Chapter 5

Nutrition of ruminants

Developing production systems for ruminants using tropical feed resources requires an understanding of the relative roles and nutrient needs of the two-compartment system represented by the symbiotic relationship between rumen micro-organisms and the host animal. Fibre-rich, low-protein forages and crop residues are the most abundant and appropriate feeds for ruminants in the tropics. Strategies to improve the utilization of these feeds should aim: (i) to provide supplements to correct the nutrient imbalances at the level of the microbes and the animal and; (ii) to increase the availability of energy to rumen microbes by “high-offer” (selective) feeding or chemical treatment (usually with urea).

The most limiting nutrients for rumen microbes are ammonia, sulphur and phosphorus. For the animal, the needs for supplements are determined by the rate of production (e.g., of work, of growth, of milk) and reproduction, and mostly involve the supply of “by-pass” (or “escape”) protein.

GENERAL CONSIDERATIONS

Introduction

In order to develop feeding systems, it is necessary to relate information on the nutritional characteristics of feed resources to the requirements for nutrients, depending on the purpose and rate of productivity of the animals in question. In the industrialized countries, this information has been incorporated in tables of “feeding standards” which interpret chemical analyses of feed resources in terms of their capacity to supply the energy, amino acids, vitamins and minerals required for the particular productive purpose. These standards are steadily becoming more sophisticated with the aim of improving their effectiveness in predicting rates of performance of intensively-fed livestock and to derive least cost formulations.
Limitations to "conventional" feeding standards

The relevance of feeding standards for developing countries, particularly those in the tropics, has been questioned from the socio-economic (Jackson, 1980) and technical (Graham, 1983; Preston, 1983) viewpoints. It has been apparent for many years that feeding standards based on assigned nutritive values (e.g., net energy) are misleading when un-conventional feed resources are used (e.g., Preston, 1972; Leng and Preston, 1976), since the levels of production achieved may be considerably less than the level predicted. More importantly, this often led to the rejection of many available feed resources which apparently were too low in digestible energy to supply the energy needed for production. It also encouraged researchers to copy feeding systems used in temperate countries, which are relatively "predictable" but which require feed resources that are unavailable and/or inappropriate on socio-economic grounds in most developing countries.

An alternative approach

The justification for a new approach to the development of feeding systems for ruminants, not based on conventional "feeding standards", is that:

- The efficiency of the rumen ecosystem cannot be characterized by any form of feed analysis.
- Feed intake on some diets bears no relationship to digestibility and is much more influenced by supplementation.
- Availability of amino acids cannot be inferred from the crude protein content of the diet.
- The energy value of a diet, and the efficiency of its utilization, are largely determined by the relative balances of glucogenic energy, long chain fatty acids and essential amino acids absorbed by the animal.

In the early 1960's, Professor Max Kleiber had expressed a similar concern for these issues and stated (as quoted by Kronfeld, 1982) "...metabolizable energy is not a homogeneous entity; instead it represents an assembly of nutrients or metabolites each of which is used with a specific efficiency for a particular purpose". To this could be added that the availability of these nutrients, and their interactions, affect the efficiency of energy utilization.
The misconceptions inherent in any system based primarily on feed analysis are that it is almost impossible to predict:

- Whether the feed can support efficient rumen function.
- The nature, amounts and the proportions of the end products of fermentative digestion.
- The potential for rumen escape of nutrients and their digestibility in the small intestine.

For these technical reasons, and also because of differing socio-economic circumstances, it has been proposed that a more appropriate objective, especially for developing countries, is to "match livestock production systems with the resources available" (Preston and Leng, 1987).

This chapter sets out the guidelines for applying these concepts to the development of feeding systems which aim to optimize the utilization of locally available feed resources and to build on traditional practices.

**Animal response to non-conventional feed resources**

It is relevant to point out that the doubts concerning the usefulness of feeding standards for ruminants in tropical countries surfaced during development work in Cuba (Preston and Willis, 1974) in the 70's when livestock production systems were being established on non-conventional feed resources (i.e., molasses-based diets). In these cases, although nutrient requirements were satisfied according to traditional feeding standards, the responses of the animals did not correspond to the predicted levels of performance. This research demonstrated that small inputs of "by-pass protein" (Peruvian fishmeal) dramatically increased growth rate and feed efficiency of cattle (Figure 5.1). In contrast, this feeding system was not able to support high levels of milk production (Figure 5.2), presumably because of the greater demands in lactation for glucogenic compounds and the relative deficiencies of these in the digestion end-products on molasses-based diets, in turn caused by the low- propionate, high-butyrate fermentation in the rumen (Marty and Preston, 1970).
Figure 5.1. Effect of replacing urea with fish meal on performance of steers fed a basal diet of molasses-urea (Source: Preston and Willis, 1974).

