Efficiency of Feed Conversion

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Each year in the United States we harvest about 15 million tons of beef, veal, pork, and lamb carcass meat, about 4 million tons of poultry meat, 1 million tons of edible offal, 60 million tons of milk, and 4 million tons of eggs. To produce these quantities of food, we feed our livestock and poultry about 600 million tons of dry matter. The cost of feed is more than half the cost of producing meat, milk, and eggs. More efficient use of feed could make available more animal products for human consumption.

The efficiency of livestock in the conversion of feed protein to protein for human consumption is limited by the cost of the feed used in maintaining breeding flocks and herds, by the varying composition of readily available feeds, and by the adequacy of the technology on which their use is based.

Dramatic improvement in efficiency of feed conversion in broiler production has made this source of "high-quality" protein cheap and plentiful. On the Delmarva Peninsula, in Maine and Mississippi, in other states and other countries, broiler chickens are reared so skillfully that we may someday expect that a pound of feed will produce a pound of live chicken.

In 1934 (at the bottom of the depression) U.S. production of commercial broilers was just under a hundred million pounds liveweight; in 1965 more than 7 billion pounds were produced—a 70-fold increase. The live price in 1934 was about 19 cents per pound; in 1965 about 15 cents. Research, development, and invention made this phenomenal increase in volume and the concomitant decrease in price possible.

The realized efficiency of conversion of feed protein into meat, milk, egg, and poultry protein available for consumption is shown in Fig. 1. Included in these estimates are the unknown but substantial amounts of purchased protein which go into the garbage or are fed to the family pets. The estimated protein in the feed supply is based on digestible protein, generally about 80 percent of the crude protein present in feed. It takes about 7.5 kg of digestible feed protein to produce a kilogram of protein for us to eat.

More than half the feed protein still comes from grass and other roughages (Table 1). Most of our cattle, beef, and sheep are still produced in the pasture or range, or they are fed harvested roughage. However, concentrate feeding of beef cattle is increasing very rapidly. In 1949–50, beef cattle consumed about 9 percent of all concentrates fed; in 1964–65, about 21 percent (*1*).

The Committee on Animal Nutrition of the National Academy of Sciences–National Research Council (NAS-NRC) has assembled authoritative estimates of the nutritive requirements of the several livestock species (*2–5*). These estimates depend on the basal metabolism of the species, environment of rearing the animals, losses of energy consumed, and others.

Many measurements of basal metabolism have been made, most of them by measurement of O_2 consumption or CO_2 production. Fewer have been made with direct measurement of heat production. During the past 30 years a consensus has developed that the basal metabolism of animals, varying in size from mouse to elephant, is proportional to the 3/4th power of body weight (*6–7*).

Efficiency of feed conversion to body tissue is limited by digestibility of the feed and by the animal's energy (carbohydrate and fat) and protein requirements for function, growth, and tissue repair. Other limiting factors include energy lost in metabolic end products, such as methane (especially by ruminants) and urea or uric acid, and in heat resulting from the metabolic processes and from exercise and excitement.

Digestible Nutrients

Air-dried feeds vary in digestibility by ruminants, from about 40 percent for wheat straw to about 80 percent for corn. Pigs and poultry digest corn as well as ruminants do, but their ability to digest roughages is limited. However, when pigs are fed pure cellulose, they may digest about 50 percent of it. In that cellulose is a principal constituent of roughage, it may be assumed the pigs do digest some when it is a component of roughage (*8*). Poultry, except geese, probably digest little roughage.

Digested feed, generally referred to as "total digestible nutrients," is used as a reference point both in research and in feed formulation. These digestible nutrients probably contain about 4.4 kilocalories per gram or 2000 kilocalories per pound. All digestible energy fed does not become available for metabolism. In ruminants, about 10 percent is lost in the urine and about 8 percent as methane. Metabolizable energy (ME) usually amounts to about 82 percent of digestible energy, but this factor is subject to variation from species to species.

Contributing to the loss of digestible energy is the methane produced during the fermentation of vegetable materials in the gut. In a cow's rumen, methane production may amount to as much as 400 liters in 24 hours and in a sheep's, as much as 50 liters (*9*).

