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Sustainability of ruminant agriculture in the new context: feeding strategies and features of animal adaptability into the necessary holistic approach

F. Bocquier^{1†} and E. González-García²

¹Montpellier SupAgro, UMR868 ERRC, Bâtiment 22, Campus SupAgro-INRA, 2 Place Pierre Viala, F-34060 Montpellier, France; ²INRA, UMR868 ERRC, F-34060 Montpellier, France

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There are numerous recent studies highlighting sustainability problems for the development of ruminant production systems (RPS) while facing increasing human food necessities and global climate change. Despite the complexity of the context, in our view the main objectives of the ruminants' physiologist should be convergent for both industrialized (IC) and developing countries (DC) in a common and global strategy of advancing knowledge. In DC, this means improving the efficiency of RPS, taking into account the unique possibility of using rangelands. For IC settings, RPS should be revisited in terms of autonomy and environment- friendly feeding and managing practices. Assuming that competition for feed/food use is still a crucial criterion, future ruminant feeding systems (FeSyst) should preferably focus on lignocellulosic sources. According to biome distributions, and the recent increases in volumes of crop residues and their by-products, the annually renewed volumes of these biomasses are considerable. Therefore, we need to redesign our strategies for their efficient utilization at the local level. For this purpose, digestion processes and rumen functioning need to be better understood. The renewed vision of ruminal digestion through the reduction of greenhouse gas emissions is also a key aspect as it is an environmental demand that cannot be ignored. With regard to other ruminants' physiological functions, accumulated knowledge could be mobilized into an integrative approach that puts forward the adaptive capacities of animals to face variability in quantity and quality of supplied feeds. Basically, the reduction of inputs that were traditionally used to ensure FeSyst will need more flexible animals. In that sense, the concepts of homeostasis and teleophoresis need to be updated and adapted to domestic species and breeds that were until now largely excluded from the dominant productive systems. In conclusion, a more holistic approach of research targets is required in which physiological functions and farmers' practices must converge and respond to each particular situation in an integral, dynamic and flexible conceptual perspective. From a scientific point of view, both for ICs and DCs, a broader range of experimental scenarios should be explored in order to arrive at innovative practices and solutions that respect environmental, ethical and economical issues. The clear challenge is to evaluate the sustainability of RPSs. This includes, in our opinion, a strong interaction with other disciplines (multi- and trans-disciplinary conception), thus structuring new relevant indicators for the evaluation sustainability.

Keywords: ruminant, sustainability, feeding, adaptive capacity, environment

Implications

Without providing a 'recipe', this review discusses the traditional and more updated aspects related to the basis of feed resources, feeding strategies for shifting current feeding and nutrition of ruminants to more lignocellulosic-based diets and issues of biological animal adaptability mechanisms that should be considered for achieving adequate system plasticity with the 'ideal animal' for each particular situation.

† E-mail: bocquier@supagro.inra.fr

Introduction

Recent and relevant events have covered two current global key themes: hunger and climate change. The World Summit on Food Security (November, 2009) and 15th United Nations Climate Change Conference in Copenhagen (COP15; UNCCC, 2009) ratified and updated the world leaders' positions around what they denominated as 'our tragic achievements in these modern days'. A declaration pledging renewed commitment to eradicate hunger from the face of the earth sustainably and at the earliest date, and the