Figure 5.2. Replacing molasses with maize grain as basis of diet of dairy cows increased rumen propionate, dry matter intake and milk yield (Clark et al., 1972).
The high potential yield of animal products from a hectare of sugar cane stimulated the subsequent research in Mexico, Mauritius and the Dominican Republic that attempted to establish cattle production systems, applying the principles developed for feeding molasses (both feed resources had similar concentrations of soluble sugars) (see Preston and Leng, 1978a,b). Research on the feeding value of derinded and chopped sugar cane (Preston et al., 1976) demonstrated that:

- Feed intake was low even though digestibility was high (60-70%)
- The animals on this feed apparently needed glucose or glucose precursors because all the sugars are fermented, rumen propionate levels are no higher than observed on high-fibre diets, and the presence of a dense population of ciliate protozoa (Valdez et al., 1977) reduced the availability of microbial protein to the animal (Bird and Leng, 1984).

The implication of these two findings is that rumen function did not provide the required balance of nutrients for productive purposes (see Leng and Preston, 1976). Recognition of the role of fermentable N and by-pass protein in low-N diets led to research aimed at increasing productivity of cattle and sheep on a range of high fibre and sugar-rich low-N feeds (Leng et al., 1977; Preston and Leng, 1984, 1987). Prior to this work, these feed resources were considered to have little value other than to support maintenance and were universally referred to as "low quality" fibrous feeds. This led to attempts to improve the digestibility of fibrous feeds by, in particular, alkali treatment (Jackson, 1977, 1978).

However, the value of alkali treatment was partially obscured by the failure to recognize that the first limitation was not digestibility but the imbalance of nutrients at the level of both the rumen and the whole animal (Preston and Leng, 1987). Combining alkali treatment (ammonia) and appropriate supplementation has finally led to a very extensive programme of straw-based feeding systems being applied on farms in China (Dolberg et al., 1994). The significance of this development is the magnitude of the contribution of straw to the total dietary dry matter and achievement of high rates of liveweight gain once thought to be the prerogative of cereal grain feeding.
Nutritive value
In order that responses in animal productivity to supplements can be predicted accurately on a particular diet, it is necessary to take account of the constraints to metabolism. These relate specifically to the relative amounts of amino acids, glucogenic energy, VFA energy and long chain fatty acid energy in the end products of fermentative and intestinal digestion, since this is what determines the animal’s productivity. Productivity of ruminants is influenced primarily by feed intake which, in turn, is determined by feed digestibility and the capacity of the diet to supply the correct balance of nutrients required by animals in different productive states. Therefore the two major variables that need to be considered are:

- The amounts and balance of nutrients required.
- The quantitative availability of nutrients from the diet.

The balance of nutrients required depends upon:

- The amounts of dietary components unchanged by rumen fermentation that are absorbed (amino acids, glucose and long chain fatty acids).
- The rates of production of the end products of fermentative digestion (which can be highly variable).
- The productive functions (pregnancy, lactation, growth, work, maintenance, depletion or repletion of bodyweight).
- The environmental factors (disease, parasitism, temperature and humidity, and other sources of stress).

The availability of nutrients from a diet is highly dependent on:

- The microbial ecosystem in the rumen which influences the availability of microbial protein, VFA energy and glucogenic energy.
- The chemical composition and physical form of the diet which influence the amounts of protein, starch and long chain fatty acids which escape the rumen fermentation.

At the present time, it is not possible to predict the nutrients required by ruminant livestock and to match these with nutrients available from digestion, because of the many interactions between the animal, its rumen
microbial ecosystem and the diet. The most widely available low-cost feeds for ruminants in the majority of developing countries are usually native pastures, crop residues and to a lesser extent agro-industrial by-products. The expensive, and often unavailable (or exported), feeds are the protein meals, derived from oilseed residues and the processing of animals, fish and cereal grains.

