29 Simple Regression Equations to Predict Digestible Crude Protein (DCP%) from Crude Protein Contents (CP%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation	R^2	SE[a]	N[b]
Cattle	1	DCP% = -2.8749 + .8648 (CP%)	.9606	.97	312
	2	DCP% = -3.3744 + .9150 (CP%)	.9430	1.12	160
	3	DCP% = -3.4762 + .8873 (CP%)	.9687	.70	229
	4	DCP% = -3.4401 + .8926 (CP%)	.8225	1.65	66
	5	DCP% = -6.8888 + 1.0000 (CP%)	.9302	3.82	50
Horses	1	DCP% = -1.7852 + .7712 (CP%)	.9250	1.19	36
	4	DCP% = - .8801 + .7862 (CP%)	.8523	1.48	13
	5	DCP% = -9.2733 + 1.1302 (CP%)	.7792	1.80	5
Rabbits	1	DCP% = -4.9740 + .9643 (CP%)	.9208	1.83	25
	4	DCP% = -2.4118 + 1.0102 (CP%)	.9195	1.19	14
	5	DCP% = 2.2786 + .8333 (CP%)	.9532	1.62	8
Sheep	1	DCP% = -3.2001 + .8870 (CP%)	.9407	1.28	511
	2	DCP% = -2.4322 + .8996 (CP%)	.9302	1.49	298
	3	DCP% = -3.2082 + .8746 (CP%)	.9293	1.16	95
	4	DCP% = -2.6026 + .8945 (CP%)	.8516	1.74	119
	5	DCP% = -2.3153 + .9054 (CP%)	.9471	3.58	107
Swine	1	DCP% = -3.8603 + .8786 (CP%)	.8926	2.52	14
	2	DCP% = -1.7250 + .8030 (CP%)	.9738	.82	25
	4	DCP% = -1.8522 + .9005 (CP%)	.8955	1.60	89
	5	DCP% = -1.2506 + .9926 (CP%)	.9710	4.30	58

[a] N = number of observations.

[b] SE = standard error estimate.

Data for sheep showed higher correlations (R^2 = .80) between DCP and CP in dry non-legumeous roughages than cattle (R^2 = .64). This was in agreement with Forbes (1950) who reported better digestibility of crude protein in low-protein forages by sheep than by cattle. This higher efficiency was related to less metabolic nitrogen excretion by sheep due to less consumption of low-protein feeds per unit of body weight (Holter and Reid, 1959).

Fresh non-legumeous roughages showed high association (R^2 = .99 and .87) between DCP and their CP contents by both cattle and sheep, respectively. The difference between dry and green feeds could be related to chemical changes in protein due to preservation treatment, the physical nature of forages and its effect upon the excretion of nitrogen. In case of hays, leaf loss would result in less protein and more fiber contents (Glover et al. 1956).

Protein supplements of milk origin showed very high predictability of DCP from their contents of CP (R^2 = .99) by both cattle and sheep.

Data for rabbits generally showed high relationship (R^2 = .92 to .99) between DCP and CP contents of dry forage and roughage subdivisions and energy and protein supplement feeds (Table 30). These results were in agreement with those of Cheeke (1980) who found that rabbits digest alfalfa and other forage protein more efficiently than poultry, swine and even ruminants.

Data from the first three classes of feedstuffs (dry forages and roughages, green feeds and pasture plants and silages) were pooled together then subgrouped into five subgroups (legumes, grasses, legumeous roughages, non-legumeous roughages and mixtures of legumes

TABLE 30 Simple Regression Equations to Predict Digestible Crude Fiber (DCP%) from Crude Protein Contents (CP%) of Subclasses of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Cattle	1	Legumes	DCP% = -2.3183 + .8456 (CP%)	.8904	.88	141
	1	Grasses	DCP% = -2.4567 + .8036 (CP%)	.9679	.41	114
	1	Legumeous roughages	DCP% = -2.7261 + .8242 (CP%)	.8793	1.32	13
	1	Non-legumeous roughages	DCP% = -1.7293 + .6670 (CP%)	.6406	2.42	30
	1	Mixture (legumes & grasses)	DCP% = -4.0905 + .9145 (CP%)	.9683	.48	14
	2	Legumes	DCP% = -2.2831 + .8708 (CP%)	.9214	.91	11
	2	Grasses	DCP% = -4.1213 + .9604 (CP%)	.9494	1.09	127
	2	Legumeous roughages	DCP% = - .3472 + .6774 (CP%)	.9328	1.37	10
	2	Non-legumeous roughages	DCP% = -2.2967 + .8794 (CP%)	.9922	.33	10
	3	Legumes	DCP% = -4.8791 + .9601 (CP%)	.9555	.44	56
	3	Grasses	DCP% = -3.1317 + .8607 (CP%)	.9074	.43	118
	3	Non-legumeous roughages	DCP% = -2.0199 + .6917 (CP%)	.6851	.82	10
	3	Mixture (legumes & grasses)	DCP% = -4.8142 + .9759 (CP%)	.9502	.48	45
	4	Plant origin	DCP% = -3.4432 + .8929 (CP%)	.8185	2.75	65
	5	Milk origin	DCP% = -2.0127 + .9936 (CP%)	.9932	.93	6
	5	Plant origin	DCP% = -8.4512 + 1.0294 (CP%)	.9326	12.30	40
Horses	1	Legumes	DCP% = -3.9330 + .9291 (CP%)	.8288	.82	9
	1	Grasses	DCP% = -1.8398 + .7200 (CP%)	.8305	1.26	15
	1	Non-legumeous roughages	DCP% = .9847 + .1725 (CP%)	.0222	1.46	8
	4	Plant origin	DCP% = - .8801 + .7862 (CP%)	.8523	2.20	13

TABLE 30 Continued.

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Horses	5	Plant origin	DCP% = -9.2733 + 1.1302 (CP%)	.7792	3.23	5
Rabbits	1	Legumes	DCP% = -4.3993 + .9731 (CP%)	.9906	.26	14
	1	Grasses	DCP% = -2.1160 + .8370 (CP%)	.9900	.83	6
	1	Legumeous roughages	DCP% = -3.5026 + .6051 (CP%)	.9549	.23	4
	4	Plant origin	DCP% = -2.4118 + 1.0102 (CP%)	.9195	1.42	14
	5	Plant origin	DCP% = -4.3965 + .9848 (CP%)	.9702	1.29	7
Sheep	1	Legumes	DCP% = -3.9735 + .9359 (CP%)	.9195	1.17	158
	1	Grasses	DCP% = -3.0070 + .8915 (CP%)	.9789	.41	219
	1	Legumeous roughages	DCP% = -2.0608 + .6756 (CP%)	.7177	2.29	24
	1	Non-legumeous roughages	DCP% = -2.6622 + .7741 (CP%)	.8037	3.88	108
	2	Legumes	DCP% = -2.5857 + .9030 (CP%)	.9078	1.30	93
	2	Grasses	DCP% = -3.9623 + 1.0338 (CP%)	.9936	.15	4
	2	Non-legumeous roughages	DCP% = -3.6936 + .9661 (CP%)	.8738	3.59	79
	3	Legumes	DCP% = -3.9461 + .9015 (CP%)	.8389	1.61	28
	3	Grasses	DCP% = -3.5236 + .9079 (CP%)	.9537	.76	39
	3	Non-legumeous roughages	DCP% = -3.2636 + .9143 (CP%)	.8226	1.82	24
	4	Plant origin	DCP% = -2.6026 + .8945 (CP%)	.8516	3.02	119
	5	Marine origin	DCP% = -15.4998 + 1.0966 (CP%)	.7429	25.57	14
	5	Milk origin	DCP% = -3.4396 + 1.0087 (CP%)	.9994	.56	4
	5	Plant origin	DCP% = -4.8322 + .9863 (CP%)	.9113	7.26	87
Swine	1	Non-legumeous roughages	DCP% = -3.5925 + .7207 (CP%)	.7751	3.43	7

TABLE 30 Continued.

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Swine	2	Legumes	DCP% = -2.7276 + .8731 (CP%)	.9432	.73	7
	2	Grases	DCP% = -2.0599 + .7991 (CP%)	.9738	.23	11
	2	Non-legumeous	DCP% = - .0936 + .6744 (CP%)	.9912	.32	4
	4	Plant origin	DCP% = -1.8728 + .8993 (CP%)	.8991	2.50	88
	5	Animal origin	DCP% = 12.6806 + .6038 (CP%)	.8492	26.73	7
	5	Marine origin	DCP% = -17.5563 + 1.1403 (CP%)	.9626	7.55	10
	5	Milk origin	DCP% = 4.6062 + .8139 (CP%)	.9268	1.06	9
	5	Plant origin	DCP% = -4.7171 + .9727 (CP%)	.9446	6.73	31

and grasses). Subgrouping of feeds was an attempt to have minimal differences in chemical composition among feeds regardless of treatment.

Table 31 shows the results of predicting DCP from CP contents of subgrouped feedstuffs for various kinds of animals. Comparison of Tables 2 and 3 showed that predictability of DCP for CP content was better upon subgrouping of feeds by cattle in cases of legumes, legumeous roughages, and especially non-legumeous roughages (R^2 = .87) than the same subdivisions in both Class 1 and Class 3 (Table 30).

Data for sheep also showed higher predicting values for subgrouped legumeous and non-legumeous roughages (Table 30) than the same subdivision of dry forages and roughages and silages. Swine also showed higher correlation between DCP and CP upon subgrouping non-legumeous roughages in dry forages and roughages and green forages and pasture plants.

Since correlations between DCP and CP of the undivided or subgrouped classes of feedstuffs for various kinds of animals (Table 29) were high, and the subdivision (Table 30) and subgrouping of feeds (Table 31) did not show superior results, it would be better and cheaper to follow the classification of feedstuffs as shown in Table 29.

Digestible Crude Protein From Proximate Analysis. Multiple regression equations were developed to predict digestible crude protein from the chemical proximate nutrients of different classes of feedstuffs for various kinds of animals (Table 32).

Correlations between DCP and proximate analysis were high (R^2 = .86 to .99). There was improvement in predictability of DCP from proximate analysis over that of DCP from CP in many cases. However, R^2 dropped from .97 to .95 in protein supplements for sheep.

TABLE 31 Simple Regression Equations to Predict Digestible Crude Proteins (DCP%) from Crude Protein Contents (CP%) of Subgroups of Feedstuffs for Different Kinds of Animals

Animal Kind	Feed Class	Feed Subgroup	Equation	R^2	SE	N
Cattle	1+2+3	Legumes	DCP% = -2.9198 + .8729 (CP%)	.8997	.86	208
	1+2+3	Grasses	DCP% = -3.3560 + .9762 (CP%)	.9530	.75	359
	1+2+3	Legumeous roughages	DCP% = -1.0634 + .7098 (CP%)	.8928	1.46	23
	1+2+3	Non-legumeous roughages	DCP% = -2.6028 + .9336 (CP%)	.8716	2.05	50
	1+2+3	Mixture (legumes & grasses)	DCP% = -4.2838 + .9413 (CP%)	.9534	.52	61
Sheep	1+2+3	Legumes	DCP% = -3.7691 + .9356 (CP%)	.9014	1.44	279
	1+2+3	Grasses	DCP% = -2.5939 + .8773 (CP%)	.9370	1.14	381
	1+2+3	Legumeous roughages	DCP% = -4.0502 + .9352 (CP%)	.8616	3.20	29
	1+2+3	Non-legumeous roughages	DCP% = -3.2615 + .8906 (CP%)	.8471	3.93	211
	1+2+3	Mixture (legumes	DCP% = -5.7640 + 1.1063 (CP%)	.8352		
Swine	1+2	Legumes	DCP% = - .5026 + .7381 (CP%)	.8424	1.56	10
	1+2	Grasses	DCP% = -2.0508 + .7954 (CP%)	.9479	.43	15
	1+2	Legumeous roughages	DCP% = -2.4631 + .9756 (CP%)	.9775	2.77	4
	1+2	Non-legumeous roughages	DCP% = -2.0497 + .6961 (CP%)	.7974	.69	14

TABLE 32 Multiple Regression Equations to Predict Digestible Crude Protein (DCP%) from Proximate Analysis of Different Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	DCP% = 2.3539 + .8075 (CP%) - .2179(EE%) - .0603(NFE%) - .0399(CF%)	.9606	.96	231
	2	DCP% = 1.2312 + .8244(CP%) - .0618(CF%) - .0304(NFE%) - .0159(EE%)	.9779	.65	142
	3	DCP% = -5.4585 + .9150(CP%) + .0062(CF%) + .0896(EE%) + .0236 (NFE%)	.9728	.66	178
	4	DCP% = -18.3253 +1.2451(CP%) - .0522(EE%) + .1395(NFE%) + .0995(CF)	.0609	1.74	29
	5	DCP% = -59.2500 + 1.6259(CP%) + .5398(NFE%) + .4232(EE%) + .5305(CF)	.9564	2.87	18
Horses	1	DCP% = -8.8359 + .9004(CP%) - .8730(EE%) + .1287(NFE%) + .0583(CF%)	.9468	1.05	32
	4	DCP% = 2.3409 + .9089(CP%) - .7553(NFE%) + .5811(EE%) + .3127(CF)	.8580	1.67	13
	5	DCP% = 6.1423 + .9117(CP%) - .4138(CF%) - .0899(NFE%)	.8507	2.56	6
Rabbits	1	DCP% = 22.1665 + .6098(CP%) -.3655(NFE%)--.1909(CF%) - .0697(EE%)	.9625	1.69	18
	4	DCP% = 29.2934 + .6050(CP%) - .4237(CF%) -3116(NFE%) - .3055(EE%)	.9683	.85	13
	5	DCP% = 13.2568 + .7207(CP%) - .3611(CF%) - .1149(EE%) -.0681(NFE%)	.9899	1.04	8
Sheep	1	DCP% = -.8186 + .8584(CP%) - .1793(EE%) -.0224(CF) - .0203(NFE%)	.9450	1.18	452
	2	DCP% = 1.5938 + .8453(CP%) - .0602(NFE%) - .0222(CF%) - .0306(EE%)	.9233	1.43	218
	3	DCP% = -.9044 + .8729(CP%) - .0522(CF%) - .0175(NFE%) - -.0199(EE%)	.9334	1.13	85
	4	DCP% = -.9636 + .9047(CP%) - .1102(CF%) - .0517(EE%) - .0070(NFE%)	.8689	1.62	115
	5	DCP% = 13.9875 + .7032(CP%) - .2783(CF%) - .1354(NFE%) - .1090(EE%)	.9056	3.15	80
Swine	1	DCP% = -23.4490 + 1.0533(CP%) + .2960(NFE%) + .3318(EE%) + .0834(CF%)	.9781	1.64	10
	4	DCP% = -6.0699 + 1.0543(CP%) - .1392(CF%) + .0593(EE%) + .0391(NFE%)	.9231	1.33	41
	5	DCP% = -164.1639 + 2.6879*CP%) + 1.7524(NFE%) + 1.6275(EE%) + 1.3106 (CF%)	.9691	3.45	13

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[a] In equation, CF%, EE%, NFE% and CP% are the percentages of crude fiber, ether extract, nitrogen free extract and crude protein, respectively.

Schneider et al. (1952) used the same model to predict the digestibility coefficients of nutrient components of proximate analysis. Models were developed to predict the digestion coefficients for these nutrients in different classes of feeds for cattle and sheep (Schneider et al. 1952).

Predicting Digestible Ether Extract (DEE)

Digestible Ether Extract From Ether Extract (EE). Table 33 shows the results of regressing digestible ether extract contents within different classes of feedstuffs for various kinds of animals. All correlation coefficients were high (R^2 = .47 to .99) for all classes of feeds by all kinds of animals (Appendix Figures 33 to 47) except that of dry forages and roughages by horses (R^2 = .10).

Highest correlations existed between DEE and EE contents of energy feeds and protein supplements followed by silages. Hence, type of feeds had an effect on the predictability of digestible ether extract from their ether extract concentrations.

Data for cattle and sheep had high association between DEE% and EE%. However, sheep had higher association than cattle in cases of dry and fresh forages and roughages and protein supplements, while cattle had higher association in case of silages and energy feeds than sheep.

Rabbits had higher correlations between DEE and EE of all classes of feeds (R^2 = .82 to .99) than those of horses (R^2 = .10 to .47).

Swine also showed high relationship between DEE and EE in all classes of feeds (R^2 = .70 to .99).

It seemed that horses digest ether extract to a less predictable extent than other animals, while sheep and cattle had the highest tendency to digest this nutrient. This was in agreement with results reported by Vandernoot and Gilbreath (1970). This difference between horses and ruminants could be due to variation in the ingesta entering the cecum of the horse and rumen of the steer. Moreover, the digestive power of bacterial enzymes could be more than that of enzymes secreted by the digestive system itself (Fonnesbeck et al. 1974).

Table 34 shows the results of predicting digestible ether extract from ether extract content of the subdivisions of different classes of feedstuffs for various classes of animals.

All subdivisions of dry forages and roughages (except legumeous roughages for cattle and horses and non-legumeous roughages for horses) showed high correlation between DEE and their contents of EE for all kinds of animals. Subdivisions of green forages and pasture plants followed the same trend. However, non-legumeous roughages had a low correlation by cattle.

Both dry legumes and grasses showed low predictability of DEE from their contents of EE by horses. Legumes had slightly lower correlation coefficients than grasses (R^2 = .13 and .28, respectively for legumes and grasses). These results were in agreement with those of Fonnesbeck et al. (1967) who reported lower digestibility of EE in alfalfa than other feeds for horses.

All subdivisions of silages had a high predictability of DEE from their content of EE for cattle (R^2 = .70 to .96) and sheep (R^2 = .83 to .86).

Predictability of DEE from EE contents of energy feeds did not change because the same data (energy feeds of plant origin) were used in both tables (33 and 34).

TABLE 33 Simple Regression Equations to Predict Digestible Ether Extract (DEE%) from Ether Extract Contents (EE%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation	R^2	SE	N
Cattle	1	DEE% = - .4423 + .6261 (EE%)	.6014	.49	233
	2	DEE% = .0704 + .4486 (EE%)	.6932	1.48	141
	3	DEE% = - .7376 + .8499 (EE%)	.9008	.50	179
	4	DEE% = - .7676 + .9740 (EE%)	.9858	.52	36
	5	DEE% = - .9534 + .9790 (EE%)	.9793	1.51	25
Horses	1	DEE% = - .0725 + .3118 (EE%)	.1054	.61	35
	4	DEE% = - .3767 + .6845 (EE%)	.6770	1.02	12
	5	DEE% = .0953 + .5032 (EE%)	.4661	2.00	5
Rabbits	1	DEE% = - .3086 + .5419 (EE%)	.8207	.630	22
	4	DEE% = - .0520 + .9287 (EE%)	.9738	.25	14
	5	DEE% = .1024 + .9506 (EE%)	.9974	.49	8
Sheep	1	DEE% = - .7630 + .7790 (EE%)	.8455	.72	460
	2	DEE% = - .1422 + .6143 (EE%)	.8505	1.05	267
	3	DEE% = - .4880 + .7689 (EE%)	.8165	.55	85
	4	DEE% = - .3978 + .8725 (EE%)	.9376	.79	118
	5	DEE% = - .0560 + .9190 (EE%)	.9894	.85	105
Swine	1	DEE% = - .3918 + .8764 (EE%)	.8051	1.40	9
	2	DEE% = -3.4223 + 1.3661 (EE%)	.7038	.76	4
	4	DEE% = -1.2470 + .9834 (EE%)	.9972	.88	42
	5	DEE% = -1.2506 + .9926 (EE%)	.9710	1.18	22

TABLE 34 Simple Regression Equations to Predict Digestible Ether Extract (DEE%) from Ether Extract Contents (EE%) Subclasses of Different Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Cattle	1	Legumes	DEE% = -.8120 + .7372 (EE%)	.6535	45.76	110
	1	Grasses	DEE% = -.2186 + .5656 (EE%)	.6263	38.68	83
	1	Legumeous roughages	DEE% = .7489 + .0480 (EE%)	.0070	46.54	7
	1	Non-legumeous roughages	DEE% = -.1234 + .5977 (EE%)	.6921	47.27	22
	1	Mixture (legumes + grasses)	DEE% = -2.1644 + .1496 (EE%)	.9181	30.82	11
	2	Legumes	DEE% = -.5476 + .8073 (EE%)	.9337	38.88	11
	2	Grasses	DEE% = .0924 + .4441 (EE%)	.7086	46.28	108
	2	Legumeous roughages	DEE% = -.2314 + .4397 (EE%)	.2011	42.48	10
	2	Non-legumeous roughages	DEE% = .2695 + .3134 (EE%)	.0435	49.02	10
	3	Legumes	DEE% = -.8486 + .8745 (EE%)	.9641	35.39	51
	3	Grasses	DEE% = -.3047 + .7497 (EE%)	.7546	59.52	75
	3	Non-legumeous roughages	DEE% = .1932 + .6124 (EE%)	.7041	34.99	10
	3	Mixture (legumes + grasses)	DEE% = -1.5576 + .9995 (EE%)	.9528	44.00	43
	4	Plant origin	DEE% = -.7676 + .9740 (EE%)	.9858	95.33	36
	5	Milk origin	DEE% = -.1512 + .9901 (EE%)	.9996	54.30	6
Horses	1	Legumes	DEE% = -.7870 + .4307 (EE%)	.1282	33.78	9
	1	Grasses	DEE% = -.5323 + .5251 (EE%)	.2781	33.16	17
	1	Non-legumeous roughages	DEE% = -.9568 + .0277 (EE%)	.0013	28.93	8
	4	Plant origin	DEE% = -.3767 + .6845 (EE%)	.6770	79.72	12
	5	Plant origin	DEE% = .0953 + .5032 (EE%)	.4661	55.93	5

TABLE 34 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Rabbits	1	Legumes	DEE% = -.9897 + .7380 (EE%)	.8389	34.23	10
	1	Grasses	DEE% = .1941 + .4254 (EE%)	.8960	29.12	6
	1	Legumeous grasses	DEE% = .1930 + .4172 (EE%)	.7864	27.20	4
	4	Plant origin	DEE% = -.0520 + .9287 (EE%)	.9738	88.31	14
	5	Plant origin	DEE% = -.0514 + .9711 (EE%)	.9900	35.91	7
Sheep	1	Legumes	DEE% = -.8360 + .7396 (EE%)	.6816	46.40	142
	1	Grasses	DEE% = -.2231 + .5753 (EE%)	.7637	49.05	183
	1	Legumeous roughage	DEE% = -.4803 + .9036 (EE%)	.9586	47.42	22
	1	Non-legumeous roughages	DEE% = -.7716 + .8194 (EE%)	.8868	52.47	111
	2	Legumes	DEE% = .2198 + .4908 (EE%)	.9316	42.86	72
	2	Grasses	DEE% = -.2258 + .6365 (EE%)	.7651	53.67	113
	2	Legumeous roughages	DEE% = .2467 + .4513 (EE%)	.8664	51.89	4
	2	Non-legumeous roughages	DEE% = -.8159 + .8346 (EE%)	.9195	64.06	79
	3	Legumes	DEE% = -1.0302 + .8577 (EE%)	.8588	39.67	26
	3	Grasses	DEE% = -.2301 + .7133 (EE%)	.8365	48.74	31
	3	Non-legumeous roughages	DEE% = -.5683 + .8261 (EE%)	.8305	65.27	24
	4	Plant origin	DEE% = -.3978 + .8725 (EE%)	.9376	90.05	118
	5	Marine origin	DEE% = .1094 + .9464 (EE%)	.9787	0.00	15
	5	Milk origin	DEE% = -.1449 + 1.0029 (EE%)	.9851	1.00	4
	5	Plant origin	DEE% = -.1387 + .9203 (EE%)	.9898	63.40	84
Swine	1	Non-legumeous roughages	DEE% = -.1753 + .8558 (EE%)	.7786	44.06	6

TABLE 34 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Swine	2	Legumes	DEE% = -.3056 + .8564 (EE%)	.7334	33.23	3
	4	Plant origin	DEE% = -1.2470 + .9834 (EE%)	.9972	98.90	42
	5	Marine origin	DEE% = -2.1518 + 1.1911 (EE%)	.9807	0.00	5
	5	Milk origin	DEE% = -.4959 + .9756 (EE%)	.9874	65.18	4
	5	Plant origin	DEE% = -1.1346 + .8894 (EE%)	.9825	57.76	10

Protein supplements of marine origin showed high (R^2 = .98) correlations between DEE and their EE contents for sheep and swine. Feeds from milk origin followed the same trend (R^2 = .99).

Protein supplements of plant origin did not change for horses and rabbits because the same data was used in Tables 33 and 34. However, correlation between DEE and EE content of protein supplement of plant origin (R^2 = .95) when compared to that of the undivided class of protein supplement in Table 38 (R^2 = .98). Sheep, on the other hand, did not have a change in correlation coefficients for this subclass of feeds (R^2 = .99), while swine had a slight increase (R^2 = .98) compared with (R^2 = .97) the undivided class.

Data from the first three classes of feedstuffs (dry forage and roughages, green feeds and pasture plants and silages) were pooled together and then subgrouped into five subgroups (legumes, grasses, legumeous roughages, non-legumeous roughages and mixtures of legumes and grasses). Then digestible ether extract (DEE) was predicted from the ether extract content (EE) of these subgroups of feedstuffs (Table 35).

Comparison of Tables 34 and 35 showed that predictability of DEE from EE content was better upon subgrouping of feeds for cattle in cases of legumes (R^2 = .92), grasses (R^2 = .71), legumeous roughages (R^2 = .16) and mixtures of grasses and legumes (R^2 = .95), but not in the case of non-legumeous roughages (R^2 = .46) than the same divisions of Class 1. However, correlations were lower than those of the same subdivisions of silages in Table 34.

Green legumes and legumeous roughages (Table 34) showed higher correlation between DEE and their content of EE for cattle than

TABLE 35 Simple Regression Equations to Perdict Digestible Ether Extract (DEE%) from Ether Extract Contents (EE%) of Subgroups of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Feed Subgroup	Equation	R^2	SE	N
Cattle	1+2+3	Legumes	DEE% = -1.0978 + .9032 (EE%)	.9158	45.76	172
	1+2+3	Grasses	DEE% = .2704 + .4457 (EE%)	.7133	59.52	266
	1+2+3	Legumeous roughages	DEE% = .2791 + .2800 (EE%)	.1650	46.35	17
	1+2+3	Non-legumeous roughages	DEE% = -.1434 + .6069 (EE%)	.4631	49.02	42
	1+2+3	Mixture (legumes & grasses)	DEE% = -1.2594 + .9750 (EE%)	.9506	.95	56
Sheep	1+2+3	Legumes	DEE% = - .2009 + .5487 (EE%)	.8556	45.89	240
	1+2+3	Grasses	DEE% = - .2989 + .6401 (EE%)	.7742	53.67	327
	1+2+3	Legumeous roughages	DEE% = - .4287 + .8042 (EE%)	.9114	51.89	27
	1+2+3	Non-legumeous roughages	DEE% = - .7627 + .8260 (EE%)	.8976	65.27	214
Swine	1+2	Non-legumeous roughages	DEE% = - .1693 + .8562 (EE%)	.7793	33.21	7

subgrouping of feeds in Table 35. However, the opposite was true for grasses and non-legumeous roughages.

Data for sheep had higher predictability of DEE from EE contents of subgrouped legumes (R^2 = .86), grasses (R^2 = .77) and non-legumeous roughages (R^2 = .90), but not in the case of legumeous roughages than the same subdivisions of dry forages and roughages in Table 34.

Moreover, subgrouped grasses and legumeous roughages showed higher correlation coefficients (R^2 = .77 and .91, respectively) than the same subdivisions of green forages and pasture plants (Table 34) by sheep. The opposite was true in case of legumes and non-legumeous roughages. However, only subgrouped non-legumeous roughages showed higher predictability (R^2 = .90) of DEE from their contents of EE than the same subdivision of silages (Table 34) by sheep.

Digestible Ether Extract From Proximate Analysis. Multiple regression equations were developed to predict digestible ether extract from proximate nutrients of different classes of feedstuffs for various kinds of animals (Table 36).

Correlations between DEE and proximate analysis were high (R^2 = .54 to .99). Generally, predicting DEE from proximate analysis improved over that of DEE from EE. However, predictability decreased in cases of protein supplements for cattle and dry forages and roughages by sheep.

Table 36 also shows differences among kinds of animals in DEE predictability from proximate analysis. Cipolloni et al. (1951) found that cattle and sheep differed in digestibility of ether extract.

TABLE 36 Multiple Regression Equations to Predict Digestible Ether Extract (DEE%) from Proximate Analysis of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation	R^2	SE	N
Cattle	1	$DEE\% = -2.6367 + .6821(EE\%) + .0036(CP\%) + .0303(NFE\%) + .0206(CF\%)$	.6639	.37	231
	2	$DEE\% = 04.4305 + .5852(EE\%) + .0827(NFE\%) + .0266(CP\%) + .0059(CF\%)$	.7461	.73	172
	3	$DEE\% = 1.2178 + .8714(EE\%) - .0061(NFE\%) - .0482(CP\%) - .0374(CF\%)$	.9134	.39	178
	4	$DEE\% = .4954 + .9587(EE\%) - .0111(NFE\%) - .0268(CP\%) - .0207(CF\%)$	.9885	.53	29
	5	$DEE\% = 18.7033 + .6627(EE\%) - .1955(NFE\%) - .2062(CP\%) - .2238(CF\%)$	.9588	1.25	18
Horses	1	$DEE\% = 7.9296 - .1596(CP\%) + .3001(EE\%) - .0924(CF\%) - .0679(NFE\%)$	.5390	.45	32
	4	$DEE\% = 35.8419 + 1.2172(EE\%) + .3348(CP\%) + .4447(CF\%) + .3562(NFE\%)$	.7947	.81	13
	5	$DEE\% = -.8287 + .4783(CF\%) - .1602(EE\%) - .0810(CP\%)$	.9818	.47	6
Rabbits	1	$DEE\% = -3.1157 + .6394(EE\%) + .0387(NFE\%) + .0231(CF\%) + .0127(CP\%)$	.8571	.41	18
	4	$DEE\% = -1.7463 + .9618(EE\%) + .0041(CP\%) + .0189(NFE\%) + .0200(CP\%)$	.9780	.28	13
	5	$DEE\% = 5.5481 + .8849(EE\%) - .0755(NFE\%) - .0842(CF\%) - .0379(CP\%)$	.9980	.35	8
Sheep	1	$DEE\% = .9113 + .6353(EE\%) - .0309(CP\%) - .0138(NFE\%) - .0106(CF\%)$	.7296	.51	452
	2	$DEE\% = .6916 + .5161(EE\%) - .0094(CF\%) - .0066(CP\%) - .033(NFE\%)$	.8794	.49	218
	3	$DEE\% = -1.0448 + .8275(EE\%) + .0149(NFE\%) - .0184(CP\%) - .0019(CF\%)$	.8430	.44	85
	4	$DEE\% = -2.1910 + .8987(EE\%) - .0173(CF\%) + .0402(CP\%) + .0195(NFE\%)$	.9470	.68	115
	5	$DEE\% = 4.0469 + .8837(EE\%) - .0483(NFE\%) - .0445(CP\%) - .0354(CF\%)$	.9938	.67	80
Swine	1	$DEE\% = 3.1105 + .7199(EE\%) - .0892(CP\%) - .0397(NFE\%)$	.8585	1.38	10
	4	$DEE\% = 1.4864 + .9638(EE\%) - .1194(CP\%) - .0456(CF\%) - .0119(NFE\%)$	.9924	.71	41
	5	$DEE\% = 8.0116 + .7522(EE\%) - .0719(CP\%) - .1689(CF\%) - .0985(NFE\%)$	.9873	.67	13

[a] In equation, CF%, EE%, NFE%, and CP% are crude fiber, ether extract, nitrogen free extract and crude protein, respectively.

Predicting Digestible Crude Fiber (DCF)

Digestible Crude Fiber From CF. Crude fiber content of feedstuffs was not a very good predictor of digestible crude fiber in certain cases by various kinds of animals (Table 37).

Dry forages and roughages showed low association ($R^2 = .001$ to .47) between DCF and their contents of CF for all kinds of animals (Appendix Figures 48 and 49). These results were in agreement with those reported by Axellson (1938), Schneider (1947) and Van Soest (1978a).

The low correlations between DCF% and CF% in the dry forages and roughages could be related in most cases to the high fiber-low protein contents of these feeds. High levels of lignin in such feeds could be an important factor that added to the low association. Sullivan (1966) reported that the digestibility coefficient of cellulose was negatively correlated with the quantity of lignin in feeds. Moreover, lignin could exert more effect on the digestibility of hemicellulose. This seemed to be the case of alfalfa where correlation coefficients between lignin and digestibility of hemicellulose was greater than that between lignin and the digestibility of cellulose (-.83 and -.57, respectively).

Lignin was not found to be digestible (Cook and Harris, 1968a; Fonnesbeck et al. 1974). Lignin might not be attacked by microorganisms in the rumen and there is no secreted digestive juice which attacks it (Cuthbertson, 1969). The process of lignification makes the plant less nutritious as the cellulose and cell constituents are protected from the action of bacteria by the coating of lignin. This process accounts for the decline in the digestibility of hays when cutting is delayed.

Fresh legumes and grasses also showed lower (R^2 = .49 and .30, respectively) correlations between DCF and their contents of CF by cattle than that of the Class 2 (R^2 = .52) in Table 37. However, legumeous and non-legumeous roughages showed higher correlation values (R^2 = .71 and .83, respectively).

Data for sheep had higher correlations between DCF and CF contents of fresh legumes (R^2 = .50), grasses (R^2 = .50) and non-legumeous forages (R^2 = .53) than the undivided class of green forages and pasture plants (R^2 = .46).

All subdivisions of silage class (Table 38) showed higher correlations (R^2 = .71, .76, .62 and .79 respectively for legumes, grasses, non-legumeous roughages and mixtures of legumes and grasses) than the undivided class of silages (R^2 = .53) by cattle, while only grass silages showed high (R^2 = .76) correlations for sheep.

Even though correlation coefficients between DCF and CF contents of protein supplements of plant origin (Table 43) were higher by sheep and swine upon subdivision of the protein supplement class, these correlation coefficients were still very low (R^2 = .19 by sheep and .24 for swine).

Data of the dry feeds, green feeds and silages were combined together and then subgrouped into legumes, grasses, legumeous roughages, non-legumeous roughages and mixture of legumes and grasses. Prodictability of digestible crude fiber from crude fiber contents of the subgroups of feedstuffs (Table 39) was higher only in case of the legumeous and non-legumeous roughages and the mixture of grasses and legumes for cattle (R^2 = .71, .69, and .57, respectively) than the same subclasses in Table 38.

TABLE 37 Simple Regression Equations to Predict Digestible Crude Fiber (DCF%) from Crude Fiber Contents (CF%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation	R^2	SE	N
Cattle	1	DCF% = -4.2516 + .6696 (CF%)	.4706	3.86	257
	2	DCF% = -4.3703 + .7739 (CF%)	.5184	3.67	161
	3	DCF% = -2.9557 + .7009 (CF%)	.5269	3.22	202
	4	DCF% = -1.3696 + .6512 (CF%)	.8457	2.05	33
	5	DCF% = -1.3151 + .4641 (CF%)	.3515	4.50	17
Horses	1	DCF% = -4.0307 + .5192 (CF%)	.2812	4.34	33
	4	DCF% = -2.8409 + .8216 (CF%)	.4211	3.79	13
	5	DCF% = -3.8004 + .2934 (CF%)	.0662	5.07	5
Rabbits	1	DCF% = -5.4769 + .0093 (CF%)	.0010	2.31	29
	4	DCF% = - .1874 + .5532 (CF%)	.5441	3.57	13
	5	DCF% = -3.2399 + .0402 (CF%)	.0201	1.48	7
Sheep	1	DCF% = -2.1653 + .6084 (CF%)	.4558	5.11	501
	2	DCF% = - .1111 + .6166 (CF%)	.5734	3.89	229
	3	DCF% = -2.9208 + .5017 (CF%)	.5488	3.70	93
	4	DCF% = -1.2641 + .6552 (CF%)	.6672	3.28	115
	5	DCF% = -2.9526 + .2932 (CF%)	.2078	4.10	82
Swine	1	DCF% = -3.7021 + .4834 (CF%)	.2074	9.43	10
	4	DCF% = - .7040 + .5822 (CF%)	.5401	2.60	50
	5	DCF% = -2.4442 + .0984 (CF%)	.0433	2.32	12

TABLE 38 Simple Regression Equations to Predict Digestible Crude Fiber (DCF%) from Crude Fiber Contents (CF%) of Subclasses of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Cattle	1	Legumes	DCF% = -4.3224 + .5987 (CF%)	.4093	8.27	117
	1	Grasses	DCF% = 2.1303 + .5415 (CF%)	.4063	8.26	97
	1	Legumeous roughages	DCF% = 20.1348 + 1.1254 (CF%)	.5983	38.93	9
	1	Non-legumeous roughages	DCF% = -3.0484 + .6512 (CF%)	.6974	24.01	22
	1	Mixture (legumes + grasses)	DCF% = 16.3938 + .0647 (CF%)	.0187	2.17	12
	2	Legumes	DCF% = -4.7578 + .7291 (CF%)	.4917	9.71	11
	2	Grasses	DCF% = -.9528 + .6762 (CF%)	.2957	12.93	128
	2	Legumeous roughages	DCF% = -2.1226 + .5811 (CF%)	.7064	11.63	10
	2	Non-legumeous roughages	DCF% = -4.6741 + .7071 (CF%)	.8317	8.96	10
	3	Legumes	DCF% = -3.0903 + .6110 (CF%)	.7120	3.45	51
	3	Grasses	DCF% = -2.5336 + .7224 (CF%)	.7611	4.23	98
	3	Non-legumeous roughages	DCF% = -2.1885 + .4668 (CF%)	.6172	1.92	10
	3	Mixture legumes + grasses)	DCF% = -6.7480 + .9024 (CF%)	.7908	3.61	43
	4	Plant origin	DCF% = -1.3693 + .6521 (CF%)	.8457	4.22	33
	5	Plant origin	DCF% = 1.3151 + .4641 (CF%)	.3515	20.22	17
Sheep	1	Legumes	DCF% = 1.3488 + .4336 (CF%)	.3868	8.32	150
	1	Grasses	DCF% = 5.4343 + .4315 (CF%)	.2501	11.95	210
	1	Legumeous roughages	DCF% = -.4218 + .5551 (CF%)	.4114	71.09	25
	1	Non-legumeous roughages	DCF% = -7.1306 + .7171 (CF%)	.5803	50.62	114

TABLE 38 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Sheep	2	Legumes	DCF% = -1.2513 + .5831 (CF%)	.5037	11.93	73
	2	Grasses	DCF% = 1.4607 + .6165 (CF%)	.5010	11.60	109
	2	Non-legumeous roughages	DCF% = 2.1000 + .4711 (CF%)	.5303	15.23	44
	3	Legumes	DCF% = -.1530 + .5208 (CF%)	.4994	9.10	28
	3	Grasses	DCF% = 1.0335 + .6458 (CF%)	.7604	7.91	37
	3	Non-legumeous roughages	DCF% = 8.5636 + .2093 (CF%)	.3512	5.19	24
	4	Plant origin	DCF% = -1.2641 + .6552 (CF%)	.6672	10.79	115
	5	Plant origin	DCF% = 3.0990 + .2844 (CF%)	.1940	16.87	81
Swine	1	Non-legumeous roughages	DCF% = -13.3042 + .7214 (CF%)	.3830	115.50	7
	4	Plant origin	DCF% = -.7040 + .5822 (CF%)	.5401	6.78	50
	5	Plant origin	DCF% = 2.0750 + .2363 (CF%)	.2371	3.03	10

Green forages and pasture plants showed close correlations (R^2 = .52 and .57) between DCF and their CF contents for cattle and sheep, respectively (Table 34). Silages followed the same trend (R^2 = .53 and .55 for cattle and sheep respectively). These high correlations could exist because nutrients are not lost in green forages and pasture plants as the case would be in dry forages and roughages. The lowered protein content of hays due to loss of leaves usually leads to higher fiber content and hence lower digestibility.

DCF showed high correlations with CF contents of energy feeds (R^2 = .54 to .85) for various kinds of animals (Appendix Figures 50 and 51) except that for horses (R^2 = .42). This high relationship could exist because of the low fiber contents of energy feeds which, by definition, do not have more than 18 percent crude fiber.