Heat Increment

The term "heat increment" (HI) describes the increase in heat production after consumption of feed when the animal is in a thermoneutral environment (*10*). For adults this thermoneutral temperature ranges from about 10° to 15°C to about 25° to 30°C. Metabolism increases above or below these ranges.

The heat increment cannot be separated directly either from heat resulting from activity or from that used in the process of metabolism, and therefore these amounts are included in the heat increment. By making this in-

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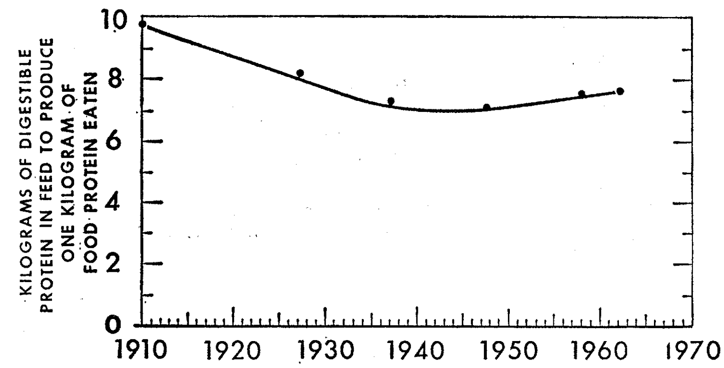


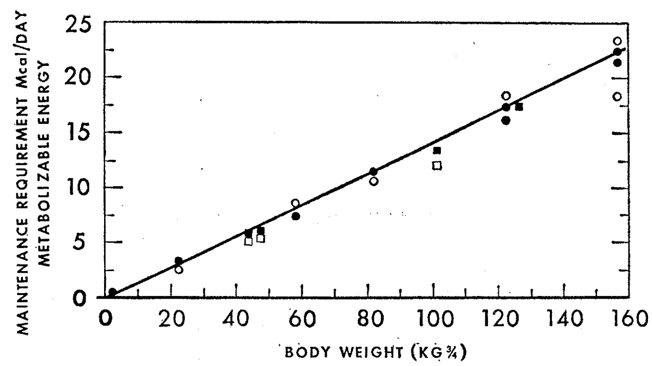


Fig. 1 (left). Digestible protein in livestock feed used to produce each kilogram of protein in meat, poultry, eggs, and dairy products eaten in the United States. Fig. 2 (right). Observed and calculated values for metabolizable energy required for maintenance of chickens, sheep, swine, and beef and dairy cattle. ○ NAS-NRC estimates for beef and dairy cattle, sheep, swine and chickens; ● Calculated values; □ Data of Thomas and Moore (*39*), Wiltbank *et al.* (*40*), and Winchester and Howe (*13*); ■ Data of Flatt (*13*).

clusion, it is valid to assume that there is similar efficiency in the use of both energy and protein above maintenance, regardless of age, species or end product.

Maintenance

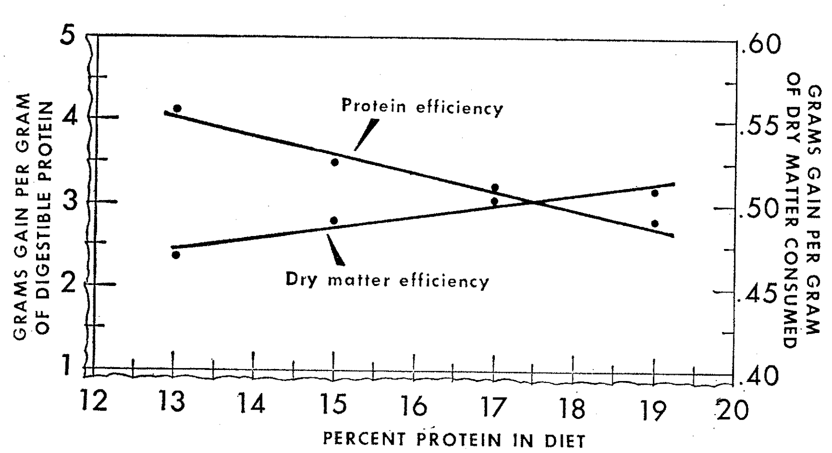
Measurement of maintenance energy varies with the conditions—principally with the amount of exercise permitted. Maintenance energy includes that for the "basal" or resting state, for the heat increment, and for muscular activity. Estimates of maintenance energy are further complicated by the fact that the live animal may change in body composition without showing change in weight. Special attention must be given to maintenance requirements of (i) mature females during nonlactating periods, either when the female is not pregnant or during early pregnancy; (ii) for mature males during nonbreeding periods; and (iii) for wintering cattle and sheep during a growing period (Fig. 2). Maintenance requirements (NAS-NRC) for sheep are relatively lower than for other classes of livestock (*11*).