Generally, energy (the basic feed resource) and fermentable nitrogen (urea) are relatively inexpensive ingredients, while the sources of amino acids and glucogenic compounds (the protein meals, cereal grains and cereal by-products) are very expensive. Since it is fermentation of carbohydrate which provides the energy for microbial growth, and as the feed is often low in digestibility, it is generally desirable to supply fermentable energy on an *ad libitum* basis. The basal diet should not therefore be restricted.

As a rule of thumb, 3 g of fermentable N per 100 g of fermentable organic matter are required to meet the needs for efficient microbial growth. It is not always necessary to provide this amount since some feed protein will be fermented to ammonia and some urea-N may enter the rumen in saliva. These processes reduce the amount of non-protein nitrogen needed. In addition there is evidence that the rumen microbes need small amounts of amino acids and other nutrients for efficient microbial growth. The potential of the diet to satisfy the requirements of the animal for amino acids, glucogenic precursors and long chain fatty acids depends on the pattern of fermentation and on the dietary protein, lipids (or their constituent fatty acids) and starch that escape fermentation and are digested in the intestines.

The extent to which the protein in a supplement escapes the rumen is partly a function of its rate of degradation (solubility) in the rumen. It is likely to be influenced greatly by the rate of flow of fluid and small particles out of the rumen. This latter characteristic will be influenced by processing of the feed (by physical or chemical means), the presence of some green forage, the amount of protein reaching the duodenum and external factors such as temperature and exercise/work.

The same factors will influence the supply of glucose and glucogenic precursors in terms of the likely by-pass of starch to the duodenum. However, the nature of rumen fermentation will have a major influence in terms of the supply of propionic acid for glucose synthesis.
RELATING NUTRIENT SUPPLY TO PRODUCTIVE STATE

Introduction

There is insufficient information available to permit the precise quantification of the proportions of the different nutrients required for different productive states. Nevertheless, an approximation of the needs of animals can be attempted. The suggested scheme attaches relative priorities to the groups of nutrients according to the physiological and biochemical processes underlying the expression of the particular productive state (see Figure 5.3).

The groups of nutrients to be varied for different productive states are:

- VFA energy.
- Glucogenic energy.
- Amino acids.
- Long chain fatty acids (LCFA).

The sources of these nutrients are summarized in Figure 5.4. VFA energy arises from the rumen fermentation of all types of organic matter principally carbohydrates. The principal way of increasing VFA energy
in a particular feed is to increase intake (e.g., by selection through high
offer level), to increase the rumen degradability (urea supplement), to
supplement with by-pass protein or to treat with alkali (ammoniation).

Figure 5.4. Sources of nutrients for metabolism (Source: Preston and Leng,
1987).

Manipulation of the rumen to provide extra protein and glucogenic
precursors is still at the experimental stage. Dietary supplementation is
the most obvious way of manipulating the supply of absorbed amino
acids, glucose and glucose precursors.

Most supplements are expensive and their use in ruminant nutrition
competes with monogastric animal and human nutrition. If the primary
feed resource is a product of low nutritive value which would have been
wasted if it were not fed to ruminants, it can be argued that the ruminant
uses these concentrate supplements more efficiently than monogastric
animals. For this reason, the term "catalytic" supplement has been used
to describe these effects (Preston and Leng, 1987). Sucked milk, given
in small amounts (<2 litres daily) as a supplement for calves given a
straw- or molasses-based diet, is a good example of a "catalytic"
supplement.
It is mandatory that research should produce response relationships to distinguish economic from biological optima. As a rule of thumb, the role of the supplement ceases to be "catalytic" when it exceeds about 30% of the diet dry matter. Beyond this point it assumes a major role and substitution occurs. The productive functions and the need for supplementary nutrients are discussed in order of the least to the most demanding.

**Work**

Work requires ATP (adenosine triphosphate) generated from the oxidation of long-chain fatty acids, with obligatory requirements for glucogenic compounds and for amino acids (to repair the wear and tear of tissues and replace protein secretions) (see Leng, 1985). The working animal can often obtain sufficient nutrients from a nitrogen-deficient diet so long as it balances the protein:energy ratio needed for tissue turnover by "burning" off acetate which is in excess of requirements. However, body weight loss may restrict the period of work. If the work period is to be prolonged and weight loss is to be minimized, then the nutrients available must be balanced so as to satisfy the needs of the working animal. The digestibility and the intake of the basal diet may also have to be increased by supplementing with urea to correct a deficiency of fermentable nitrogen in the rumen. This may be the only manipulation necessary, but supplements rich in fat and by-pass protein could be beneficial particularly where the animal is in a productive state (e.g., pregnant or lactating). If weight loss continues because work is prolonged, it may be necessary to increase the degradability of the basal diet, for instance by ammoniation (urea treatment).