Correlations between DCF and CF contents of protein supplements were low for all kinds of animals (R^2 = .02 to .35).

Classes of feedstuffs were subdivided into more related subclasses. Table 38 shows the results of regressing DCF with CF contents of subdivisions of different classes of feedstuffs for various kinds of animals.

Dry legumes, grasses and mixtures of legumes and grasses showed lower correlations for cattle and sheep than the undivided class of dry forages and roughages in Table 42. Dry legumeous roughages showed higher (R^2 = .60) for cattle and lower (R^2 = .41) correlations for sheep, while dry non-legumeous roughages showed higher correlations (R^2 = .70, .56 and .38 respectively) for cattle, sheep and swine than the undivided class of dry roughages and forages.

TABLE 39 Simple Regression Equations to Predict Digestible Crude Fiber (DCF%) from Crude Fiber Contents (CF%) of Subgroups of Feedstuffs for Different Kinds of Animals

Animal Kind	Feed Class	Feed Subgroup	Equation	R^2	SE	N
Cattle	1+2+3	Legumes	DCF% = -2.4183 + .5565 (CF%)	.4295	7.70	179
	1+2+3	Grasses	DCF% = - .0903 + .6342 (CF%)	.4520	9.12	323
	1+2+3	Legumeous roughages	DCF% = -5.4648 + .7259 (CF%)	.7079	25.39	19
	1+2+3	Non-legumeous roughages	DCF% = -4.3428 + .6499 (CF%)	.6921	19.86	42
	1+2+3	Mixture (legumes + grasses)	DCF% = -5.5876 + .8370 (CF%)	.5700	7.79	57
Horses	1+2	Legumes	DCF% = - .5327 + .3955 (CF%)	.4318	1.94	9
	1+2	Grasses	DCF% = 4.1429 + .3129 (CF%)	.0820	14.26	16
	1+2	Non-legumeous roughages	DCF% = -13.3042 + .7214 (CF%)	.3930	52.71	8
Rabbits	1+1	Legumes	DCF% = 3.3997 + .0692 (CF%)	.0495	5.70	17
	1+2	Grasses	DCF% = 8.1381 - .1013 (CF%)	.1195	4.47	7
	1+2	Legumeous roughages	DCF% = 3.7292 - .0305 (CF%)	.1645	.36	3
Sheep	1+2+3	Legumes	DCF% = .9108 + .4676 (CF%)	.4114	9.99	251
	1+2+3	Grasses	DCF% = 3.6053 + .5129 (CF%)	.3770	12.38	356
	1+2+3	Legumeous roughages	DCF% = 2.1551 + .5050 (CF%)	.4500	60.94	30
	1+2+3	Non-legumeous roughages	DCF% = -1.4696 + .5748 (CF%)	.5408	40.32	182
Swine	1+2	Legumes	DCF% = -10.8875 + .8521 (CF%)	.7468	16.05	4
	1+2	Non-legumeous roughages	DCF% = -10.4312 + .7540 (CF%)	.3140	115.50	7

Dry forages and roughages and green forages and pasture plants had low correlations between DNFE and their NFE contents (R^2 = .004 to .46). However, silages had higher correlations (R^2 = .53 and .79, respectively) by both cattle and sheep than the first two classes of feeds (Table 41).

Energy feeds and protein supplements showed high predictability of DNFE from their contents of NFE (R^2 = .50 to .99) for various kinds of animals (Appendix Figures 52 to 63) except that of protein supplements (R^2 = .17) by rabbits.

Asplund and Harris (1971) and Clemens (1968) also observed that NFE digestibility increased in mixed rations than that of individual feeds. Schnieder (1947) observed that, with low quality roughages fed to sheep, the effect of crude fiber and NFE on digestibility differed from that of forages of better quality. The digestibility of organic matter of such poor feeds declined as the content of NFE increased. That decline could be due to larger quantity of lignin that the usual proximate analysis method did not include in the fiber fraction and becomes a part of the NFE as it was calculated by subtraction.

Data for cattle, in general, had lower correlations between DNFE and NFE contents of different classes of feedstuffs than that of sheep. These results were in agreement with those reported by Cipolloni et al. (1951) and Fonnesbeck et al. (1974).

The relationship between DNFE and NFE in dry forages and roughages was negative by horses (R^2 = .004). Darlington and Hershberger (1968) observed that the apparent digestibility of NFE was inversely related to the percentage of crude fiber in the diet. However, Vanderroot and

Hence, it could be concluded that subdividing or subgrouping classes of feedstuffs could not result in much higher predictability of DCF from CF contents of the undivided classes of feedstuffs.

Digestible Crude Fiber From Proximate Analysis. Multiple regression equations were developed to predict digestible crude fiber from proximate analysis of different classes of feedstuffs for various kinds of animals (Table 40).

It was found that DCF could be predicted from proximate analysis with higher precision than from CF contents of the different classes of feedstuffs for various kinds of animals. One exception was that of energy feeds by sheep where correlation coefficient dropped from .67 to .61.

The increase in correlation coefficients of DCF predictability from proximate analysis was high by horses and rabbits in all classes of feedstuffs.

The higher precision in predictability of DCF from proximate analysis than from CF contents of feeds showed that the digestibility of one nutrient is not a result of the concentration of that nutrient alone, but also a result of the presence of other nutrients in the feeds.

Predicting Digestible Nitrogen Free Extract (DNFE)

Digestible Nitrogen Free Extract From NFE. Table 41 shows the results of regressing digestible nitrogen free extract from nitrogen free extract content of different classes of feedstuffs for various kinds of animals.

TABLE 40 Multiple Regresstion Equations to Predict Digestible Crude Fiber (DCF%) from Proximate Analysis of Different Classes of Feedstuffs for Different Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	DCF% = -6.8893 + .6230(CF%) - .1804(CP%) + 1.1266(EE%) + .0838(NFE%)	.5423	3.67	231
	2	DCF% = -11.2689 + .7804(CF%) + .7200(EE%) + .0766(NFE%) + .0389(CP%)	.6870	2.83	142
	3	DCF% = -27.4737 + .9718(CF%) + .7742(EE%) + .2410(NFE%) + .1906(CP%)	.5562	3.21	178
	4	DCF% = -19.3683 + .8880(CF%) + .1984(NFE%) + .1305(EE%) + .1236(CP%)	.9034	1.83	29
	5	DCF% = 18.2150 + .0570(CF%) + .1370(EE%) + -.2495(CP%) - .1165(NFE%)	.4160	4.77	18
Horses	1	DCF% = 47.0784 - .0870(CF%) + 2.3521(EE%) - .7984(CP%) - .5925(NFE%)	.5412	3.22	32
	4	DCF% = -185.4977 + 3.1968(CF%) + 1.8570(NFE%) + 1.9098(CP%) + 1.4290(EE%)	.7844	2.90	13
	5	DCF% = 61.4298 - .6428(CP%) - 1.9282(EE%) - .5910(NFE%)	.9906	.88	6
Rabbits	1	DCF% = 25.5253 - .3409(NFE%) - .1787(CP%) - .1034(CF%) + .0814(EE%)	.3012	2.43	18
	4	DCF% = 8.7037 + .4261(CF%) - .16687(EE%) - .0514(NFE%)	.7461	5.05	13
	5	DCF% = 19.2732 - .2526(NFE%) - .1739)CP%) + .0101(CF%)	.9142	.56	8
Sheep	1	DCF% = -6.4535 + .6576(CF%) + .0874(EE%) + .0429(NFE%) + .0470(CP%)	.4679	5.16	452
	2	DCF% = 12.5135 + .4946(CF%) - .2716(CP%) - .1227(NFE%) - .1078(EE%)	.6216	3.69	218
	3	DCF% = 8.8076 + .4521(CF%) - .2728(CP%) + .2671(EE%) - .0457(NFE%)	.5720	3.70	85
	4	DCF% = 3.7906 + .5587(CF%) - .2935(EE%) - .1298(CP%) + .0222(NFE%)	.6127	2.92	115
	5	DCF% = -17.9255 + .5359(CF%) + .2454(NFE%) + .2166(CP%) + .1200(EE%)	.2985	3.99	80
Swine	1	DCF% = -49.8271 + 1.5645(EE%) + .4822(NFE%) + .7138(CP%) + .8285(CF%)	.4587	11.02	10
	4	DCF% = 27.0344 + .3165(CF%) - .5191(CP%) - .2591(NFE%) - .2378(EE%)	.5962	2.75	41
	5	DCF% = -64.8890 + .7337(NFE%) + .8426(CF%) + .7018(CP%) + .6273(EE%)	.5375	1.93	13

[a] In equation, CF%, EE%, NFE% and CP% are the percentages of crude fiber, ether extract, nitrogen free extract and crude protein, respectively.

Dry forages and roughages and green forages and pasture plants had low correlations between DNFE and their NFE contents (R^2 = .004 to .46). However, silages had higher correlations (R^2 = .53 and .79, respectively) by both cattle and sheep than the first two classes of feeds (Table 41).

Energy feeds and protein supplements showed high predictability of DNFE from their contents of NFE (R^2 = .50 to .99) for various kinds of animals (Appendix Figures 52 to 63) except that of protein supplements (R^2 = .17) by rabbits.

Asplund and Harris (1971) and Clemens (1968) also observed that NFE digestibility increased in mixed rations than that of individual feeds. Schnieder (1947) observed that, with low quality roughages fed to sheep, the effect of crude fiber and NFE on digestibility differed from that of forages of better quality. The digestibility of organic matter of such poor feeds declined as the content of NFE increased. That decline could be due to larger quantity of lignin that the usual proximate analysis method did not include in the fiber fraction and becomes a part of the NFE as it was calculated by subtraction.

Data for cattle, in general, had lower correlations between DNFE and NFE contents of different classes of feedstuffs than that of sheep. These results were in agreement with those reported by Cipolloni et al. (1951) and Fonnesbeck et al. (1974).

The relationship between DNFE and NFE in dry forages and roughages was negative by horses (R^2 = .004). Darlington nad Hershberger (1968) observed that the apparent digestibility of NFE was inversely related to the percentage of crude fiber in the diet. However, Vandernott and

TABLE 41 Simple Regression Equations to Predict Digestible Nitrogen Free Extract (DNFE%) from Nitrogen Free Extract Contents (NFE%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation	R^2	SE	N
Cattle	1	DNFE% = 13.4867 + .3476 (NFE%)	.1443	4.81	258
	2	DNFE% = 12.4175 + .3513 (NFE%)	.1684	5.496	161
	3	DNFE% = - 2.9557 + .7009 (NFE%)	.5269	3.53	211
	4	DNFE% = -12.9801 + 1.0143 (NFE%)	.6967	9.10	41
	5	DNFE% = - 1.1514 + .8010 (NFE%)	.5782	7.99	24
Horses	1	DNFE% = 26.9449 - .0621 (NFE%)	.0037	6.65	37
	4	DNFE% = -39.5597 + 1.3530 (NFE%)	.7776	7.13	13
	5	DNFE% = -27.0507 + 1.3838 (NFE%)	.5031	11.68	5
Rabbits	1	DNFE% = 5.4590 + .4767 (NFE%)	.1848	5.45	27
	4	DNFE% = -22.8619 + 1.2291 (NFE%)	.8372	5.40	15
	5	DNFE% = 10.1879 + .5148 (NFE%)	.1723	7.28	8
Sheep	1	DNFE% = - 2.1653 + .6084 (NFE%)	.4558	5.21	494
	2	DNFE% = .6533 + .6886 (NFE%)	.4435	5.84	229
	3	DNFE% = -11.2644 + .9536 (NFE%)	.7925	4.34	93
	4	DNFE% = -23.0740 + 1.1809 (NFE%)	.8580	5.90	120
	5	DNFE% = - 8.6021 + 1.0261 (NFE%)	.8993	5.31	92
Swine	1	DNFE% = -13.6636 + .9233 (NFE%)	.3333	13.74	10
	2	DNFE% = 20.1553 + .2370 (NFE%)	.3953	3.58	4
	4	DNFE% = -15.3319 + 1.1085 (NFE%)	.8584	6.40	52
	5	DNFE% = - 1.8361 + .9702 (NFE%)	.9860	2.70	19

Gilbreath (1970) reported that geldings digest NFE better than steers fed grass hays.

The differences in digestibility of cell wall carbohydrates among species of animals could be due to conditions favoring or reducing anaerobic bacterial fermentation (Fonnesbeck et al. 1974). Sheep seemed to have better digestibility of NFE than cattle. Cippoloni et al. (1951) also observed differences in NFE digestibility among sheep and cattle fed roughages.

When classes of feedstuffs were subdivided into more related feeds, correlations between DNFE and their NFE contents increased in most cases (Table 42) over those reported in Table 41. Dry, fresh and ensiled legumes showed higher correlations for all animals involved.

Grass hays, however, showed low correlations between DNFE and NFE for cattle, horses and sheep. The same trend existed in grasses fed green to cattle, while fresh grasses had high correlations by rabbits and sheep (R^2 = .67 and .56, respectively).

Differences were observed to exist between the digestibilities of (NDF) neutral detergent fiber fraction (which was supposed to contain the NFE fraction) of grasses and legumes (Donker et al. 1976; Van Soest 1964). However, Christiansen (1979) found that NDF was more digestible in grasses than in alfalfa for sheep.

Grass silages also had higher predictability of DNFE from their NFE contents for cattle (R^2 = .87) and sheep (R^2 = .81).

Dry legumeous roughages had higher association between DNFE and their NFE content by cattle (R^2 = .60), rabbits (R^2 = .66) and sheep

(R^2 = .67) than dry forages and roughages in Table 41. Fresh legumeous roughages by cattle followed the same trend (R^2 = .80).

Dry non-legumeous roughages had higher correlations between DNFE and their NFE contents than Class 1 feeds in Table 41 for all kinds of animals. This increase was very little in the case of horses. Green non-legumeous roughages followed the same trend in cattle and sheep. Ensiled non-legumeous roughages also showed high correlations by cattle (R^2 = .79) and sheep (R^2 = .83).

Dry mixtures of legumes and grasses had a close relationship between DNFE and their NFE contents (R^2 = .92) by cattle. This relationship was low in case of horses (R^2 = .33).

Data for all animals had the same correlation coefficient values for energy feeds as in Table 42. Since data were not subdivided for this class of feeds because there was only data for plant origin feeds.

Protein supplements were subdivided into different subclasses. Data were available for feeds of milk origin and plant origin (Table 43). DNFE was better predicted from NFE content of feeds of milk origin by cattle, sheep and swine (R^2 = .99).

Protein supplements of plant origin showed slight increase in predictability of DNFE from their NFE contents than those of undivided protein supplements (Table 41). However, predictability for rabbits, sheep, and swine decreased slightly.

Hence, forage type seemed to affect the relationship between digestible nitrogen free extract and their nitrogen free extract content. This effect could be related to similarity in chemical composition (Schneider et al. 1950).

TABLE 42 Simple Regression Equations to Predict Digestible Nitrogen Free Extract (DNFE%) from Nitrogen Free Extract Contents (NFE%) of Subclasses of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Cattle	1	Legumes	DNFE% = -4.1709 + .8244 (NFE%)	.6600	3.59	120
	1	Grasses	DNFE% = 11.0832 + .3608 (NFE%)	.0743	25.44	95
	1	Legumeous roughages	DNFE% = -8.8984 + .8971 (NFE%)	.6002	37.73	9
	1	Non-legumeous roughages	DNFE% = -13.2725 + .8383 (NFE%)	.5931	40.72	22
	1	Mixture (legumeous + grasses)	DNFE% = -17.9388 + 1.0434 (NFE%)	.9206	.33	12
	2	Legumes	DNFE% = -9.0871 + .9547 (NFE%)	.4412	14.39	11
	2	Grasses	DNFE% = 16.1245 + .2412 (NFE%)	.0916	29.14	128
	2	Legumeous roughages	DNFE% = -5.2298 + .8358 (NFE%)	.8034	7.29	10
	2	Non-legumeous roughages	DNFE% = -1.9476 + .7139 (NFE%)	.3588	38.58	10
	3	Legumes	DNFE% = -6.0482 + .8252 (NFE%)	.6469	5.93	51
	3	Grasses	DNFE% = -21.3989 + 1.0687 (NFE%)	.8753	9.01	107
	3	Non-legumeous roughages	DNFE% = -22.1956 + 1.1200 (NFE%)	.7907	9.46	10
	3	Mixture (legumes + grasses)	DNFE% = -1.7764 + .6429 (NFE%)	.5547	12.77	43
	4	Plant origin	DNFE% = -12.9801 + 1.0143 (NFE%)	.6979	82.85	41
	5	Milk origin	DNFE% = - .7486 + .0101 (NFE%)	.9996	.71	6
	5	Plant origin	DNFE% = -7.5501 + .8944 (NFE%)	.6483	56.49	18
Horses	1	Legumes	DNFE% = -7.5637 + .8723 (NFE%)	.5469	6.48	9
	1	Grasses	DNFE% = 20.8469 + .0854 (NFE%)	.0116	21.07	17
	1	Non-legumeous roughages	DNFE% = - .0607 + .3401 (NFE%)	.1543	61.80	8

TABLE 42 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Horses	1	Mixture (legumes + grasses)	DNFE% = -37.9411 + .1589 (NFE%)	.3265	11.67	3
	4	Plant origin	DNFE% = -39.5597 + .1353 (NFE%)	.7776	50.80	13
	5	Plant origin	DNFE% = -27.0507 + 1.3838 (NFE%)	.5031	135.70	5
Rabbits	1	Legumes	DNFE% = -10.1217 + .9363 (NFE%)	.5472	8.33	15
	1	Grasses	DNFE% = -9.8614 + .7307 (NFE%)	.6754	15.27	7
	1	Legumeous roughages	DNFE% = -5.1003 + .5920 (NFE%)	.6610	2.70	4
	4	Plant origin	DNFE% = -22.8619 + 1.2291 (NFE%)	.8372	29.12	15
	5	Plant origin	DNFE% = 13.0202 + .4047 (NFE%)	.1215	55.17	7
Sheep	1	Legumes	DNFE% = -4.4867 + .8002 (NFE%)	.7379	6.32	150
	1	Grasses	DNFE% = -4.2166 + .6968 (NFE%)	.3909	20.96	202
	1	Legumeous roughages	NDFE% = -4.7584 + .7483 (NFE%)	.6727	29.52	25
	1	Non-legumeous roughages	DNFE% = -16.4061 + .9366 (NFE%)	.5628	44.15	115
	2	Legumes	DNFE% = 4.7382 + .6251 (NFE%)	.5900	7.92	73
	2	Grasses	DNFE% = -11.3521 + .8847 (NFE%)	.5624	22.53	109
	2	Non-legumeous roughages	DNFE = -3.1798 + .8349 (NFE%)	.4694	67.72	44
	3	Legumes	DNFE% = -10.1032 + .9503 (NFE%)	.8116	6.01	28
	3	Grasses	DNFE% = -11.3087 + .9138 (NFE%)	.8077	16.56	37
	3	Non-legumeous roughages	DNFE% = -15.6676 + 1.1076 (NFE%)	.8317	23.25	24
	4	Plant origin	DNFE% = -23.0740 + 1.1809 (NFE%)	.8580	34.82	120
	5	Milk origin	DNFE% = 1.0559 + .9405 (NFE%)	.9924	5.41	4
	5	Plant origin	DNFE% = -10.5969 + 1.0645 (NFE%)	.8961	26.56	86

TABLE 42 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Swine	1	Non-legumeous roughages	DNFE% = -19.2616 + 1.0416 (NFE%)	.3642	135.3	7
	4	Plant origin	DNFE% = -15.3319 + 1.1085 (NFE%)	.8584	40.93	52
	5	Milk origin	DNFE% = -4.1873 + 1.0683 (NFE%)	.9928	1.63	4
	5	Plant origin	DNFE% = -.1716 + .9048 (NFE%)	.9657	6.60	10

TABLE 43 Simple Regression Equations to Predict Digestible Nitrogen Free Extract (DNFE%) from Nitrogen Free Extract Contents (NFE%) of Subgroups of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Feed Subgroup	Equation	R^2	SE	N
Cattle	1+2+3	Legumes	DNFE% = -6.6669 + .8735 (NFE%)	.6293	5.42	182
	1+2+3	Grasses	DNFE% = 1.9184 + .5852 (NFE%)	.4305	29.50	330
	1+2+3	Legumeous roughages	DNFE% = -6.0709 + .8451 (NFE%)	.6717	19.32	19
	1+2+3	Non-legumeous roughages	DNFE% = -12.2061 + .8631 (NFE%)	.5675	35.58	42
	1+2+3	Mixture (legumes + grasses)	DNFE% = -3.3155 + .6896 (NFE%)	.6084	10.51	57
Sheep	1+2+3	Legumes	DNFE% = -1.7563 + .7491 (NFE%)	.6693	8.01	251
	1+2+3	Grasses	DNFE% = -8.9056 + 81.56 (NFE%)	.5188	22.30	348
	1+2+3	Legumeous roughages	DNFE% = -9.0103 + .8733 (NFE%)	.6320	46.23	30
	1+2+3	Non-legumeous roughages	DNFE% = -12.9492 + .9296 (NFE%)	.4953	63.51	183
Swine	1+2	Legumes	DNFE% = -7.0510 + .9012 (NFE%)	.9057	3.69	4
	1+2	Non-legumeous roughages	DNFE% = -8.1783 + .7774 (NFE%)	.3252	123.30	8

Data of classes of dry forages and roughages, green feeds and pasture plants and silages were pooled together then subgrouped into legumes, grasses, legumeous roughages, non-legumeous roughages and mixtures of legumes and grasses. Results of predicting DNFE from NFE contents of the subgrouped feeds were shown in Table 43. Correlations between DNFE and NFE contents of subgrouped feeds were generally higher than those reported in Table 41.

Subgrouped legumes showed high correlation (R^2 = .91) between DNFE and their NFE content for swine, while the subgrouped non-legumeous roughages had lower (R^2 = .32) correlation than that of dry and fresh feeds in Table 41. This decline in correlation could be related to the separation of the legumeous feeds that had higher protein and lower crude fiber contents than that of the non-legumeous roughages. Hence, digestibility of NFE was affected.

Digestible Nitrogen Free Extract From Proximate Analysis. Multiple regression equations were developed to predict digestible nitrogen free extract from the chemical analysis of different classes of feedstuffs for various kinds of animals (Table 44).

Except that of energy feeds for cattle, all correlation coefficients of predicting DNFE from proximate analysis of different classes of feeds for all kinds of animals involved were higher than those found in Table 46. R^2 ranged from .46 to .99.

Data for sheep had higher correlation between DNFE and proximate analysis in all cases except in fresh feeds than that of cattle.

These results indicated that the predictability of digestible nitrogen free extract was greatly affected by the chemical composition

TABLE 44 Multiple Regression Equations to Predict Digestible Nitrogen Free Extract (DNFE%) from Proximate Analysis of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	$DNFE\% = -4.0631 - .1094(CF\%) + .6693(NFE\%) + .5366(CP\%)$	.4593	3.86	231
	2	$DNFE\% = -6.7674 + .8442(NFE\%) + .4691(CP\%) - .2102(CF\%) + .1068(EE\%)$	.6644	3.17	142
	3	$DNFE\% = -5.5357 + .8221(NFE\%) - .3430(CF\%) + .1648(CP\%) + .2056(EE\%)$	.8857	2.78	178
	4	$DNFE\% = 74.1671 + .1393(NFE\%) - 1.0516(CF\%) - 1.0908(CP\%) - .9979(EE\%)$	.6696	10.64	29
	5	$DNFE\% = 37.5804 + .4771(NFE\%) - .3518(CP\%) - .6103(EE\%) - .7675(CF\%)$	.8461	5.56	18
Horses	1	$DNFE\% = 5.9180 + .7157(CP\%) + 4.2482(EE\%) - .2531(CF\%) - .1950(NFE\%)$	.6269	4.37	32
	4	$DNFE\% = -116.1260 + 2.0766(NFE\%) + 2.2062(CP\%) - .3824(EE\%) - .2378(CF\%)$	.8339	7.27	13
	5	$DNFE\% = 53.4750 - 5.3545(EE\%) + .3437(NFE\%) - .4198(CP\%)$	.9933	2.35	6
Rabbits	1	$DNFE\% = 44.3427 + .1333(NFE\%) - .5473(CF\%) - 2.9537(EE\%)$	.4931	4.79	18
	4	$DNFE\% = 14.6281 + .8798(NFE\%) - 3.1303(EE\%) - .3450(CF\%) - .1836(CP\%)$	.9442	4.17	13
	5	$DNFE\% = -1.5714 - 1.3284(CF\%) + .9424(NFE\%) + .2251(CP\%) - .0930(EE\%)$	.9526	2.73	8
Sheep	1	$DNFE\% = -14.0983 + .8507(NFE\%) + .5463(CP\%) - .2634(EE\%) - .0539(CF\%)$	.6684	4.02	452
	2	$DNFE\% = -12.3235 + .8984(NFE\%) + .5449(CP\%) - .1428(CF\%) + .1063(EE\%)$	.6363	4.78	218
	3	$DNFE\% = -4.2472 + .9408(NFE\%) - .3055(CF\%) + .3828(CP\%) - .7518(EE\%)$	.8927	3.18	85
	4	$DNFE\% = 3.9774 + .9125(NFE\%) - .5022(CF\%) - .4106(EE\%) - .1713(CP\%)$	.8679	5.71	115
	5	$DNFE\% = 21.6608 + 1.1592(NFE\%) + .2693(CP\%) - .1287(CF\%) + .0389(EE\%)$	.9250	4.64	80
Swine	1	$DNFE\% = -16.8197 - .6160(CF\%) + 2.0209(EE\%) + .8790(NFE\%) + 1.0589(CP\%)$	.7660	11.27	10
	4	$DNFE\% = 104.6490 - .0704(NFE\%) - .9568(EE\%) - 1.7018(CP\%) - 1.5865(CF\%)$	.8627	6.23	41
	5	$DNFE\% = -44.7077 + 1.3815(NFE\%) + .3237(CF\%) + .6131(EE\%) + .4647(CP\%)$	.9899	2.34	13

[a] In equation, CF%, EE%, NFE% and CP% are percentages of crude fiber, ether extract, nitrogen free extract and crude protein, respectively.

of feedstuffs. These results were in agreement with those of Asplund and Harris (1969) and Clemens (1968).

Predicting Total Digestible Nutrients (TDN)

Estimating the TDN value of feedstuffs from their proximate analysis was approached by four methods. First was to predict the digestibility of the components of proximate analysis (CF, EE, NFE and CP) from their proximate contents in feedstuffs. Then TDN was calculated by the conventional way.

The second method was to estimate TDN from the digestible nutrients by multiple regression equations.

The third method was to predict TDN from each nutrient of proximate analysis by simple regression equation.

The fourth method was to predict TDN from proximate analysis of feedstuffs by a multiple regression equation. Another, more complicated, multiple regression equation that involved interactions among proximate nutrient was also used.

TDN From Digestible Nutrients. TDN was calculated from digestible nutrients by the conventional way:

$$TDN = DCF + DEE \times 2.25 + DNFE + DCP$$

The predicted values of digestible nutrients reported in Tables 29 to 44 could be used for the calculation of TDN.

In the seond approach, TDN values were regressed with the digestible values of CP, CF, EE, and NFE (Table 45). TDN was highly correlated with the digestible nutrients (R^2 = .90 to .99) contents of the different classes of feedstuffs for various kinds of animals. Data

TABLE 45 Multiple Regression Equations to Predict Total Digestible Nutrients (TDN%) from Digestible Nutrient Components of Proximate Analysis of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	TDN% = 1.8310 + 1.0222(DNFE%) + .8760(DCF%) + .9202(DCP%) + 2.3343(DEE%)	.9464	1.67	231
	2	TDN% = -.2612 + .9242(DCFE%) + 1.0898(DNFE%) + .9258(DCP) + 1.3251(DEE%)	.9639	1.67	142
	3	TDN% = -1.4976 + 1.0031(DNFE%) + 2.3598(DEE) + 1.0479(DCF + 1.0370(DCP%)	.9764	1.16	178
	4	TDN% = .1251 + .9957(DNFE%) + 2.2392(DEE%) + .9986(DCF%) + 1.0097(DCP%)	.9984	.58	29
	5	TDN% = .1968 + 1.0023(DCF%) + .9969(DCP%) + .9983(DNFE%) + 2.2405(DEE%)	.9999	.12	18
Horses	1	TDN% = -.1432 + .9714(DNFE%) + .10033(DCF%) + 1.0522(DCP%) + 3.0615(DEE%)	.9834	1.30	32
	4	TDN% = -.6356 + 1.0150(DNFE%) + .9600(DCF%) + 1.1134(DCP%) + 1.3792(DEE%)	.9728	2.61	13
	5	TDN% = 12.5295 + .7620(DNFE%) + 1.5671(DCF%) + .8902(DCP%)	.9985	1.17	6
Rabbits	1	TDN% = .3324 + .9948(DCP%) + .9974(DNFE%) + .9617(DCF%) + 2.2794(DEE%)	.9998	.21	18
	4	TDN% = 4.0052 + .9594(DNFE%) + .9956(DCP%) + .8727(DCF%) + 1.7778(DEE%)	.9985	.46	13
	5	TDN% = -1.3260 + 1.1149(DCP%) + .8572(DNFE%) + .9971(DCF%)	.9962	1.63	8
Sheep	1	TDN% = .9987 + .9820(DNFE%) + .9811(DCF%) + .9954(DCP%) + 2.1319(DEE%)	.9868	1.06	452
	2	TDN% = 2.5237 + 1.0089(DNFE%) + 1.0246(DCF%) + 1.1936(DCP% + .7769(DEE%)	.8426	4.05	218
	3	TDN% = -.1948 + 1.0042(DNFE%) + 1.0262(DCP%) + .9857(DCF%) + 2.2632(DEE%)	.9971	.50	85
	4	TDN% = -.1626 + 1.0015(DNFE%) + 2.2054(DEE%) + 1.0127(DCP%) + 1.0106 (DCF%)	.9879	1.38	115
	5	TDN% = 1.7049 + 2.1029(DEE%) + .9671(DNFE%) + .9705(DCP%) + 1.0323(DCF%)	/9046	4.74	80
Swine	4	TDN% = .0140 + 2.2447(DEE%) + 1.0002(DNFE%) + .9953(DCF%) + 1.00158 DCF%)	.9999	.05	41

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[a] In equation, DCF, DEE, DNFE, and DCP were the digestible percentages of crude fiber, ether extract, nitrogen free extract and crude protein, respectively.

for sheep, however, had a slightly lower correlation (R^2 = .84) in case of green forages and pasture plants.

Digestible nitrogen free extract contributed more to predictability of TDN than other nutrients in cases of dry forages and roughages by cattle, horses, sheep and swine. NFE had the same kind in case of silages for sheep and cattle, green forages and pasture plants for sheep, energy feeds by cattle, horses, rabbits and sheep and protein supplements for horses.

Digestible ether extract contributed more to predictability of TDN than other digestible nutrient contents of protein supplements for sheep and swine and energy feeds by swine. Digestible crude fiber contributed better for TDN estimation in green forages and pasture plants and protein supplements by cattle. However, DCP contributed more in cases of dry forages and roughages and protein supplements by rabbits.

Hence, digestible nutrients behaved differently in contributing to predictability of TDN values depending on the kind of animals and the class of feedstuffs they were fed.

Predicting Total Digestible Nutrients From Each Proximate Nutrient Content.

TDN From Crude Fiber. TDN values were regressed with crude fiber contents of different classes of feedstuffs for various classes of animals (Table 46). As expected, TDN was negatively correlated with crude fiber. Correlations of TDN and CF contents of dry roughages and forages, green forages and pasture plants and silages were low for all kinds of animals (R^2 = .001 to .44). Two exceptions were those of

TABLE 46 Simple Regression Equations to Predict Total Digestible Nutrients (TDN%) from Crude Fiber Contents (CF%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation	R^2	SE	N
Cattle	1	TDN% = 75.2671 - .6114 (CF%)	.1800	7.75	420
	2	TDN% = 55.3657 + .0778 (CF%)	.0012	10.33	212
	3	TDN% = 81.4570 - .7028 (CF%)	.2323	6.48	269
	4	TDN% = 87.4555 - .8741 (CF%)	.2959	8.18	176
	5	TDN% = 84.5827 - .6220 (CF%)	.1862	9.62	124
Horses	1	TDN% = 69.0273 - .6291 (CF%)	.1016	9.59	37
	4	TDN% = 91.1190 - 1.9582 (CF%)	.3582	8.60	12
	5	TDN% = 103.4529 - 2.3640 (CF%)	.3931	13.51	5
Rabbits	1	TDN% = 72.5824 - .9053 (CF%)	.4378	7.95	30
	4	TDN% = 93.6811 - .8929 (CF%)	.4012	7.75	14
	5	TDN% = 110.7313 - 2.8711 (CF%)	.8156	2.58	6
Sheep	1	TDN% = 68.1937 - .7455 (CF%)	.1226	8.58	546
	2	TDN% = 62.3987 - .1588 (CF%)	.0439	8.91	229
	3	TDN% = 203.2016 - 5.1503 (CF%)	.5433	8.57	93
	4	TDN% = 93.8608 - 1.4540 (CF%)	.2764	10.67	120
	5	TDN% = 81.9327 - .2855 (CF%)	.0237	9.26	79
Swine	1	TDN% = 68.1937 - .7455 (CF%)	.1226	21.31	17
	2	TDN% = 62.3987 - .1588 (CF%)	.0439	7.92	28
	4	TDN% = 93.8608 - 1.4540 (CF%)	.2764	9.90	81
	5	TDN% = 81.9327 - .2855 (CF%)	.0237	10.09	46
in vitro	2	TDN% = 86.3382 - .9201 (CF%)	.7290	2.83	32
	3	TDN% = 74.7393 - .4906 (CF%)	.3016	3.51	92

green forages (R^2 = .73) for in vitro studies and silages (R^2 = .54) by swine.

Since high contents of crude fiber in feedstuffs depresses digestibility, it was expected to have negative relationship between CR and TDN. This was in agreement with Meyer and Lofgreen (1956) and Stallcum et al. (1976) who reported negative correlation between TDN and CF in alfalfa hay and forages.

Stallcup et al. (1976) found that TDN was negatively correlated with CF content of sorghum-sudan forage (R^2 = .66). However, this correlation dropped in cases of sorghum (R^2 = .21) and corn (R^2 = .002) silages. When data of all experiments were pooled together, TDN was not related to crude fiber content of these feeds (R^2 = .10).

Energy feeds and protein supplements also showed low, negative correlations between TDN and their CF contents (R^2 = .02 to .40) except that of protein supplements (R^2 = .82) by rabbits.

Classes of feedstuffs were subdivided into more related subclasses. Table 47 shows the results of regressing TDN values with CF contents of subclasses of different feedstuffs for various kinds of animals.

Correlations between TDN and CF contents of the subdivisions of dry forages and roughages did not show appreciable improvement over that of the undivided class except in the case of legume and grass hays (R^2 = .83 and .79, respectively) by rabbits.

Subdivisions of green forages and pasture plants did not have improved correlations between TDN and their CF contents over the un divided class except that of legumeous roughages by sheep (R^2 = .93).

TABLE 47 Simple Regression Equations to Predict Total Digestible Nutrients (TDN%) from Crude Fiber Contents (CF%) of Subclasses of Different Classes of Feedstuffs

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Cattle	1	Legumes	TDN% = 72.7304 - .4954 (CF%)	.1945	16.78	175
	1	Grasses	TDN% = 89.9890 - 1.1216 (CF%)	.2379	75.55	159
	1	Legumeous roughages	TDN% = 99.0743 - 1.0297 (CF%)	.2747	269.40	15
	1	Non-legumeous roughages	TDN% = 60.2597 - .2498 (CF%)	.0728	66.31	55
	1	Mixture (legumes + grasses)	TDN% = 70.5105 - .4411 (CF%)	.1869	6.76	16
	2	Legumes	TDN% = 83.0158 - .8022 (CF%)	.3816	39.90	16
	2	Grasses	TDN% = 64.9693 - .2431 (CF%)	.0068	103.60	174
	2	Legumeous roughages	TDN% = 26.0216 + .9876 (CF%)	.4319	106.30	10
	2	Non-legumeous roughages	TDN% = 58.4065 - .0782 (CF%)	.0044	418.20	10
	2	Mixture (legumes + grasses)	TDN% = 16.8147 + 1.4162 (CF%)	.1644	232.30	3
	3	Legumes	TDN% = 74.6304 - .5377 (CF%)	.2261	20.95	67
	3	Grasses	TDN% = 88.2279 - .8918 (CF%)	.4172	63.14	140
	3	Non-legumeous roughages	TDN% = 63.6742 - .4757 (CF%)	.2955	39.30	12
	3	Mixtures (legumes + grasses)	TDN% = 63.4438 - .0770 (CF%)	.0015	55.65	51
	4	Plant origin	TDN% = 88.1419 - .9292 (CF%)	.3378	61.92	173
	5	Animal origin	TDN% = 67.9869 + .5856 (CF%)	.0350	20.26	9
	5	Marine origin	TDN% = 79.0405 - 4.2010 (CF%)	.0178	49.17	10
	5	Plant origin	TDN% = 90.5130 - .9580 (CF%)	.3716	149.10	99
Horses	1	Legumes	TDN% = 69.8210 - .5462 (CF%)	.1959	11.56	9
	1	Grasses	TDN% = 39.7650 + .2331 (CF%)	.0167	40.41	17

TABLE 47 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Horses	1	Non-legumeous roughages	TDN% = 26.9008 + .2060 (CF%)	.0150	175.30	8
Rabbits	1	Legumes	TDN% = 83.5378 - 1.0964 (CF%)	.8350	14.74	17
	1	Grasses	TDN% = 74.7556 - 1.1444 (CF%)	.7948	19.97	7
	1	Legumeous roughages	TDN% = 45.3199 - .3948 (CF%)	.5072	11.03	4
Sheep	1	Legumes	TDN% = 70.2834 - .4542 (CF%)	.2453	17.62	184
	1	Grasses	TDN% = 85.6315 - .9169 (CF%)	.2369	57.14	219
	1	Legumeous roughages	TDN% = 60.0854 - .1236 (CF%)	.0128	190.00	25
	1	Non-legumeous roughages	TDN% = 56.5164 - .1483 (CF%)	.0417	126.2	116
	2	Legumes	TDN% = 51.8573 + .3297 (CF%)	.0457	81.33	73
	2	Grasses	TDN% - 69.3943 - .2916 (CF%)	.0352	71.48	125
	2	Legumeous roughages	TDN% = 89.1674 - .7356 (CF%)	.9345	5.07	4
	2	Non-legumeous roughages	TDN% = 71.7364 - .4547 (CF%)	.0871	165.20	45
	3	Legumes	TDN% = 69.2724 - .3430 (CF%)	.1116	31.35	28
	3	Grasses	TDN% = 80.1661 - .5929 (CF%)	.3361	41.84	37
	3	Non-legumeous roughages	TDN% = 65.6603 - .2751 (CF%)	.0890	163.00	24
	4	Plant origin	TDN% = 87.8860 - 1.0092 (CF%)	.3071	173.00	121
	5	Plant origin	TDN% = 95.8459 - 1.1155 (CF%)	.2855	535.16	84
Swine	1	Non-legumeous roughages	TDN% = 53.3647 - .3795 (CF%)	.0214	648.60	8
	2	Legumes	TDN% = 83.1737 - .7856 (CF%)	.4070	5.94	7
	2	Grasses	TDN% = 83.1737 - .7856 (CF%)	.4070	37.95	12

TABLE 47 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Swine	2	Non-legumeous roughages	TDN% = 45.8097 + .7237 (CF%)	.3671	76.59	7
	4	Plant origin	TDN% = 93.8608 - 1.4540 (CF%)	.2764	33.93	84
	5	Animal origin	TDN% = 65.0595 - .3777 (CF%)	.2052	21.13	6
	5	Marine origin	TDN% = 99.3415 - 21.5175 (CF%)	.5052	91.29	6
	5	Plant origin	TDN% = 91.6315 - .9834 (CF%)	.3231	37.39	31

Correlations between TDN and crude fiber contents of the subdivisions of energy feeds did not show higher increases over the undivided class of energy feeds for all kinds of animals.

Only protein supplements of plant origin (Table 47) showed slight increase (R^2 = .37) for cattle over the undivided class of protein supplements. Protein supplements of animal, marine and plant origin showed higher correlations over the undivided class of protein supplements by swine, however.