Several workers have pointed out that production and feed consumed above that required for maintenance [when the tissues are not losing more energy than is gained (*11*)] have a linear relationship. Kleiber (*6*) reasoned that the law of diminishing returns does not apply to animal feeding because an animal must produce either an animal product or heat. There is a linear relation between energy retained by growing and fattening cattle and feed consumed above maintenance (*12*); and Flatt *et al.* (*13*) found a similar relation with respect to milk production. However, there is an indication that there is a higher requirement per kilogram of milk produced by high-yielding cows (*14*).

Breakdown of body tissues produces small amounts of nitrogenous wastes which are excreted in the urine and into the intestine. In mammals, urea is the principal nitrogenous end product; in birds, it is uric acid. It is difficult to distinguish between nitrogenous excretory products resulting from tissue breakdown and similar products resulting from the metabolism of nitrogenous products in ingested feed.

Animals with one stomach, such as poultry and swine, must have minimum amounts of ten essential amino acids in their diets. Methionine and lysine appear to be the most limiting amino acids in unsupplemented corn-soy diets for poultry.

Ruminants have in their paunches a complex microbial flora which, to a varying extent, is capable of synthesizing essential amino acids from other amino acids and from simpler nitrogenous compounds, such as urea and ammonia, under appropriate conditions. Within rather wide limits, efficiency of feed conversion of growing animals increases as digestible protein in the diet increases, while, conversely, efficiency of protein utilization decreases (*15*) (Fig. 3).



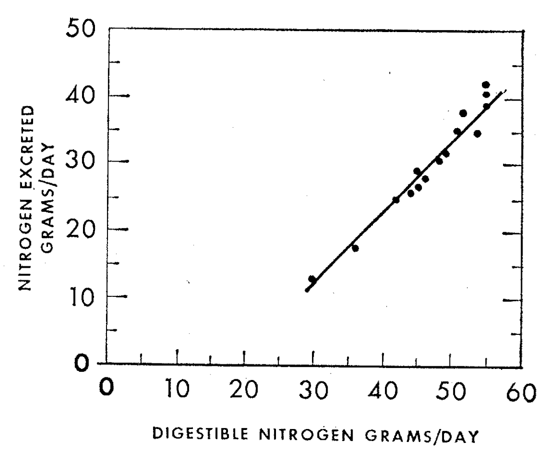


Fig. 3 (left). Efficiency of feed and protein conversion of pigs affected by level of protein in the diet. Fig. 4 (right). Nitrogen excretion is proportional to digestible nitrogen ingested.

Table 1. Livestock and livestock products produced in the United States in 1949–50 and 1959–60, and the feed concentrates used in total and percent output (*1*).

Product	Production (billions of pounds)		Feed concentrates fed			
			Millions of tons		Pounds fed per pound of production	
	1950	1960	1950	1960	1950	1960
Milk cows (milk)	116.7	122.4	18.6	26.4	0.318	0.398
Sheep (liveweight)	1.3*	1.7	0.6	1.2	0.90*	1.50
Hogs (liveweight)	19.9	20.2	46.6	44.6	4.7	4.4
Eggs	7.4	7.8	18.1	15.9	4.9	4.1
Chickens (liveweight)	2.9	1.6	8.5	3.8	6.0	4.8
Broilers (liveweight)	1.9	6.0	3.2	7.5	3.4	2.5
Turkeys (liveweight)	0.8	1.5	2.1	3.3	5.2	4.4
Oother cattle (liveweight)	21.2†	28.7†	13.7	27.5	1.2	1.9

* *Agricultural Statistics* (U.S. Dept. of Agriculture). † All beef and veal.