The mature, unproductive ruminant does not appear to require nutrients over and above those provided by an efficient fermentative digestion. Since the heavily working animal uses largely long chain fatty acids and glucose (Pethick and Lindsay, 1982; Leng, 1985), the supplements used should contain or provide these substrates. This is particularly important in the case of long chain fatty acids, since their absorption and use for fat deposition or mobilization and for work will be much more efficient and will require less glucose oxidation than fat synthesis from acetate and subsequent utilization in muscle metabolism.
Maintenance
Maintenance alone obviously requires less energy expenditure than work so there is a proportionately higher demand for amino acids (relative to energy) than in the working animal. This will always be provided by a rumen system which is adequate in fermentable nitrogen. Animals in negative energy balance for an extended period on low-nitrogen roughage-based diets extract more digestible energy from the basal diet when this is supplemented with fermentable nitrogen (see Table 5.1).

Table 5.1. Liveweight change of pregnant cows and calf birthweights in response to supplements providing fermentable nitrogen and sulphur alone or with by-pass protein (Source: Lindsay et al., 1982).

<table>
<thead>
<tr>
<th>Hay intake (kg DM/d)</th>
<th>Live weight change (kg/d)</th>
<th>Birth weight of calf (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spear grass</td>
<td>-0.81</td>
<td>22</td>
</tr>
<tr>
<td>Spear grass+urea+S</td>
<td>-0.31</td>
<td>31</td>
</tr>
<tr>
<td>Spear grass+urea/S+ by-pass protein*</td>
<td>0.75</td>
<td>32</td>
</tr>
</tbody>
</table>

* 1 kg/d of protein pellet (80% cottonseed meal, 10% fish meal, 10% meat meal

Growth
Growing animals have a very high requirement for amino acids for tissue synthesis and glucose for oxidation in specific tissues (e.g., brain). In addition, considerable amounts of glucose must be oxidized to provide the NADPH required to synthesise fat from acetate. It is imperative to recognize that high growth rates cannot be supported on the products of fermentative digestion and that by-pass protein supplements are essential to take advantage of the VFA energy absorbed.

Many factors influence the level of protein supplementation to be used. Response relationships must be established which relate protein supply to animal productivity for each basal (carbohydrate) resource and for the available protein sources. The response pattern will vary according to the nature of the basal diet and the particular protein supplement. Data taken from Bangladesh and Cuba demonstrate this rationale.

Cattle on ammoniated (urea-treated) rice straw, when supplemented with only 50 g/d fish meal, increased their liveweight gain threefold (Figure 5.5). On a molasses-based diet of higher energetic potential, 450
g/d of fishmeal were needed to raise liveweight gain from 300 to 900 g/day (Figure 5.1).

Figure 5.5. Adding small amounts of a by-pass protein (fish meal) to a basal diet of ammoniated (urea ensiling) rice straw dramatically increases gain in live and carcass weight (Source: Saadullah, 1984).

Reproduction
Improvements in fertility brought about through nutrition are usually attributed to increased energy intake. There is, however, information to show that the supply of glucogenic precursors relative to total energy is an important feature of the improved energy status which results in increased fertility.

Conception and puberty
Recent studies have demonstrated that even when the protein supply is adequate, the "quality" of the energy can also be a limiting factor. At the same metabolizable energy intake (the basal diet was low-N Coastal Bermuda grass pasture), puberty was reached at lower liveweights when glucose availability in the animal was enhanced by supplementation with monensin (Table 5.2). This is not a recommended practice but serves to demonstrate the concept. There are, of course, ways of increasing the
glucogenic potential of the absorbed nutrients without recourse to chemical additives (e.g., by the use of by-pass protein).

Table 5.2. Increasing rumen propionate production (by feeding monensin) in heifers fed grass hay increased fertility as evidenced by greater proportion of heifers cycling at end of test period (Source: Mosely et al., 1982).