TDN From Ether Extract. Table 48 shows the results of predicting TDN from ether extract contents of different kinds of feedstuffs for various kinds of animals. There was no relationship between TDN and ether extract content of dry forages and roughages, green forages and pasture plants and silages for various kinds of animals. Correlation was high (R^2 = .88) in green forages and pasture plants for in vitro studies, however.

Correlations between TDN and EE contents of energy feeds were high by cattle (R^2 = .71) and swine (R^2 = .80). The correlations by horses, rabbits and sheep were negative, however.

Protein supplements also showed variations in correlation between TDN and their EE contents for various kinds of animals. Rabbits had a high correlation (R^2 = .73) while sheep and swine had low correlation (R^2 = .21). The correlation coefficient was .41 for cattle.

Increased ether extract (addition of fat) decreased digestibility of ration in sheep (Swift et al. 1948) and cellulose digestibility (Summers et al. 1957). Moreover, the presence of non-digestible lipids in browse plants tend to decrease digestibility (Cook and Harris, 1968a.

TABLE 48 Simple Regression Equations to Predict Total Digestible Nutrients (TDN%) from Ether Extract Contents (EE%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation	R^2	SE	N
Cattle	1	TDN% = 50.6263 + 2.0873 (EE%)	.0647	8.26	407
	2	TDN% = 50.1459 + 1.5528 (EE%)	.1299	9.92	197
	3	TDN% = 54.7150 + 1.6481 (EE%)	.0987	6.84	251
	4	TDN% = 76.4605 + 1.0995 (EE%)	.7077	9.76	173
	5	TDN% = 69.7135 + 1.2746 (EE%)	.4081	10.08	130
Horses	1	TDN% = 26.4729 + 8.4551 (EE%)	.3570	7.90	36
	4	TDN% = 83.8520 - 2.4447 (EE%)	.1357	12.29	12
Rabbits	1	TDN% = 40.3828 + 2.0168 (EE%)	.0771	10.49	28
	4	TDN% = 92.8724 - 2.8604 (EE%)	.1938	8.99	14
	5	TDN% = 68.2649 + 1.9379 (EE%)	.7329	13.66	6
Sheep	1	TDN% = 52.7071 + 1.0413 (EE%)	.0401	9.07	514
	2	TDN% = 60.8814 - .6223 (EE%)	.0156	12.74	286
	3	TDN% = 57.7079 + .9049 (EE%)	.0074	8.87	94
	4	TDN% = 79.0604 - .2590 (EE%)	.0041	12.77	120
	5	TDN% = 74.3145 + .7930 (EE%)	.2092	11.50	101
Swine	1	TDN% = 41.5084 + 2.0070 (EE%)	.0500	22.17	17
	2	TDN% = 52.7616 + 2.0019 (EE%)	.0719	7.80	28
	4	TDN% = 76.8297 + 1.2169 (EE%)	.7957	11.91	85
	5	TDN% = 75.7205 + .9238 (EE%)	.2090	10.43	58
in vitro	2	TDN% = 48.7562 + .2225 (EE%)	.8787	1.91	30
	3	TDN% = 45.4236 + 4.3771 (EE%)	.2812	3.56	91

Hence, it is suggested that nutritive lipids should be analyzed for and reported separately from non-nutritive lipids (Harris, 1970).

The variation in predictability of TDN from EE within classes of feedstuffs suggested that kind of animals had an effect on this predictability. However, it could be also suggested that there was lack of agreement among workers that contributed to the data. Moreover, these fluctuations could be due to the nature of the mixture and species of feedstuffs studied (Barnes, 1973).

Table 49 shows the results of regressing TDN with ether extract contents of subdivisions of different classes of feedstuffs for various kinds of animals.

TDN had a low correlation with EE contents of subdivisions of dry forages and roughages by cattle and sheep. Dry mixtures of legumes and grasses, however, had a negative correlation (R^2 = .42) by cattle.

Legume hays had higher correlations between TDN and their EE contents than the undivided dry forages and roughages for horses (R^2 = .56), rabbits (R^2 = .49) and swine (R^2 = .76). Correlation was high in grass hays for rabbits (R^2 = .60).

Subdivisions of silages had low correlations between TDN and their EE contents by cattle and sheep. However, ensiled mixtures of legumes and grasses had a high correlation (R^2 = .53) by cattle.

Energy feeds of plant origin had lower correlation between TDN and their contents of EE than undivided energy feeds for cattle (R^2 = .39) and swine (R^2 = .74). While energy feeds of animal origin had higher correlations (R^2 = .97) by cattle.

TABLE 49 Simple Regression Equations to Predict Total Digestible Nutrients (TDN%) from Ether Extract Contents (EE%) of Subclasses of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Cattle	1	Legumes	TDN% = 56.1917 + .7485 (EE%)	.0255	87.20	173
	1	Grasses	TDN% = 42.3090 + 4.6214 (EE%)	.1684	71.90	149
	1	Legumeous roughages	TDN% = 45.0728 + 7.2223 (EE%)	.0881	78.96	14
	1	Non-legumeous roughages	TDN% = 48.4778 + 1.2042 (EE%)	.0565	72.96	55
	1	Mixture (legumes + grasses)	TDN% = 61.7847 + 2.4414 (EE%)	.4212	59.40	16
	2	Legumes	TDN% = 49.7095 + 4.3418 (EE%)	.6211	73.70	14
	2	Grasses	TDN% = 49.4228 + 1.6230 (EE%)	.1537	77.00	161
	2	Legumeous roughages	TDN% = 45.9066 + .4460 (EE%)	.0008	74.00	10
	2	Non-legumeous roughages	TDN% = 50.3491 + 2.3010 (EE%)	.0454	79.80	10
	2	Mixtures (legumes + grasses)	TDN% = -27.8663 + 26.0102 (EE%)	.7987	0.00	3
	3	Legumes	TDN% = 50.7361 + 2.1030 (EE%)	.3832	72.90	63
	3	Grasses	TDN% = 60.3004 + .7346 (EE%)	.0148	82.90	126
	3	Non-legumeous roughages	TDN% = 55.9023 - 2.2054 (EE%)	.1652	57.50	12
	3	Mixtures (legumes + grasses)	TDN% = 46.2346 + 3.4440 (EE%)	.5284	76.00	51
	4	Plant origin	TDN% = 76.9097 + 1.0073 (EE%)	.3858	96.80	168
	4	Animal origin	TDN% = 74.3176 + 1.1575 (EE%)	.9726	0.00	9
	5	Animal origin	TDN% = 64.9527 + .5664 (EE%)	.3777	0.00	11
	5	Marine origin	TDN% = 60.7991 + 1.5305 (EE%)	.3366	0.00	10
	5	Milk origin	TDN% = 80.7738 + 1.5339 (EE%)	.9612	90.30	10
	5	Plant origin	TDN% = 73.0580 + .7734 (EE%)	.1804	95.06	100

TABLE 49 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Horses	1	Legumes	TDN% = 38.2589 + 6.1296 (EE%)	.5636	56.70	9
	1	Grasses	TDN% = 37.4168 + 3.8351 (EE%)	.1136	63.20	17
	4	Plant origin	TDN% = 83.8520 - 2.4447 (EE%)	.1357	99.58	13
Rabbits	1	Legumes	TDN% = 35.9395 + 6.2642 (EE%)	.4864	75.40	16
	1	Grasses	TDN% = 24.5191 + 3.8564 (EE%)	.6040	52.02	6
	1	Legumeous roughages	TDN% = 23.2224 + 4.0280 (EE%)	.6408	39.20	4
	1	Non-legumeous roughages	TDN% = 13.6571 + 12.5546 (EE%)	.5402	86.30	25
	4	Plant origin	TDN% = 92.8724 - 2.8605 (EE%)	.1938	98.33	14
	5	Plant origin	TDN% = 66.2454 + 2.2073 (EE%)	.4644	95.64	7
Sheep	1	Legumes	TDN% = 52.5894 + 1.7594 (EE%)	.1011	70.50	150
	1	Grasses	TDN% = 47.0837 + 3.7962 (EE%)	.2370	77.60	221
	1	Legumeous roughages	TDN% = 54.5607 + .4348 (EE%)	.0024	86.30	25
	1	Non-legumeous roughages	TDN% = 48.6408 + .4943 (EE%)	.0186	78.00	116
	2	Legumes	TDN% = 67.2435 - 1.6210 (EE%)	.5068	76.23	79
	2	Grasses	TDN% = 55.4537 + 1.5788 (EE%)	.0265	80.30	125
	2	Legumeous roughages	TDN% = 37.6188 + 20.5612 (EE%)	.9262	81.79	4
	2	Non-legumeous roughages	TDN% = 51.7942 + .5632 (EE%)	.0095	91.70	80
	3	Legumes	TDN% = 55.1822 + .9474 (EE%)	.0003	69.50	28
	3	Grasses	TDN% = 59.5856 + 1.3525 (EE%)	.0121	75.00	39
	3	Non-legumeous roughages	TDN% = 56.9051 - .7552 (EE%)	.0081	86.33	24
	4	Plant origin	TDN% = 79.0604 - .2590 (EE%)	.0041	99.30	121

TABLE 49 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Sheep	5	Marine origin	TDN% = 68.1353 + .5277 (EE%)	.0281	0.00	15
	5	Plant origin	TDN% = 75.0366 + .8023 (EE%)	.2361	99.90	86
Swine	1	Legumes	TDN% = 29.5041 + 5.2493 (EE%)	.7595	0.00	4
	1	Legumeous roughages	TDN% = 74.0767 + .3205 (EE%)	.0026	91.16	3
	1	Non-legumeous roughages	TDN% = 32.4304 + 2.9966 (EE%)	.1700	83.00	8
	2	Legumes	TDN% = 53.5925 + 1.7683 (EE%)	.4456	62.64	7
	2	Grasses	TDN% = 39.7223 + 7.6214 (EE%)	.6322	68.73	12
	2	Non-legumeous roughages	TDN% = 75.8988 - 6.4410 (EE%)	.5854	74.44	7
	4	Plant origin	TDN% = 76.9096 + 1.1795 (EE%)	.7443	110.00	89
	5	Animal origin	TDN% = 61.9892 + .7934 (EE%)	.1967	87.20	8
	5	Marine origin	TDN% = 79.1568 - -.0082 (EE%)	.0000	104.40	10
	5	Milk origin	TDN% = 87.2977 + .9723 (EE%)	.5784	110.40	10
	5	Plant origin	TDN% = 78.6620 - .6125 (EE%)	.1246	100.90	31

Predictability of TDN from EE concentration in protein supplements of marine origin was lower than that of undivided protein supplements (Table 48) for cattle ($R^2 = .34$), sheep ($R^2 = .03$) and swine ($R^2 = .00$). However, higher correlations were obtained from protein supplements of milk origin by cattle ($R^2 = .96$) and swine ($R^2 = .58$).

Protein supplements of plant origin had lower correlations between TDN and their EE contents than undivided protein supplements for cattle, rabbits and swine ($R^2 = .18$, .46 and .12, respectively). This relationship was slightly higher for sheep ($R^2 = .24$).

TDN From Crude Protein. Results of predicting TDN from crude protein contents of different classes of feedstuffs for various kinds of animals are presented in Table 50. Crude protein was not a good predictant of TDN in most cases. However, dry forages and roughages had high correlation ($R^2 = .56$) for rabbits (Appendix Figure 64). CP concentration in green forages and pasture plants was also a good predictant of TDN ($R^2 = .88$) for in vitro studies.

Silages had low negative correlations between TDN and their CP contents by cattle and sheep. This correlation was low but positive for in vitro studies (Table 50).

Low negative correlations were obtained from regressing TDN with EE contents of energy feeds and protein supplements for various kinds of animals except by sheep which had a low but positive correlation.

Table 51 shows the results of predicting TDN from CP contents of subdivided classes of feedstuffs for various kinds of animals.

TDN predictability from CP did not improve upon subdividing classes of feedstuffs into more related feeds. There were few cases

TABLE 50 Simple Regression Equations to Predict Total Digestible Nutrients (TDN%) from Crude Protein Contents (CP%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation	R^2	SE	N
Cattle	1	TDN% = 47.2737 + .6615 (CP%)	.2012	7.58	431
	2	TDN% = 43.4815 + 1.0607 (CP%)	.2432	8.76	213
	3	TDN% = 61.3886 - .0532 (CP%)	.0010	7.41	284
	4	TDN% = 82.8744 - .1533 (CP%)	.0052	9.41	191
	5	TDN% = 84.3363 - .0796 (CP%)	.0064	10.59	126
Horses	1	TDN% = 34.3634 + 1.1138 (CP%)	.3825	7.67	32
	4	TDN% = 89.6809 - 1.1909 (CP%)	.1758	11.25	12
	5	TDN% = 80.4225 - .0728 (CP%)	.0002		
Rabbits	1	TDN% = 22.9636 + 1.3074 (CP%)	.5625	7.34	26
	4	TDN% = 97.9768 - 1.0344 (CP%)	.1689	9.14	14
	5	TDN% = 107.6627 - .4456 (CP%)	.0324	7.89	6
Sheep	1	TDN% = 47.1748 + .6622 (CP%)	.1708	8.64	536
	2	TDN% = 50.4548 + .6577 (CP%)	.0960	11.76	299
	3	TDN% = 62.6533 - .1252 (CP%)	.0022	9.08	94
	4	TDN% = 81.0968 - .2697 (CP%)	.0096	12.77	122
	5	TDN% = 85.0961 - .1074 (CP%)	.0159	11.50	101
Swine	1	TDN% = 29.3163 + 1.3519 (CP%)	.2588	19.58	17
	2	TDN% = 52.3900 + .4659 (CP%)	.1269	7.56	28
	4	TDN% = 87.9718 - .3022 (CP%)	.0107	12.97	91
	5	TDN% = 91.1507 - .1954 (CP%)	.0838	10.21	58
in vitro	1	TDN% = 49.0817 + .4488 (CP%)	.0635	2.35	82
	2	TDN% = 51.6564 + 2.4140 (CP%)	.8830	1.86	31
	3	TDN% = 53.7990 + 1.2639 (CP%)	.3752	3.32	92

where predictability of TDN from CP was higher than that reported in Table 49 for the undivided classes. Correlation of TDN with CP contents of legume hays for rabbits ($R^2 = .77$), protein supplements of marine origin for sheep ($R^2 = .60$) and swine ($R^2 = .53$).

In vitro studies had a high ($R^2 = .88$) correlation between TDN and CP contents of green grasses.

These results were in agreement with those of Sullivan (1964) who predicted TDN from CP contents of 101 grass hay samples ($R^2 = .44$) and 54 samples of alfalfa hay samples ($R^2 = .31$). However, Meyer and Lofgreen (1956) reported high correlation ($R^2 = .59$) between CP content of alfalfa hay (31 samples and 152 digestibility trials) and TDN.

It was expected that CP was not a good predictant of TDN values of feedstuffs. Digestible crude protein was included in the calculations of TDN because protein served as a source of heat and energy when more is provided than required to meet protein needs of the body. However, not all determined proteins were true proteins but could come from nonprotein nitrogen sources.

The potential energy in protein (measured by their complete combustion in a bombcalorimeter) was considerably greater than that in carbohydrates. This is true because with protein, oxygen is required to oxidize the carbon and some of the hydrogen atoms (which is not the case in carbohydrate oxidation). The heat of water formation is much higher in protein oxidation than in that of carbohydrates. Thus, typical pure protein yields 5.25 to 5.75 kilocalories of gross energy per gram (Lloyd et al. 1978).

TABLE 51 Simple Regression Equations to Predict Total Digestible Nutrients (TDN%) from Crude Protein (CP%) of Subclasses of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Cattle	1	Legumes	TDN% = 47.9101 + .5653 (CP%)	.1491	17.31	182
	1	Grasses	TDN% = 43.9073 + 1.1156 (CP%)	.2032	78.26	162
	1	Legumeous roughages	TDN% = 25.8942 + 2.8522 (CP%)	.3035	258.70	15
	1	Non-legumeous roughages	TDN% = 46.4038 + .8083 (CP%)	.0820	65.54	55
	1	Mixtures (legumes + grasses)	TDN% = 55.2303 + .1031 (CP%)	.0176	9.20	17
	2	Legumes	TDN% = 43.3524 + 1.0709 (CP%)	.3493	39.42	17
	2	Grasses	TDN% = 42.5101 + 1.1615 (CP%)	.2614	77.01	174
	2	Legumeous roughages	TDN% = 38.4031 + .8848 (CP%)	.1736	154.61	10
	2	Non-legumeous roughages	TDN% = 58.1582 - .1572 (CP%)	.0107	369.00	10
	3	Legumes	TDN% = 44.3719 + .8337 (CP%)	.2339	20.54	68
	3	Grasses	TDN% = 63.3617 - .1018 (CP%)	.0010	79.32	153
	3	Non-legumeous roughages	TDN% = 52.7394 - .3988 (CP%)	.0125	55.09	12
	3	Mixtures (legumes + grasses)	TDN% = 51.5992 + .6104 (CP%)	.0580	51.47	52
	4	Plant origin	TDN% = 82.6616 - .1265 (CP%)	.0035	89.50	183
	4	Animal origin	TDN% = 68.2114 + .5579 (CP%)	.0047	81.92	8
	5	Animal origin	TDN% = 76.0278 - .1059 (CP%)	.1829	13.69	10
	5	Marine origin	TDN% = 37.3171 + .5690 (CP%)	.1829	40.46	10
	5	Plant origin	TDN% = 68.8506 + .2860 (CP%)	.0736	179.40	98
Horses	1	Legumes	TDN% = 54.8736 - .1573 (CP%)	.0080	14.26	9
	1	Grasses	TDN% = 44.3671 + .2688 (CP%)	.0307	27.28	15
	1	Non-legumeous roughages	TDN% = 8.9006 + 6.8683 (CP%)	.2951	125.50	8

TABLE 51 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Rabbits	1	Legumes	TDN% = 19.2568 + 1.6968 (CP%)	.7749	21.96	15
	1	Grasses	TDN% = 29.0887 + .7308 (CP%)	.5368	54.52	6
	1	Legumeous roughages	TDN% = 22.3055 + .8405 (CP%)	.4251	12.87	4
Sheep	1	Legumes	TDN% = 46.2041 + .6183 (CP%)	.2372	18.41	159
	1	Grasses	TDN% = 46.4600 + .9391 (CP%)	.2872	62.33	234
	1	Legumeous roughages	TDN% = 43.7464 + 1.3256 (CP%)	.1205	169.30	25
	1	Non-legumeous roughages	TDN% = 47.1605 + .3335 (CP%)	.0222	128.80	116
	2	Legumes	TDN% = 51.5589 + .5081 (CP%)	.0618	64.75	93
	2	Grasses	TDN% = 51.0783 + .9929 (CP%)	.1011	149.70	125
	2	Legumeous roughages	TDN% = 68.0053 + .4083 (CP%)	.0465	73.91	4
	2	Non-legumeous roughages	TDN% = 34.7991 + 1.5531 (CP%)	.2579	185.00	79
	3	Legumes	TDN% = 49.9539 + .4968 (CP%)	.0720	32.75	28
	3	Grasses	TDN% = 63.6740 + .0651 (CP%)	.0003	128.60	39
	3	Non-legumeous roughages	TDN% = 56.8963 + .2289 (CP%)	.0031	167.40	24
	4	Plant origin	TDN% = 81.0968 - .2697 (CP%)	.0096	212.50	123
	5	Marine origin	TDN% = 11.8790 + .8809 (CP%)	.3674	31.53	14
	5	Milk origin	TDN% = 87.0283 + .0959 (CP%)	.3674	16.93	4
	5	Plant origin	TDN% = 78.4717 + .1158 (CP%)	.0047	538.10	87
Swine	1	Non-legumeous roughages	TDN% = 24.7611 + 1.9146 (CP%)	.1306	576.30	8
	2	Legumes	TDN% = 59.9607 - .0404 (CP%)	.0029	8.95	7
	2	Grasses	TDN% = 45.5744 + 1.1299 (CP%)	.3571	41.15	12

TABLE 51 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Swine	2	Non-legumeous roughages	TDN% = 55.3667 + .3565 (CP%)	.0552	114.30	7
	4	Plant origin	TDN% = 87.9619 - .3032 (CP%)	.0108	383.40	93
	5	Animal origin	TDN% = 63.6170 + .0517 (CP%)	.0102	98.59	8
	5	Marine origin	TDN% = 24.3148 + .7765 (CP%)	.5262	80.99	10
	5	Plant origin	TDN% = 75.5544 + .1649 (CP%)	.0597	51.94	31
In vitro	1	Mixtures (legumes + grasses)	TDN% = 49.0817 + .4488 (CP%)	.0635	5.54	82
	2	Grasses	TDN% = 51.6564 - 2.4140 (CP%)	.8830	3.47	31
	3	Grasses	TDN% = 53.7990 + 1.2639 (CP%)	.3752	11.01	92

Nevertheless, the amount of nutritionally useful energy of protein was not greatly different from that of carbohydrates. This was so because amino group that was split off in the deaminization of each amino acid forms urea, which was eliminated in urine. Urea contains combustible carbon and hydrogen and this part of the potential energy from protein is lost from the body. In humans, it amounted to about 1.5 kilocalories per gram of protein. Hence, the maximum usable energy from typical protein does not exceed 5.50 ± 1.25 kilocalories per gram. This amount was more reduced by the incomplete digestion to about 4 kilocalories per gram (Lloyd et al. 1978).

Carbohydrates usually yield to the body about 95 percent of its potential energy as compared only to about 70 percent in the case of protein. Therefore, protein was usually not the preferred source of energy in nutrition (Lloyd et al. 1978).

TDN From Nitrogen Free Extract. As expected, NFE was not a good predictant of TDN values. Table 52 shows the results of regressing TDN with NFE contents of different classes of feedstuffs for various kinds of animals. All correlation values were low except that of green forages and pasture plants for in vitro studies (R^2 = .62) and energy feeds for rabbits (R^2 = .53). Moreover, NFE had negative relationship with TDN in dry forages and roughages by cattle, horses and rabbits and by cattle in green forages and pasture plants.

TDN showed a negative correlation with NFE content of energy feeds for swine, while negative correlation existed in protein supplements by cattle and rabbits.

TABLE 52 Simple Regression Equations to Predict Total Digestible Nutrients (TDN%) from Nitrogen Free Extract Contents (NFE%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation	R^2	SE	N
Cattle	1	TDN% = 63.6572 - .1623 (NFE%)	.0201	7.04	300
	2	TDN% = 72.5979 - .3773 (NFE%)	.0552	10.36	185
	3	TDN% = 47.7941 + .2929 (NFE%)	.1122	7.09	218
	4	TDN% = 59.1645 + .2943 (NFE%)	.0933	11.31	55
	5	TDN% = 100.3740 - .3949 (NFE%)	.0535	12.68	28
Horses	1	TDN% = 76.2283 - .6483 (NFE%)	.1739	9.20	37
	4	TDN% = 14.9152 + .8249 (NFE%)	.3984	7.31	12
	5	TDN% = 35.0380 + .8374 (NFE%)	.1674	15.82	5
Rabbits	1	TDN% = 71.3809 - .6113 (NFE%)	.1017	9.89	27
	4	TDN% = 33.1642 + .7113 (NFE%)	.5348	6.60	15
	5	TDN% = 117.1816 - .8090 (NFE%)	.0574	12.65	6
Sheep	1	TDN% = 53.2130 + .0445 (NFE%)	.0011	9.22	505
	2	TDN% = 55.2286 + .1368 (NFE%)	.0109	9.11	229
	3	TDN% = 36.4313 + .5546 (NFE%)	.2996	7.62	93
	4	TDN% = 35.0107 + .6213 (NFE%)	.3563	10.29	122
	5	TDN% = 80.6600 + .0498 (NFE%)	.0032	11.08	88
Swine	1	TDN% = 29.9188 + .4983 (NFE%)	.0413	22.88	12
	2	TDN% = 51.6878 + .1304 (NFE%)	.0175	8.02	28
	4	TDN% = 109.3016 - .3284 (NFE%)	.1368	11.90	74
	5	TDN% = 79.2383 + .1577 (NFE%)	.0534	10.13	35
in vitro	2	TDN% = - 2.2911 + 1.0972 (NFE%)	.6175	3.36	32
	3	TDN% = 30.7473 + .5660 (NFE%)	.3393	3.41	92

TDN predictability from NFE did not improve upon subdividing classes of feedstuffs (Table 53). However, there were cases where correlation increased. Green legumeous roughages had high correlation (R^2 = .65) between TDN and their NFE content by cattle. Correlations for ensiled non-legumeous roughages by cattle and sheep (R^2 = .78 and .63, respectively) were also high.

Fresh legumes had a high negative (R^2 = .57) correlation between TDN and their NFE contents by swine. Negative correlations were also observed in many of the subdivisions for various kinds of animals (Table 53).

In vitro studies had a high correlation (R^2 = .62) between TDN and NFE for fresh grasses.

Nitrogen free extract was calculated by difference. That was the subtraction of crude fiber, crude protein, ether extract and ash percentages from one hundred on dry matter basis. Hence, an error in determining the other nutrients would be pooled in NFE value.

Besides data being collected from many sources, variations in the relationship between NFE and TDN could be due to the nature of NFE. It was found that NFE was less digestible than crude fiber in many cases (Crampton and Maynard 1938; Morrison, 1956) and sometimes NFE was a negative value because of the way it was calculated.

Lignin was partially soluble in alkali and cellulose was partially soluble in acid (Cuthbertson, 1969). Hence, soluble portions of lignin and cellulose would be calculated in the NFE content of feeds and not in their crude fiber content. This effect would be more pronounced as plants advance in maturity (Cook and Harris, 1968a). Thus, NFE would

TABLE 53 Simple Regression Equations to Predict Total Digestible Nutrients (TDN%) from Nitrogen Free Extract Contents (NFE%) of Subclasses of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Cattle	1	Legumes	TDN% = 47.5066 + .2471 (NFE%)	.0359	18.55	135
	1	Grasses	TDN% = 87.8131 + .6557 (NFE%)	.1009	55.82	113
	1	Legumeous roughages	TDN% = 58.9908 + .0279 (NFE%)	.0002	178.50	12
	1	Non-legumeous roughages	TDN% = 49.5336 + .0508 (NFE%)	.0033	103.80	28
	1	Mixtures (legumes + grasses)	TDN% = 43.9356 + .2948 (NFE%)	.0470	6.31	12
	2	Legumes	TDN% = 63.0594 - .0278 (NFE%)	.0002	61.60	11
	2	Grasses	TDN% = 81.8449 - .5990 (NFE%)	.1466	95.82	153
	2	Legumeous roughages	TDN% = -17.4807 + 1.6848 (NFE%)	.6464	66.16	10
	2	Non-legumeous roughages	TDN% = 8.5215 + .9892 (NFE%)	.3369	193.70	10
	3	Legumes	TDN% = 51.7254 + .1923 (NFE%)	.0195	30.09	52
	3	Grasses	TDN% = 38.2078 + .4821 (NFE%)	.2842	30.06	113
	3	Non-legumeous roughages	TDN% = -2.7914 + 1.2155 (NFE%)	.7830	11.66	10
	3	Mixtures (legumes + grasses)	TDN% = 82.0419 - .5001 (NFE%)	.1712	46.61	43
	4	Plant origin	TDN% = 59.1645 + .2943 (NFE%)	.0933	127.90	55
	5	Milk origin	TDN% = 152.8751 - .9257 (NFE%)	.4608	477.80	6
	5	Plant origin	TDN% = 81.5324 + .0229 (NFE%)	.0005	147.20	26
Horses	1	Legumes	TDN% = 33.3395 + .4627 (NFE%)	.1531	12.17	9
	1	Grasses	TDN% = 58.5792 - .2300 (NFE%)	.0438	39.29	17
	1	Non-legumeous roughages	TDN% = 56.5303 - .4419 (NFE%)	.1069	158.90	8
	4	Plant origin	TDN% = 14.9152 + .8249 (NFE%)	.3984	186.60	13

TABLE 53 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Horses	5	Plant origin	TDN% = 35.0380 + .8374 (NFE%)	.1674	250.30	5
Rabbits	1	Legumes	TDN% = 21.9140 + .6632 (NFE%)	.0591	80.29	15
	1	Grasses	TDN% = 63.8166 - .5134 (NFE%)	.1611	81.66	7
	1	Non-legumeous roughages	TDN% = -14.8646 + .9981 (NFE%)	.6701	7.38	4
	4	Plant origin	TDN% = 33.1642 + .7113 (NFE%)	.5348	43.63	15
	5	Plant origin	TDN% = 135.9467 - 1.5383 (NFE%)	.3949	1154.70	7
Sheep	1	Legumes	TDN% = 53.5862 + .0816 (NFE%	.0075	24.52	150
	1	Grasses	TDN% = 65.5047 - .1872 (NFE%)	.0129	73.49	212
	1	Legumeous roughages	TDN% = 48.7298 + .1477 (NFE%)	.0123	190.10	25
	1	Non-legumeous roughages	TDN% = 35.5953 + .3163 (NFE%)	.0488	125.30	116
	2	Legumes	TDN% = 63.9355 - .0781 (NFE%)	.0022	85.37	73
	2	Grasses	TDN% = 51.8236 + .1855 (NFE%)	.0172	72.82	109
	2	Non-legumeous roughages	TDN% = 50.0915 + .2655 (NFE%)	.0328	175.00	45
	3	Legumes	TDN% = 41.8006 + .4507 (NFE%)	.1650	29.46	28
	3	Grasses	TDN% = 51.7522 + .2324 (NFE%)	.0714	58.51	37
	3	Non-legumeous roughages	TDN% = 12.7155 - 1.0639 (NFE%)	.6315	61.86	24
	4	Plant origin	TDN% = 35.0107 + .6213 (NFE%)	.3563	173.80	123
	5	Plant origin	TDN% = 81.5324 + .0229 (NFE%)	.0005	468.70	86
Swine	1	Non-legumeous roughages	TDN% = 29.5559 + .4015 (NFE%)	.0223	505.00	7
	2	Legumes	TDN% = 86.8120 - .6650 (NFE%)	.1169	3.88	7

TABLE 53 (Continued)

Animal Kind	Feed Class	Feed Subclass	Equation	R^2	SE	N
Swine	2	Grasses	TDN% = 17.1383 + .8505 (NFE%)	.1169	56.52	12
	2	Non-legumeous roughages	TDN% = 89.2969 + .5248 (NFE%)	.1405	104.00	7
	4	Plant origin	TDN% = 109.3016 - .3284 (NFE%)	.1368	303.70	77
	5	Animal origin	TDN% = 75.7226 - 1.7411 (NFE%)	.0870	123.30	5
	5	Milk origin	TDN% = 141.4413 - .8605 (NFE%)	.2775	452.90	8
	5	Plant origin	TDN% = 85.0931 - .0601 (NFE%)	.0088	68.92	21
in vitro	2	Grasses	TDN% = -2.2911 - 1.0972 (NFE%)	.6175	11.28	32
	3	Grasses	TDN% = 30.7473 + .5660 (NFE%)	.3393	11.64	92

vary much in value and would appear less digestible than crude fiber in many feedstuffs.

Predicting TDN From Proximate Analysis. The numerical value of total digestible nutrients of feedstuffs was a function of the digestibility of the nutrient components of the proximate analysis of these feeds. A multiple regression model was developed to predict TDN from the crude fiber, ether extract, nitrogen free extract and crude protein contents of different classes of feedstuffs for various kinds of animals (Table 54).

In general, predictability of TDN from proximate analysis of feedstuffs was higher than that from each of the proximate nutrients alone.

TDN was highly correlated with the proximate analysis of protein supplements ($R^2 = .60$ to $.99$) and energy feeds ($R^2 = .51$ to $.72$) for various kinds of animals except that of cattle in both classes of feeds ($R^2 = .31$ and $.18$, respectively). TDN of silages was also highly correlated with proximate analysis by sheep ($R^2 = .56$ and in vitro studies ($R^2 = .78$), but the correlation was less by cattle ($R^2 = .46$).

TDN was also closely predictable from the proximate analysis of dry forages and roughages for horses ($R^2 = .58$), rabbits ($R^2 = .66$) and swine ($R^2 = .65$). However, the correlations by cattle and sheep were low ($R^2 = .27$ and $.26$, respectively).

In vitro studies showed high correlation between TDN and proximate analysis of green forages and pasture plants ($R^2 = .99$) followed by cattle ($R^2 = .48$) than sheep ($R^2 = .26$).

Stallcup et al. (1976) predicted TDN from crude fiber and crude protein contents of sorghum-sudan forages, sorghum and corn silages fed

TABLE 54 Multiple Regression Equations to Predict Total Digestible Nutrients (TDN%) from Proximate Analysis of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	TDN% = -17.2649 + 1.2120(CP%) + .8352(NFE%) + 2.4637(EE%) + .4475(CF%)	.2666	6.18	231
	2	TDN% = -21.7656 + 1.4284(CP%) + 1.0277(NFE%) + .4867(CF%) + 1.2321(EE%)	.4846	6.55	142
	3	TDN% = -21.9391 + .4590(CF%) + 3.0016(EE%) + .9736(NFE%) + 1.0538(CP%)	.4638	5.52	178
	4	TDN% = 40.2625 - .1379(CF%) + 1.1903(EE%) + .4228(NFE%) + .1969(CP%)	.1794	13.41	29
	5	TDN% = 40.3227 - .7007(CF%) + 1.4218(EE%) + .4448(NFE%) + .5398(CP%)	.3086	12.30	18
Horses	1	TDN% = 75.2547 + .2881(CP%) + 6.4262(EE%) - .6399(CF%) - .5582(NFE%)	.5809	6.52	32
	4	TDN% = -377.5763 + 4.6775(NFE%) + 6.2671(CP%) + 3.4433(CF%) + 2.2294(EE%)	.6073	9.93	13
	5	TDN% = 141.7459 - 7.1150(EE%) - .5464(NFE%) - .5445(CP%)	.9528	6.52	6
Rabbits	1	TDN% = 82.9403 + .4865(CP%) - .7720(CF%) - 1.4971(EE%) - .4589(NFE%)	.6601	8.20	18
	4	TDN% = 45.9509 + .5799(NFE%) - 3.0546(EE%) + .5228(CP%) - .2851(CF%)	.7160	6.49	13
	5	TDN% = 44.7854 - 1.8044(CF%) + 1.8273(EE%) + .605(CP%) + .3556(NFE%)	.9996	.51	8
Sheep	1	TDN% = -14.8356 + 1.3310(CP%) + .7923(NFE%) + .5133(CF%) + .9787(EE%)	.2649	7.90	452
	2	TDN% = 1.6899 + 1.3844(CP%) + .7526(NFE%) - .8279(EE%) + .3673(CF%)	.2623	8.78	218
	3	TDN% = 1.0340 + .9150(NFE%) + .9702(CP%) + 1.3513(EE%) + .0798(CF%)	.5566	6.25	85
	4	TDN% = 2.6407 - .1043(CF%) + .9194(NFE%) + 1.2159(EE%) + .6964(CP%)	.5074	8.83	115
	5	TDN% = -37.3039 + .3618(CF%) + 2.1302(EE%) + 1.3630(NFE%) + 1.3048(CP%)	.6036	9.67	80
Swine	1	TDN% = -83.6226 + 2.6329(CP%) + 5.5166(EE%) + 1.5715(NFE%) + .3089(CF%)	.6475	20.77	10
	4	TDN% = 128.7149 + 1.0303(EE%) - .3148(NFE%) - 1.5125(CF%) - 1.4292(CP%)	.6863	8.68	41
	5	TDN% = -256.2451 + 2.1029(CF%) + 4.5654(EE%) + 3.6518(NFE%) + 3.6976(CP%)	.9458	3.36	13

TABLE 54 (Continued)

Animal Kind	Feed Class	Equation	R^2	SE	N
in vitro	2	$TDN\% = -112.8198 + 2.8853(EE\%) + 2.3409(CP\%) + 1.7986(NFE\%) + 1.9004(CF\%)$	.9878	.64	30
	3	$TDN\% = -41.7373 + 1.8600(CP\%) + 3.4831(EE\%) + .9790(NFE\%) + .9498(CF\%)$	.7793	2.01	92

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[a] In equation, CF, EE, NFE, and CP were percentages of crude fiber, ether extract, nitrogen free extract and crude protein, respectively.

to steers. TDN was highly ($R^2 = .90$) predictable from crude fiber and crude protein contents of sorghum-sudan forages but not of corn ($R^2 = .47$) or sorghum ($R^2 = .33$) silages. When data of all feeds were pooled, correlation between TDN and crude fiber and crude protein dropped ($R^2 = .16$).

TDN predicatbility from proximate analysis was lower for cattle than for other kinds of animals, compared in this study among the different classes of feedstuffs. In vitro studies, rabbits, swine and horses showed high predictability for TDN from proximate analysis. Data for sheep had high predictability for protein supplements, silages, and energy feeds but low predictability for dry forages and roughages and green forages and pasture plants (Table 54).

Multiple regression equations developed to predict TDN from proximate analysis (Table 54) also showed that certain nutrients contributed more TDN predictability. These same nutrients were not good predictants of TDN when they were used alone in simple regression equations.

Crude protein was found to contribute the highest for TDN predictability than other independent variables in equations of dry and green feeds for various kinds of animals. However, CP was the least contributing variable in cases of energy feeds and protein supplements by cattle, sheep and swine and silages for cattle.

Crude fiber behaved almost the opposite of CP. CF was contributed least than other independent variables in predicting TDN values of dry forages and roughages for cattle and swine and green forages and pastures and silages for sheep. However, it contributed best in cases of energy feeds for cattle and sheep, protein supplements by cattle, rabbits, sheep and swine and silages by cattle.

Ether extract contributed better than other nutrients in predicting TDN values of protein supplements for horses, energy feeds for swine and green forages and pasture plants for in vitro studies, while nitrogen free extract was best in cases of energy feeds by horses and rabbits and silages by sheep.

There were many associative effects that might affect TDN value of feedstuffs. The level of one component of the proximate analysis could exert a great effect on the digestibility of the others and hence, the value of TDN would fluctuate.

Harris et al. (1972) developed mathematical model to predict TDN% from proximate analysis showing the interactions among four components of the proximate analysis (namely, crude fiber, ether extract, nitrogen-free extract and crude protein) of five classes of feedstuffs for various kinds of animals (Table 55). This model (Harris et al. 1972) was modified and used for the new data. Results (Table 55) showed improved predictability of TDN from proximate nutrients and their interaction over that shown in Table 54.

The variability in the correlation coefficients in class 1 for the different kinds of animals could be related to:

a. large number of data involved in case of cattle and sheep. Hence, the many sources of data would add to variability. On the other hand, less data were used in case of horses, rabbits and swine. Hence, limited number of source of data might give better results.

b. animals such as cattle and sheep could had been fed various roughages and forages that could greatly vary in chemical composition.