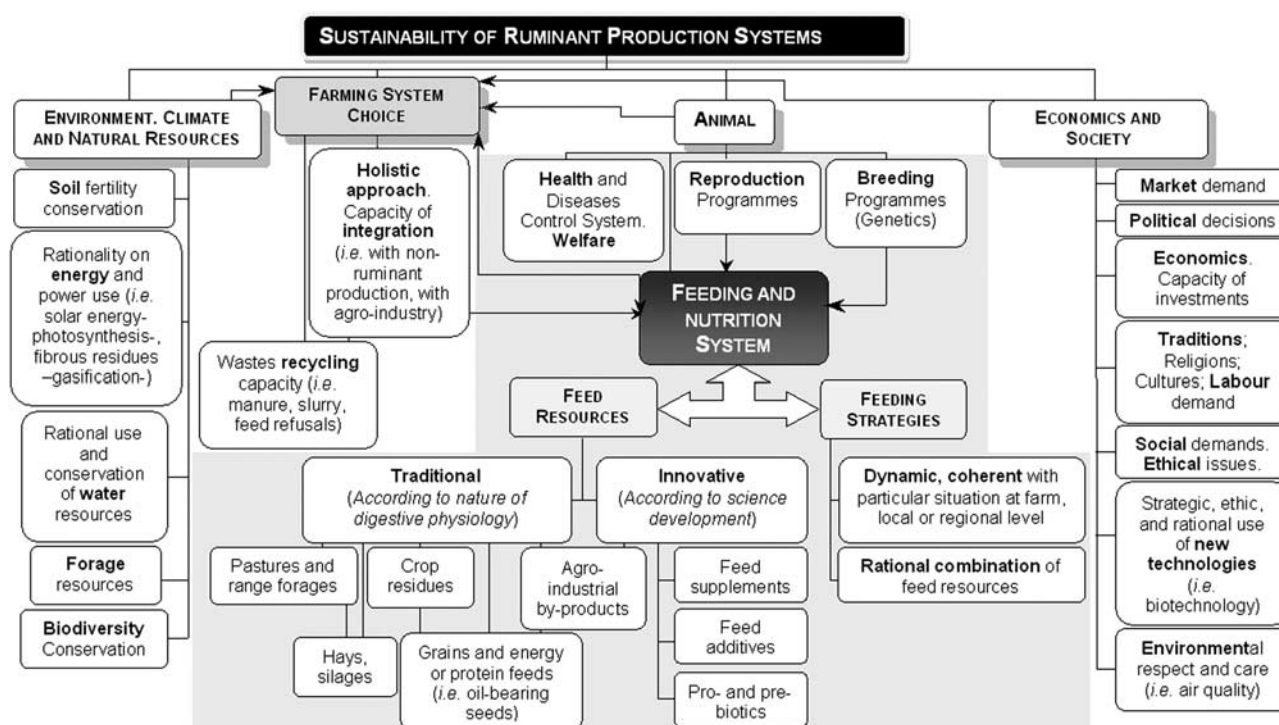


Figure 1 Sustainability of ruminant agriculture is the overall result of the interaction among multi-dynamic functions. That is warranting a rational progress at all levels (farm, local, regional, national and international) without compromising environmental stability (i.e. avoiding soil erosion, desertification or greenhouse gases emissions), whereas contributing to food security and poverty alleviation programmes. Rational feeding and nutrition systems are essential in this goal.

'Copenhagen Accord' signed by 115 heads of state or governments taking on responsibility for limiting growth of greenhouse gases (GHG), were their respective and more tangible outputs. Livestock production and, specifically, ruminants, are actively involved in both global goals.

The Food and Agricultural Organization estimates that 1.02 billion people were undernourished worldwide in 2009. There are more hungry people now than at any time since 1970, the earliest year for which comparable statistics are available (FAO, 2009a).

Furthermore, while commodity prices have always fluctuated with changes in supply and demand, world agriculture now appears to be undergoing a structural shift towards a higher demand-growth path. Many countries, especially those in Asia, have entered a period of faster economic growth, generating demand for more meat and dairy products (FAO, 2007). In addition, projected growth in agrofuel demand over the next decade is likely to push commodity prices 12% to 15% above the levels that would have prevailed in 2017, if demand for agrofuels were held at 2007 levels (OECD-FAO, 2008). Looking ahead, it is expected that agrofuels will remain a significant source of increased demand for agricultural commodities – and for the associated resources used to produce them.

In such a contemporary scenario, ruminants are considered to play an important role. However, ruminant production sustainability constitutes a hot topic that has been the subject of numerous publications and conflicting reports in recent decades (Delgado *et al.*, 1999; Steinfeld *et al.*, 2006; The World Bank, 2009).

In this study, we focus on key points contributing to efficiency of ruminant production in developing (DC) and industrialized countries (IC), as well as the basis for continuing in the future, and facing the challenges of the new context. We update basic and relatively new strategies on feeding/nutrition and discuss interesting mechanisms on animal adaptability (see Figure 1).