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Monensin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liveweight, kg Initial</td>
<td>219</td>
<td>219</td>
</tr>
<tr>
<td>Final</td>
<td>313</td>
<td>319</td>
</tr>
<tr>
<td>Feed intake, kg/d</td>
<td>8.0</td>
<td>7.7</td>
</tr>
<tr>
<td>Rumen VFA, molar %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetic</td>
<td>74</td>
<td>69</td>
</tr>
<tr>
<td>Propionic</td>
<td>19</td>
<td>26</td>
</tr>
<tr>
<td>Butyric</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Fertility (% cycling)</td>
<td>58</td>
<td>92</td>
</tr>
</tbody>
</table>

The effects of by-pass protein on conception rates of cows grazing sub-tropical pasture during the dry season are shown in Table 5.3. A supplement providing fermentable energy (molasses) was much less effective, confirming the report of Moseley et al. (1982) that it is the "quality" of the energy (i.e., energy in the form of glucogenic compounds) which is the critical issue.

Table 5.3. Liveweight and conception rates of beef cows (with first calves at foot) grazing native pasture are improved by feeding by-pass protein (cotton seed meal); a supplement of fermentable energy (molasses) had little effect (Source: Hennessy, 1986).

<table>
<thead>
<tr>
<th></th>
<th>No suppl</th>
<th>Molasses</th>
<th>Cottonseed meal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liveweight (kg)</td>
<td>302</td>
<td>332</td>
<td>343</td>
</tr>
<tr>
<td>Pregnancy (%)</td>
<td>10</td>
<td>20</td>
<td>60</td>
</tr>
</tbody>
</table>

**Growth of the foetus**
The growth of the conceptus has little effect on the protein and energy demand of ruminants until the last third of gestation when most of the foetal tissues are deposited. Because of the time course of growth of the
conceptus which increases the daily need for nutrient to only a small extent, it appears that rumen function even on diets of low digestibility can support the birth of a viable offspring of normal weight. This was shown in studies in which urea was included in the drinking water of ewes on nitrogen deficient pasture (Table 5.4).

Table 5.4. Urea supplementation in the drinking water of ewes grazing low-nutritive value pasture reduces ewe weight loss, increases lamb survivability and increases pre-weaning growth rate of the lambs (from: Stephenson et al., 1981).

<table>
<thead>
<tr>
<th>Pasture</th>
<th>Pasture + urea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ewes lambed</td>
<td>20</td>
</tr>
<tr>
<td>N intake (g/d)</td>
<td>8</td>
</tr>
<tr>
<td>Ewe liveweight change (kg)</td>
<td>-12</td>
</tr>
<tr>
<td>Lambs surviving</td>
<td>12</td>
</tr>
<tr>
<td>Lamb birthweight (kg)</td>
<td>2.9</td>
</tr>
<tr>
<td>Lamb growth (g/d)</td>
<td>35</td>
</tr>
</tbody>
</table>

Increases in calf birth weight were recorded when pregnant cattle, given a basal diet of hay of low digestibility (45%), were supplemented with urea. However, to prevent bodyweight loss and/or promote weight gain of the dam through pregnancy, it was necessary to provide additional by-pass protein (Table 5.1).

It appears that urea supplementation enhances milk production to a level that ensures survival of the offspring. But to allow the young animal to grow, milk yield must be further stimulated by feeding a by-pass protein meal.

Male reproduction
Male reproduction has been enhanced under grazing conditions by supplementary feeding. Lindsay et al. (1982) showed that bulls could be maintained in good condition on poorly digestible, low-nitrogen spear grass pasture by providing 1 kg daily of a protein supplement (Table 5.5).
Table 5.5. Effect of supplements of by-pass protein (cottonseed meal, meat meal and fish meal) on reproductive parameters of bulls grazing dry pasture (0.4% N in DM) (Source: Lindsay et al., 1982).

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>By-pass protein</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial weight (kg)</td>
<td>433</td>
<td>433</td>
</tr>
<tr>
<td>Liveweight change (kg)</td>
<td>-40</td>
<td>+14</td>
</tr>
<tr>
<td>Roughage intake (kg/d)</td>
<td>5.55</td>
<td>7.74</td>
</tr>
<tr>
<td>Change in scrotal circumference (mm)</td>
<td>-20</td>
<td>+0.7</td>
</tr>
</tbody>
</table>

More importantly, the circumference of the scrotum decreased considerably when no supplement was fed; and it is known that a bull with a lower scrotal circumference is less fertile and has a lower libido (Blockey, 1980). This shows quite clearly that protein nutrition influences male fertility. As with female fertility there appears to be evidence for beneficial responses to manipulating propionate production in the rumen. At the same feed intake, bulls reached puberty earlier and, at puberty, had a greater scrotal circumference and larger testicles (Neuendorff et al., 1982).