TABLE 55 Regression Equations to Predict Total Digestible Nutrients (TDN%) from Proximate Analysis and their Interactions in Five Classes of Feedstuffs for Various Kinds of Animals and In Vitro Studies

Kind Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	$TDN = -43.9321 - 3.5995(CP\%) - .1817(CF\%) + 52.2729(EE\%) + 1.6715(NFE\%) - .6388(CFEE\%) + .0583(NFE \cdot CP\%) + .0634(CP^2\%) + .0176(CF^2\%) - .4550(EE \cdot NFE\%) - .6979(EE \cdot CP\%) - .1852(EE^2) - .0076(EE \cdot NFE\%) + .6300(CF \cdot CP\%)$	.3061	6.07	294
	2	$TDN = 263.1763 + 3.3836(CP\%) - 16.7781(EE\%) - 8.4772(NFE\%) - 5.4756(CF\%) - .1188(CP^2\%) + .0684(NFE^2\%) + .3334(EE \cdot CP\%) + .3299(EE \cdot NFE\%) + .0859(CF \cdot NFE\%) + .0162(CF \cdot CP\%) + .0149(NFE \cdot CP\%)$	.4943	7.83	186
	3	$TDN = 115.8144 + .0925(CF\%) + 37.0241(EE\%) - 3.9951(NFE\%) - 16.0341(CP\%) + .0388(NFE^2\%) - .0363(CF^2\%) + .1846(NFE \cdot CP\%) + .2029(CF \cdot CP\%) - .4531(CF \cdot EE\%) - .2903(EE^2\%) - .3639(EE \cdot NFE\%) + .1460(CP^2\%) - .0211(CF \cdot NFE\%)$	.5826	4.86	205
	4	$TDN = 318.0640 - 4.3952(CF\%) - 17.9332(EE\%) - 2.4859(NFE\%) + .0872(CF^2\%) + .0120(CF \cdot CP\%) + .0954(EE\%) + .4699(EE \cdot CP\%) + .2004(CF \cdot EE\%) - 13.4243(CP\%) + .1544(EE \cdot NFE\%) + .1175(CP^2\%) + .1221(NFE \cdot CP\%)$	.3230	11.64	47
	5	$TDN = 320.0851 - .2610(EE \cdot NFE\%) - 1.975(CF\%) - 13.2412(CP\%) + 15.1398(EE\%) - .2758(EE^2\%) + .1157(CP^2\%) + .1235(NFE \cdot CP\%) + .0277(CF \cdot EE\%) - .0474(CF^2) - 2.4193(NFE\%) + .0158(CF \cdot NFE\%)$	.7996	7.69	27
Horses	1	$TDN = -10.9736 + 53.5961(EE\%) - 2.1873(NFE\%) + .1372(CF \cdot NFE\%) - 4.0890(CF\%) - 5.5422(EE^2\%) - .3610(EE \cdot NFE\%) + .0103 NFE \cdot CP\%) + 7.0904(CP\%) - .6895(EE \cdot CP\%) - .0700(CP^2\%) - .0627(CF \cdot CP\%)$	.7840	5.56	33
	4	$TDN = -1602.0550 + 62.3350(CF\%) - 31.3721(EE\%) + 29.7356(CP\%) + 17.6142(NFE\%) + .0859(CF \cdot EE\%) + 5.6659(EE^2\%) - .5813(CF \cdot NFE\%) - .4418(CF^2\%) - .5259(CP^2\%)$	.9522	6.57	13

TABLE 55 (Continued)

Animal Kind	Feed Class	Equation	R^2	SE	N
Rabbits	1	TDN = -102.8963 - 6.7781(CF%) + 10.448(NFE%) - .1321(NFE^2%) - .2042 (CF·EE%) + .3952(CP%) + .8215(EE^2%) + .0662(CF^2%) + .0539(CF·NFE%) - 6.4583(EE%) + .0389(CF·CP%)	.7617	6.97	25
	4	TDN = 153.9993 + 3.2822(CF%) + 22.1575(EE%) - .1854(EE·NFE%) - 2.3957 (CP%) - .2661(CF·CP%) - .7698(NFE%) + .0232(NFE·CP%) - .0578 (CF^2%) - 1.0317(EE^2%) - .5705(CF·EE%).	.9635	4.66	14
Sheep	1	TDN = -15.0300 + .6022(CP%) - 1.0176(CF%) + .0198(CF^2%) - 1.2309 (EE%) - .0170(NFE^2%) - .0665(EE^2%) - .0052(CF·EE%) + 2.2291(NFE%) + .1227(EE·CP%) + .0167(CF·CP%) + .0380(EE·NFE%) - .0059(CP^2%)	.2996	7.83	499
	2	TDN = 119.6182 + 5.5596(CP%) - 1.9423(EE%) + 7.7037(CF%) - .0645(CF·NFE%) - .0534(CF^2%) - .0794(CP^2%) - .1305(CF·CP%) + .2033(EE·CP%) + 1.0157(NFE%) + .0119(NFE^2%) + .0096(NFE·CP%) + .0341(EE^2%)	.3706	7.41	230
	3	TDN = 02.5691 + .7719(NFE%) + .8916(CP%) - .7376(CF%) + 8.3607(EE%) + .0204(CF^2%) - .0323(CP^2%) + .2418(EE·CP%) - .3449(EE^2) + .0236 (NFE·CP%) - .0037(CF·NFE%) - .0733(EE·NFE%) - .0274(CF·EE%) - .0033(NFE^2%)	.6015	6.15	94
	4	TDN = 0316.0256 - .3111(CF%) + 3.4869(NFE%) - .0807(CF·EE%) + 9.5770 (CP%) + 0.266(EE^2%) + .1218(EE·CP%) - .0740(CF·CP%) - .1466 (CP^2%) - .0693(NFE·CP%) - .0130(NFE^2%) - .0429(EE·NFE%) + .0245 (CF^2%) + 2.3885(EE%) + .0127(CF·NFE%)	.6233	8.32	121
	5	TDN = 252.7714 - 4.1815(CF%) - 10.2581(CP%) - 1.8358(NFE%) + .0863 (CP^2%) + 5.1145(EE%) + .095(NFE·CP%) - .0755(EE·NFE%) + .0185(CF·	.6071	7.78	79

TABLE 55 (Continued)

Animal Kind	Feed Class	Equation	R^2	SE	N
Sheep	5 (cont.)	$\mathrm{EE}\%) + .0505(\mathrm{CF.NFE}\%) + .1443(\mathrm{CF}\cdot\mathrm{CP}\%) - .1124(\mathrm{EE}^2\%) + .0445 (\mathrm{EE}\cdot\mathrm{CP}\%) + .0307(\mathrm{CF}^2\%)$			
Swine	1	$\mathrm{TDN} = .0424 + 4.7207(\mathrm{CP}\%) + .1555(\mathrm{CF}^2\%) - .0646(\mathrm{NFE}^2\%) + .4392(\mathrm{CF}\cdot\mathrm{EE}\%) - 10.4687(\mathrm{CF}\%) + 7.1102(\mathrm{NFE}\%) - 9.5318(\mathrm{EE}\%) - .1023(\mathrm{NFE}\cdot\mathrm{CP}) + .0321(\mathrm{CP}^2\%) - .1609(\mathrm{EE}^2\%)$	.9996	1.37	13
	2	$\mathrm{TDN} = 201.5302 + 1.1791(\mathrm{CF}\cdot\mathrm{EE}\%) - 8.5106(\mathrm{CP}\%) - 1.0688(\mathrm{CF}\%) - 67.2139 (\mathrm{EE}\%) + 4.1225(\mathrm{EE}^2\%) - .0224(\mathrm{CF}^2\%) + .1146(\mathrm{NFE}\cdot\mathrm{CP}\%) + .3823(\mathrm{EE}\cdot\mathrm{NFE}\%) + .1456(\mathrm{CP}^2\% + .0340(\mathrm{CF}\cdot\mathrm{CP}\%) - 1.9604(\mathrm{NFE}\%) + .0096 (\mathrm{NFE}^2\%) - - .1521(\mathrm{EE}\cdot\mathrm{CP}\%)$	.7611	5,39	29
	4	$\mathrm{TDN} = 0129.214 + .5865(\mathrm{EE}\%) + .5222(\mathrm{CF}\%) + .1260(\mathrm{CF}^2\%) + 1,1725(\mathrm{NFE}\%) - .2231 (\mathrm{NFE}\cdot\mathrm{CP}\%) - .3747(\mathrm{CF}\cdot\mathrm{CP}\%) - .3445(\mathrm{CP}^2\%) - .0332(\mathrm{EE}^2\%) - .0597 (\mathrm{CF}\cdot\mathrm{EE}\%) + 26.3066(\mathrm{CP}\%)$	.6739	7.41	65
	5	$\mathrm{TDN} = 0293.3780 - 26.2819(\mathrm{CF}\%) + 13.2892(\mathrm{NFE}\%) + 37.3087(\mathrm{EE}\%) + 3.7791 (\mathrm{CP}\%) - .0988 (\mathrm{NFE}^2\%) - .3106(\mathrm{EE}\cdot\mathrm{CP}\%) + .3090(\mathrm{CF}\cdot\mathrm{CP}\%) - .3694(\mathrm{EE}^2\%) + .2154(\mathrm{CF}\cdot\mathrm{NFE}\%) - .0692(\mathrm{CF}\cdot\mathrm{EE}\%) + .3244(\mathrm{CF}^2\%) - .4557(\mathrm{EE}\cdot\mathrm{NFE}\%) - .0921(\mathrm{NFE}\cdot\mathrm{CP}\%)$	.8617	5.56	27
In vitro	2	$\mathrm{TDN} = -118.9516 + 1.8868(\mathrm{CF}\%) + 2.4639(\mathrm{EE}\%) + 2.6049(\mathrm{CP}\%) + 1.8917(\mathrm{NFE}\%) + .0281(\mathrm{CF}\cdot\mathrm{CP}\%) + .1221(\mathrm{EE}^2\%) - .1004(\mathrm{CP}^2\%)$	.9929	.54	30
	3	$\mathrm{TDN} = 205.0618 - 8.5977(\mathrm{CP}\%) + 7,3467(\mathrm{CF}\%) - .0539(\mathrm{CF}^2\%) + 18.7139(\mathrm{EE}\%) - .0673(\mathrm{CF}\cdot\mathrm{NFE}\%) + 3,4836(\mathrm{NFE}\%) - .2538(\mathrm{EE}\cdot\mathrm{NFE}\%) + .6825(\mathrm{EE}\cdot\mathrm{CP}\%) - .8150(\mathrm{EE}^2\%) + .0867(\mathrm{NFE{:}CP}\%) + .0749(\mathrm{CP}^2\%) + .0951(\mathrm{CF}\cdot\mathrm{CP}\%)$	.8698	1.62	92

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[a] In equation, CF, EE, NFE and CP are the percentages of crude fiber, ether extract, nitrogen free extract and crude protein, respectively.

while horses, rabbits, and swine could have been fed more refined forages.

Better correlations were found in classes 2 and 3 (green feeds and silages) than in class 1. However, these correlations were still lower for cattle and sheep than those of swine and in vitro studies. The same discussion could be followed in this case, too.

TDN values had high correlations with proximate analysis of class 4 (energy feeds) for all animals except cattle.

Besides variations among workers and feeds used in their research, higher levels of carbohydrates (molasses, sugar, corn) could alter the digestibility of other components of feeds suchas crude fiber and nitrogen (Cook and Harris, 1968b; Ewing, 1915; Slyter et al. 1971). However, sheep should have followed the same trend. It could be possible that significant differences existed between data from cattle and sheep digestion trials. However, the direction and magnitude of these differences may be functions of the feed and of the nutrients involved (Cipolloni et al. 1951). Moreover, Cipolloni et al. (1951) found that individual nutrient species-by-feed interaction. This interaction means that cattle digest a certain nutrient significantly better than sheep with certain feeds and the reverse is true with other feeds (Cipolloni et al. 1951; Keating et al. 1965; Barnes, 1977).

<u>TDN From Proximate Analysis and Qualitative Factors.</u> Table 56 shows the coefficients of the proximate nutrients (CF, EE, NFE, and CP) and the qualitative factors involved in this study (Animal kind, subclasses of feedstuffs, stage of maturity and parts eaten). Correlation

TABLE 56 Regression Coefficients of Proximate Nutrients and Regression Adjustments of Qualitative Factors to Predict Total Digestible Nutrients (TDN%)

Factor	Regression Coefficients and Adjustments
Proximate Nutrients:	Regression Coefficients
Regression Constant	57.9877
Regression Coefficient of	
Crude fiber	-.2803
Ether extract	+.6400
Nitrogen free extract	+.0511
Crude protein	+.2324
Animal Kind	Regression Adjustments
Cattle	+2.2755
Horses	-3.7272
Rabbits	-3.3601
Sheep	+1.7576
Swine	+2.2009
In vitro studies	+.7898
Classes of Feedstuffs:	
Dry forages and roughages	
Legumes	+6.9449
Grasses	+6.2908
Legumeous roughages	+10.9268
Non-legumeous roughages	+5.5511
Mixture (legumes + grasses)	+2.5859
Green Forages and Pasture Plants:	
Legumes	+7.6866
Grasses	+8.1098
Legumeous roughages	+7.0297
Non-legumeous roughages	+10.2948
Mixture (legumes + grasses)	+5.4451
Silages:	
Legumes	+6.9527
Grasses	+11.8330
Legumeous roughages	+3.0057
Non-legumeous roughages	+5.4200
Mixture (legumes + grasses)	+9.1871

TABLE 56 (Continued)

Factor	Regression Coefficients and Adjustments
Energy Feeds:	
Plant origin	+23.1111
Animal origin	+13.5176
Protein Supplements:	
Animal origin	+5.3303
Avian origin	-7.0512
Marine origin	+11.4391
Milk origin	-171.4902
Plant origin	-16.8792
Stage of maturity:	
Unknown	+.4909
Early and late vegetative and regrowth-early vegetative	+3.6824
Early bloom and mid-bloom	+1.2136
Full and late bloom	+.2308
Milk and dough stages	+1.5960
Mature	+.0183
Post-ripe and stem cured	-6.2321
Parts:	
Aerial parts	-9.1517
Bran	-12.1556
Browse	-24.3061
Carcasses (carcass meat trim, carcass residues, meat and bones...)	-18.7441
Casein and milk by-products	178.1841
Chaff	-26.6555
Cobs	-17.1238
Cones	-10.6312
Fats (grease, lard, tallow)	7.5418
Fodder	-8.5077
Fruits	-9.2794
Grains	-5.8022
Hatchery by-products	-15.1397
Hulls	-12.0141
Leaves	-11.6540
Meat (plant nuts)	-12.2050
Mill residues, mill by-products, baker by-products	-5.0804

TABLE 56 (Continued)

Factor	Regression Coefficients and Adjustments
Carbohydrate supplements (molasses, starch, sugars..)	-6.6851
Nuts	-35.1210
Nuts with shells	0
Oils	-6.0256
Pods	-6.7400
Pulp	-4.7130
Roots and tubers	-25.8973
Screenings and mixed screenings	-9.3190
Seeds	-16.5581
Shells	-14.8261
Stems and twigs	-11.6219
Stillage	-10.4520
Stover	-9.9234
Straw	-17.7732
Viscera	0
Whole plants and mixed parts	-189.3800

between TDN values and proximate analysis plus qualitative factors was high ($R^2 = .64$) for such kind of data.

TDN values were calculated as follows:

$$TDN\% = .2324\ (CP\%) + .0511\ (NFE\%) + .6400\ (EE\%) - .2803\ (CF\%) + (57.9877 \pm \text{coefficient(s) of qualitative factor(s)}).$$

Hence, the equation for predicting TDN is modified according to the covariance of the animal kind, forage type, stage of maturity and parts consumed.

Christiansen (1979) and Fonnesbeck et al. (1981b) used chemical analysis and feed descriptive factors to predict DE for sheep. The addition of indicator variables to regression equations increased R^2 from .099 to .81 for crude protein and .56 to .80 for crude fiber.

The technique of using quantitative and qualitative factors was suggested to be used for feed evaluation since it permits a physical description to be translated into numerical values (Fonnesbeck et al. 1981b). The international feed vocabulary of feedstuffs that was suggested by Harris (1976) on an international feed description basis could be satisfactorily used for this purpose.

Predicting Digestible Energy (DE)

Estimation of DE was compared with five different equation models as follows:

1. DE was calculated as the summation of digestible proximate nutrients (percent digested).
2. From digestible proximate nutrients by the use of multiple regression equations.
3. From each proximate nutrient by simple regression equations.

4. From proximate analysis by multiple regression equations.
5. From the values of TDN by simple regression equations.

Digestible Energy From Digestible Nutrients. Predicted values of the digestible nutrients (%) (Tables 29 to 45) were used to calculate DE (kilocalories per kilogram of dry matter) of each class of feedstuffs for various kinds of animals as follows:

$$DE = \frac{5.72\ (DCP) + 9.5\ (DEE) + 4.79\ (DCF) + 4.03\ (DNFE)}{100}$$

where 5.72 , 9.5, 4.79, and 4.03 are the conventional caloric values (kilocalories per gram or megacalories per kilogram) of protein, ether extract, crude fiber and nitrogen free extract, respectively.

This method can provide an estimate of DE when a calorimeter is not available in the laboratory to estimate gross energy (GE) of feed and feces as follows:

$$GE = \frac{5.72\ (CP) + 9.50\ (EE) + 4.79\ (CF) + 4.03\ (NFE)}{100}$$

Then,

$$DE = \frac{GE \times GE\ \text{Digestibility Coefficient}}{100}$$

Lofgreen (1951) calculated DE from the following equation:

$$DE\ (\%) = \frac{\text{Energy in DCP + Energy in DCF + Energy in DNFE +}}{\text{Energy in CP + Energy in CF + Energy in NFE +}}$$

$$\frac{\text{Energy in DEE}}{\text{Energy in EE}} \times 100$$

The value of DE resulted from this equation was multipled by the percentage of organic matter of a certain feed (since DE was found to be affected only by organic matter content of the feed). That was to express DE on the same basis of TDN.

Recently, Christiansen (1979) developed the following equation to estimate DE from estimated digestible protein (YCP), available carbohydrates (YAC), total lipids (YTL), cellulose (YCL) and hemicellulose (YHC):

$$DE = 4(YCP + YAC + YCL + YHC) + 9(YTL)$$

DE values estimated by this equation were found to be nearly the same as values estimated directly by regression equations from nutrient contents of feedstuffs for sheep (Christiansen, 1979; Fonnesbeck et al. 1981a).

Digestible Energy From Digestible Proximate Nutrients. Multiple regression equations were developed to estimate DE from the digestible nutrients (DCP, DCF, DEE, and DNFE) of different classes of feedstuffs for various kinds of animals (Table 57). These equations showed that DE was highly predictable from digestible proximate nutrients (R^2 = .79 to .99).

DNFE was observed to contribute more for DE estimation than other digestible nutrients in cases of dry forages and roughages by cattle, green forages and pasture plants by cattle and energy feeds by cattle and rabbits. While DCP contributed more to the estimation of DE in cases of dry forages and roughages for horses and rabbits and silages for sheep.

DEE contributed more for DE prediction than other digestible nutrients in cases of silages by cattle and dry forages and roughages and green forages and pasture plants by sheep. DCF was observed to be the second best predictant for DE with dry forages and roughages by

TABLE 57 Multiple Regression Equations to Predict Digestible Energy (DE) from Digestible Proximate Nutrients of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	DE = .4519 + .0384(DNFE) + 0271(DCF) + .0504(DCP) + .0746(DEE)	.7863	.09	52
	2	DE = -.5164 + .0576(DNFE) + .0422(DCF) + .1386(DEE) + .0287(DCP)	.9571	.07	14
	3	DE = .1430 + .0137(DEE) + .0677(DCP) + .0505(DCF) + .0365(DNFE)	.8389	.12	52
	4	DE = -.1422 + .0384(DNFE) + .1658(DCP) + .0508(DCF)	.9897	.07	6
Horses	1	DE = .2030 + .0800(DCP) + .2681(DEE) + .0245(DNFE) + .0206(DCF)	.7918	.32	7
Rabbits	1	DE = .3421 + .0487(DCP) + .0381(DNFE) + .0202(DCF) + .0277(DEE)	.9670	.09	13
	4	DE = .1012 + .0395(DNFE) + .0425(DCF) + .0456(DCP) + .1479(DEE)	.9446	.11	12
Sheep	1	DE = .4304 + .0745(DEE) - .0339(DNFE) + .0360(DCF) + .0555(DCP)	.9303	.09	79
	2	DE = .6893 + .0603(DEE) - .0737(DCP) + .0905(DCF) + .0175(DNFE)	.8650	.11	14
	3	DE = -1.0032 + .0947(DCP) + .0434(DNFE) + .0635(DCF) + .1484(DEE)	.8714	.08	13

[a] In equation, DE = Megacalories per kilogram of dry matter. DCF, DEE, DNFE and DCP are the percentages of digestible crude fiber, ether extract, nitrogen free extract and crude protein, respectively.

cattle, green forages and pasture plants for cattle and energy feeds for rabbits (Table 57).

Digestible Energy From Each Proximate Nutrient

Digestible Energy From Crude Fiber. DE was regressed with CF contents of different classes of feedstuffs for various kinds of animals (Table 58). CF was not a good predictant of DE (R^2 = .003 to .45) except in cases of protein supplements (Appendix Figure 65) and dry forages and roughages for rabbits (R^2 = .80 and .51, respectively).

Correlations between DE and CF were negative except in cases of energy feeds for cattle, silages for sheep and protein supplements for swine.

Stallcup et al. (1976) found similar results with steers fed forages and silages. Low negative correlations existed between DE and CF contents of sorghum-sudan forages (R^2 = .50), sorghum silages (R^2 = .25) and corn silages (R^2 = .001). When data for all forages pooled together, correlation between DE and CF did not improve (R^2 = .18).

Crude fiber influences the digestibility of all nutrients because undigested CF hinders the action of digestive enzymes on the other nutrients especially in plant parts such as stems, seeds and seed coats, and also for cells with fibrous membranes (Schneider, 1947). CF was considered a poor predictant of DE for sheep (Christiansen, 1979; Fonnesbeck et al. 1981a).

However, Drennan and Maguire (1970) and Morgan (1976) reported DE to be highly negatively correlated with CF and ADF contents of swine feeds. Henry (1976) also found apparent digestible energy to be highly estimated from CF contents of swine diets.

TABLE 58 Simple Regression Equations to Predict Digestible Energy (DE) from Crude Fiber (CF%) Contents of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	DE = 3.0150 - .0135 (CF%)	.0540	.20	118
	2	DE = 3.8673 - .0309 (CF%)	.1547	.26	15
	3	DE = 2.7243 - .0039 (CF%)	.0039	.29	129
	4	DE = -.3070 + 1.7308 (CF%)	.2490	.33	12
Horses	1	DE = 2.9830 - .0285 (CF%)	.2395	.21	43
Rabbits	1	DE = 3.2326 - .0401 (CF%)	.5104	.34	19
	4	DE = 4.0580 - .0394 (CF%)	.4532	.31	14
	5	DE = 5.1232 - .1201 (CF%)	.7969	.32	7
Sheep	1	DE = 4.2334 - .0512 (CF%)	.4525	.30	253
	2	DE = 2.8651 - .0092 (CF%)	.0160	.26	14
	3	DE = 2.7132 + .0021 (CF%)	.0031	.19	15
Swine	4	DE = 4.0113 - .0656 (CF%)	.4345	.34	41
	5	DE = 3.3700 + .0142 (CF%)	.0157	.58	48

[a] In equation, DE = Megacalories per kilogram of dry matter.

Cell wall content was found to be a good single predictant of DE for various kinds of animals (Fonnesbeck et al. 1975).

Digestible Energy From Ether Extract. DE did not have a close relationship (Table 59) with EE contents of different classes of feedstuffs for various kinds of animals (R^2 = .001 to .28) except in case of protein supplements (R^2 = .63) for rabbits.

Stallcup et al. (1976) reported high correlations between DE and EE contents of 14 silage samples (R^2 = .79). However, the number of samples was small. EE was not a major component of silages and may not be a reliable predictant of DE for wilages (Stallcup et al. 1976).

Fat content of a diet could increase or decrease the digestibility of all nutrients in a diet, depending on its fat content. Swift (1947) found that the apparent digestibility of all nutrients in sheep rations increased upon increasing the level of fat 6.4 percent. However, this digestibility decreased when ether extract level increased up to 9.7 percent.

EE concentration in feedstuffs used in this study ranged from less than one percent to as much as 28 percent. Hence, predictability of DE could be greated affected by such variations in EE contents.

Digestible Energy From Crude Protein. Table 60 presents the results of predicting DE from CP contents of different classes of feedstuffs for various kinds of animals. All correlations were low (R^2 = .005 to .40) except that of dry forages and roughages for rabbits (R^2 = .58). Rabbits reported to have higher efficiency of protein utilization than other animals (Cheeke, 1980). Low negative correlations between DE and CP contents of energy feeds and protein supplements

TABLE 59 Simple Regression Equations to Predict Digestible Energy (DE) from Ether Extract Contents (EE%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	DE = 2.5046 + .0317 (EE%)	.0134	.20	118
	2	DE = 2.9147 - .0241 (EE%)	.0130	.28	15
	3	DE = 2.2977 + .0878 (EE%)	.2139	.25	126
	4	DE = 2.9044 + .1407 (EE%)	.0054	.40	13
Horses	1	DE = 1.7837 + .0705 (EE%)	.0321	.24	43
Rabbits	1	DE = 1.5477 + .1531 (EE%)	.1006	.48	17
	4	DE = 3.8729 - .0564 (EE%)	.0436	.41	14
	5	DE = 3.4486 + .0678 (EE%)	.6288	.50	8
Sheep	1	DE = 2.2176 + .1454 (EE%)	.2830	.34	246
	2	DE = 1.8598 + .0503 (EE%)	.1136	.50	64
	3	DE = 2.8163 - .0100 (EE%)	.0012	.19	15
Swine	4	DE = 3.5557 + .0182 (EE%)	.0206	.45	43
	5	DE = 3.4712 + .0092 (EE%)	.0054	.64	53

[a] In equation, DE = Megacalories per kilogram of dry matter.

TABLE 60 Simple Regression Equations to Predict Digestible Energy (DE) from Crude Protein Contents (CP%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	DE = 2.4153 + .0121 (CP%)	.0900	.19	119
	2	DE = 2.2242 + .0571 (CP%)	.2250	.25	15
	3	DE = 2.3157 + .0301 (CP%)	.1804	.26	137
	4	DE = 2.6950 + .0846 (CP%)	.0046	.38	14
Horses	1	DE = 1.4381 + .0501 (CP%)	.3988	.19	43
Rabbits	1	DE = 1.0597 + .0556 (CP%)	.5811	.32	15
	4	DE = 3.9515 - .0199 (CP%)	.0387	.39	14
	5	DE = 4.4632 - .0065 (CP%)	.0049	.82	8
Sheep	1	DE = 2.1387 + .0395 (CP%)	.3291	.33	267
	2	DE = 1.7894 + .0363 (CP%)	.0717	.51	63
	3	DE + 2.6199 + .0094 (CP%)	.0347	.18	15
Swine	4	DE = 4.4591 - .0061 (CP%)	.1631	.42	42
	5	DE = 3.8681 - .0064 (CP%)	.0392	.60	49

[a] In equation, DE = Megacalories per kilogram of dry matter.

for rabbits and swine were observed (Table 59) silages fed to steers were found to have negative correlations (R^2 = .58) between DE and their CP contents (Stallcup et al. 1976).

Cook and Child (1977) reported low correlations between DE and total protein contents of spring-summer (mixed grass and short grass) ranges for cattle (Table 15). However, DCP showed higher correlation with DE in both types of ranges (R^2 = .55 and .44, respectively). Christiansen (1979) and Fonnesbeck et al. (1981b) found that CP was not a good predictant of DE when used as the single independent variable.

Digestible Energy From Nitrogen Free Extract. DE was poorly correlated with NFE contents of different classes of feedstuffs for various kinds of animals (Table 61). However, energy feeds had a relatively high negative correlation (R^2 = .52) by cattle. All correlations between DE and NFE were negative except those of energy feeds and protein supplements for swine.

By a new system of feed analysis Fonnesbeck et al. (1975) determined the soluble carbohydrates (readily available carbohydrates) and found that DE was highly predictable from soluble carbohydrate contents of feeds by sheep, swine and rats (Table 14). When data were pooled, predictability of DE did not drop. It was also found that NFE was less digestible than crude fiber in many cases (Crampton and Maynard, 1938; Morrison, 1956) and sometimes NFE was a negative value due to the way it is calculated.

TABLE 61 Simple Regression Equations to Predict Digestible Energy (DE) from Nitrogen Free Extract Contents (NFE%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	DE = 2.8107 - .2422 (NFE%)	.0173	.20	116
	2	DE = 3.0501 - .0054 (NFE%)	.0061	.28	15
	3	DE = 3.0054 - .0077 (NFE%)	.0506	.28	137
	4	DE = 105.0335 - 1.2422 (NFE%)	.5200	.28	13
Horses	1	DE = 2.1965 - .0050 (NFE%)	.0082	.24	43
Rabbits	1	DE = 3.3461 - .0348 (NFE%)	.1755	.39	16
	4	DE = 1.7545 - .0266 (NFE%)	.4397	.30	15
	5	DE = 5.3408 - .0336 (NFE%)	.0690	.79	8
Sheep	1	DE = 3.3900 - .0150 (NFE%)	.0312	.40	229
	2	DE = 3.0424 - .0107 (NFE%)	.0703	.25	14
	3	DE = 3.1621 - .0094 (NFE%)	.0704	.18	15
Swine	4	DE = 2.4690 + .0162 (NFE%)	.1752	.41	24
	5	DE = 3.2947 + .0120 (NFE%)	.0972	.62	27

[a] In equation, DE = Megacalories per kilogram of dry matter.

Digestible Energy From Proximate Analysis. Multiple regression equations were developed to predict DE from the proximate chemical components (CP, CF, EE and NFE) of different classes of feedstuffs for various kinds of animals (Table 62). Correlations between DE and proximate analysis were fairly high (R^2 = .49 to .79) except in cases of dry forages and roughages by cattle (R^2 = .09) and sheep (R^2 = .13) and silages for cattle (R^2 = .30).

CP was observed to be the primary independent variable in predicting DE of dry forages and roughages for cattle, horses and rabbits, green forages and pasture plants for cattle and protein supplements for swine. While NFE was the primary independent variable in cases of green forages and pasture plants for sheep, silages for sheep and energy foods for cattle.

CF was the primary independent variable when predicting DE of dry forages and roughages for sheep and energy feeds for rabbits and swine. While EE was the primary independent variable in case of silages for cattle.

Stallcup et al. (1976) developed multiple regression equations to predict DE from proximate analysis for steers. DE was highly correlated (R^2 = .95) with CF and CP contents of sorghum-sudan forages. However, the correlation dropped (R^2 = .46 and .25) in cases of corn and sorghum silages, respectively. When data on all forages were pooled, the relationships between DE and CF and CP contents dropped further (R^2 = .01).

TABLE 62 Multiple Regression Equations to Predict Digestible Energy (DE) from Proximate Analysis of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	$DE = 2.0789 + .0152(CP) + .0053(NFE) + .0235(EE)$	.0951	.19	115
	2	$DE = 22.2196 - .2012(CP) - .1722(CF) - .2272(NFE) - .3604$	.5205	.22	15
	3	$DE = -.2875 + .0707(EE) + .0279(CF) + .0262(NFE) + .0522(CP)$	.2991	.24	124
	4	$DE = -498.9298 + 5.7631(NFE) + 22.3768(CF) - 4.0007(EE)$	.7944	.20	11
Horses	1	$DE = -3.5789 + .1141(CP) + .0597(NFE) + .0422(CF) + .0839(EE)$	.4926	.18	43
Rabbits	1	$DE = 3.3752 + .0218(CP) - .0916(EE) - .0196(NFE) - .0246(CF)$	.6483	.30	13
	4	$DE = .0306 + .0021(CF) - .0949(EE) + .0415(NFE) + .0711(CP)$	.5788	.32	13
Sheep	1	$DE + -.0183 - .0033(CF) + .4011(NFE) + .0944(EE) + .0485(CP)$	.5180	.29	226
	2	$DE = 3.6155 - .0652(NFE) + .0276(CP) + .0638(CF) - .1289(EE)$	.6713	.17	14
	3	$DE = 6.4266 - .0424(NFE) - .0543(EE) - .0389(CP) - .0342(CF)$	.1309	.20	15
Swine	4	$DE = 2.6707 - .0794(CF) + .0701(EE) + .0173(NFE)$	.7474	.27	18
	5	$DE = 1.5744 + .0570(CP) +.1168(EE) + .0621(NFE)$	.5995	.36	23

[a] In equation, DE = Megacalories per kilogram of dry matter. CF, EE, NFE and CP are the percentages of crude fiber, ether extract, nitrogen free extract and crude protein, respectively.

However, Stallcup et al. (1976) estimated DE of silages from various chemical components and found that DE was predicted from CP and CF ($R^2 = .67$) and from EE and CP ($R^2 = .81$).

Morgan (1976) found that DE was highly related ($R^2 = .88$) to CP, acid ether extract and NFE contents of energy feeds for swine. Moreover, Fonnesbeck et al. (1975) also found high correlations between the chemical analysis of 11 diets (1 to 55 percent cell wall contents) fed to various kinds of animals (rabbits, rats, sheep and swine). However, chemical analysis used were those proposed by Fonnesbeck and Harris (1973). Christiansen (1979) used the same system of chemical analysis plus the proximate analysis and found that DE was highly related to chemical components of feeds for sheep.

Upon comparing Tables 57 and 62, it seemed that the use of digestible proximate nutrients (DCP, DCF, DEE and DNFE) of different classes of feedstuffs would give better prediction results of DE than proximate analysis for various kinds of animals.

Digestible Energy From TDN. DE was highly correlated ($R^2 = .53$ to $.97$) with TDN values of different feedstuffs for various kinds of animals (Table 63).

Predictability of DE from TDN values of dry forages and roughages was highest for rabbits ($R^2 = .94$) followed by sheep ($R^2 = .90$), cattle ($R^2 = .69$) as shown in Appendix Figures 66, 67 and 68, respectively, then horses ($R^2 = .62$). However, data for cattle had higher correlations ($R^2 = .94$ and $.74$, respectively) for green forages and pasture

TABLE 63 Simple Regression Equations to Predict Digestible Energy (DE) from Total Digestible Nutrients (TDN%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	DE = .6383 + .0337 (TDN%)	.6931	.12	79
	2	DE = -.1990 + .0448 (TDN%)	.9419	.07	14
	3	DE = .4322 + .0354 (TDN%)	.7441	.15	82
	4	DE = -.0728 + .0430 (TDN%)	.9555	.07	13
Horses	1	DE = -.9411 + .0601 (TDN%)	.6178	.28	7
Rabbits	1	DE = .0247 + .0445 (TDN%)	.9442	.12	19
	4	DE = .4550 + .0381 (TDN%)	.8529	.15	15
	5	DE = .8565 + .0373 (TDN%)	.9732	.13	8
Sheep	1	DE = -.0278 + .0452 (TDN%)	.8974	.13	119
	2	DE = .0196 + .0429 (TDN%)	.9019	.17	64
	3	DE = .9759 + .0284 (TDN%)	.5319	.14	17
Swine	4	DE = -.0060 + .0435 (TDN%)	.9216	.13	39
	5	DE = -.2664 + .0480 (TDN%)	.8989	.20	43

[a] In equation, DE = Megacalories per kilogram of dry matter.

plants and silages (Appendix Figures 69 and 70) than did sheep (R^2 = .90 and .53; Appendix Figures 71 and 72, respectively). DE of energy feeds showed high correlations (Appendix Figures 73, 74 and 75) with their TDN values by cattle (R^2 = .95), swine (R^2 = .92) and rabbits (R^2 = .85).

DE was also highly predicted from TDN values of protein supplements (R^2 = .97 and .90, respectively) by swine (Appendix Figure 76) and rabbits (Appendix Figure 77).

Close relationship between DE and TDN were also found by Harris and Asplund (1968) for sheep and Morgan (1976) for swine. Moreover, level of energy intake did not appear to affect the estimation of DE from TDN (Harris and Asplund, 1968). Appendix Figures 66 to 77 show that their regression coefficients (intercepts) were not equal to zero. Under such conditions, Harris and Asplund (1968) suggested that the use of a regression equation to predict the dependent variable (Y) was more accurate than the use of a conversion factor.

Predicting Metabolizable Energy (ME)

Metabolizable energy values of different classes of feedstuffs were predicted by five approaches. First, ME was estimated from digestible proximate nutrients by the use of multiple regression equations. The second method involved the use of simple regression to predict ME from each of the proximate nutrients. The third method was to predict ME from the proximate analysis by multiple regression equations. The fourth and fifth approaches involved the use of simple regression to estimate ME from TDN and DE values of feedstuffs.

Metabolizable Energy From Digestible Proximate Nutrients. ME was estimated from the digestible proximate nutrients of different classes of feedstuffs for only cattle and sheep (Table 64) because there were not enough data for the other kinds of animals. Predictability of ME from digestible proximate nutrients was high (R^2 = .73 to .99).

DNFE was the primary independent variable in predicting ME of silages and energy feeds by cattle and second variable in cases of silages for sheep. While DCP was the primary independent variable in estimating ME of dry forages and roughages for both cattle and sheep. DCF however, was the primary variable affecting predictability of ME of silages by sheep, and the second variable in cases of dry forages and roughages by cattle and sheep and energy feeds by cattle.

These results were in agreement with those of Nehring and Haenlein (1973) who reported high correlations (R^2 = .99) between ME and digestible nutrients. Van Es (1978) also predicted ME for cattle and sheep from digestible nutrients and from digestible dry matter and DCP by the use of multiple regression equation. Sugar content of dry matter of feeds was also introduced in such equations.

Metabolizable Energy From Each Proximate Nutrient

Metabolizable Energy From Crude Fiber. ME was poorly correlated with CF contents of the different classes of feedstuffs for various kinds of animals (Table 65). Correlations were negative between ME and CF contents of dry forages and roughages by cattle and sheep, silages by sheep and energy feeds by swine. Morgan (1976) found, however, that ME was closely related (R^2 = -.97 and -.95, respectively) to CF and ADF contents of energy feeds for swine.

TABLE 64 Multiple Regression Equations to Predict Metabolizable Energy (ME) from Digestible Proximate Nutrients of Different Classes of Feedstuffs for Cattle and Sheep

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	$ME = .2148 + .0377(DCP) + .0193(DCF) + .0369(DNFE) + .0304(DEE)$	.7284	.04	32
	3	$ME = -.3129 + .0405(DNFE) + .0561(DCP) + .0508(DCF)$	.9446	.05	7
	4	$ME = .1091 + .0392(DNFE) + .0691(DCF) + .0456(DCP)$	.9859	.07	6
Sheep	1	$ME = -.0189 + .0462(DCP) + .0370(DCF) + .0338(DNFE) + .0683(DEE)$	.9592	.05	30
	3	$ME = -.3801 + .0342(DCF) + .0348(DNFE) + .1671(DEE) + .5434(DCF)$	.8559	.06	9

[a] In equation, ME = Megacalories per kilogram of dry matter. DCF, DEE, DNFE and DCP are the percentages of digestible crude fiber, ehter extract, nitrogen free extract and crude protein, respectively.

TABLE 65 Simple Regression Equations to Predict Metabolizable Energy (ME) from Crude Fiber Contents (CF%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	$ME = 2.8511 - .0251\ (CF\%)$	.3833	.11	39
	3	$ME = 2.3647 + .0010\ (CF\%)$	.0003	.15	11
	4	$ME = -.2917 + 1.5075\ (CF\%)$	.2681	.27	12
Sheep	1	$ME = 3.4225 - .0353\ (CF\%)$	.4034	.17	49
	3	$ME = 2.5325 - .0109\ (CF\%)$	.2062	.11	9
Swine	4	$ME = 3.7678 - .0622\ (CF\%)$	.4787	.31	26
	5	$ME = 2.8142 - .0277\ (CF\%)$	.0393	.64	32

[a] In equation, ME = Megacalories per kilogram of dry matter of feedstuffs.

Metabolizable Energy From Ether Extract. Table 66 presents the results of regressing ME with EE contents of different classes of feedstuffs for various kinds of animals. Correlations between ME and EE were low (R^2 = .01 to .12) except in case of silages for cattle (R^2 = -.54). Negative correlations existed between ME and EE contents of silages by cattle and sheep, green forages and pasture plants by sheep, energy feeds and protein supplements by swine.

Metabolizable Energy From Crude Protein. ME had low correlations with CP contents of different classes of feedstuffs for various kinds of animals (Table 67). Correlations were negative between ME and CP contents of silages by cattle and sheep, green forages and pasture plants by sheep, energy feeds and protein supplements by swine.

Metabolizable Energy From Nitrogen Free Extract. ME was not related to NFE contents of the different classes of feedstuffs for

TABLE 66 Simple Regression Equations to Predict Metabolizable Energy (ME) from Ether Extract Contents (EE%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	ME = 1.9558 + .0379 (EE%)	.0112	.14	39
	3	ME = 2.6821 - .0537 (EE%)	.5417	.10	10
	4	ME = .6610 + .5082 (EE%)	.1125	.30	13
Sheep	1	ME = 1.9864 + .1122 (EE%)	.1794	.19	38
	2	ME = 1.5700 - .0162 (EE%)	.0088	.43	43
	3	ME = 2.3144 - .0291 (EE%)	.0130	.13	9
Swine	4	ME = 3.2124 + .0530 (EE%)	.1144	.40	29
	5	ME = 3.3338 - .0603 (EE%)	.1247	.62	34

[a] In equation, ME = Megacalories per kilogram of dry matter.