Also, animals that are fed an adequate diet ad libitum excrete nitrogen in proportion to the intake of digestible nitrogen (Fig. 4). In general, protein deposition proceeds at a steady rate to maturity (Fig. 5). On the other hand, animals of the same age, sex, and species in the same favorable environment will store fat in direct proportion to metabolizable energy ingested (Fig. 6).

Measurements of Feed Efficiency

Measurements of feed efficiency in terms of units of feed producing a unit of liveweight fail to account for the wide variations in the nutritive value of feeds. The use of a standard such as the corn equivalent feed units (CFU) in United States Department of Agriculture statistics on feed disappearance helps to equate these differences (*15*). Expression of feed efficiency as feed units per unit gain also fails to account for differences in the ultimate size and composition of the carcass. Nevertheless, much information may be gained by comparing efficiencies under NAS-NRC requirements and imputed efficiencies now achieved in practice (Fig. 7). Two facts are striking. First, feed for the dam is a very large part of the feed cost of producing beef and lamb, and it is relatively small in producing pigs and broilers. Second, the NAS-NRC requirements approximate existing imputed efficiencies for the beef, lamb, and broiler enterprises, namely about 10, 14, and 3 CFU per unit of liveweight, respectively. However, the imputed efficiency for a swine enterprise, about 5.5 CFU per unit of liveweight is more than 50 percent in excess of NAS-NRC requirements. This difference may result from the method of partitioning feed disappearance, but surely it also indicates important possibilities for improvement in feeding practices.

The feed efficiency for beef, lamb, milk, and swine production imputed from feed disappearance data has improved but little during the past 25 years. The efficiency of egg production has increased about 20 percent—an increase reflecting the steady increase in egg production per hen. The feed efficiency of broiler production has improved steadily from an imputed requirement of about 4.9 CFU per unit of liveweight of broiler produced to less than 3 CFU (Fig. 8).

For feeding beef cows during the first 3 to 4 months after calving the NAS-NRC recommends that sufficient nutrients be provided to sustain production of 10 kg of milk per day; this is a liberal allowance. The milk produced should yield sufficient nutrients so that the nurtured calf weighs 110 kg at 120 days of age. In calculating the general cost of protein production, we must add about 15 percent to the cost of the cow to account for cows that had been bred but failed to raise a calf.

With respect to lamb production, the values (Fig. 9) are based on the assumption that the ewe raises a single lamb. If the ewe weans twins, the cost of the feed for the ewe would obviously be half. However, our estimated lamb crop averages slightly less than one lamb per ewe. Apart from protein food, the dam will also produce about 2 kg of clean wool, which is pure protein. The feed-disappearance value in 1963 was 15.6 kg of corn feed equivalents per kilogram of liveweight produced; the calculated value based on NAS-NRC requirements was 14.3 kg (*16*).

For pigs, the calculated value on the sow feed allowance of 3.6 kg per kilogram of liveweight should probably be discounted by 0.2 or 0.3 kg to compensate for reproductive failure. Even with a generous discount of 0.4 kg for this factor, there is a gross discrepancy between the resultant 4 kg per kilogram of liveweight produced and the value computed from feed disappearance which was about 5.7 in 1963 (*16*). The value of 2.9 kg per kilogram of liveweight for feed fed to pigs was frequently attained under test conditions—but not usually.