**Milk production**

The major constraint to milk production on diets based on crop residues and agro-industrial by-products appears to be the availability of glucogenic compounds to provide the glucose for lactose synthesis and for oxidation to provide the NADPH for synthesis of fatty acids (e.g., Figure 5.2).

There is good evidence that, in large ruminants, about 50% of the fatty acids of milk arise from dietary fat. A dietary source of lipid can thus reduce considerably any imbalance caused by relative deficiencies of glucogenic energy and amino acids in the end products of rumen digestion. For many feeding systems in the tropics the level of fat in the diet could be a primary constraint to milk production. This could be particularly important in diets based on molasses or sugar cane. Supplementation of lactating animals, particularly on diets based on tropical pastures, crop residues and sugar-rich agro-industrial by-products, should aim to correct the imbalances of nutrients for milk production. By-pass protein usually increases feed intake and as a consequence promotes milk production. But to balance energy quality,
fat must be mobilized and glucose diverted from oxidation and tissue synthesis to lactose production. In these circumstances, animals tend to lose body weight (Orskov et al., 1977). Dietary fat may reduce this effect. Adding a source of by-pass starch in such a diet balances the ratio of glucogenic precursors to protein and energy and will tend to prevent body fat mobilization. The points to be stressed are that:

- By-pass protein because of its effects on feed intake almost always stimulates milk production and depending on the imbalance in nutrients (fermentation pattern) may cause animals to mobilize body reserves. This may be prevented by the use of high-fat, high-protein meals that supply both protein and long chain fatty acids for digestion post ruminally.
- By-pass starch or manipulation of the rumen to give higher propionate production, because it balances nutrients for milk production, may prevent mobilization of body reserves without large effects on feed intake and therefore on milk production. But because it balances the nutrients for milk production, efficiency of energy utilization is increased and body weight is often increased.

Wool and hair production
The effect of nutrition on wool production appears to be dependent almost entirely on the quantity, and quality, of the balance of amino acids absorbed. Therefore, feed intake is the primary limitation to wool or fibre growth although at any one feed intake, wool growth can be stimulated by altering the balance of protein relative to energy in the products of fermentative digestion (e.g., removing protozoa from the rumen). Thus on diets that require fermentative digestion, including those based on sugars or fibre, a by-pass protein supplement will increase wool growth (Table 5.6).

GUIDELINES FOR DEVELOPING FEEDING STRATEGIES FOR RUMINANTS
Introduction
When fibre-rich crop residues and by-products are the primary feed resource for ruminants, feeding strategies must be based on a clear understanding of the relative roles and nutritional needs of rumen microorganisms and of the host animal (see above).
Table 5.6. Goats (G) and sheep (S) fed highly fermentable feeds need by-pass nutrients in order to produce wool; diet was 3% oat hay, 25% maize flour, 15% molasses, 15% sucrose, 12.5% barley grain, 4.5% urea, 0.5% minerals/vitamins; by-pass supplements were formaldehyde protected casein alone or plus cracked rice (Source: Throckmorton and Leng, 1984).

<table>
<thead>
<tr>
<th></th>
<th>Basal</th>
<th>By-pass protein</th>
<th>By-pass protein</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G</td>
<td>S</td>
<td>G</td>
</tr>
<tr>
<td>Daily liveweight gain (g)</td>
<td>32</td>
<td>45</td>
<td>68</td>
</tr>
<tr>
<td>Patch weight at 105 days (mg/cm²/2/d)</td>
<td>0.54</td>
<td>0.74</td>
<td>0.82</td>
</tr>
<tr>
<td>Feed intake (g/d)</td>
<td>465</td>
<td>538</td>
<td>604</td>
</tr>
<tr>
<td>Feed conversion (DM)</td>
<td>14.8</td>
<td>11.9</td>
<td>8.9</td>
</tr>
<tr>
<td>Rumen fluid half life (hr)</td>
<td>16.1</td>
<td>14.1</td>
<td>8.6</td>
</tr>
</tbody>
</table>