TABLE 67 Simple Regression Equations to Predict Metabolizable Energy (ME) from Crude Protein Contents (CP%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	ME = 1.8281 + .0143 (CP%)	.3348	.11	40
	3	ME = 2.5816 - .0125 (CP%)	.4186	.11	11
	4	ME = .7535 + .2226 (CP%)	.0507	.30	14
Sheep	1	ME = 2.0272 + .0231 (CP%)	.2448	.20	49
	2	ME = 1.6283 - .0176 (CP%)	.0212	.43	43
	3	ME = 2.3196 - .0083 (CP%)	.0418	.13	9
Swine	4	ME = 4.489 - .0812 (CP%)	.2892	.35	26
	5	ME = 3.168 - .0028 (CP%)	.0076	.63	30

[a] In equation, ME = Megacalories per kilogram of dry matter.

various kinds of animals (Table 68). ME had low negative correlations with NFE contents of dry forages and roughages by cattle and sheep, and energy feeds by cattle.

Metabolizable Energy From Proximate Analysis. Multiple regression equations were developed to predict ME values of different classes of feedstuffs from their proximate analysis for various kinds of animals (Table 69). Correlations between ME and proximate analysis were found to be high (R^2 = .52 to .96).

NFE was the primary independent variable in predicting ME of silages by sheep, energy feeds by cattle and protein supplements by swine. While NFE was the second variable in cases of dry forages and roughages and silages by cattle.

TABLE 68 Simple Regression Equations to Predict Metabolizable Energy (ME) from Nitrogen Free Extract Contents (NFE%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	ME = 2.1611 - .0035 (NFE%)	.0327	.11	37
	3	ME = 2.0398 + .0069 (NFE%)	.3726	.12	11
	4	ME = 50.3868 - .5802 (NFE%)	.1821	.29	13
Sheep	1	ME = 3.2922 - .0194 (NFE%)	.1150	.21	32
	3	ME = 1.6116 + .0134 (NFE%)	.3201	.11	9
Swine	4	ME = 3.0648 + .0057 (NFE%)	.0523	.25	8
	5	ME = 3.2486 + .0070 (NFE%)	.0239	.77	9

[a] In equation, ME = Megacalories per kilogram of dry matter.

CF was the primary independent variable in predicting ME of dry forages and roughages by cattle and energy feeds by swine. While CP was the primary independent variable in cases of dry forages and roughages by sheep, and second in cases of energy feeds and protein supplements by swine.

EE was observed to be the main independent variable in estimating ME of silages by cattle, and second in cases of dry forages and roughages and silages by sheep.

These results were in agreement with those of Morgan (1976) who reported high correlations (R^2 =.94) between ME and proximate analysis of mixed diets for swine. Vermorel (1978) also used the same approach to estimate ME of commercial concentrates for cattle in France. Moreover, Nehring and Haenlein (1973) developed multiple regression equations to predict ME from proximate analysis for various kinds of animals.

Metabolizable Energy From TDN. ME was highly correlated (R^2 = .71 to .950) with TDN values of different classes of feedstuffs for various kinds of animals (Table 70). However, ME had a poor relationship with TDN contents of dry forages and roughages by cattle (R^2 = .29). While ME was highly predictable (R^2 = .95) from TDN of the same class of feedstuffs by sheep and swine (Appendix Figure 78).

Green forages and pasture plants showed high correlations (R^2 = .71) between ME and their TDN values by sheep (Appendix Figure 79).

Data for cattle and sheep (Appendix Figure 86) had high correlations (R^2 = .78 and .90, respectively) between ME and TDN content of silages.

TABLE 69 Multiple Regression Equations to Predict Metabolizable Energy (ME) from Proximate Analysis of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	$ME = -.1532 + .0018(CF) + .0299(NFE) + .0462(CP) + .0958(EE)$	.7068	.08	36
	3	$ME = .1018 - .0986(EE) + .0236(NFE) + .0482(CP) + .0417(CF)$	.6891	.11	10
	4	$ME = -449.8459 + 5.1898(NFE) -3.1324(EE) + 19.3652(CF)$	.7656	.18	11
Sheep	1	$ME = -1.6625 + .0641(CP) + .0873(EE) + .0513(NFE) + .0175(CF)$	.5163	.17	30
	3	$ME = 7.9872 - .0529(NFE) + .0730(EE) - .0823(CF) - .0852(CP)$	.6898	.09	9
Swine	4	$ME = 5.8057 - .1396(CF) + .0398(CP) - .0281(NFE)$	.8392	.22	5
	5	$ME = -2.8003 + .0665(NFE) + .0812(CP) + .0887(EE) - .0207(CF)$	.9627	.22	8

[a] In equation, ME = Megacalories per kilogram of dry matter. CF, EE, NFE and CP are the percentages of crude fiber, ether extract, nitrogen free extract and crude protein, respectively.

TABLE 70 Simple Regression Equations to Predict Metabolizable Energy (ME) from Total Digestible Nutrients Values (TDN%) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	ME = .4912 + .0270 (TDN%)	.2870	.11	40
	3	ME = -.8350 + .0467 (TDN%)	.7790	.07	11
	4	ME = .1132 + .0347 (TDN%)	.8019	.14	13
Sheep	1	ME = -.0293 + .0367 (TDN%)	.9014	.07	34
	2	ME = -.1682 + .0375 (TDN%)	.7116	.23	43
	3	ME = -.1391 + .0374 (TDN%)	.9038	.07	13
Swine	1	ME = 8.0476 + 38.5059 (TDN%)	.9465	.12	5
	4	ME = -.2313 + .0430 (TDN%)	.9183	.13	25
	5	ME = -.5798 + .0456 (TDN%)	.7894	.25	28

[a] In equation, ME = Megacalories per kilogram of dry matter.

ME was also highly predictable from TDN contents of energy feeds (R^2 = .80 and .92, respectively) by cattle and swine (Appendix Figures 81 and 82). Protein supplements showed that ME was highly predicted (R^2 = .79) from their TDN values for swine (Appendix Figure 83).

These results were in agreement with the findings of Harris and Asplund (1968) for sheep and Morgan (1976) for swine. However, the low correlations between ME and TDN contents of dry forages and roughages could be due to the wide variations in the data. This variation could be due to combining observations of dairy and beef cattle, and also variations among contributors for the data.

Appendix Figures 78 to 83 show that the regression coefficients of the regression equation $Y = bo + b_1x_1$, was not zero. Hence, the use of the regression equation to predict the dependent variable (ME in this case) is more accurate than the use of a conversion factor (Harris and Asplund, 1968).

Metabolizable Energy From DE. ME was closely predictable (R^2 = .77 to .97) from DE values of different classes of feedstuffs for various kinds of animals (Table 71). However, correlation between ME and DE values of energy feeds was lower by cattle (R^2 = .66) than other correlations reported in Table 71.

High correlations existed between ME and DE values of dry forages and roughages by cattle (R^2 = .87; Appendix Figure 84), sheep (R^2 = .93; Appendix Figure 85) and swine (R^2 = .96). Silages had the same trend for cattle (R^2 = .92; Appendix Figure 86) and sheep (R^2 = .94; Appendix Figure 87).

TABLE 71 Simple Regression Equations to Predict Metabolizable Energy (ME) from Digestible Energy (DE) of Different Classes of Feedstuffs for Various Kinds of Animals

Animal Kind	Feed Class	Equation[a]	R^2	SE	N
Cattle	1	ME = -.5199 + .9990 (DE)	.8739	.05	40
	3	ME = -.3958 + .9607 (DE)	.9176	.04	11
	4	ME = .7066 + .6454 (DE)	.6605	.18	14
Sheep	1	ME = .0268 + .8041 (DE)	.9337	.06	52
	2	ME = -.1964 + .8846 (DE)	.7705	.21	43
	3	ME = -.5120 + 1.0188 (DE)	.9413	.06	13
Swine	1	ME = 35.9620 + .8605 (DE)	.9628	.08	8
	4	ME = -.1332 + .0010 (DE)	.9716	.18	54
	5	ME = -.1906 + .0009 (DE)	.9050	.20	45

[a] In equation, ME = Megacalories per kilogram of dry matter.

Only sheep had enough data to predict ME from DE contents of green forages and pasture plants (Appendix Figure 88). The correlation existed between the two energy measures was also high ($R^2 = .77$).

Energy feeds and protein supplements showed close relations ($R^2 = .97$ and $.90$, respectively) between ME and their DE values for swine (Appendix Figures 89 and 90). ME was also highly correlated ($R^2 = .66$) with DE contents of energy feeds for cattle.

These results were in agreement with the finding of Harris and Asplund (1968) for sheep and Morgan (1976) for swine. Harris and Asplund (1968) observed a slight effect on the estimation of ME from DE upon the increase of level of energy intake by sheep. Appendix Figures 84 to 90 indicated that bo in the equation $Y = bo + b_1x_1$, was not equal to zero in any case. Hence, the use of a regression equation to estimate ME from DE contents of feedstuffs could be more accurate than the use of a conversion factor such as that used by NRC publications. Harris and Asplund (1968) arrived to the same conclusion.

Predicting Nitrogen-Corrected Metabolizable Energy ME_n and Net Energy of Production NE_p for Poultry

Nitrogen-Corrected Metabolizable Energy and NE_p From Each Proximate Nutrient. Only crude protein contents of class 1 of feedstuffs was a good predictor of ME_n by poultry ($R^2 = .51$). Other chemical entities showed low correlations ($R^2 = .01$ to $.47$) with ME_n (Table 72). However, NE_p was highly correlated with EE contents of dry forages ($R^2 =.75$) and energy feeds ($R^2 = .58$), CP contents of dry forages

(R^2 = .59) and NFE contents of energy feeds (R^2 = .74) (Table 73). Other chemical entities were not good predictors of NE_p (R^2 = .03 yo .47).

Nitrogen-Corrected Metabolizable Energy and NE_p From Proximate Analysis. Both ME_n and NE_p were highly correlated with proximate analysis of the different classes of ffedstuffs (Tables 72 and 73). ME_n was highly correlated (R^2 = .99) with proximate analysis of dry forages. ME_n and NE_p were highly correlated (R^2 = .99 and .95, respectively for ME_n and NE_p).

NFE was found to contribute the highest for ME_n and NE_p predictability than other independent variables in equations for energy feeds. The same trend was observed for CF in protein supplements. CF was also observed to contribute the highest for ME_n predictability than other independent variables in equations for dry forages (mainly alfalfa meal and oat by-products).

EE was observed to contribute the second highest for both ME_n and NE_p predictability than other independent variables in equations for energy feeds and protein supplements for poultry (Table 72 and 73).

These results were in agreement with those of Carpenter and Clegg (1956) who observed a close relationship between ME of poultry feeds with their CP, EE, starch and sugar contents when these components were used in predictive equations. Sibbald et al. (1963) also developed equations to predict ME and ME_n of poultry feeds equations from their chemical composition (Table 16). These equations had sufficient precision for pratical purposes. ME_n was calculated from ME as follows:

TABLE 72 Simple and Multiple Regression Equations to Predict Nitrogen-Corrected Metabolizable Energy (ME_n) from Each Proximate Nutrient and Proximate Analysis of Different Classes of Feedstuffs for Poultry[a]

Class of Feeds	Type of Equation	Regression Constant	Regression Coefficient of				R^2	SE	N
			CF%	EE%	NFE%	CP%			
1	Simple	2877.8888	-54.1202	--	--	--	.3520	479.92	49
		593.4239	--	240.7798	--	--	.4407	445.88	48
		1159.9293	--	--	8.4544	--	.0240	403.89	8
		382.5811	--	--	--	59.6928	.5105	420.35	49
	Multiple	-17119.6500	148.3062	-58.6034	219.7269	310.6656	.9923	50.88	8
4	Simple	3652.8547	-88.3714	--	--	--	.4619	710.71	219
		2658.5056	--	53.7982	--	--	.4758	922.09	246
		1019.4234	--	--	27.9971	--	.2628	813.51	8
		3140.5896	--	--	--	-23.8509	.0124	933.01	250
	Multiple	-2487.8410	-53.5281	89.4545	74.1416	--	.9997	33.34	5
5	Simple	2973.2312	-57.6640	--	--	--	.4145	474.25	322
		2356.8593	--	62.8031	--	--	.1320	655.33	386
		2817.9503	--	--	-14.4411	--	.1658	655.96	15
		1543.4111	--	--	--	21.3901	.3704	555.64	398
	Multiple	165.6395	-12.5731	22.3950	18.8966	38.8508	.7848	428.69	12

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[a] ME_n = Kilocalories per kilogram dry matter. CF%, EE%, NFE% and CP% were the percentages of crude fiber, ether, extract, nitrogen free extract and crude protein, respectively, in feedstuffs (dry matter basis).

TABLE 73 Simple and Multiple Equations to Predict Net Energy for Production (NE_p) from Each Proximate Nutrient and From Proximate Analysis of Different Classes of Feedstuffs for Poultry[a]

Class of Feeds	Type of Equation	Regression Constant	Regression Coefficient of				R^2	SE	N
			CF%	EE%	NFE%	CP%			
1	Simple	1698.2853	-34.3972	--	--	--	.4730	228.94	21
		90.9689	--	243.4182	--	--	.7537	156.51	21
		--	--	--	--	--	--	--	--
		143.8642	--	--	--	33.8399	.5939	200.97	21
4	Simple	2671.0383	-77.9360	--	--	--	.5141	412.96	125
		1896.7830	--	41.1791	--	--	.5848	560.84	145
		-2186.7146	--	--	54.4002	--	.7443	259.78	16
		2428.7467	--	--	--	-30.4187	.0368	553.26	146
	Multiple	-1300.0400	-78.1232	89.7994	36.7648	32.1155	.9547	123.38	16
5	Simple	2094.3971	-37.3423	--	--	--	.3064	386.24	176
		1629.4113	--	38.2162	--	--	.1034	438.65	173
		311.6020	--	--	24.2705	--	.4531	385.25	6
		1250.2493	--	--	--	11.6819	.2247	401.41	174
	Multiple	1390.5150	-21.8482	31.3552	--	5.9682	.9996	14.19	6

[a] NE_p = Kilocalories per kilogram dry matter/ CF%, EE%, NFE% and CP% were percentages of crude fiber, ether extract, nitrogen free extract and crude protein, respectively, in feedstuffs (dry matter basis).

$ME_n = ME \pm (NB \times 8.22$ kilocalories) when NB = nitrogen balance and 8.22 = energy equivalent in uric acid. The factor 8.7 was sometimes used (Harris, 1966).

Net Energy For Production (NE_p) From ME_n. Table 74 shows the results of regression NE_p with ME_n of poultry feedstuffs. High correlations were observed between NE_p and ME_n of dry forages ($R^2 = .67$), energy feeds ($R^2 = .84$) and protein supplements ($R^2 = ,76$) as shown in Appendix Figures 92, 92 and 93, respectively. These figures demonstrated that there would be more precision when estimating NE_p from ME_n for poultry by using a regression model than by using a regression model than by a conversion factor. Sibbald and Price (1977) developed similar models to estimate true metabolizable energy (TME) from apparent metabolizable energy (AME) for wheat and oats.

The difference TME - AME (within grains) increased with increasing value of AME. This trend was associated with voluntary intake of AME assay diets of low energy grains (Sibbald, 1976). Sibbald and Price (1976 a, b) also found that the bulk density of barley (kg/bushel) was highly correlated with TME (kcal/g dry matter).

TABLE 74 Simple Regression Equations to Predict Net Energy for Production (NE_p) from Nitrogen-Corrected Metabolizable Energy (ME_n) of Different Classes of Feedstuffs for Poultry[a]

Class of Feeds	Equation	R^2	SE	N
1	$NE_p = 173.5088 + .4337(ME_n)$	.6664	181.41	28
4	$NE_p = 164.1448 + .6728(ME_n)$	.8362	422.28	212
5	$NE_p = 229.6481 + .6243(ME_n)$	.7620	221.35	265

[a] NP_p and ME_n were measured Kilocalories per Kilogram dry matter

SUMMARY AND CONCLUSIONS

Data on the proximate nutrient content, digestibility and energy utilization available from the International Feedstuffs Institute (Utah State University) were used to develop mathematical models for estimating energy and protein utilization of five classes of feedstuffs for various kinds of animals.

The International Databank System is a system for collection, calculation and retrieval of data on the composition of animal feeds (Harris et al. 1968a).

Data are usually collected from three major sources. First source is the collaborating laboratories; second is published data in literature and the third source is data from centers related to the International Network of Feed Information Centers (INFIC).

Feedstuffs were divided into eight classes. However, only the following five classes were used in this study: dry forages and roughages; pasture, range plants, and forages fed green; silages; energy feeds; and protein supplements.

Classes of feedstuffs were subdivided into more related subclasses (legumes, grasses, legumeous roughages, non-legumeous roughages, and mixtures of legumes and grasses for the first three classes of feedstuffs; feeds of animal or plant origins for energy feeds; and feeds of animal, avian, marine, milk or plant origins for protein supplements).

Furthermore, the first three classes of feedstuffs were combined together then subgrouped into five subgroups; legumes, grasses, legumeous roughages, non-legumeous roughages and mixture of legumes and grasses. Energy feeds were subgrouped into feeds of plant or animal origins. Protein supplements were also subgrouped into feeds of plant or animal origins.

Biological and chemical data were sorted by kind of animal within each class, subclass or subgroup of feedstuffs into the following animal kinds: cattle, horses, poultry, rabbits, sheep, swine and in vitro studies whenever data were available.

Mathematical models (simple and multiple regression equations) were developed to estimate digestible crude protein, total digestible nutrients, digestible energy and metabolizable energy from chemical analysis of the different classes of feedstuffs for various kinds of animals. Digestible energy was estimated from total digestible nutrients. Metabolizable energy was also estimated from total digestible nutrients and digestible energy. Moreover, qualitative factors or physical descriptions of feedstuffs (Harris, 1976) were included in a model along with chemical composition (quantitative factors) of feeds.

Digestible crude protein (DCP) was found to be highly correlated with crude protein concentration in the different classes (R^2 = .74 to .97), subdivisions of classes (R^2 = .64 to .99), subgroups (R^2 = .83 to .98) and proximate analysis (R^2 = .86 to .99) of feedstuffs for various kinds of animals. An exception was that of the (subdivision) dry, non-legumeous roughages for horses.

Digestible ether extract (DEE) was also highly correlated with ether extract concentration of classes (R^2 = .47 to .99), subdivisions of classes (R^2 = .46 to .99), subgroups (R^2 = .46 to .95) and proximate analysis (R^2 =.53 to .99) of feedstuffs for various kinds of animals. However, there were a few exceptions where DEE was not highly predicted from ether extract content.

Digestible crude fiber (DCF) was found to be highly correlated with crude fiber contents of green forages and pasture plants, silages and energy feeds in most cases. Subdividing and subgrouping of feedstuffs improved, in many cases, predictability of DCF from their crude fiber contents. However, DCF was highly predictable from proximate analysis of the different classes of feedstuffs for various kinds of animals with few exceptions.

Digestible nitrogen free extract (DNFE) was highly correlated with nitrogen free extract contents of silages for cattle and sheep (R^2 = .53 and .79, respectively); energy feeds for cattle (R^2 = .70), horses (R^2 = .77), rabbits (R^2 = .84), sheep (R^2 = .86) and swine (R^2 = .86); and protein supplements for cattle (R^2 = .58), horses (R^2 = .50), sheep (R^2 = .90) and swine (R^2 = .99). Subdivision and subgrouping of feedstuffs resulted in an improved predictability of DNFE in certain cases. Proximate analysis, however, resulted in high correlations with DNFE (R^2 = .63 to .99) for various kinds of animals with exceptions of dry forages and roughages for cattle and rabbits.

Total digestible nutrients (TDN) was accurately predictable from digestible values of four components of proximate analysis (DCP, DEE, DCF and DNFE) of the different classes of feeds for various kinds of animals (R^2 = .84 to .99). However, TDN was poorly predicted when each proximate nutrient was used as a single independent variable in a simple regression equation. There were few exceptions, however.

TDN was highly negatively correlated (R^2 = .93) with CF content of green legumeous roughages for sheep and of legumes and grass hays for rabbits (R^2 = .83 and .79, respectively). In vitro studies showed high negative correlations (R^2 = .73) between TDN and green feeds and pasture plants.

TDN was also highly correlated with EE contents of energy feeds for cattle (R^2 = .71) and swine (R^2 = .80), energy feeds of animal origin for cattle (R^2 = .97), protein supplements of marine origin for cattle (R^2 = .96) and green legumeous roughages for sheep (R^2 = .93). TDN was also highly estimated from EE contents of legume hays (R^2 = .76), fresh grasses (R^2 = .63), energy feeds of plant origin (R^2 = .74) and protein supplements of milk origin (R^2 = .58) for swine. In vitro studies also showed high correlation between TDN and EE concentration in green feeds and pasture plants.

TDN was highly predictable from CP content of dry forages and roughages for rabbits (R^2 = .56) and green feeds and pasture plants for in vitro studies (R^2 = .88). Subdividing classes of feedstuffs resulted in improved predictability of TDN from CP contents of legume hays (R^2 = .77) and protein supplements of marine origin for swine (R^2 = .53).

TDN was only highly estimated from NFE content of green feeds and pasture plants for in vitro studies. However, subdividing classes of feedstuffs resulted in improved TDN estimation from NFE contents of fresh grasses (R^2 = .65) for cattle and ensiled nonlegumeous roughages for cattle (R^2 = .78) and sheep (R^2 = .63), dry nonlegumeous roughages (R^2 = .67) and energy feeds of plant origin (R^2 = .53) for rabbits.

The use of the four proximate nutrients in multiple regression models improved, in most cases, estimation of TDN over that from a single independent variable. TDN was well predicted from proximate analysis of dry forages and roughages for horses ($R^2 = .58$), rabbits ($R^2 = .66$) and swine ($R^2 = .65$); silages for sheep ($R^2 = .56$); energy feeds for horses ($R^2 = .61$), rabbits ($R^2 = .72$), sheep ($R^2 = .51$) and swine ($R^2 = .95$).

In vitro studies showed high correlations between TDN and proximate analysis of green feeds and pasture plants ($R^2 = .99$) and silages ($R^2 = .78$).

The use of a more complicated model to show interactions among proximate nutrients resulted in a general improvement in predictability of TDN.

Including physical descriptions (qualitative factors) of feedstuffs (forage type, stage of maturity and parts eaten) along with chemical analysis (quantitative factors) in a complex model, showed a promising way to predict TDN ($R^2 = .64$).

Digestible energy (DE) was calculated from predicted values of the four proximate nutrients by the following equation:

$$DE = \frac{5.7\ (DCP) + 9.5\ (DEE) + 4.79\ (DCF) + 4.03\ (NFE)}{100}$$

Moreover, DE was found to be highly predicted from digestible proximate nutrients by the use of multiple regression equation ($R^2 = .79$ to $.99$) for various kinds of animals. However, DE was not highly correlated with each proximate nutrient when used as a single variable in simple regression models. There were few exceptions, however. DE was highly negatively correlated with crude fiber contents of dry forages and roughages (R^2 = .51) and protein supplements (R^2 = .80) for rabbits.

DE was also highly related to EE contents of protein supplements for rabbits (R^2 = .63), and with CP content of dry forages and roughages for rabbits.

DE was negatively correlated (R^2 = .52) with NFE content of energy feeds for cattle.

DE was highly predicted from proximate analysis (R^2 = .50 to .79) of different classes of feedstuffs for various kinds of animals except in cases of dry forages and roughages for cattle and silages for cattle and sheep.

DE was highly correlated with TDN values of different classes of feedstuffs for various kinds of animals (R^2 = .53 to .97).

Metabolizable energy (ME) was highly estimated from digestible proximate nutrients (R^2 = .73 to .99) of different classes of feedstuffs for cattle and sheep.

The use of each proximate nutrient as a single independent variable to predict ME by simple regression models did not result in precise correlations in most cases. However, ME was highly negatively correlated with EE content of silages for cattle (R^2 = .54).

When the four proximate nutrients were used in multiple regression models, high ME estimation was obtained (R^2 = .52 to .96). Moreover, ME was highly predicted from TDN (R^2 = .71 to .95) and DE (R^2 = .66 to .97) values of different classes of feedstuffs for various kinds of animals. An exception was estimating ME from TDN value of dry forages and roughages for cattle.

In general, the use of digestible proximate nutrients as independent variables in multiple regression equations resulted in high precision in estimating TDN, DE and ME.

TDN, DE and ME were also highly predicted from proximate analysis in most cases. However, the use of each proximate nutrient as a single independent variable did not give promising results, with few exceptions.

Subdividing and subgrouping could be useful in predicting TDN from a single nutrient in limited cases.

The inclusion of physical descriptions of feedstuffs with proximate analysis could be a promising way to estimate the nutritive value of feedstuffs. It is suggested that processing or treatment be included and method could be applied to predict DE and ME. It is also recommended that workers report feed descriptions according to the International Feed vocabulary (Harris, 1976).

ME_n was highly correlated with proximate analysis (R^2 = .78 to .99), but not with each proximate nutrient content of poultry feedstuffs. NE_p for poultry followed the same trend with proximate analysis (R^2 = .95 to .99). However, NE_p was closely correlated with EE (R^2 = .75) and CP (R^2 = .59) contents of dry forages and EE (R^2 = .58) and NFE (R^2 = .74) contents of energy feeds. Moreover, NE_p was closely predictable from ME_n values of poultry feeds (R^2 = .67 to .84).

Due to the nature of data, it was difficult to give certain interpretations about the results reported.

The use of simple regression methods to estimate DE from TDN and ME from TDN and DE is a useful method especially when TDN data are available. It is recommended that simple regression equations be used instead of conversion factors when shifting from one energy system to another.

Whether any of the prediction equations would be suitable for practical application would depend upon the magnitude of error that could be tolerated.

It is recommended that data available from the International Databank System at the International Feedstuffs Institute (Utah State University) be plotted and checked for wild values every 6 to 12 months.

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APPENDIX

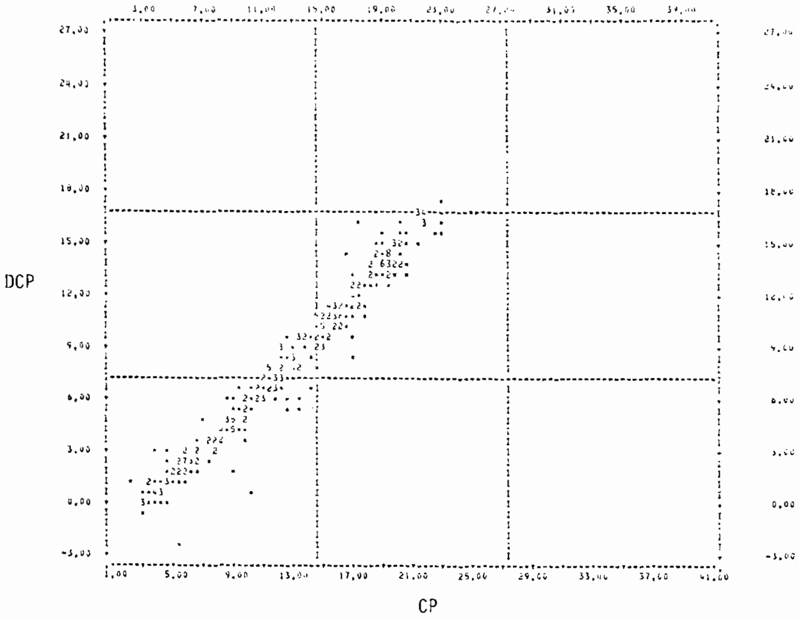

FIGURE 14 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of dry forages and roughages for cattle.

Key: In all graphs, * = one observation; 1 to 9 = number of observations that had the same value.

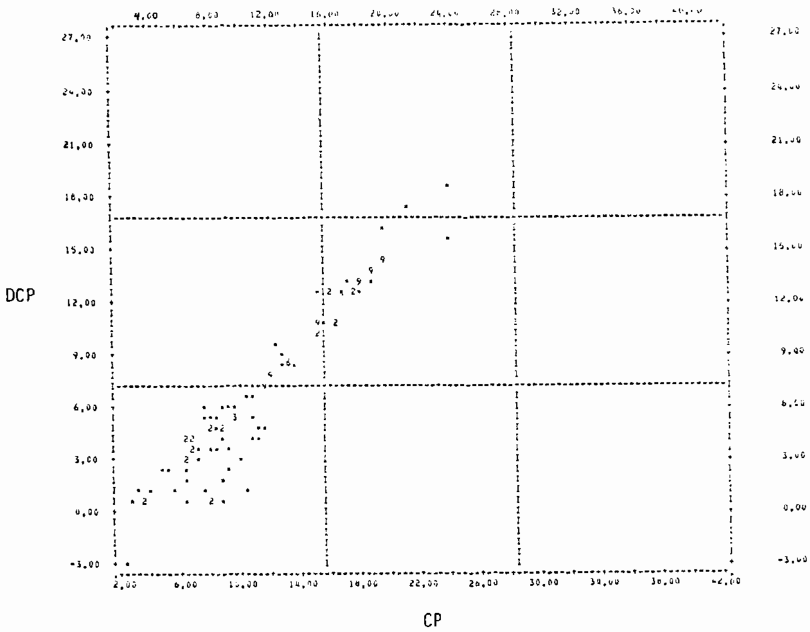

FIGURE 15 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of pasture, range plants and forages fed green for cattle.

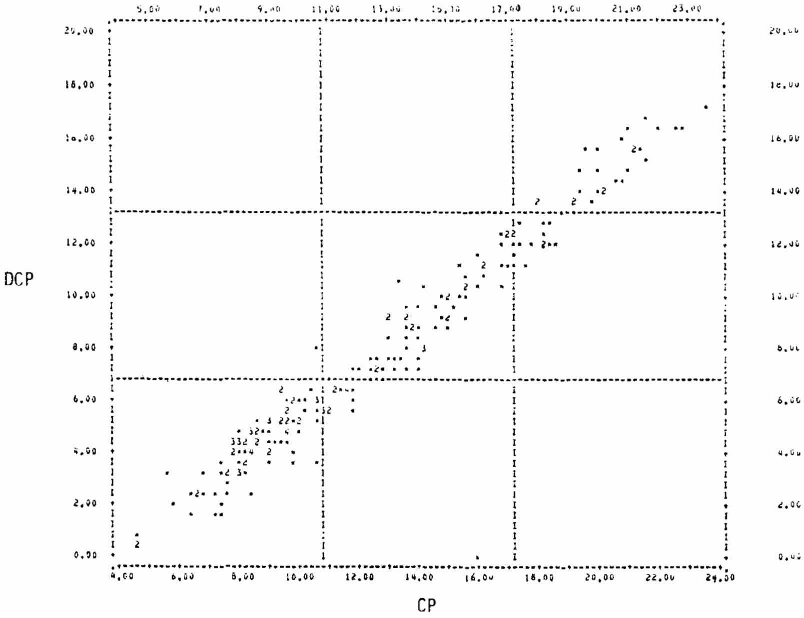

FIGURE 16 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of silages for cattle.

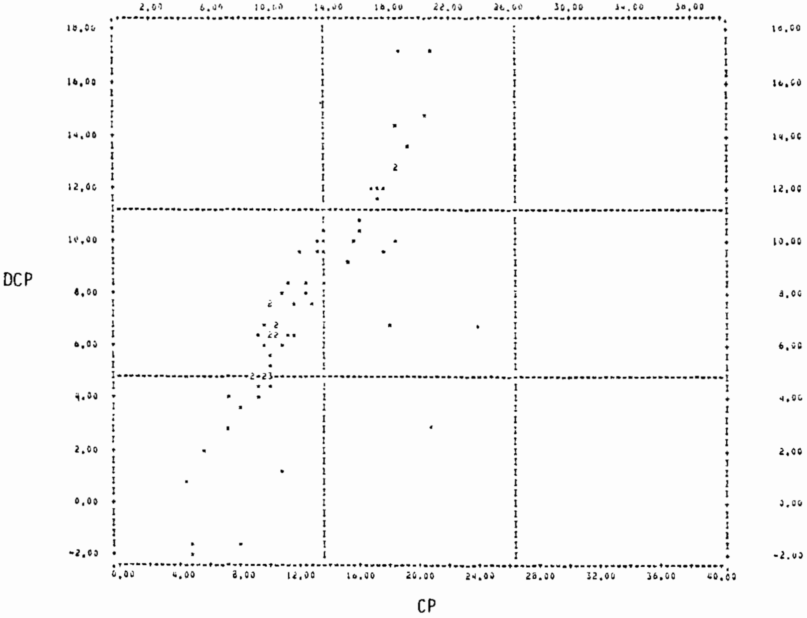

FIGURE 17 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of silages for cattle.

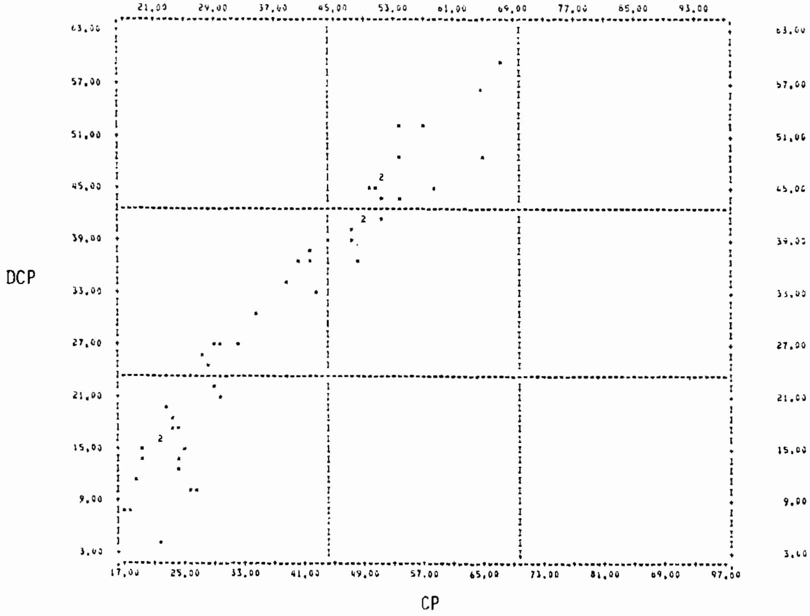

FIGURE 18 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of protein supplements for cattle.

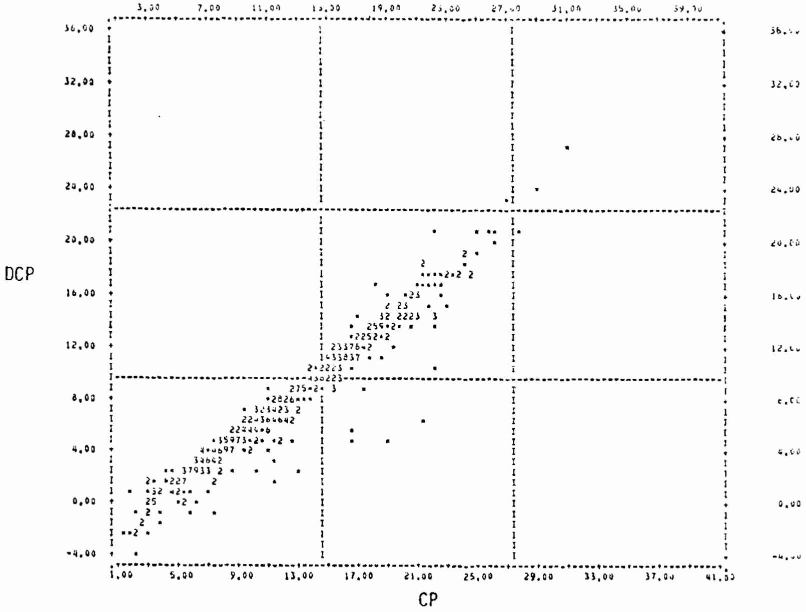

FIGURE 19 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of dry forages and roughages for sheep.

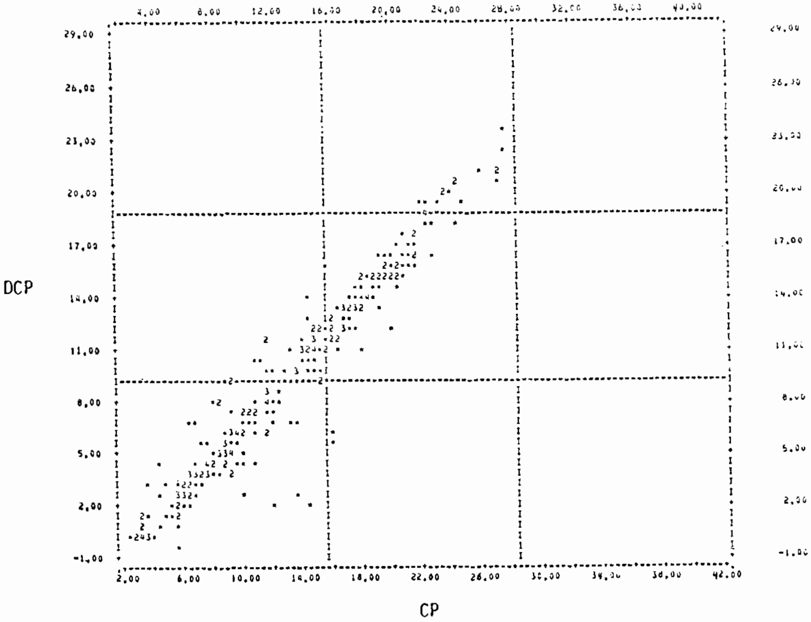

FIGURE 20 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of pasture, range plants and forages fed green for sheep.

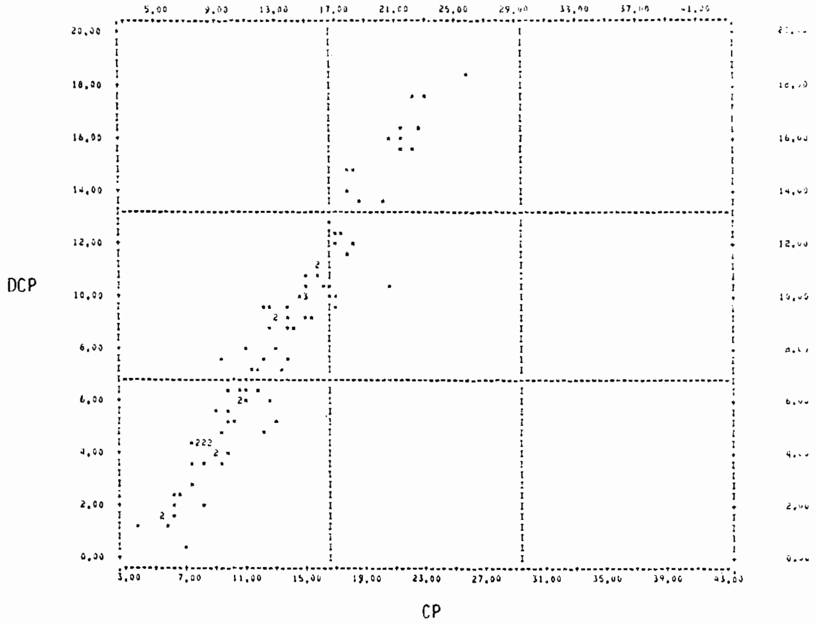

FIGURE 21 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of silages for sheep.

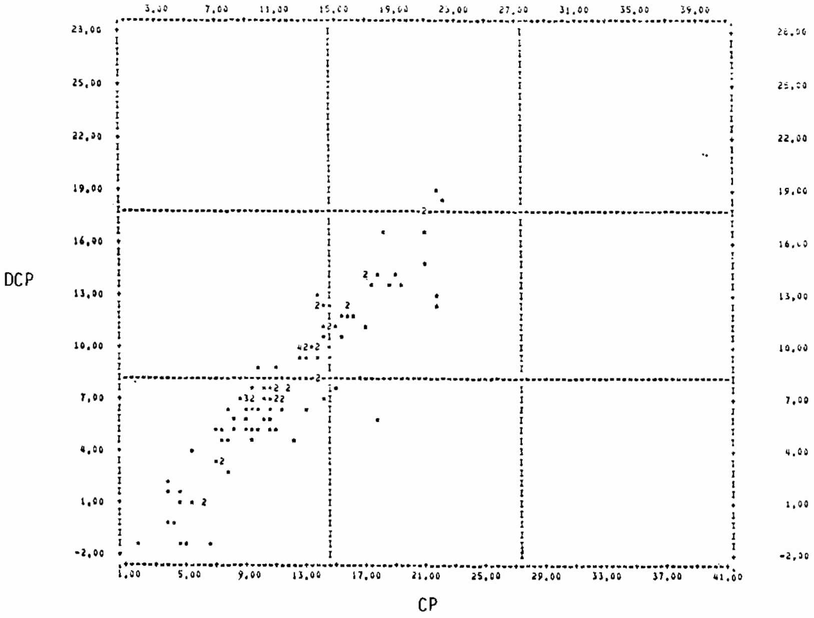

FIGURE 22 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of energy feeds for sheep.