Our vision is to conceive a permanent feedback in the conceptual base development and experience exchange in a common and global strategy for both, the DCs or ICs. Flexible, dynamic, integral and holistic thinking is essential for an adequate interpretation of our perspective about the problem we are dealing with (Figure 1). The sustainability of ruminant production systems (RPS) will pass by warranting the sustainability of their feeding systems (FeSysts).

General overview of the current status of ruminant production at the global level

In general, when we (scientists) talk of 'ruminants', immediately it is assumed that we are talking about the most common domestic large (cattle (dairy, beef or multipurpose), buffalos) and small (sheep, goats (dairy, meat, wool, cashmere, dual or multipurpose)) traditionally used species. However, in practice, there are other less known and studied ruminant species that feed, and actually contribute to the life of millions of inhabitants all over the world (e.g. camels in arid and semi-arid regions; llamas and alpacas in the Andes; yak in Highland Central Asia and reindeer in Circumpolar

Table 1 Population of the main domesticated ruminant species by world region and its changes during the last two decades

Specie	Population (millions of head)		Percentage of change	Percentage of Global population
	1984	2004		
World region				
Cattle				
Developing	827.7	1018.4	23.0	76.3
Developed	426.1	316.1	-25.8	23.7
Total	1253.8	1334.5	6.4	-
Buffaloes				
Developing	132.7	172.0	29.6	99.6
Developed	0.5	0.7	40.0	0.4
Total	133.2	172.7	29.7	-
Sheep				
Developing	585.1	691.8	18.2	66.6
Developed	534.0	347.0	-35.0	33.4
Total	1119.1	1038.8	-7.2	-
Goats				
Developing	455.4	748.0	64.3	95.9
Developed	27.2	32.0	18.5	4.1
Total	482.6	780.0	61.6	-
Camels				
Developing	17.7	18.6	5.1	98.4
Developed	0.3	0.3	-	1.6
Total	18.0	18.9	5.0	-

Source: FAOSTAT, 2009.

Eurasia). The lack of literature in such 'forgotten' species is immense. In our view, for a better future, animal science must take into account the much broader spectrum of ruminant species more seriously.

Table 1 shows the population change during the last two decades for the main domesticated ruminant species, according to the regions of the world. Although the most dramatic growth in cattle populations over the period 1984 to 2004 was posted in smaller countries such as Gabon (up 463% to 35 000 head), Djibouti (249% to 297 000), Egypt (123% to 3.9 million) and Cambodia (108% to 3 million), the largest absolute increase in national herds was recorded by Brazil (up 64.3 million), China (47.5 million) and Sudan (17.3 million). In contrast, led by the United States (down 18.5 million) and the European Union (EU) – following reform of the Common Agricultural Policy – herd numbers in many ICs fell. Thus, by 2004, over three-quarters of the global herd were to be found in DCs (>66%; Table 1; FAOSTAT, 2009).

Water buffaloes are found primarily in southern Asia, where they are used as both draft and dairy animals. Over half of the global buffalo population of 172.7 million resides in Asia, with three countries (India, Pakistan and China) accounting for 85%, and 10 countries contributing 97% of the global total. India harbours the highest number of cattle (around 210 million) and buffaloes (around 84 million).

Sheep are distributed more widely, with 131 countries reporting flocks in 2004. Nine countries, headed by China (157.3 million head), have national flocks of over 25 million, accounting for 52% of the global population. Sheep numbers in ICs have fallen by 35% over the last 20 years (Table 1), in large part due to the decline in sheep flocks in countries that

were formerly part of the USSR (down 90.7 million head –62%) or under Soviet influence in Eastern Europe, in Australia (32%) and New Zealand (43%). Sheep numbers in the DCs have grown by 106 million head to 691.8 million (up 18%) – with the biggest increase in China, Sudan, Iran and India.

Goat herds are largely concentrated in DCs (96%; Table 1) where they provide hides, milk, meat and mohair. The sharp increase in the global goat herd (+297 million – up 62%) is, once again, attributable largely to a substantive increase in Chinese (169%), Bangladeshi (154%), Pakistani (91%) and Indian (21%) stocks. Many African countries have seen a doubling in their goat herds, aided, in part, by the promotion of the acquisition of goats as a means of consolidating food security and livelihoods in the region.