* Wool or hair clipped from a 10 cm² mid-side patch

The new approach identifies high fibre forages as the most important category of tropical feeds and emphasizes that these are imbalanced sources of nutrients for both rumen micro-organisms and the animal. The recent advances in understanding of rumen function and the role of "by-pass" or "escape" nutrients has revealed important ways forward for improving productivity of ruminants in the tropics. These concepts have been tested and applied on a wide scale in many tropical countries and can be summarized as follows:

The research which led to the new concepts of "balancing nutrients" has shown that provided the protein to energy ratio in absorbed nutrients is high, productive efficiency can be up to tenfold that predicted from traditional feed evaluation methods (Leng, 1990). The breakthrough came when the ruminant animal was treated as a two compartment system (Figure 5.6) (Leng and Preston, 1976; Preston and Leng, 1987) in which there is:

- A microbial fermentative digestion system that functions efficiently when there is a balanced supply of microbial nutrients within an appropriate ecosystem.

and where:
The animal relies on the products of the microbial system and those digestible feed components that escape the rumen fermentation.

Figure 5.6. Nutritional strategy for feeding the ruminant (Source: Preston and Leng, 1987)

The results of applying these concepts have substantiated the hypothesis that ruminants in the tropics fed on fibrous crop residues and dry pastures were not deficient in energy per se but were inefficiently utilizing the feed that was available. Therefore, when nutrients were more closely balanced there were substantial gains in productivity.

The rumen microbial system alters the nutrients finally made available to the animal converting fibrous carbohydrate, sugars and starches and soluble protein to microbial cells, short chain organic acids and waste products in the form of methane, carbon dioxide and heat. The critical issue for the animal is the ratio of protein (from microbial and dietary origin) to energy yielding substrates (the P/E ratio expressed as g protein/ MJ of energy from volatile fatty acids available for metabolism), since this determines efficiency and level of productivity (Preston and Leng, 1987). However, even when the rumen system is optimized by providing an array of essential nutrients for microbes, the P/E ratio is usually still inadequate to support optimum efficiency of utilization of the basal feed resource.

The demonstration in Cuba (Preston et al., 1967) that flame-dried fish meal (a protein known to escape the rumen fermentation) dramatically increased rate and efficiency of liveweight gain on highly digestible but low protein diets (molasses and urea), led to the broader
understanding of the critical role of: (i) supplying nutrients to the rumen microbial eco-system, and (ii) of protein supplements to the animal, as factors determining rate and efficiency of ruminant production from forage-based diets. This in turn led to the introduction of the concept of "by-pass protein" (Leng et al., 1977).

Another important step in the understanding of tropical ruminant nutrition has been to appreciate that, when animals are in an environment where the temperature is less than their body temperature, they will oxidize acetogenic substrate to maintain body temperature. This results in an increase in the effective P/E ratio in the metabolites available for production. Conversely, when environmental temperatures exceed body temperature the resultant heat stress causes a rise in basal metabolic rate and the catabolism of protein. In practice, this means that the requirement for protein (amino acids) per unit energy substrate will generally be greater for ruminants in tropical environments than for those in temperate environments. In summary the major features of the new approach are:

- In the tropics there is a greater response by ruminants to supplementation strategies as compared with responses in temperate countries.
- Feed evaluation standards developed in temperate countries have little application in the tropics and have been positively detrimental to development of sustainable livestock production systems in those regions.

The proposed strategy considers the ruminant animal as composed of two subsystems:
- The rumen
- The animal

**Feeding the rumen microbes**

- The first need is for ammonia (>200 mg/litre of rumen fluid to maximize intake as well as digestibility) (Figure 5.7), most conveniently ensured by free access to multinutritional blocks based on urea-molasses.
• Macro and micro-minerals (P, S and Co are most important but will be supplied usually by other dietary components (e.g., in multi-nutritional block, in green forage and/or by-pass protein supplement)
• Other micro-nutrients (amino acids, peptides, branched chain acids) will rarely be deficient as these arise from lysis of microbes and are supplied by other dietary components as in the case of minerals).
• An optimum ecosystem to promote rapid colonization of basic substrate. A small quantity of highly digestible green forage (about 2 kg fresh matter/100 kg liveweight is usually sufficient) is the best way of safeguarding this parameter (Figure 5.8).
• Maximum rate of intake of fermentable carbohydrate. Usually the most appropriate way will be by ensuring free choice selection of the basal feed which in the case of a fibrous crop residue means, wherever possible, offering more than 50% in excess of needs (Owen 1994; Figure 5.9). In general, the less digestible the basal feed, the higher degree of offer is required (e.g., at least twice the expected intake in the case of residual pressed sugar cane stalk (Figure 5.9)). The other approach is to treat with ammonia (by urea-hydrolysis) (see Chapter 7).