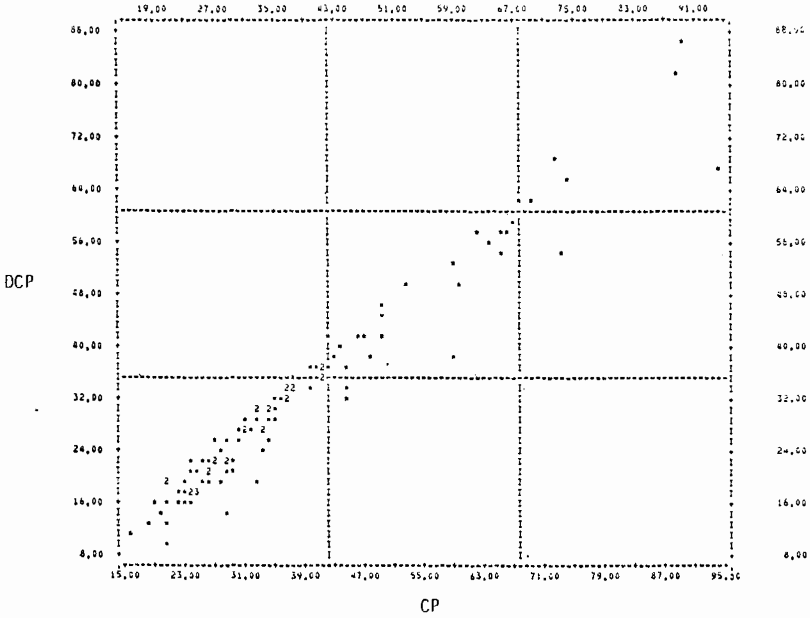

FIGURE 23 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of protein supplements for sheep.

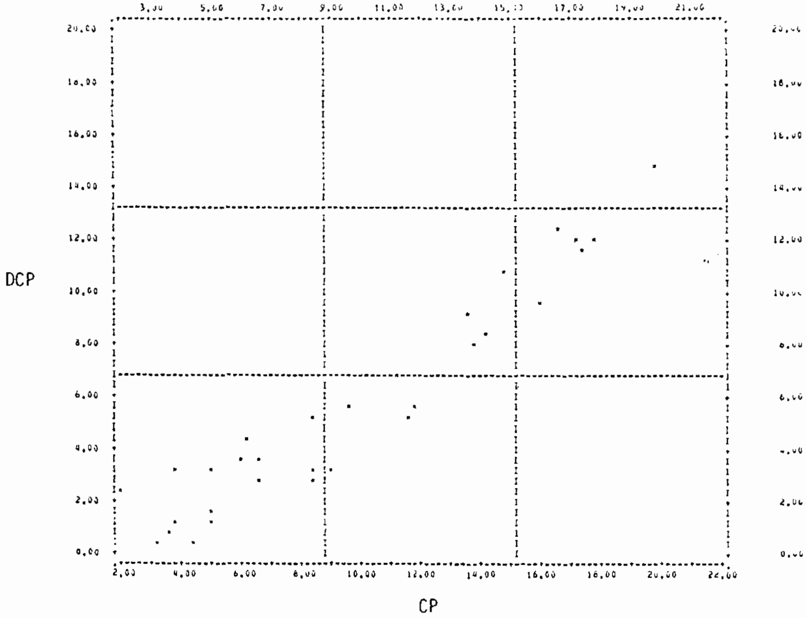

FIGURE 24 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of dry forages and roughages for horses.

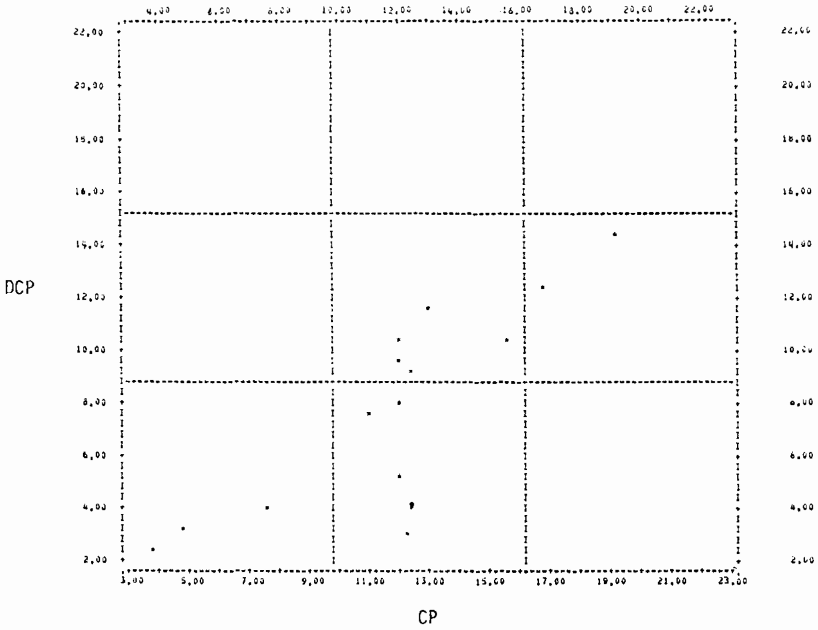

FIGURE 25 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of energy feeds for horses.

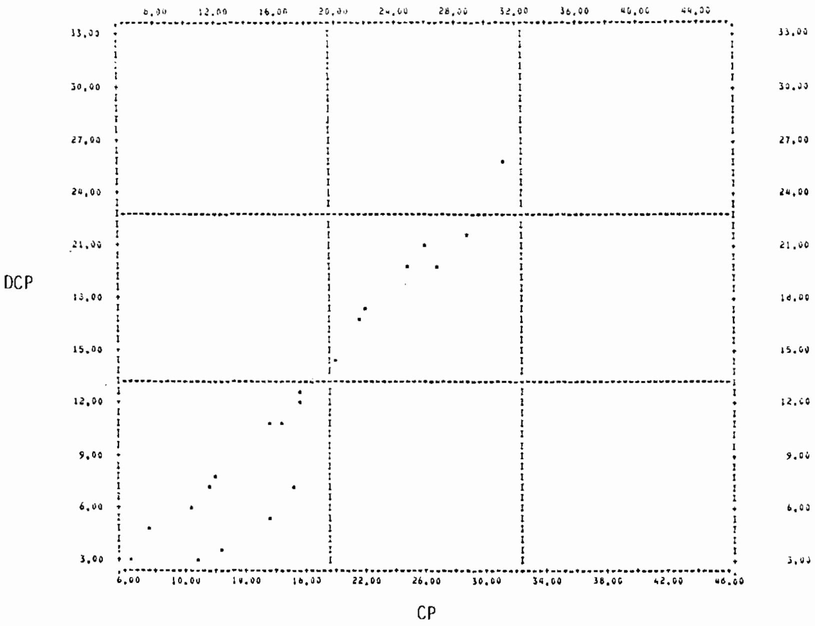

FIGURE 26 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of dry forages and roughages for rabbits.

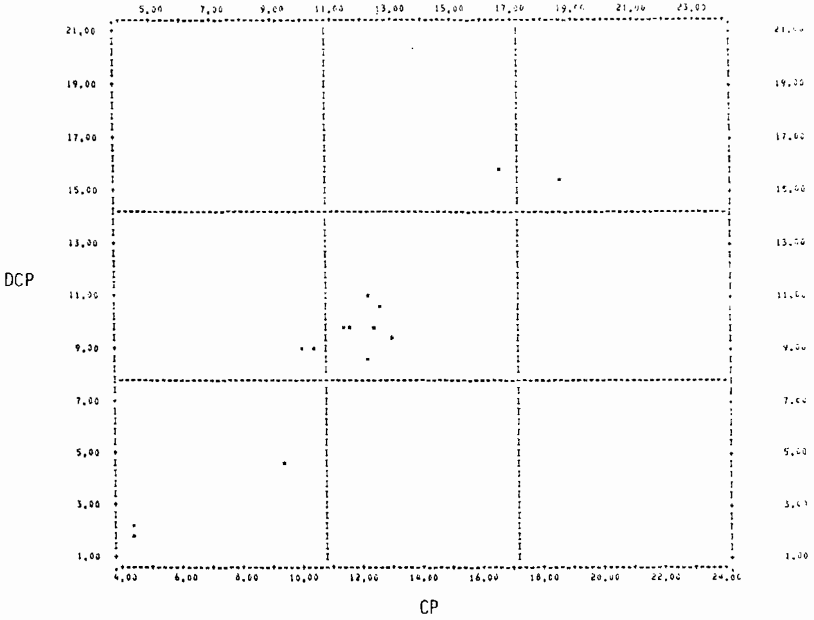

FIGURE 27 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of energy feeds for rabbits.

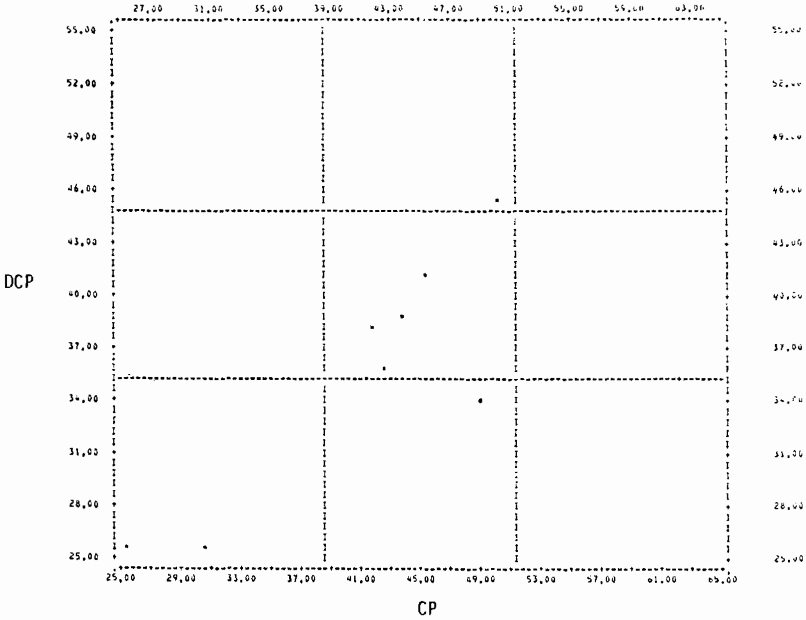

FIGURE 28 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of protein supplements for rabbits.

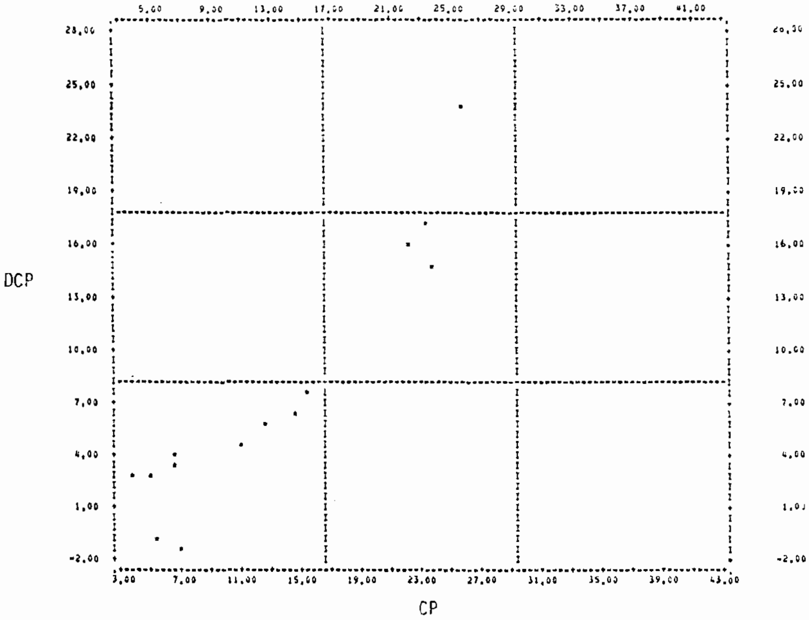

FIGURE 29 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of dry forages and roughages for swine.

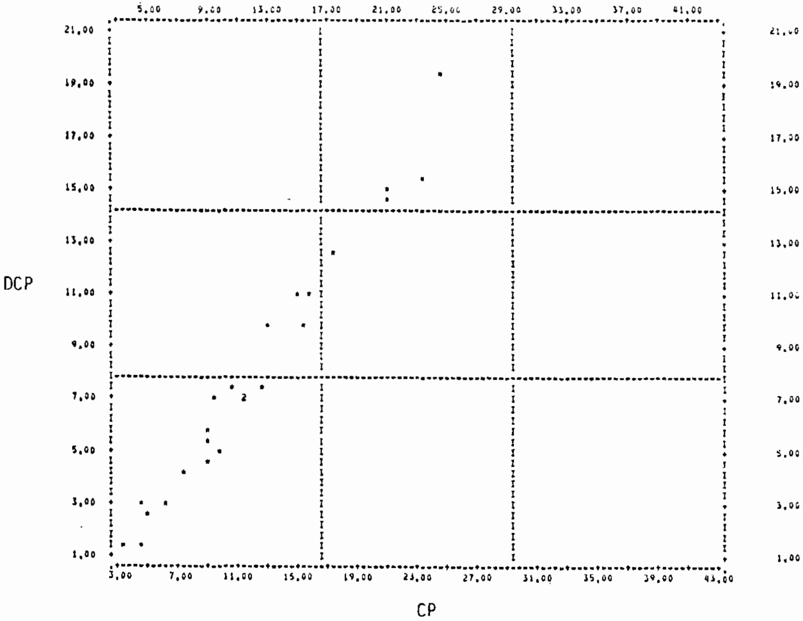

FIGURE 30 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of pasture, range plants and forages fed green for swine.

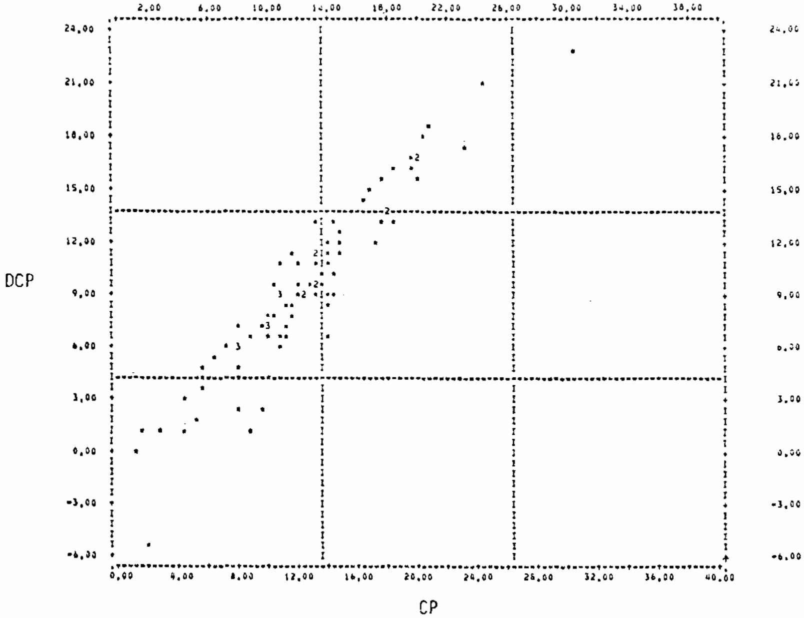

FIGURE 31 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of energy feeds for swine.

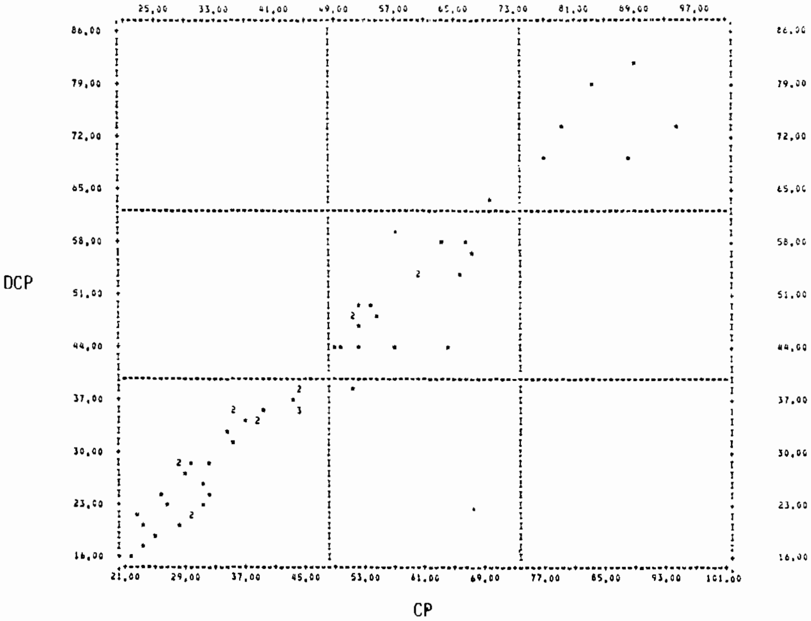

FIGURE 32 Predicting digestible crude protein (DCP%) from crude protein content (CP%) of protein supplements for swine.

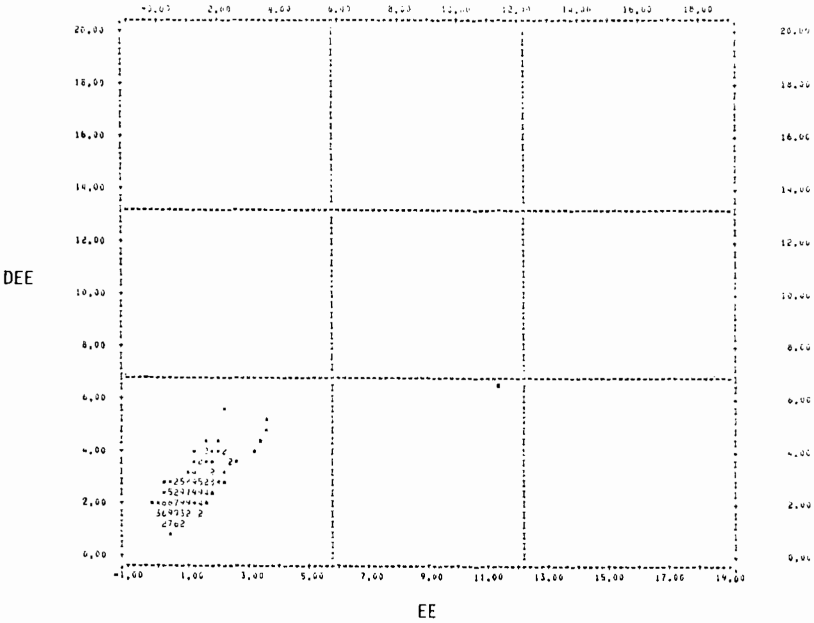

FIGURE 33 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of dry forages and roughages for cattle.

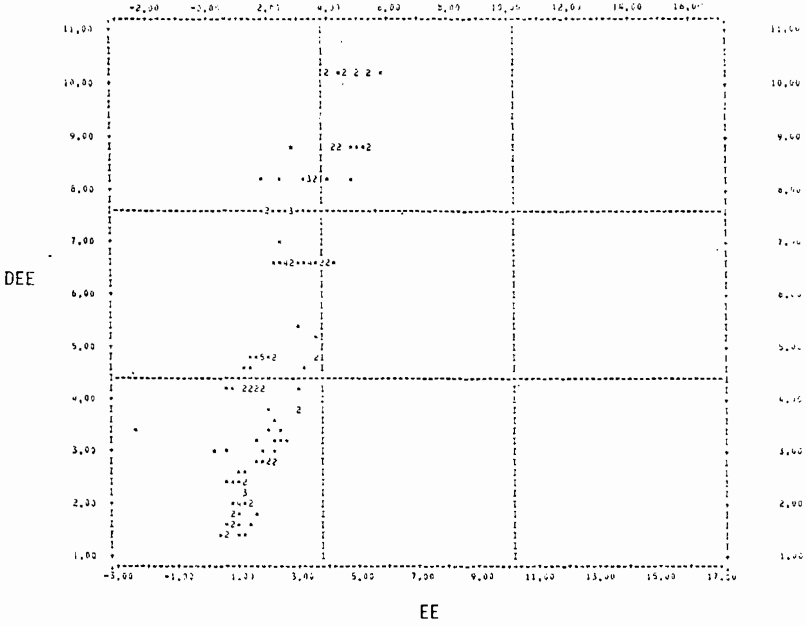

FIGURE 34 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of pasture, range plants and forages fed green for cattle.

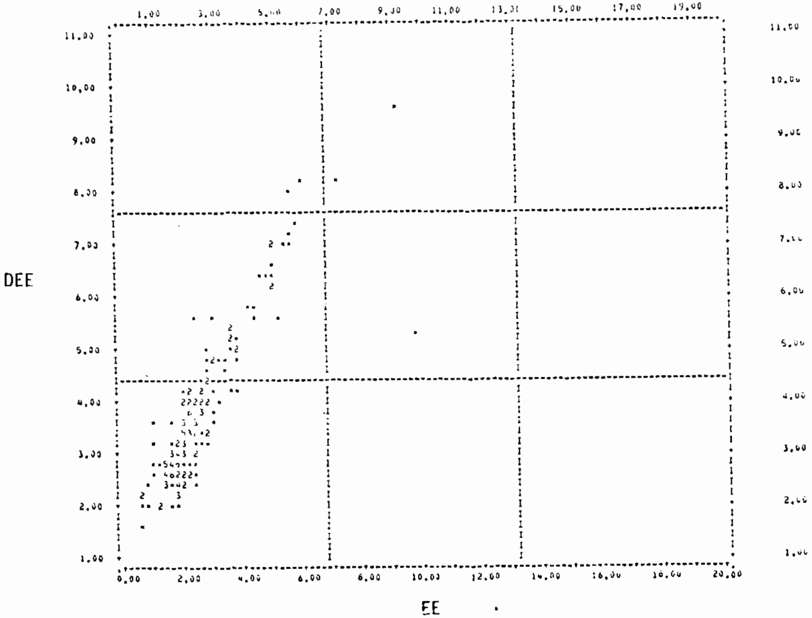

FIGURE 35 Predicting digestible ether extract (DEE%) from ether extract of content (EE%) of silages for cattle.

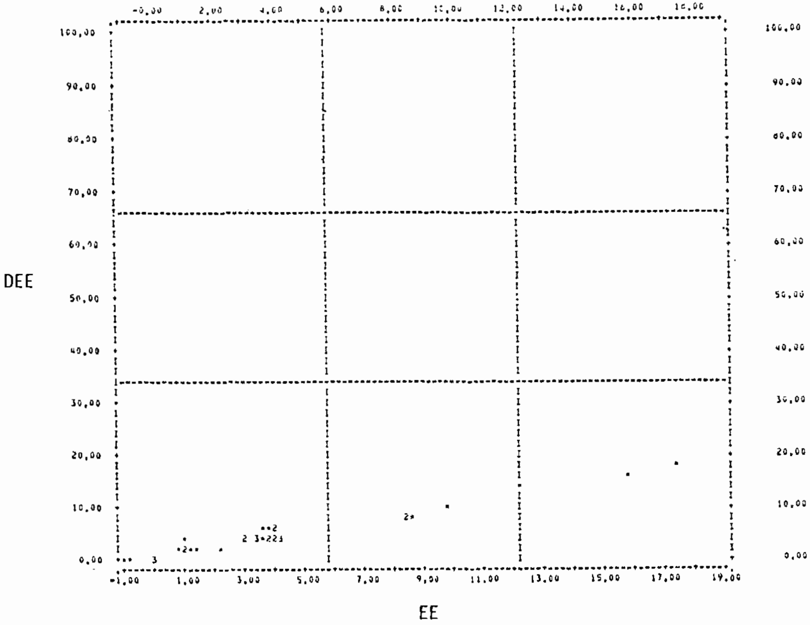

FIGURE 36 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of energy feeds for cattle.

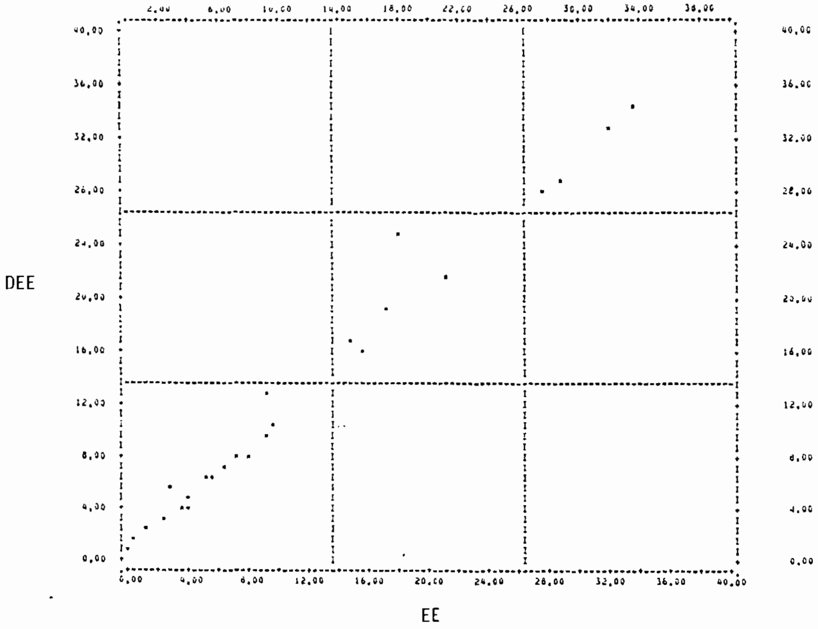

FIGURE 37 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of protein supplements for cattle.

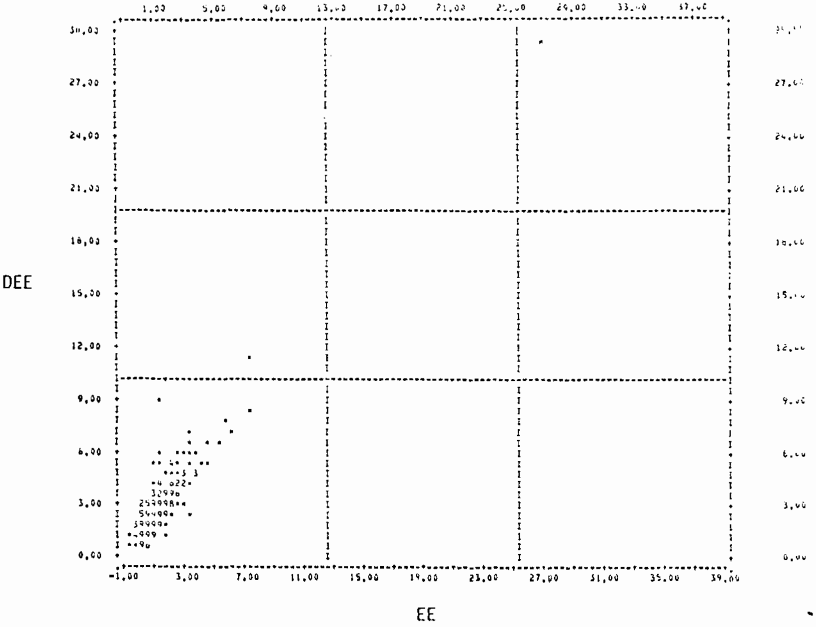

FIGURE 38 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of dry forages and roughages for sheep.

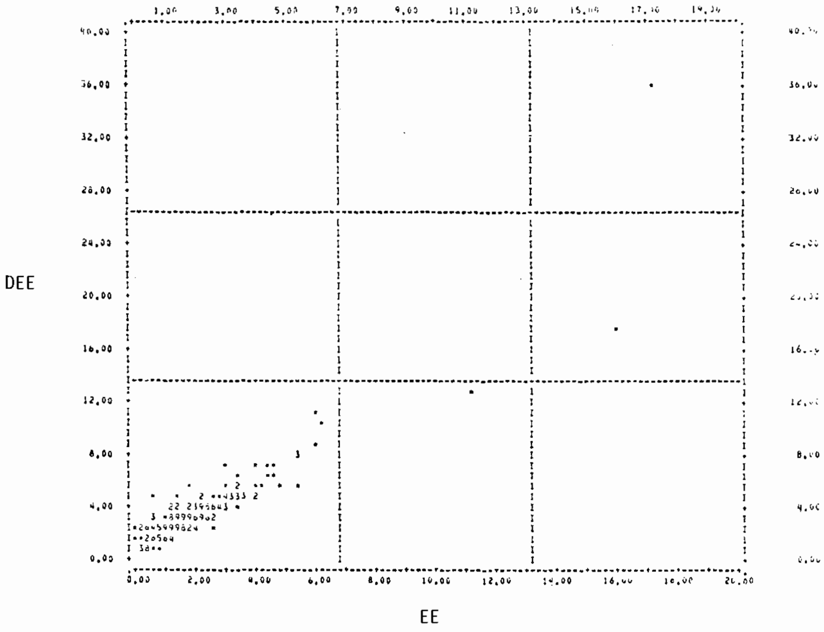

FIGURE 39 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of pasture, range plants and forages fed green for sheep.

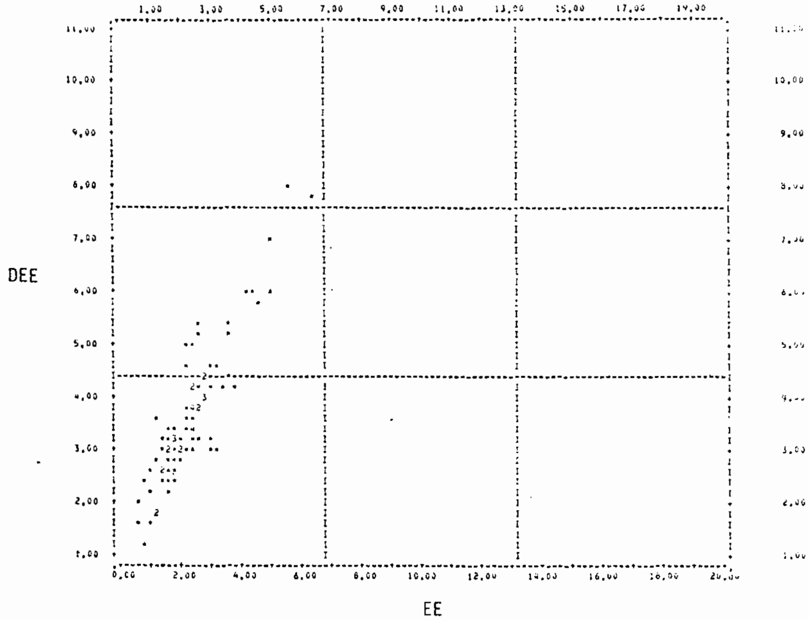

FIGURE 40 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of silages for sheep.

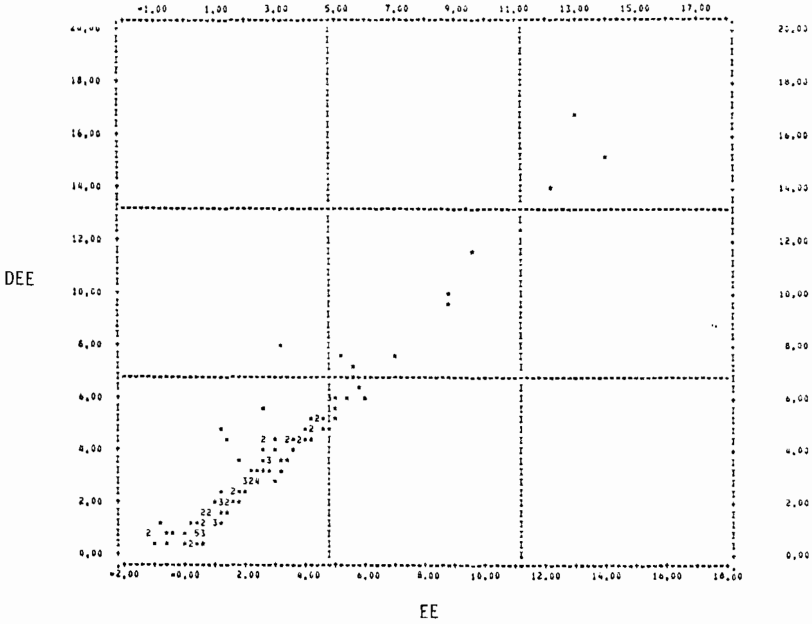

FIGURE 41 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of energy feeds for sheep.

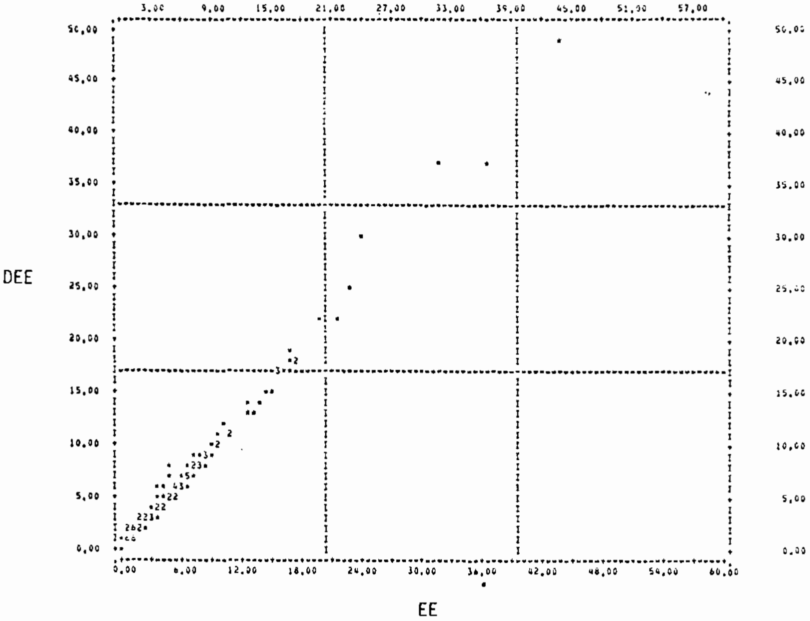

FIGURE 42 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of protein supplements for sheep.

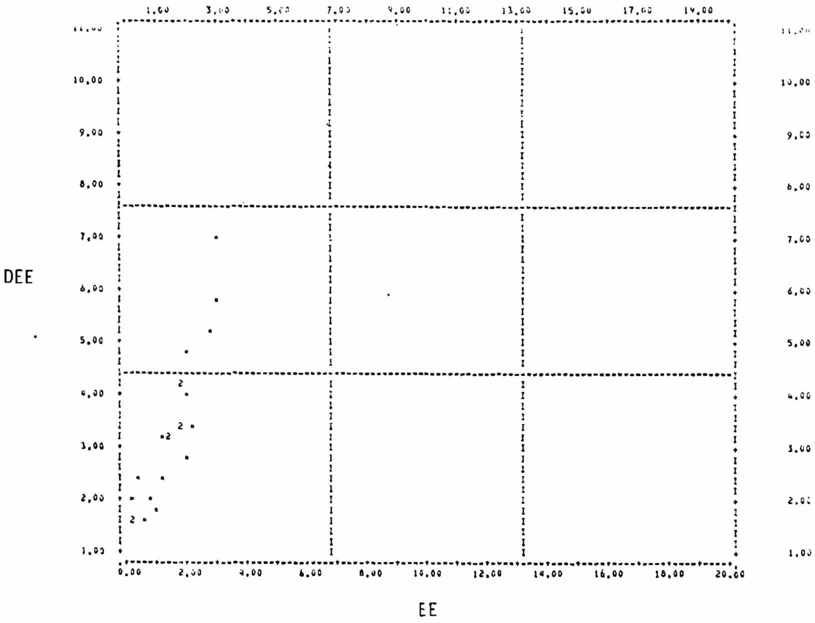

FIGURE 43 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of dry forages and roughages for rabbits.

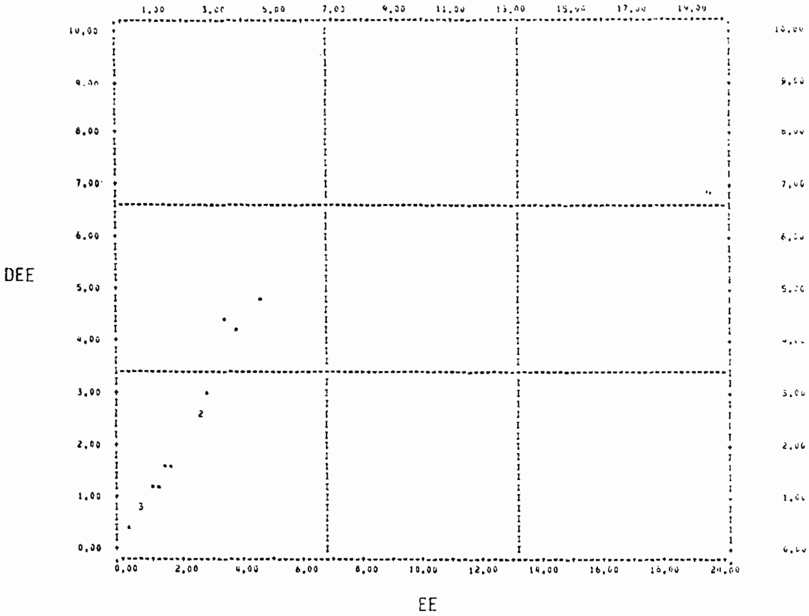

FIGURE 44 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of dry forages and roughages for swine.

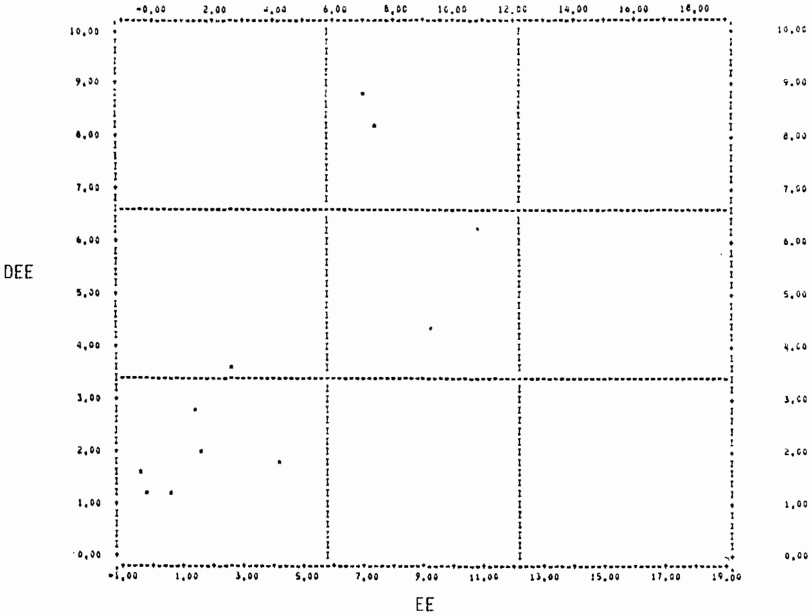

FIGURE 45 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of dry forages and roughages for swine.

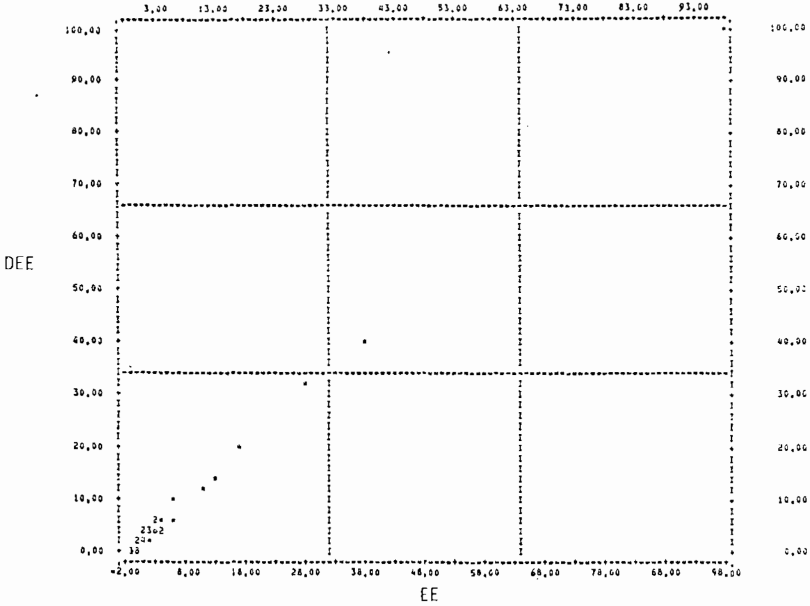

FIGURE 46 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of energy feeds for swine.