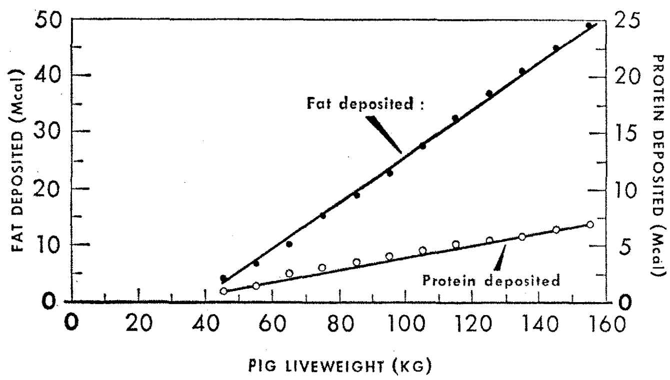
Efficiency of Nitrogen Conversion

The conversion of protein to flesh, milk, or eggs is highly efficient. It is estimated that 7 kilocalories of metabolizable energy may be required for each gram of protein converted to flesh, milk, egg, or wool (*17*). In a cow producing 50 kg of milk per day, the direct energy cost of putting 1.75 kg of protein into the milk represents only about 2.5 percent of the metabolizable energy ingested daily. The cow is not more efficient in this regard than other livestock species—probably all animals are about equally efficient. For example, Mayer (*18*) compared the efficiency of conversion of food calories into tissue calories by rats, chickens, cattle, and pigs of weanling age. All of them had an efficiency of about 35 percent.

Digestible protein is transformed into

Table 2. Annual feasible production and efficiency of several livestock species—milk and eggs (*3, 4, 25, 26, 38*).

Animal	Liveweight (kg)	Milk or egg production annual (kg)	Energy in product (Mcal)	Metabolizable energy in feed eaten (Mcal)	Energetic efficiency (%)	Protein in product (kg)	Digestible protein in feed eaten (kg)	Protein efficiency (%)
Cow	700	10,000	7500	17,000	44	350	744	47
Goat	60	500	375	1500	25	17.5	40	44
Ewe	65	200	245	1400	17.5	13	30	43
Sow	200	1000	1225	3700	33	55	144	38
Hen	1.8	17.1	25.6	128	20	1.95	5.4	36



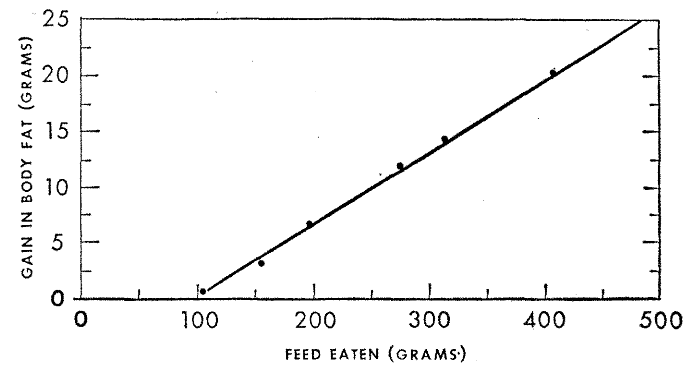


Fig. 5 (left). As pigs grow bigger, they grow fatter—but protein continues to be deposited at about 0.5 Mcal per day. Fig. 6 (right). Fat deposition in chicks fed different amounts of feed during the period when the animals are 9 to 23 days of age.

milk or egg protein at similar rates of efficiency by all classes of livestock. But within each class, the amount of milk or eggs produced per female in a given period greatly affects the apparent efficiency since the maintenance requirement of the female may be divided among as many or as few units of milk or eggs as are produced during the period (Table 2).

Efficiency of conversion of digestible protein into food protein is shown in Fig. 9. Values for steer and lamb blocks are based on the assumption that each dam rears one offspring a year. This is approximately correct for the ewe, but probably only about 80 percent of beef cows do this. The appropriate correction for reproduction failure would bring the efficiency of producing steer protein to about 10 percent.