Figure 5.7. The optimum rumen ammonia concentration to optimize both fibre digestibility and intake is about 200 mg/litre (Source: Perdok, 1987).
Figure 5.8. Adding a small amount of *Leucaena* hay to a maize stover diet increases rate of maize stover digestion in cattle (Source: Kabatange and Shayo, 1991).

![Bar graph showing maize stover rumen DM loss (% 24h) for control, 1 kg/d leucaena, and 2 kg/d leucaena.]

Figure 5.9. Effect of level of offer on intake of residual pressed cane stalk (Owen, 1994).

![Bar graph showing intake of DM (g/d) and DM in feed refusals (%) for different levels of offer (% LW, DM basis).]
**Feeding the animal**

The aim is to increase the protein/energy (P/E) in the nutrients absorbed for metabolism by:

- Increasing the efficiency of rumen function.
- Supplying by-pass protein.

The amounts of supplement to be provided will be dictated by the marginal value of animal product added per unit of additional supplement. This in turn will be determined by the shape of the response curve between output and input. Examples of such relationships are given for sugar cane in Mexico (Figure 5.10) and wheat straw in China (Figure 5.11).

Supplying foliages with natural protection as a function of the protein (many tropical tree foliages contain phenolic and other substances that react with the protein during chewing, thus protecting it from rumen fermentation) usually will be the most economical way.

Results are given in Figure 5.12 for the effects on milk production in goats of supplementing a basal diet of King grass with the foliage of *Erythrina poepiggiana*. Milk yield was a direct function of the amount of legume foliage added.

**Figure 5.10. Fattening cattle with sugar cane; the effect of by-pass nutrients present in rice polishings (Source: Preston et al., 1976).**
Figure 5.11. Response curve to cottonseed cake of steers fattened on a basal diet of ammoniated wheat straw at two locations in China (Source: Dolberg et al., 1994).

Figure 5.12. Milk production of goats fed King grass: effect of giving *Erythrina* tree foliage (Source: Esnaola and Ríos, 1990).
Controlling (reducing the numbers and/or activity of) the rumen protozoa will increase the flow of protein to the small intestine, and thus increase the P/E ratio and hence the productive parameters (Preston and Leng, 1987). This has been conclusively demonstrated in experiments where protozoal populations have been eliminated by detergents (e.g., see Figure 5.13).

Figure 5.13. Effect of defaunation on growth of lambs fed straw, sugar, urea and cottonseed meal (BP protein) (Source: Navas and Leng, 1991).

Many tropical tree and shrub foliages contain secondary plant compounds that naturally inhibit protozoal activity. However, although reductions in rumen protozoal numbers have been obtained by supplementing the animal with foliages from trees such as *Enterolobium cyclocarpum* (Kang *et al.*, 1994) or with seeds rich in saponins from the tree *Sapindus saponaria* (Diaz *et al.*, 1993), it has not yet proved feasible to translate these effects into practical production systems.

For some production traits (e.g., growth and milk production) it will be advantageous to supply by-pass oil since this can be incorporated directly into milk and body fat, and is less costly (biochemically) than
synthesizing fat from acetate and glucose. On high-fibre diets, such as crop residues and pasture, "un-protected" lipid added above 5% of the diet dry matter will depress fibre digestion. This negative effect can be avoided by "protecting" the lipids with calcium salts to form insoluble soaps (Palmquist and Jenkins, 1982; Palmquist, 1984).

There may be other indirect benefits from use of oil. Thus, Rodriguez et al. (Rodriguez, L. and Cuellar, P., 1994, unpublished data) mixed 6% crude palm oil and 2% calcium hydroxide with the leaves of the legume tree *Erythrina fusca* and found that the intake of leaves was increased. Supplementing crossbred (F₁ Holstein x Zebu) cows (basal diet was grazing on African Star grass pasture) with 6 kg/day of this mixture (6% oil, 2% calcium hydroxide and 92% leaves) supported the same milk production as 4 kg daily of concentrates.