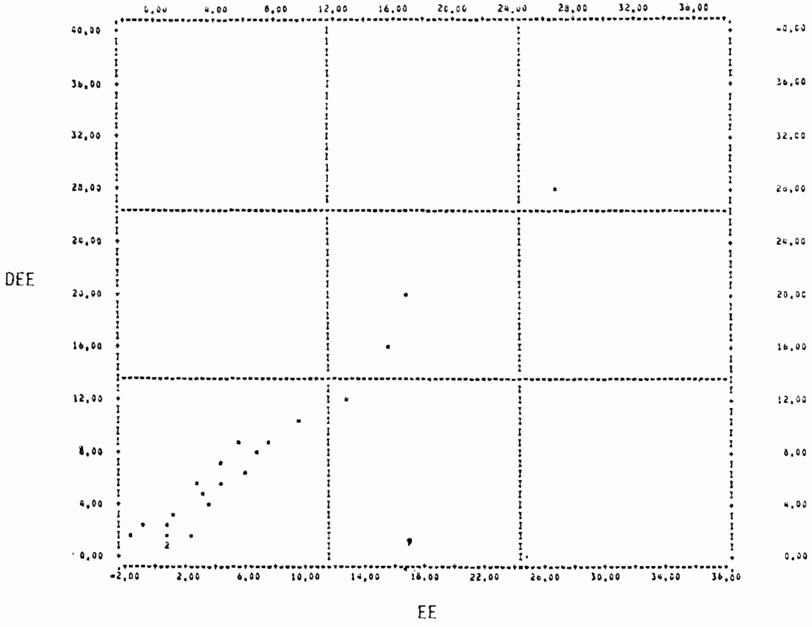

FIGURE 47 Predicting digestible ether extract (DEE%) from ether extract content (EE%) of protein supplements for swine.

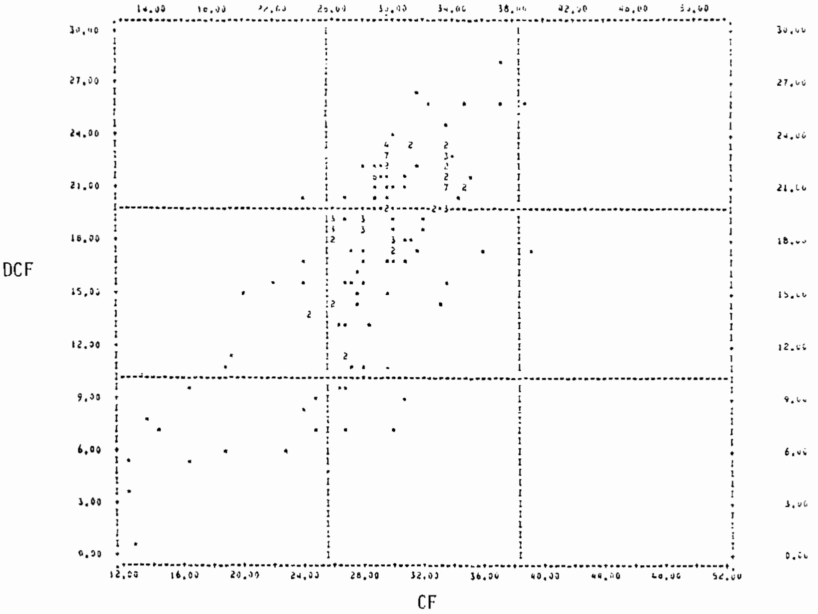

FIGURE 48 Predicting digestible crude fiber (DCF%) from crude fiber content (CF%) of pasture, range plants and forages fed green for cattle.

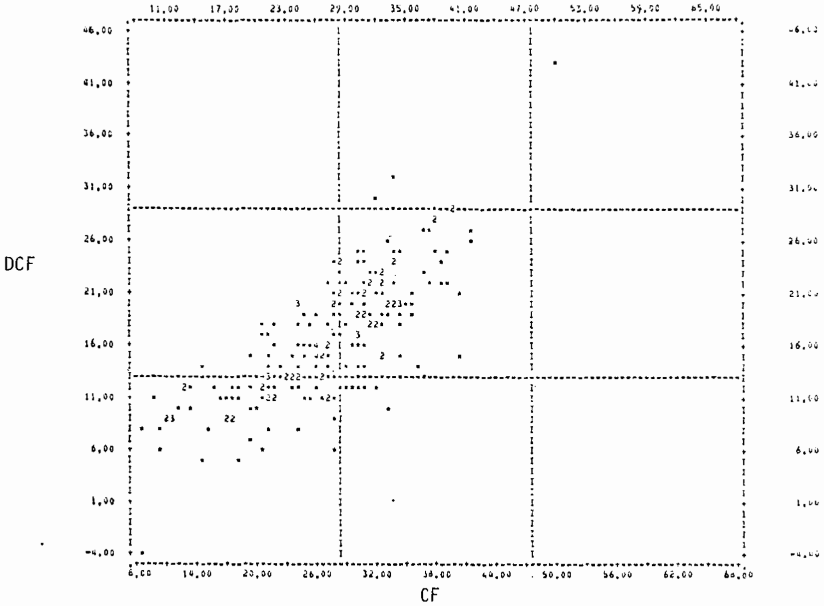

FIGURE 49 Predicting digestible crude fiber (DCF%) from crude fiber content (CF%) of pasture, range plants and forages fed green for sheep.

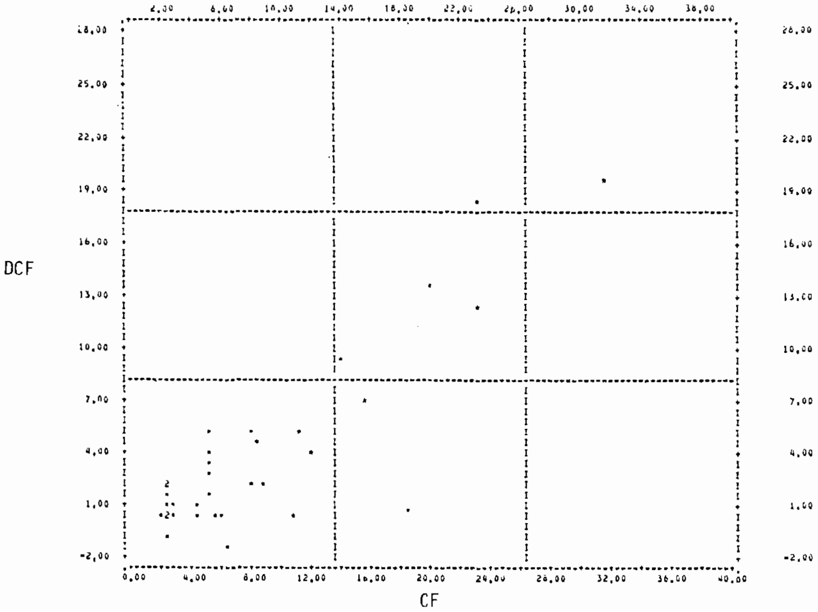

FIGURE 50 Predicting digestible crude fiber (DCF%) from crude fiber content (CF%) of energy feeds for cattle.

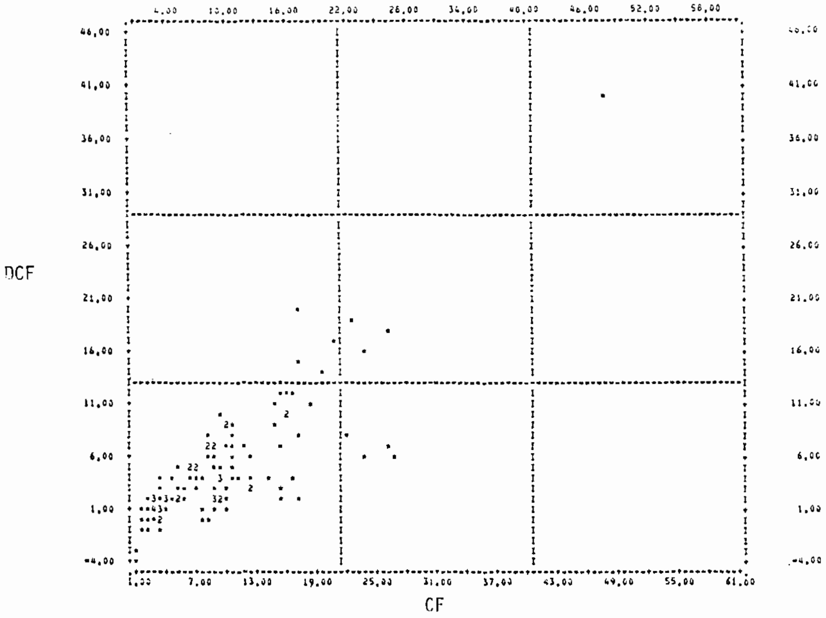

FIGURE 51 Predicting digestible crude fiber (DCF%) from crude fiber content (CF%) of energy feeds for sheep.

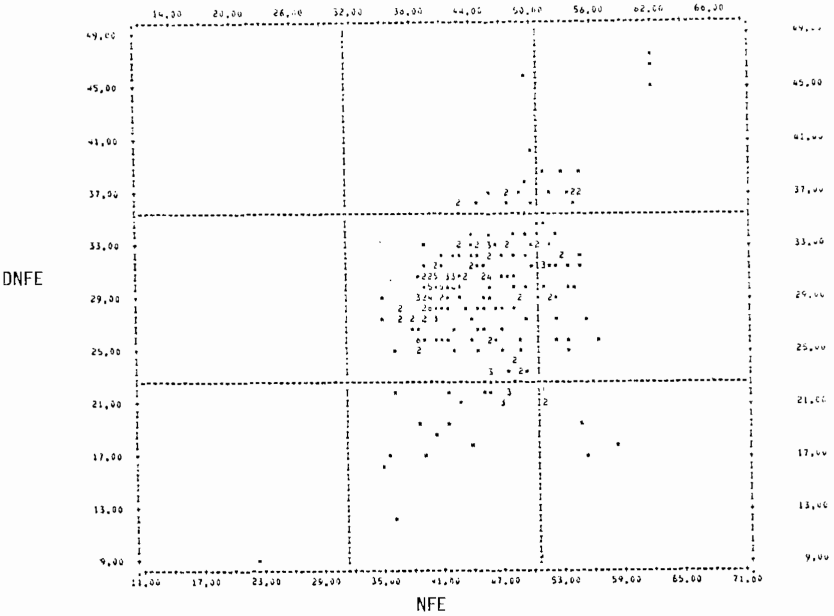

FIGURE 52 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of dry forages and roughages for cattle.

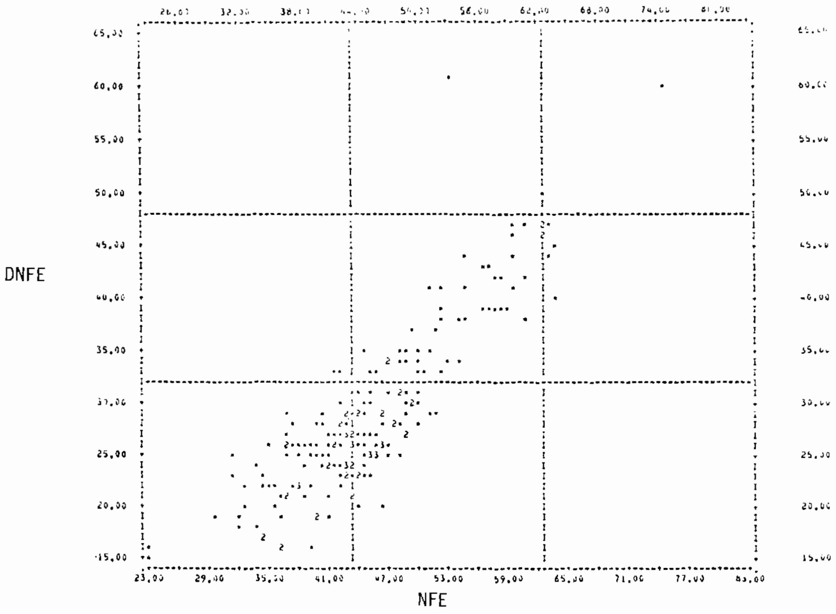

FIGURE 53 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of silages for cattle.

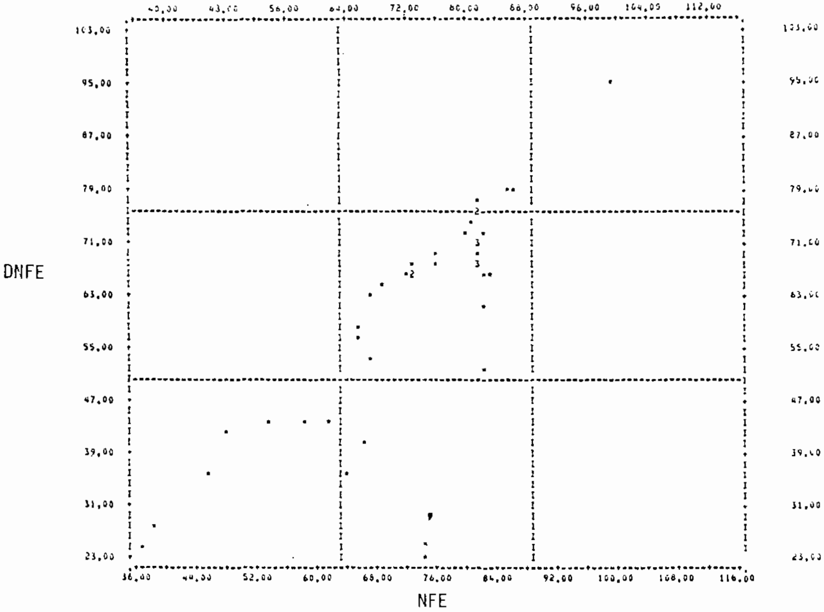

FIGURE 54 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of energy feeds for cattle.

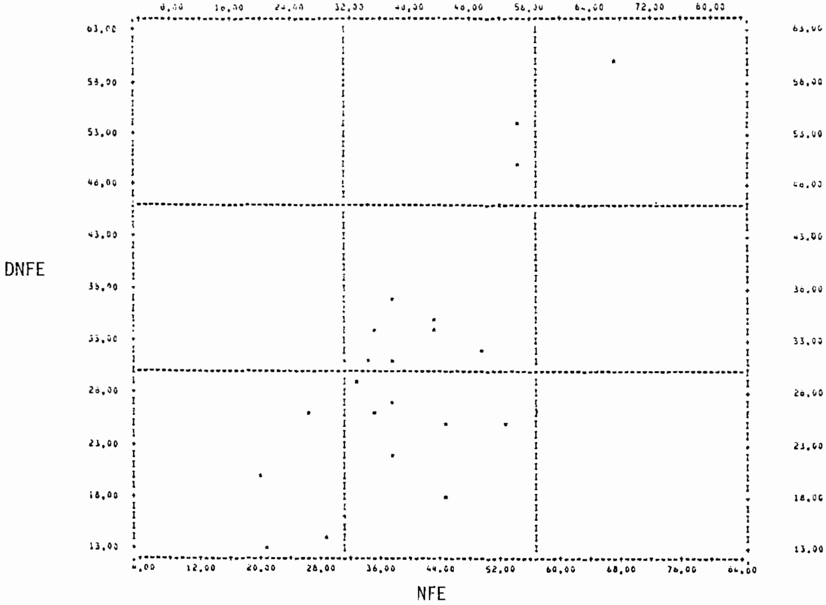

FIGURE 55 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of protein supplements for cattle.

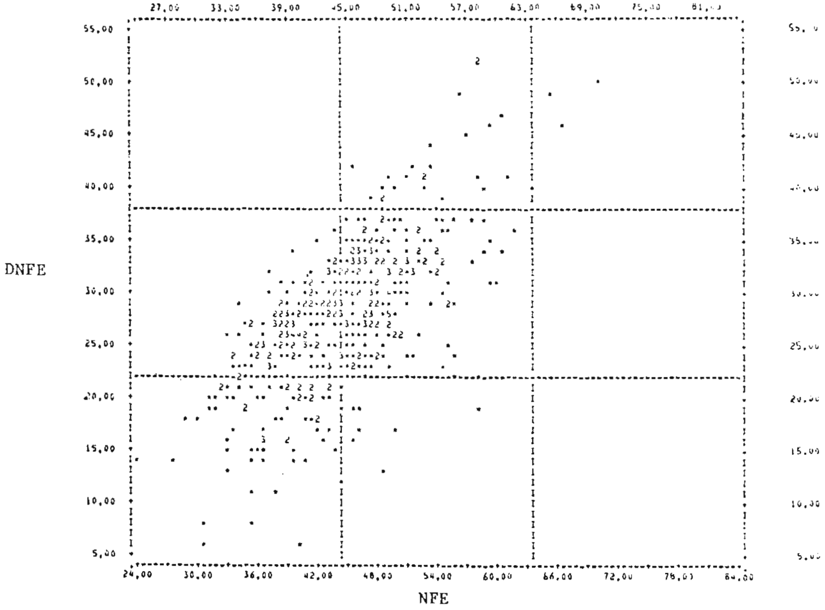

FIGURE 56 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of dry forages and roughages for sheep.

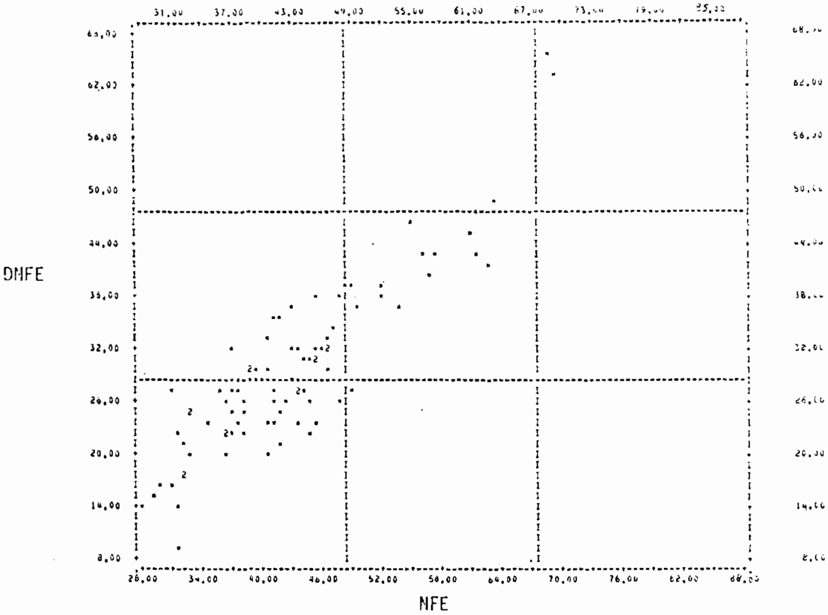

FIGURE 57 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of silages for sheep.

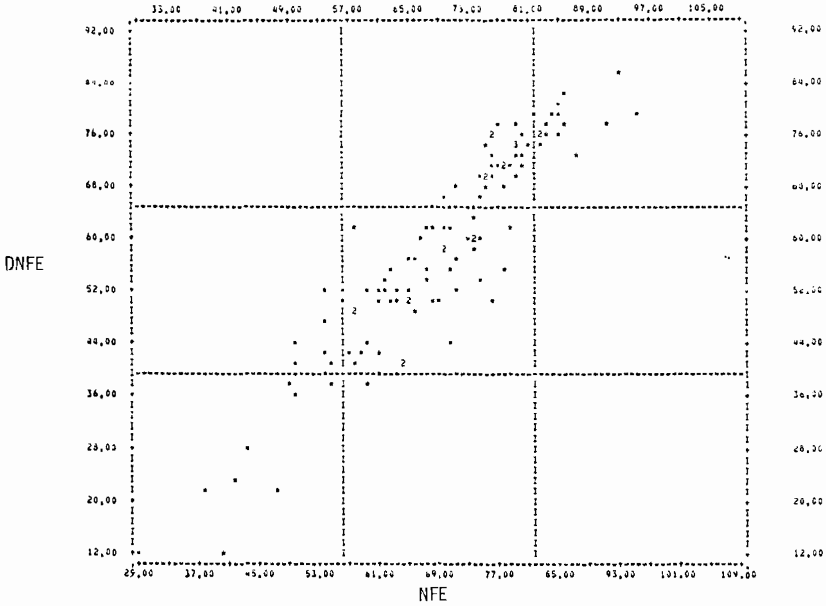

FIGURE 58 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of energy feeds for sheep.

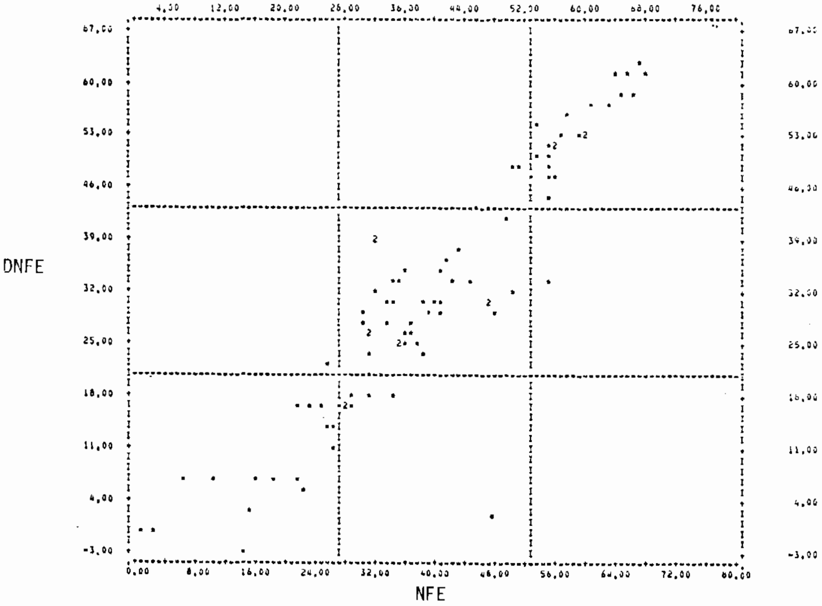

FIGURE 59 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of protein supplements for sheep.

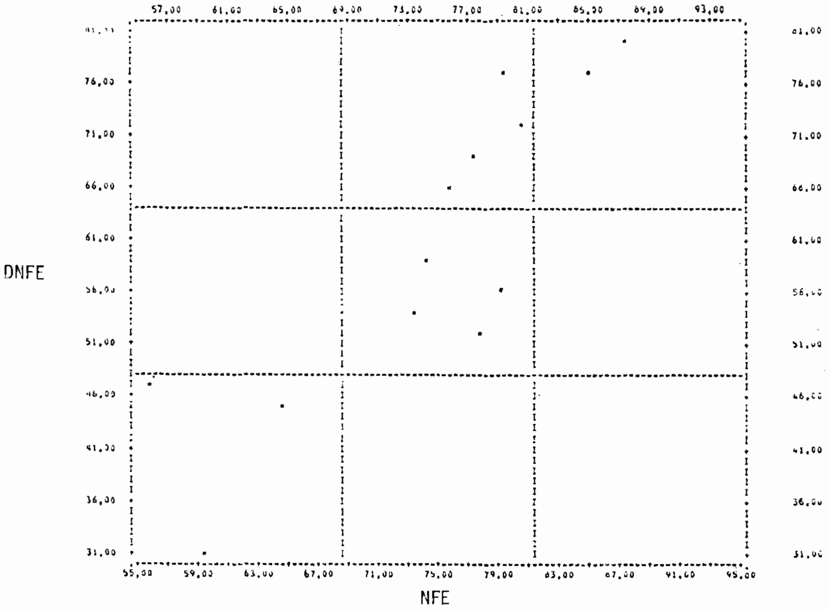

FIGURE 60 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of energy feeds for horses.

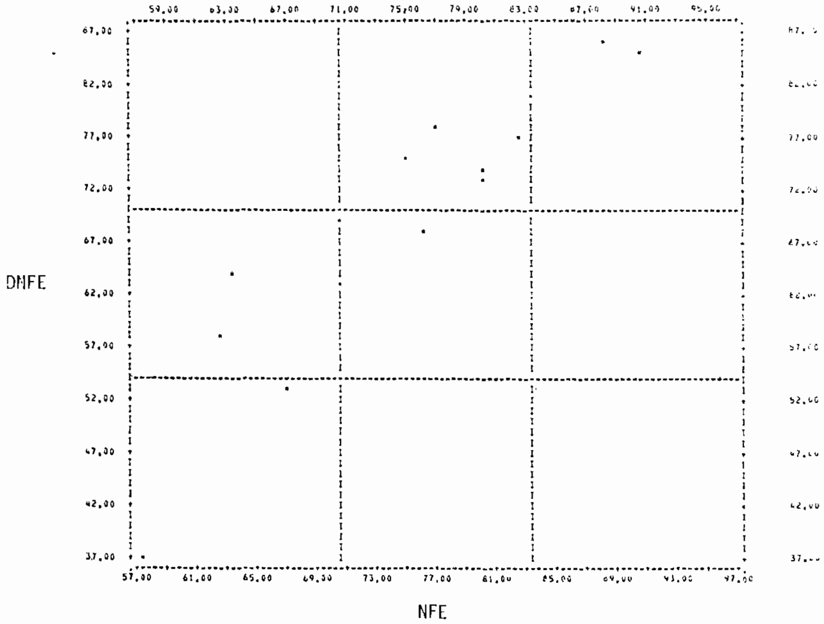

FIGURE 61 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of energy feeds for rabbits.

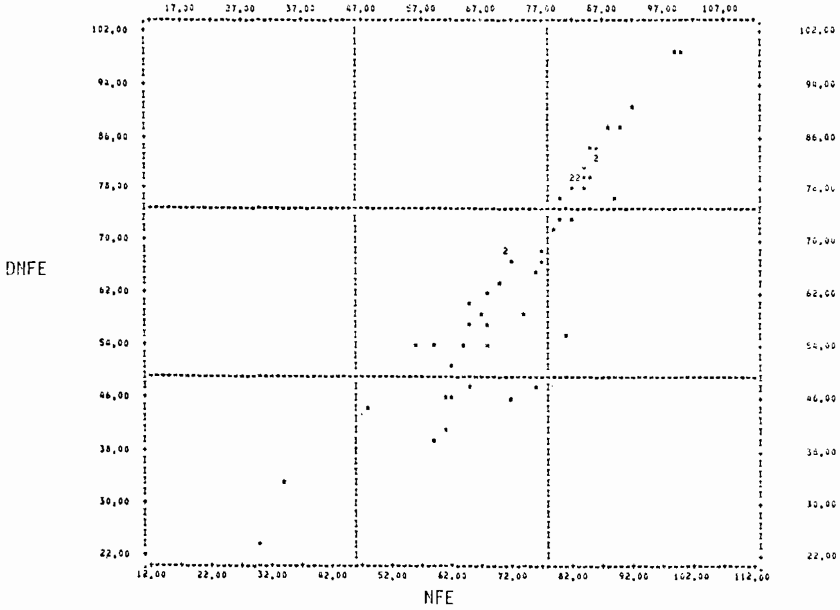

FIGURE 62 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of energy feeds for swine.

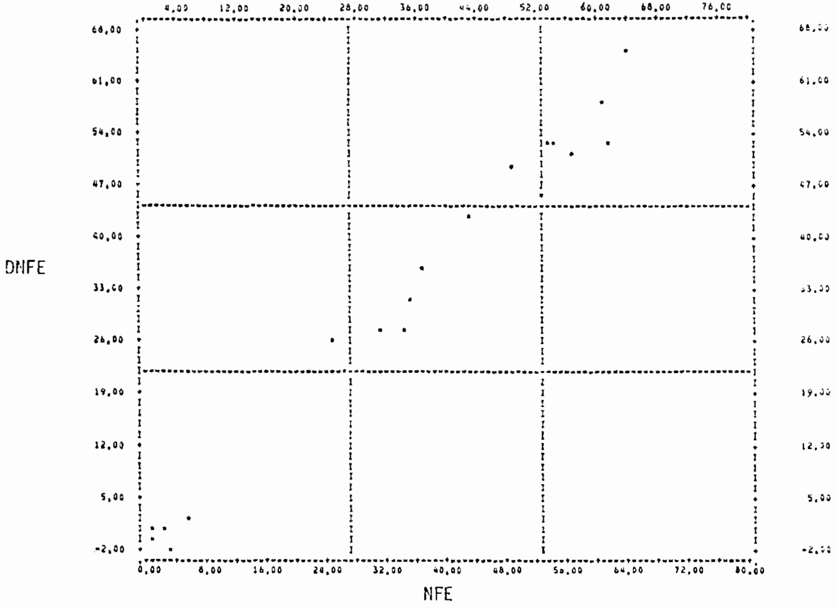

FIGURE 63 Predicting digestible nitrogen free extract (DNFE%) from nitrogen free extract content (NFE%) of protein supplements for swine.

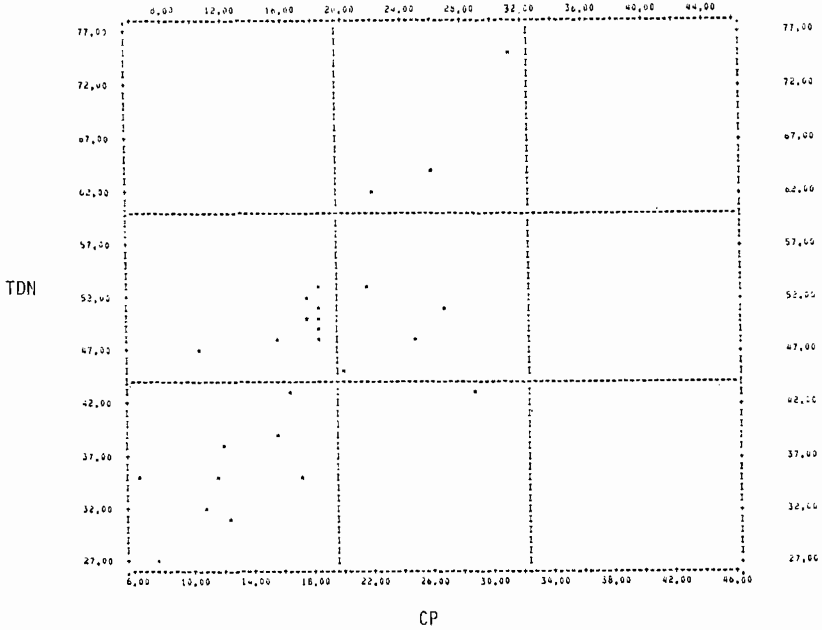

FIGURE 64 Predicting total digestible nutrients (TDN%) from crude protein content (CP%) of dry forages and roughages for rabbits.

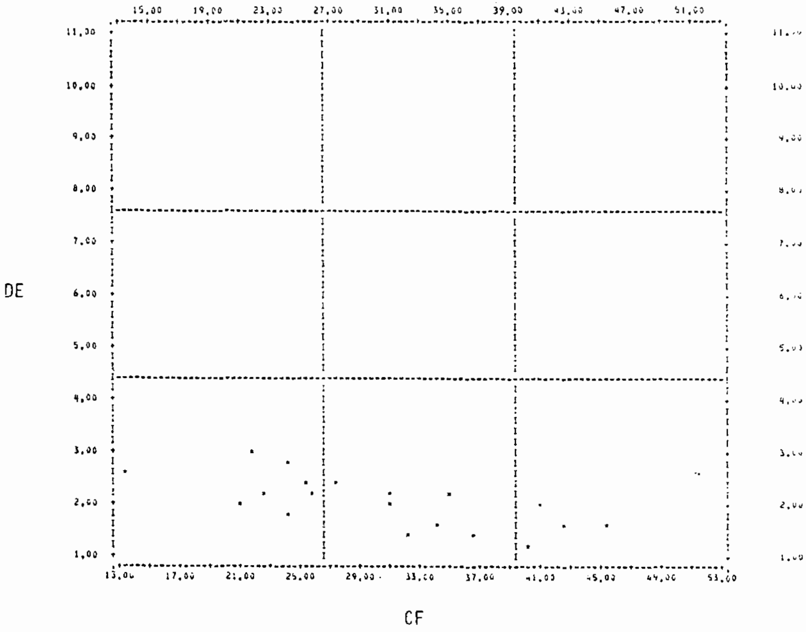

FIGURE 65 Predicting digestible energy (DE = Mcal/kg) from crude fiber content (CF%) of dry forages and roughages for rabbits.

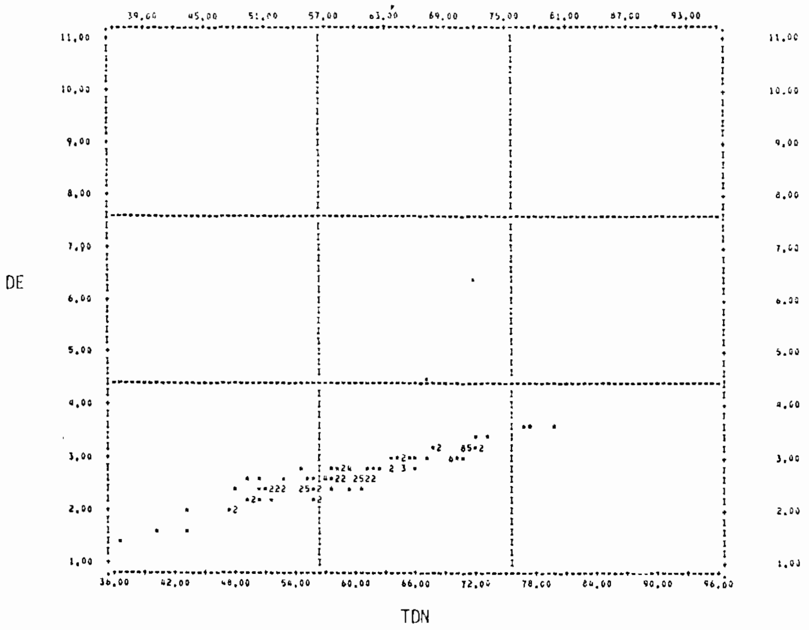

FIGURE 67 Predicting digestible energy (DE = Mcal/kg) from TDN% of dry forages and roughages for sheep.

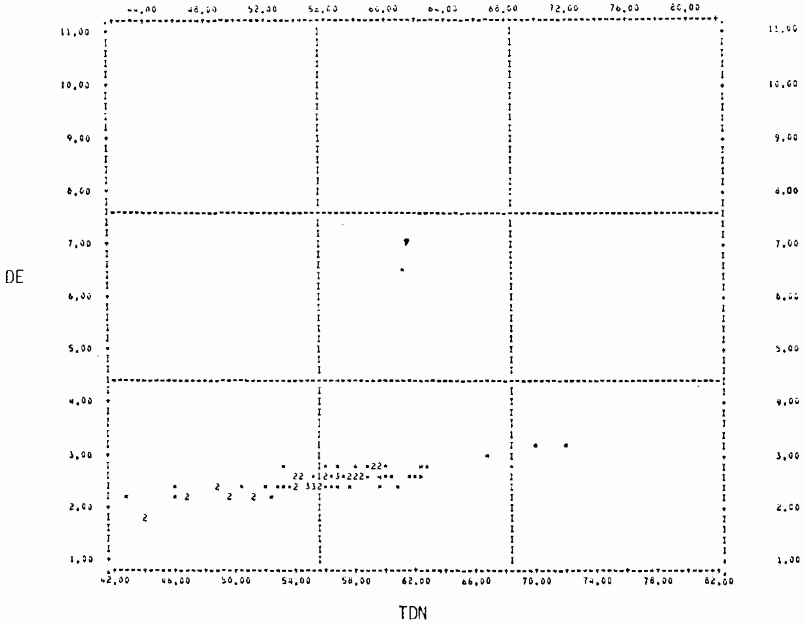

FIGURE 68 Predicting digestible energy (DE = Mcal/kg) from TDN% of dry forages and roughages for cattle.

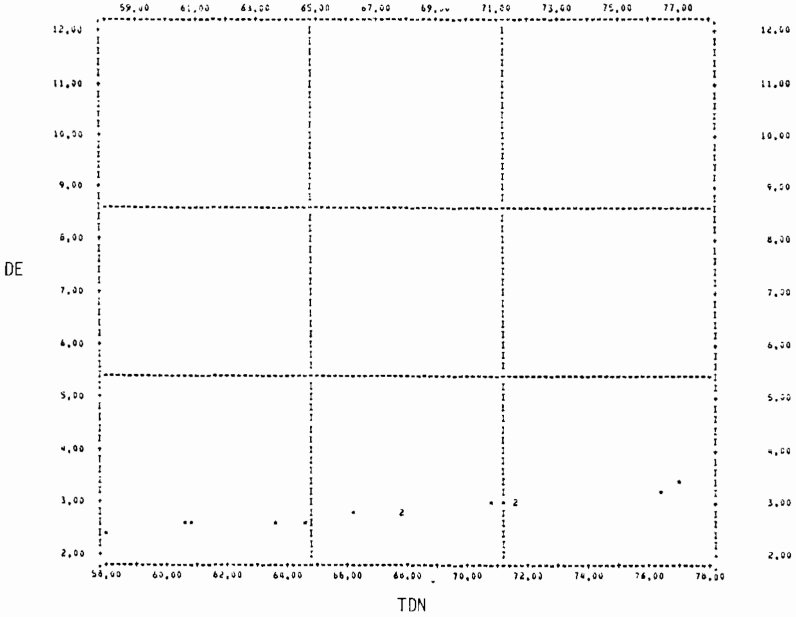

FIGURE 69 Predicting digestible energy (DE = Mcal/kg) from TDN% of pasture, range and forages fed green for cattle.

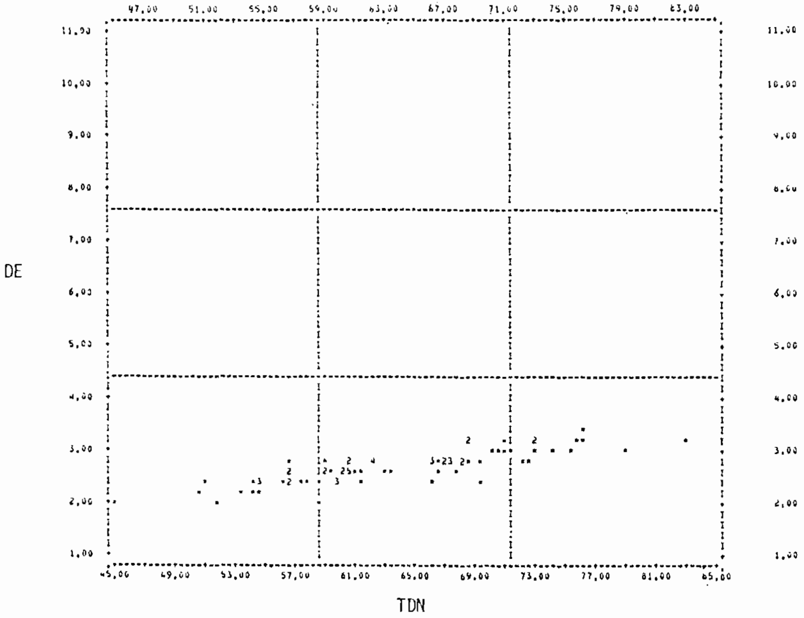

FIGURE 70 Predicting digestible energy (DE = Mcal/kg) from TDN% of silages for cattle.

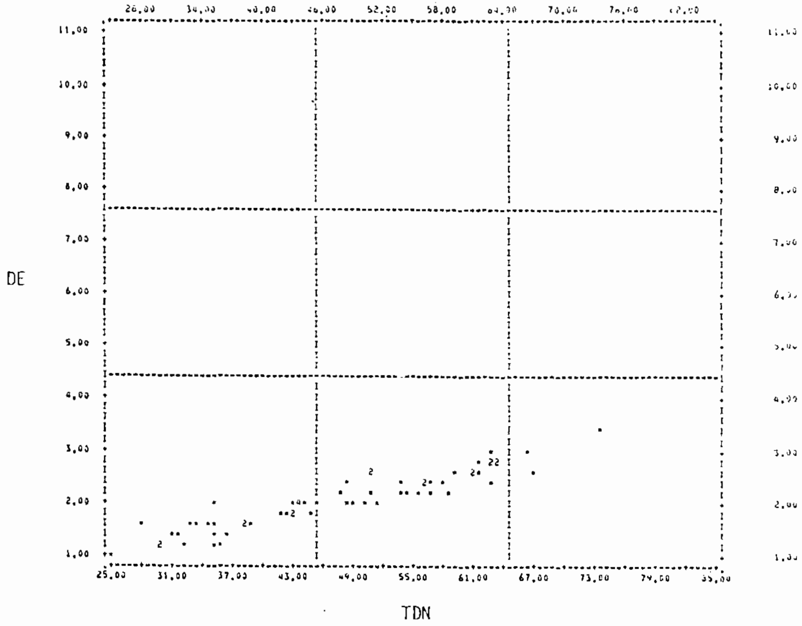

FIGURE 71 Predicting digestible energy (DE = Mcal/kg) from TDN% of pasture, range and forages fed green for sheep.