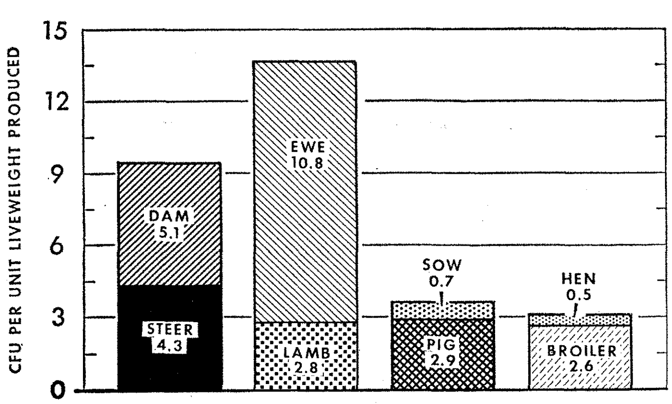
Should the practice of rearing dairy calves for beef rather than for veal become general here, as in Ireland and the United Kingdom, some increase in protein efficiency would result since much less milk—perhaps 150 kg or its equivalent, instead of up to 1000 kg for the suckled calf—would be required. This might improve protein efficiency from the present 10 percent to as much as 15 percent, a very significant improvement.

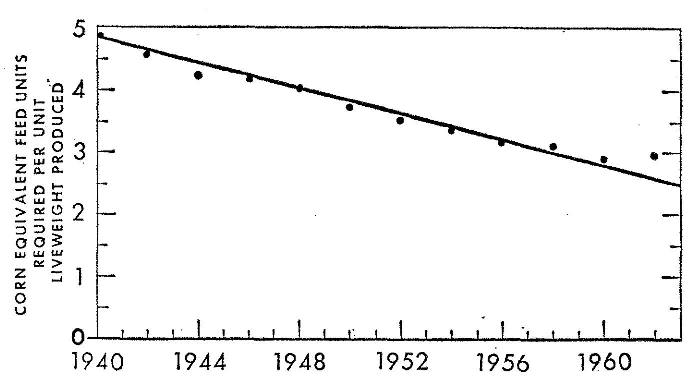
Another project to increase protein production is based on the fact that many ewes rear twins; current research on hormone-induced ovulation may lead to crops of spring and winter lamb from the same ewe flock. Two litters a year are now ordinary practice in pig-rearing. If, under such a system, each ewe produced three lambs during a year, the protein efficiency of lamb production could be doubled.

Sources of Variation and Inefficiencies

As animals of the same species and similar genetic capacity grow larger, efficiency of feed conversion into live body weight appears to decrease steadily. The apparent decrement in efficiency is enhanced by change in body composition as weight increases and as the fat content increases concomitantly.

In considering the number of kilo-





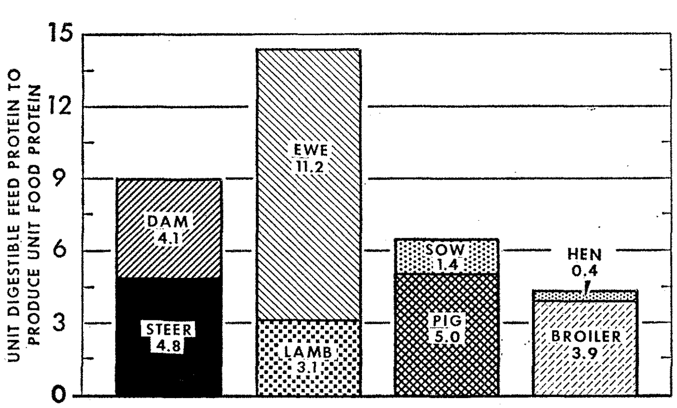


Fig. 7 (top left). Corn equivalent feed units to produce unit liveweight (NAS-NRC) require good husbandry.

Fig. 8 (left). Corn equivalent feed units required to produce unit liveweight of broilers.

Fig. 9 (above). Digestible protein required to produce unit food protein.

grams of feed necessary to produce food protein, the following experiments are of interest. Cahill *et al.* (*19*) reared calves from 2 weeks of age to a slaughter weight of 840 pounds (1 kilogram equals 2.2 pounds) in 306 days at a feed cost of 4.9 pounds of feed per pound of gain. As an adjunct to milk production, this may be construed as a measure of the current maximum economy of beef producton. A 1-pound gain in weight is estimated to equal in calorie value the digestible energy of 1 pound of the feed used; thus a caloric efficiency of about 20 percent and a protein efficiency of about 30 percent in terms of live body weight.