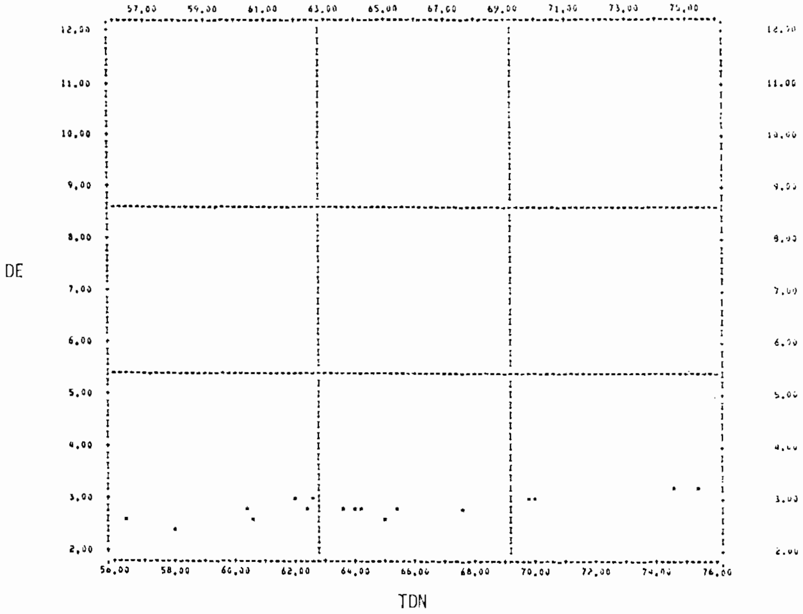

FIGURE 72 Predicting digestible energy (DE = Mcal/kg) from TDN% of silages for sheep.

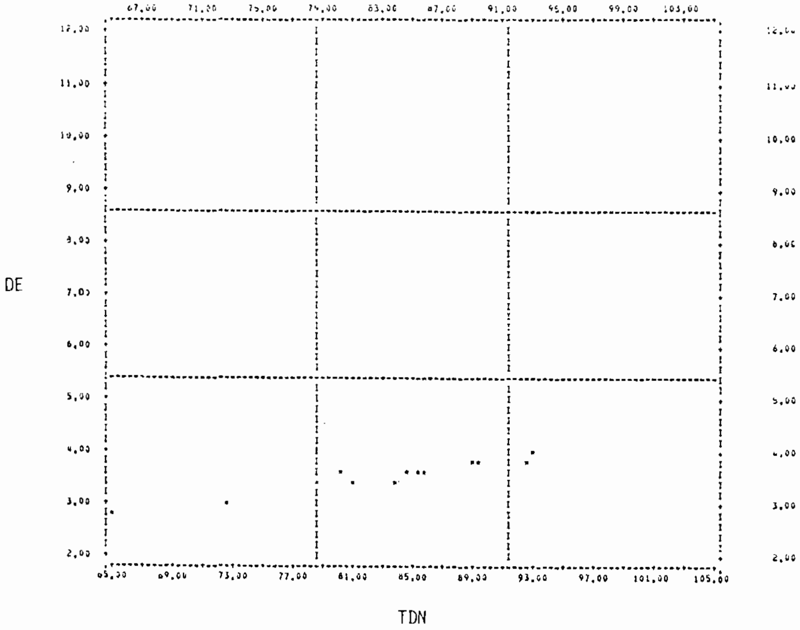

FIGURE 73 Predicting digestible energy (DE = Mcal/kg) from TDN% of feed energy for cattle.

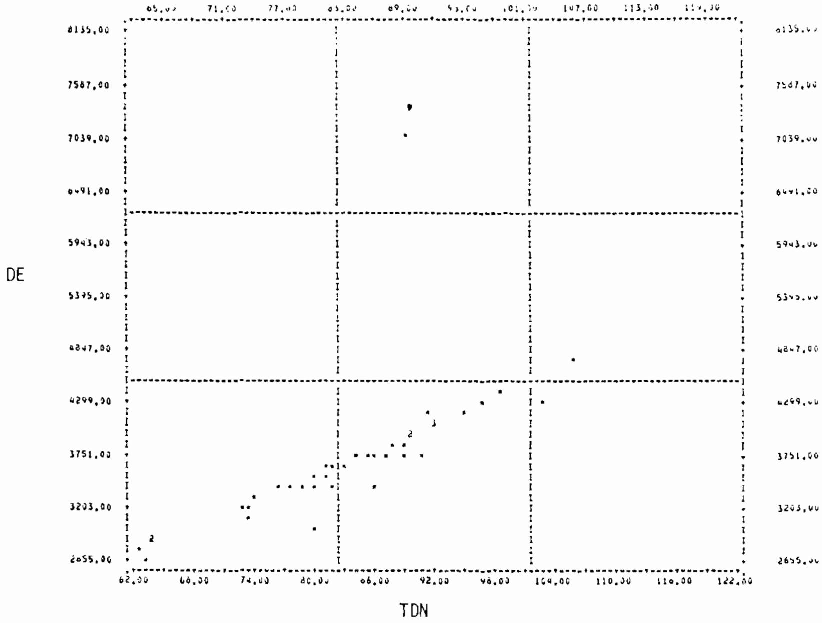

FIGURE 74 Predicting digestible energy (DE = Mcal/kg) from TDN% of energy feeds for swine.

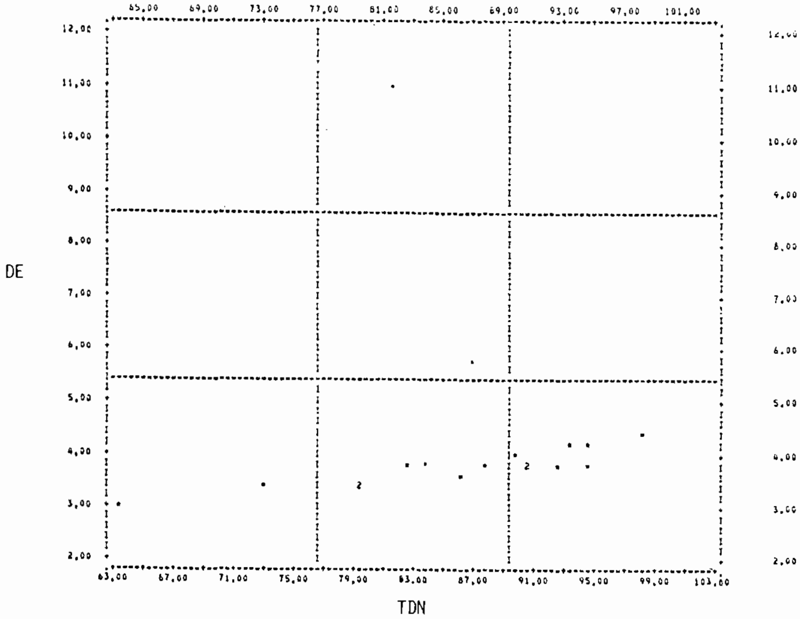

FIGURE 75 Predicting digestible energy (DE = Mcal/kg) from TDN% of energy feeds for rabbits.

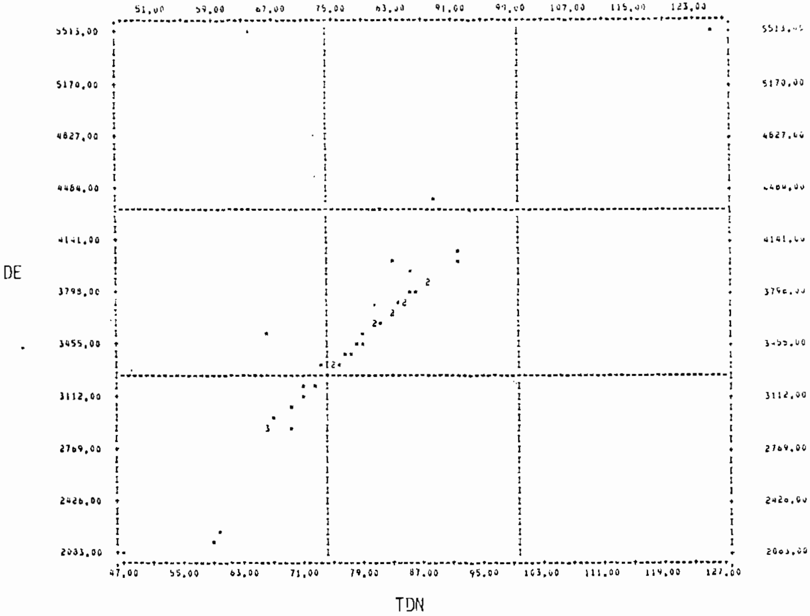

FIGURE 76 Predicting digestible energy (DE = Mcal/kg) from TDN% of protein supplements for swine.

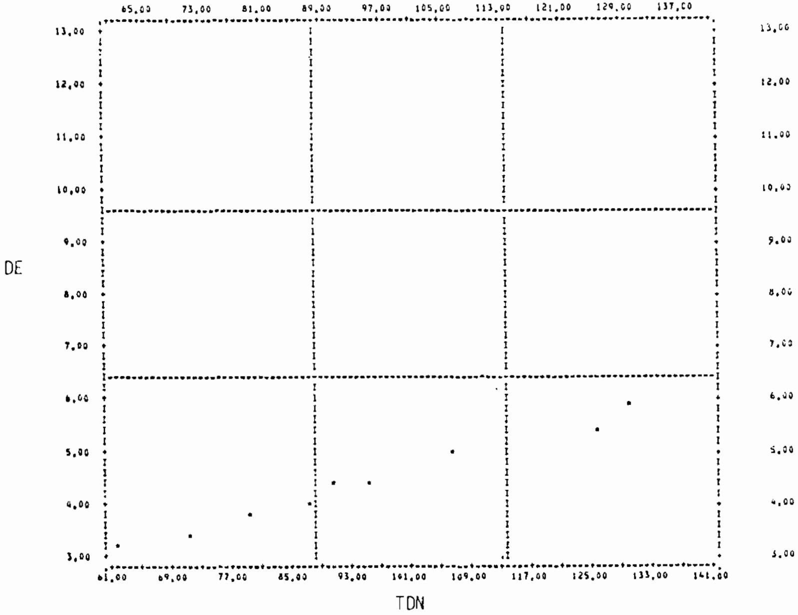

FIGURE 77 Predicting digestible energy (DE = Mcal/kg) from TDN% of protein supplements for rabbits.

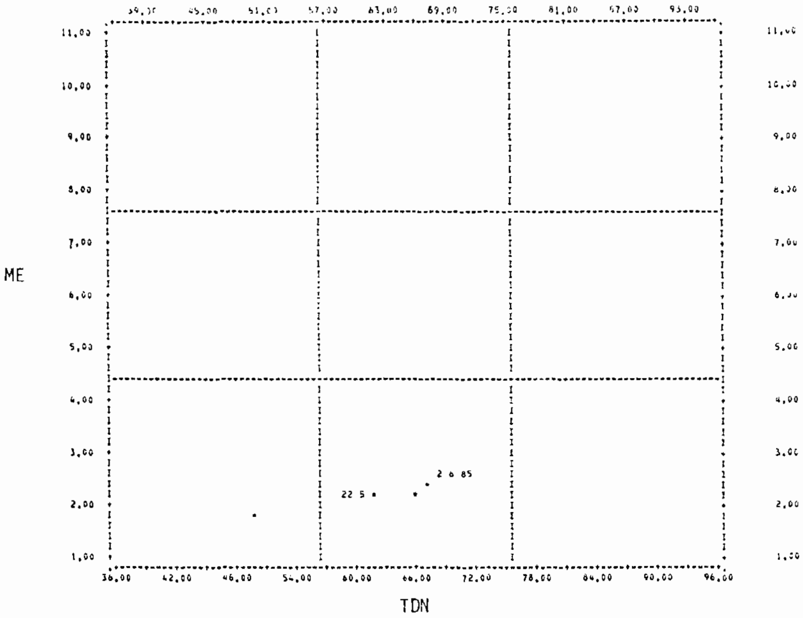

FIGURE 78 Predicting metabolizable energy (ME = Mcal/kg) from TDN% of dry forages and roughages for sheep.

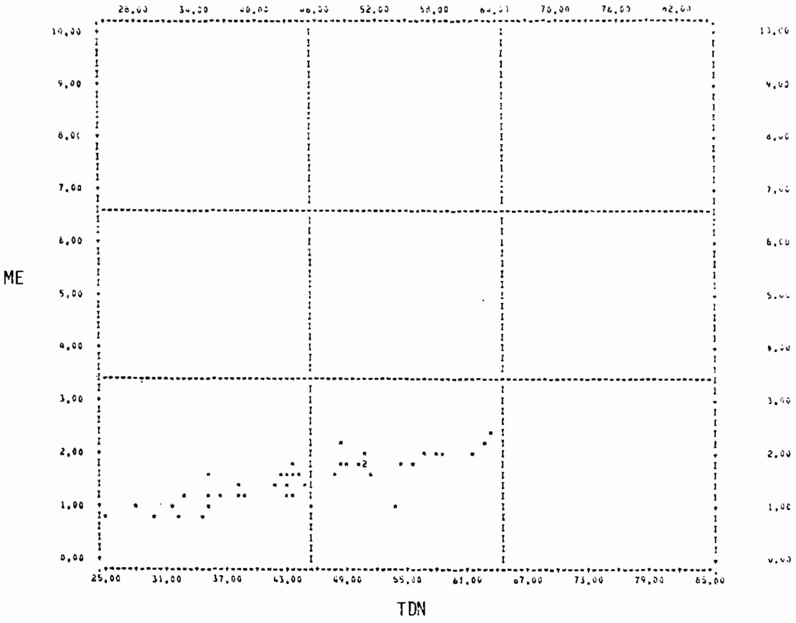

FIGURE 79 Predicting metabolizable energy (ME = Mcal/kg) from TDN% of pasture, range and forages fed green for sheep.

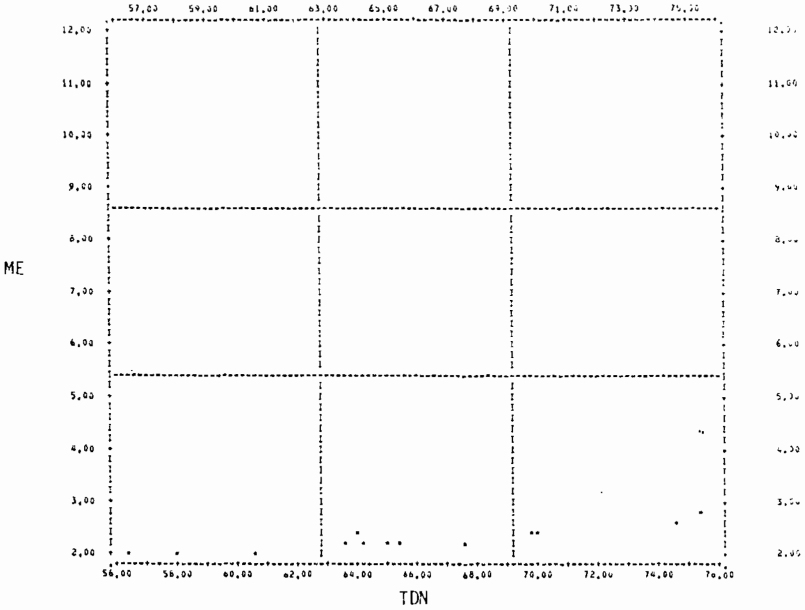

FIGURE 80 Predicting metabolizable energy (ME = Mcal/kg) from TDN% of silages for sheep.

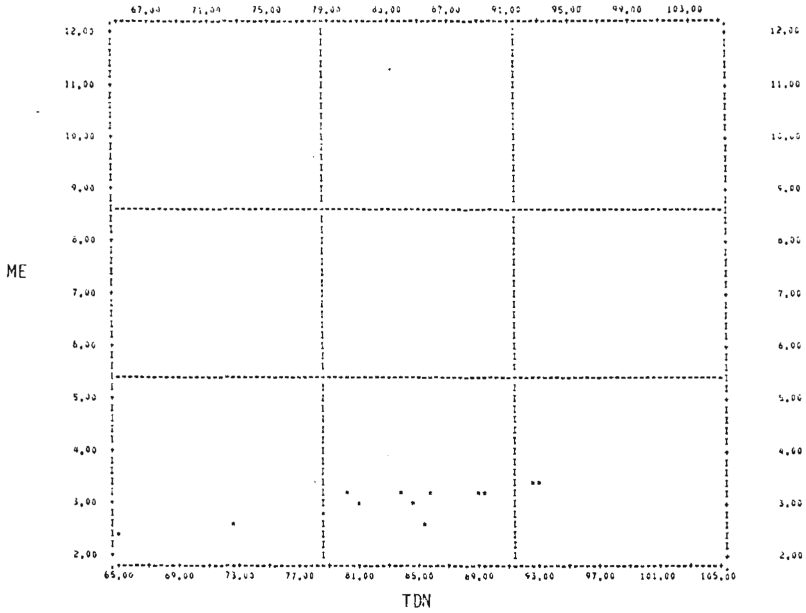

FIGURE 81 Predicting metabolizable energy (ME = Mcal/kg) from TDN% of energy feeds for cattle.

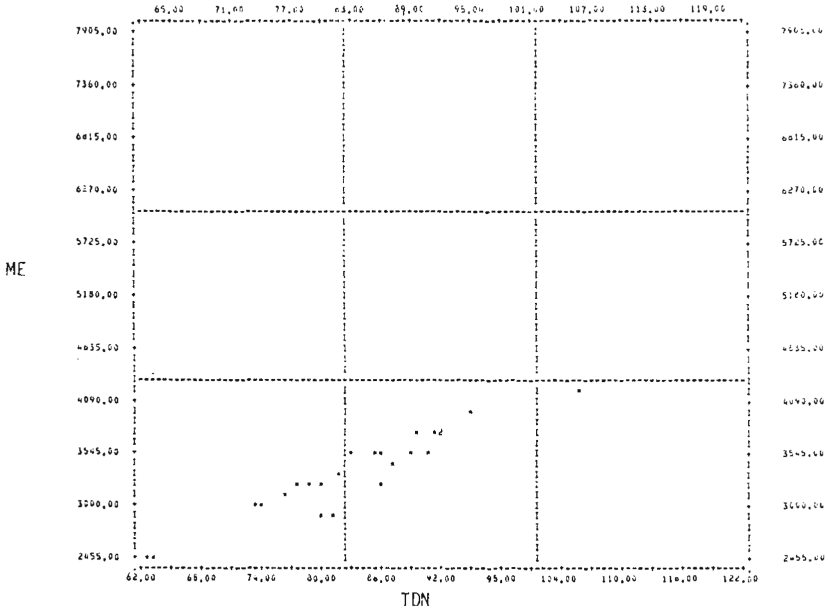

FIGURE 82 Predicting metabolizable energy (ME = Mcal/kg) from TDN% of energy feeds for swine.

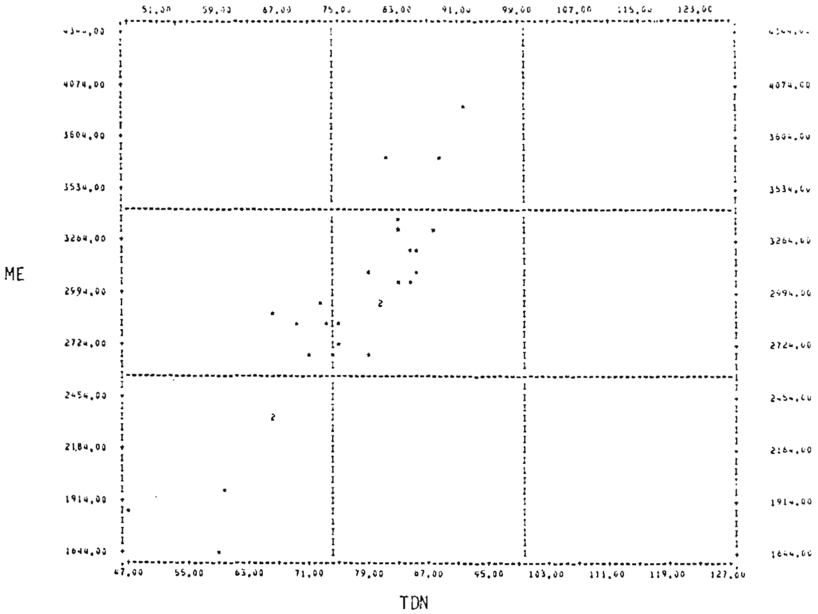

FIGURE 83 Predicting metabolizable energy (ME =Mcal/kg) from TDN% of protein supplements for swine.

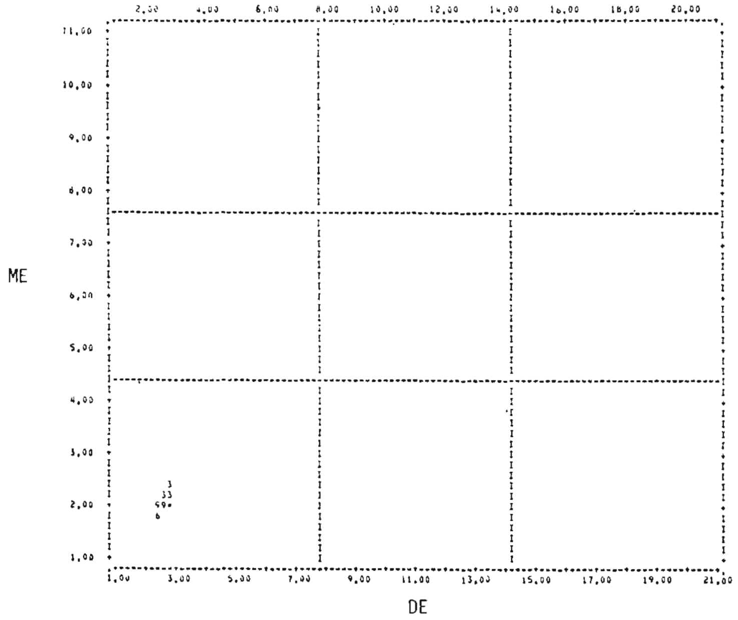

FIGURE 84 Predicting metabolizable energy (ME = Mcal/kg) from digestible energy (DE = Mcal/kg) content of dry forages and roughages for cattle.

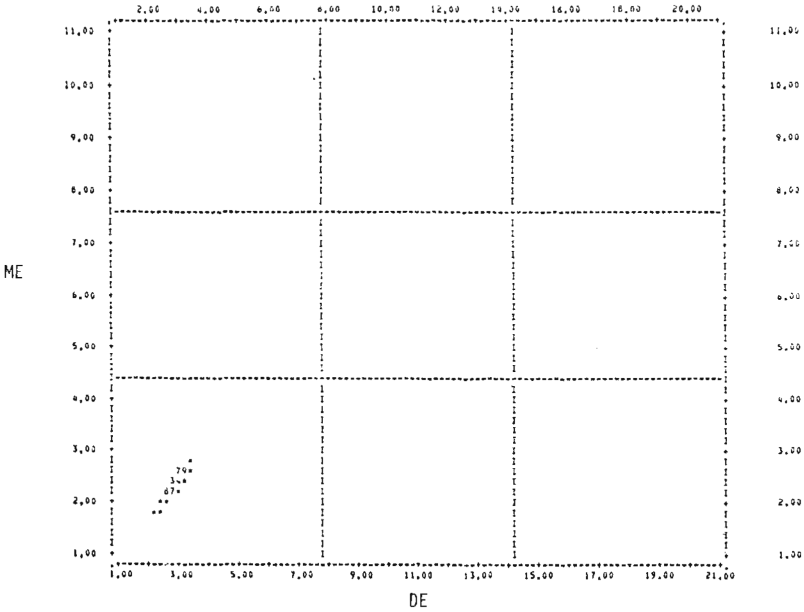

FIGURE 85 Predicting metabolizable energy (ME = Mcal/kg) from digestible energy (DE = Mcal/kg) content of dry forages and roughages for cattle.

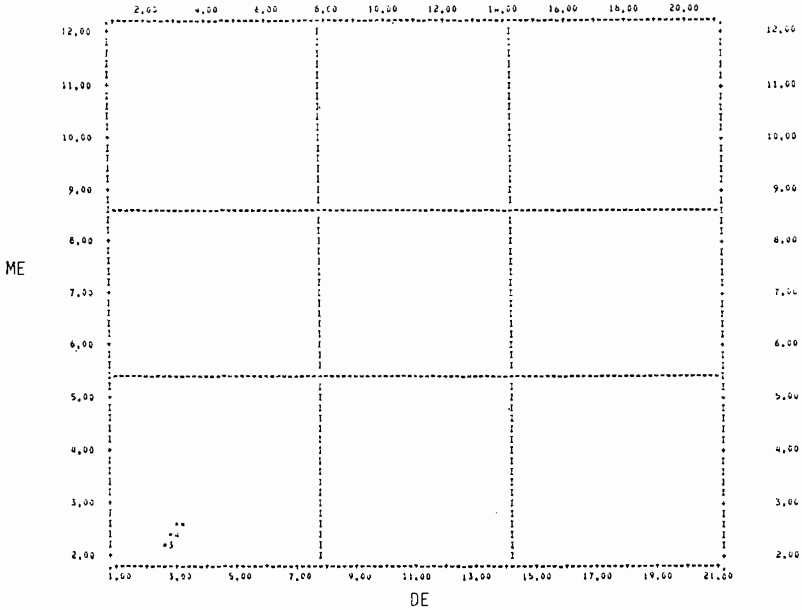

FIGURE 86 Predicting metabolizable energy (ME = Mcal/kg) from digestible energy (DE = Mcal/kg) content of silages for cattle.

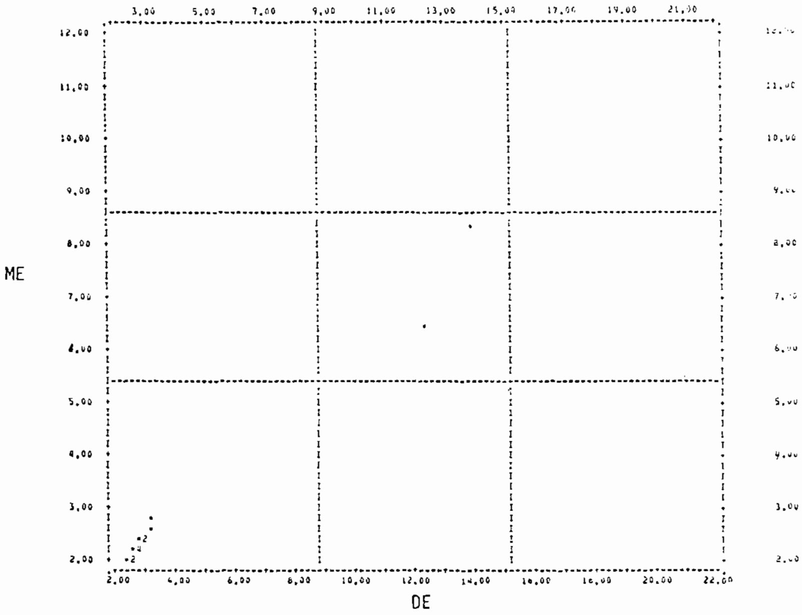

FIGURE 87 Predicting metabolizable energy (ME = Mcal/kg) from digestible energy (DE = Mcal/kg) content of silages for sheep.

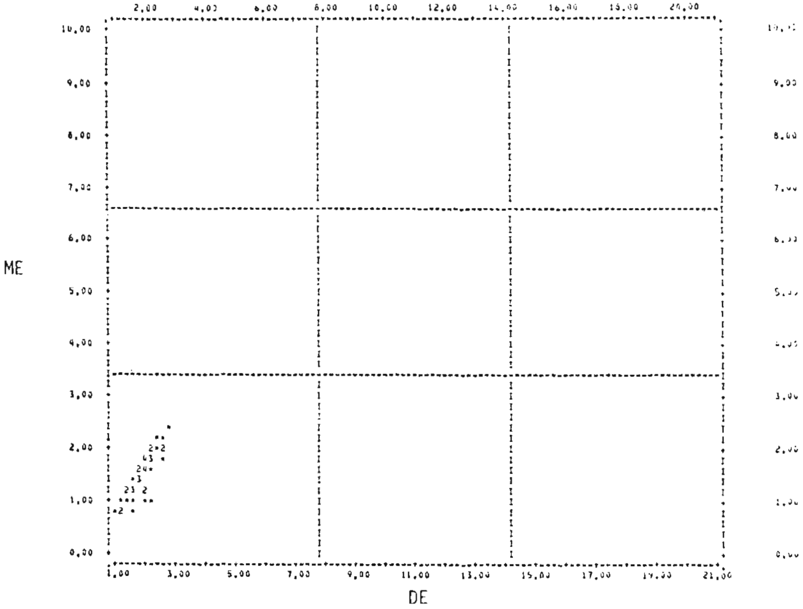

FIGURE 88 Predicting metabolizable energy (ME = Mcal/kg) from digestible energy (DE = Mcal/kg) content of pasture, range plants and forages fed green for sheep.

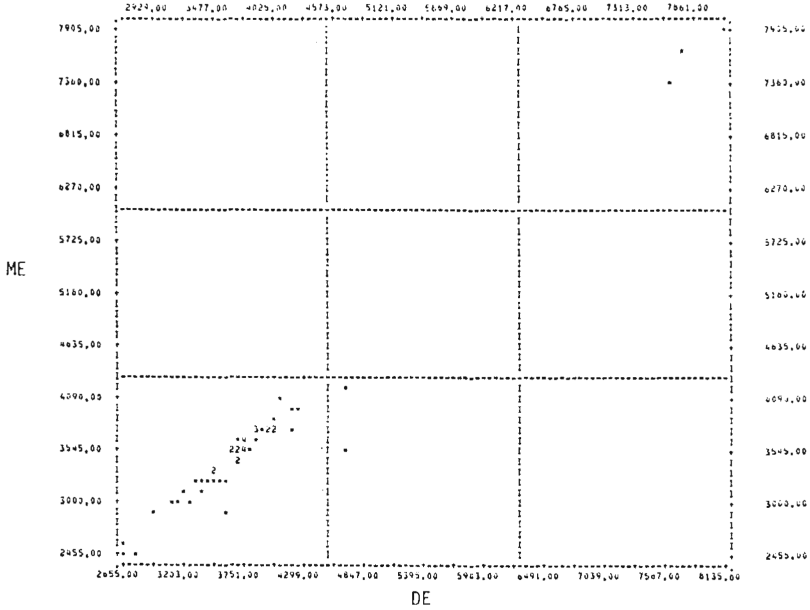

FIGURE 89 Predicting metabolizable energy (ME = Mcal/kg) from digestible energy (DE = Mcal/kg) content of energy feeds for swine.

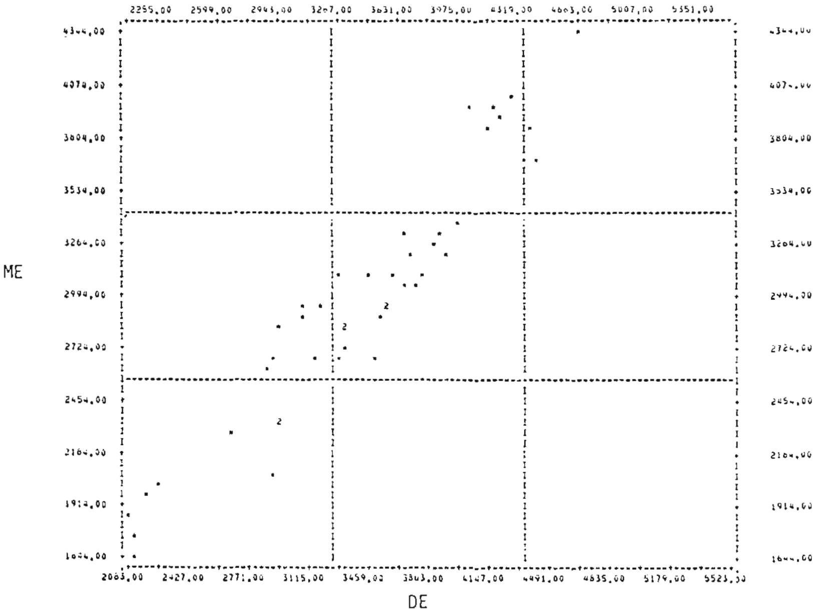

FIGURE 90 Predicting metabolizable energy (ME = Mcal/kg) from digestible energy (DE = Mcal/kg) content of protein supplements for swine.

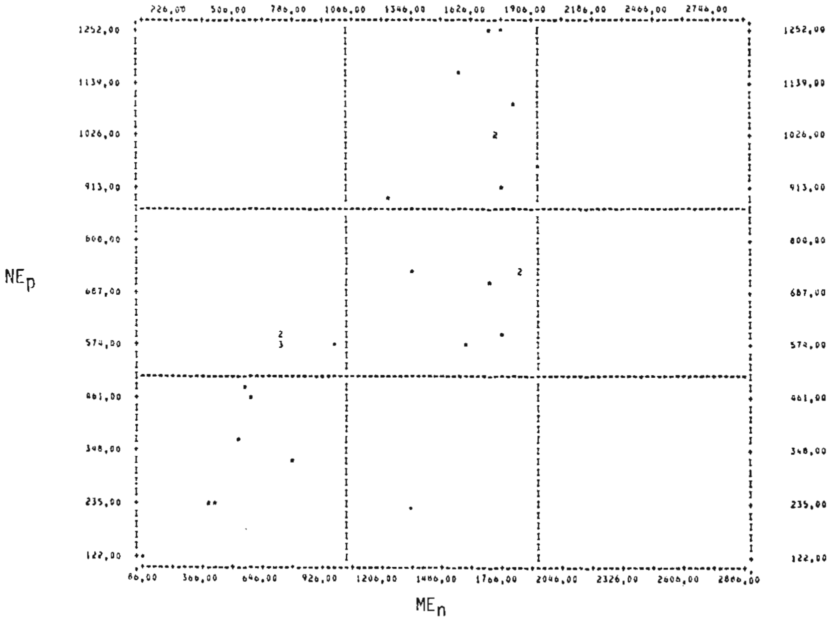

FIGURE 91 Predicting net energy for production (NE_p = kcal/kg) from nitrogen-corrected metabolizable energy (ME_n = kcal/kg) of dry forages for poultry.

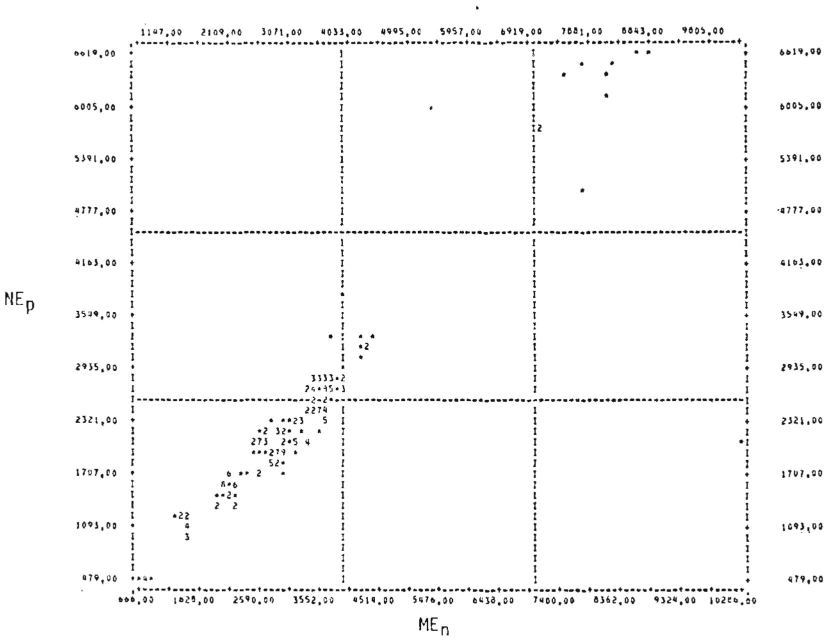

FIGURE 92 Predicting net energy for production (NE_p = kcal/kg) from nitrogen-corrected metabolizable energy (ME_n = kcal/kg) of energy feeds for poultry.

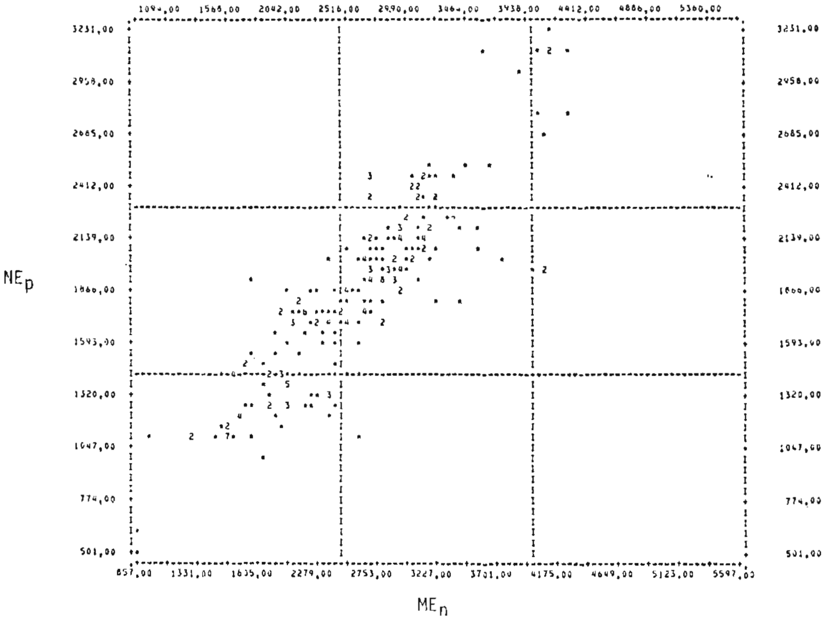

FIGURE 93 Predicting net energy for production (NE_p = kcal/kg) from nitrogen-corrected metabolizable energy (ME_n = kcal/kg) of protein supplements for poultry.

VITA

Muhammad Fadel Wardeh

Candidate for the Degree of

Doctor of Philosophy

Dissertation: Models for Estimating Energy and Protein Utilization for Feeds

Major Field: Animal Science

Biographical Information:

Personal Data: Born at Taldarah, Salamieh, Syria, January 9, 1943; Married with three children.

Education: Attended Taldarah Elementary School, graduated from Alibin Abi Taleb High School, Salameih, Syria in 1962; received the Bachelor of Agriculture Science and Agriculture Engineer Diploma from the American University of Beirut, Lebanon in 1968; 1969 completed requirements for the Master of Science degree at the American University of Beirut, Lebanon, with a major in Animal Production; 1981 completed the requirements for the Doctor of Philosophy degree at Utah State University, with a major in Animal Science (Animal Nutrition).

Professional Experience: 1968-69, graduate assistant at the American University of Beirut, Lebanon; 1970-71, Head of Animal Production division at Deraa dairy station, Syria; 1971, Head of Animal Production, Directory of State Farms, Ministry of Agriculture and Agrarian Reform, Damascus, Syria; 1971-72, Head of Animal Science Division and Director of Der-El-Hajar Research Station, Directory of Agricultural Scientific Research, Damascus, Syria; 1973-75, Head of the Third Poultry Project, Damascus, Syria; 1976-78, Animal Production Specialist at the Arab Center for the Studies of Arid Lands and Dry Zones (League of the Arab States), Damascus, Syria; 1978-81, Graduate research assistant at the Department of Animal, Dairy and Veterinary Sciences, Utah State University; published 12 papers in Arabic and a co-author of "Arab and Middle East Tables of Feed Compositions" published by Utah State University and the Arab Center for the Studies of Arid Lands and Dry Zones, 1979.