Matrone (*20*) has reported that, up to 3 weeks of age, his cage-reared piglets gained 1 pound of liveweight for each pound of dry feed and, up to 6 weeks, 1 pound for 1.1 to 1.3 pounds of various dry rations. The conversion of dried feed by silver salmon (*Oncorhynochus kesutch*) for the 38-week feeding period was 1.62 pounds of food for 1 pound of fish. The feed contained 52.4 percent protein, 29.1 percent carbohydrate, 9.4 percent fat, and 9.1 percent ash (*21*). This is very effective use of feed protein. We can, with our rapidly growing rainbow trout, now produce a pound of gain with a pound of dry food (*22*).

Limitations of Feed and Size

Smaller ruminants may, in fact, have a faster turnover rate in the rumen than larger forms, the fermentation rate per gram of dry matter in the rumen of the 3.69-kg suni being five times greater than that of 240-kg zebu, and 2.7 times that of a 50-kg gazelle. Therefore, it seems probable that if this inverse relation between body weight and fermentation rate extends beyond this known range, then ruminant-like digestion is possible in very small animals (*23*).

Lamprey (*24*) estimated that there is an aggregate biomass consisting of a dozen herbivorous species of 207,000 pounds per square mile in the dry season on the East African Tarangire game preserve. On the basis of Brody's (*25*) conclusion that metabolism is proportional to the 3/4th power of the body weight, Lamprey calculated the productivity of the reserve as equal to that of better managed and watered ranges used by livestock.

The animal uses its own fat and flesh, depleting them to maintain balance among its needs, and repleting them as available feed permits. Kleiber (*6*) stated that the relation of food capacity to body size is proportional to the 3/4th power of body weight and that all animals are limited in intake to four to five times their equivalent for basal metabolism. Caloric intake is limited by the capacity to ingest dry matter, so that digestibility of the feed provides a further restraint. It is impossible (*26*) for a very high-yielding cow to eat enough to sustain peak production. Kleiber found that cows used as much as 10 to 15 megacalories per day of body tissues in addition to feed energy during the peak period of lactation when milk production was about 40 kg per day. Later in lactation, these cows stored as much as 15 Mcal per day. The dramatic effect of lactation and egg production on feed intake does not permit the cow or hen to exceed its capacity for nutrient ingestion.

The NAS-NRC requirements are almost identical with the requirements estimated by Byerly in 1941. At that time (*27*), diets for laying hens generally contained about 2.5 Mcal of metabolizable energy per kilogram. The NAS-NRC table assumes diets of 2.85 Mcal per kilogram of metabolizable energy and Sell's and Hodgson's (*28*) diets for laying hens contained about 3 Mcal per kilogram of metabolizable energy. If we ignore caloric content, the NAS-NRC requirements almost exactly fit Sell and Hodgson's daily metabolic (DM) requirements about 20 percent below those observed (Fig. 1).

Does the laying hen have a higher heat increment than other classes of livestock? Does ad libitum feed consumption of diets as high in metabolizable energy as those of Sell and Hodgson's provide calories in excess of requirements (*28*)?

Genetic Factors

There is a high correlation between feed intake, gross efficiency of feed conversion, and genetic capacity. So high is the correlation (about 0.5) that weight, for age of healthy animals reared in the same environment, is a factor exhibiting high heritability. Weight may, therefore, be used as a basis for genetic modification of efficiency. Simple mass selection and heterosis provide the genetic bases for the improvement in efficiency of feed conversion in broiler production (*29*). Research on nutritional disease, parasites, and management skill have improved efficiency from an estimated 4 CFU in 1945 to 3 CFU currently, in terms of the ratio of liveweight gain to feed consumption (Fig. 8).

Genetic effects are of two sorts; selection of breeding stock based on sire or sibling or individual performance produces improved efficiency in the next generation for highly heritable traits. These traits include rate of gain in all classes of livestock, and milk production in dairy cattle. Heterosis resulting from crossing widely unrelated genetic stocks improves reproductive efficiency, uniformity, and maternal ability. Cross breeding contributes indirectly to improved feed efficiency in pigs, broilers, laying hens, lambs, and weanling calves.

Controlled Versus Limited Feeding

Traditionally, feed intake has been limited to estimated requirement for milk cows by permitting free consumption of roughage and feeding concentrates. Recently, however, the cost of labor and relative prices of hay and concentrates have impelled many dairymen to undertake ad libitum concentrate feeding. This practice leads to reduction in roughage consumption by many cows, unless roughage and concentrates are inseparably mixed.

Two equalized groups studied by Hooven and Plowman (*30*) illustrate this point. One group was fed ad libitum; the other was limited to 110 percent of estimated requirement. The ad libitum group obtained about 29 percent of their net energy intake from roughage; the regulated group more than 56 percent of theirs. Average milk production of each group was about 6000 kg. The ad libitum group ingested more energy and gained more weight than the regulated group.

Feeding studies by Winchester and Howe (*31*) are of particular interest. One set of identical twin steer calves was fed ad libitum to a slaughter weight of 454 kg. Another set was held for 180 days at a constant weight of about 150 kg. The calves held at constant weight for 6 months were then fed ad libitum until they too weighed 454 kg. The members of each twin pair required about the same total amount of metabolizable energy to reach final weight, although the restricted calves required 138 and 71 days longer, respectively, than their co-twins fed ad libitum to reach the final weight.

This finding confirmed the soundness of the long-established practice born of necessity of carrying cattle and sheep through long winter periods or drought periods, at low planes of nutrition. Protracted drought periods may exhaust vitamin A reserves. Pregnant ewes underfed too severely may suffer "pregnancy disease," with concomitant loss of ewes and their newborn young. Emaciated animals are sensitive to cold, but when they have access to roughage—even straw or dry, weathered range grass—the heat increment consequent to its ingestion will keep them warm and living even at −40°F (−40°C). Without a source of feed energy, animals may die of cold at −10°F.

Feed Substitutes and Supplements

Quantitatively, the most important means of saving protein in livestock production is well under way. Virtanen (*32*) has recently demonstrated that moderately high levels of milk production can be supported on diets consisting of chemically identified materials, with urea or other nonprotein as the sole source of nitrogen. Even more important is the increase, in the United States, in use of urea in feed, a usage based on research, experience, and promotion (*33*). Urea can provide one-third of the nitrogen requirements for ruminant feeding. Urea is not as efficient as oilseed meal as a supplement to dry-range forage and other low digestibility roughages used for wintering cattle and sheep; but this is an inviting problem in current research. Efficiency of assimilation of urea nitrogen is enhanced by readily available carbohydrate, such as starch in the diet. High ratios of cellulose to starch, which characterize straw, stover, and dry range forage reduce efficiency of urea nitrogen (*34*).

Virtanen's feed contained potato starch, cellulose, and sucrose in the following proportions: potato starch, 50 to 60 percent of the total carbohydrates; cellulose, 25 to 30 percent; and sucrose, 17 to 23 percent. Apparently the proportion of starch cannot be reduced very much without an accompanying drop in milk production.

Stilbestrol is generally used as a supplement for feedlot cattle. It was first used in producing meat chickens, but the practice was dropped after the report by Lorenz in 1938 (*35*) that stilbestrol hastened fattening in chickens. In beef cattle, stilbestrol does not hasten fattening but does increase rate of gain and improve feed efficiency.

Several antibiotics are widely used in poultry and swine production at concentrations of about 10 parts per million in the feed. They generally improve efficiency of feed conversion in growing and fattening these anmals (*3*, *36*).

Conclusions

Under optimum conditions, young healthy individuals of each livestock species may convert about one-third of the digestible protein in its feed into tissue protein in its body. Of this tissue protein, we use about half as food.

Lactating mammals and laying hens, genetically selected for high production and fed an adequate diet ad libitum, may convert as much as 50 and 30 percent, respectively, of ingested digestible feed protein into food protein.

Beef cattle, sheep, and wild ruminants convert to food protein the roughage supplied by plants and plant materials not eaten by man. Increasing use of nonprotein nitrogen compounds as a substitute for feed protein for beef and dairy cattle and for sheep can spare increasing quantities of feed protein for human food without curtailing our meat and milk supply (*37*). Substantial improvement in efficiency of feed conversion can be achieved through further research (*38*).

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