Such a majority of ruminant populations in DCs, and the most recent tendencies, support the idea of the importance of paying more attention to what is happening in these regions. In addition, responding to the challenges posed by global warming, oil market and the emergence of agrofuels sector, will require a paradigm shift in the practice of agriculture and in the role of livestock within the farming system. It should aim to maximize plant biomass production from locally available diversified resources, processing of the biomass on farms to provide food, feed and energy and recycling of all waste materials (Preston, 2009).

Feeding and nutrition of ruminants in the new context

The feed resources: redesigning strategies

If we assume that competition for feed/food use (e.g. between ruminants and non-ruminants or non-ruminants

and humans) is still a crucial criterion, future ruminant FeSysts should focus preferably on maximizing the use of lignocellulosic feedstuffs (i.e. agro-industrial by-products), which, in most cases, represent an environmental threat. However, eventual competition for lignocelluloses in the second generation of agrofuel systems must be considered.

In times of rising energy claims, it seems opportune to remember that plants are by far the most important, and the only renewable, energy-producing source, the only basic food-manufacturing process in the world (Ensminger *et al.*, 1990). Transformation of this primary resource is done by herbivores and is highly optimized by ruminants with their morphological and physiological adaptations for converting roughage and low-quality fibrous sources efficiently and directly into useful goods for humans. This statement is basic, but it is relevant to keep it in mind for the future and success of ruminant agriculture. The need to optimize the capture of solar energy will become increasingly important as the world enters the oil decline phase.

In integrated crop-livestock production systems, using fibrous resources as a direct raw material for energy production at the farm level gives another dimension to enhancing farm sustainability. Net plant productivity has to be addressed, especially in tropical countries with their access to abundant energy from the sun. For example, after the extraction of sugarcane juice (which is used for animal feeding), bagasse is used for gasification (Preston, 2009).

Pasture and range forages. Although the trend during the recent decades has been to feed more concentrated feeds widely, more than 50% of the feed consumed in the RPS nowadays consists of forage (harvested roughage and pasture) and their conserved forms (hay, silage). Thus, despite human pressure, ruminants 'insist' on their preference (and physiological need) for herbage. Approximately 60% of the world's pasture land (almost half the world's usable surface) is classified as grazing land (de Haan *et al.*, 1997). In ICs, for example, roughage accounts for more than 60% of all livestock feed, even in a context in which feedlots and high-technology industry dominate the market.

In traditional ruminant-producing regions, grass-based systems of milk production predominate. For example, in New Zealand, virtually all dairy production is based on the grassland, with over 90% of the total nutrient requirements coming from grazing (Hodgson, 1990). In the EU, over 95% of milk production is based on the grassland, which is often managed intensively.

In DCs (e.g. tropics and subtropics), finding the ideal conditions for grain/cereal production is often thought to be difficult. Farming systems rely strongly on the use of local pastures and forages, going from small stakeholders with few animals, few land and cut-and-carry-based systems (e.g. rustic confinement for goat production in Central and Latin America; agriculture of subsistence) to large extensive grazing systems with large amounts of land dedicated to natural and/or genetically improved grasslands (e.g. beef production with the local *Brahman* herd in natural grasslands in Brazil).

The great natural biodiversity of the tropics and subtropics positively supports a great spectrum of alternatives.

Extensive grasslands cover about 25% of the world surface and contribute to the livelihoods of more than 800 million people, including many poor smallholders. However, about 20% of the world's pastures and rangelands, with more than 70% in dry areas, have been degraded to some extent, mostly through overgrazing, compaction and erosion created by livestock keeping. Dry lands are particularly affected by these trends, as livestock are often the only source of livelihoods for the people living in these areas. Clearing of land for feed crop production and expansion of pastures for livestock production have been the driving forces behind deforestation, which causes significant environmental damage, releasing enormous amounts of CO₂ into the atmosphere and causing the extinction of many animal and plant species each year (FAO, 2005 and 2008). Solutions in that direction are imminent. Mixing grazing systems (i.e. agrosilvopastoral, with grasses, legumes, shrubs and trees), for example, would avoid this tendency while enhancing livestock production in the context of biodiversity protection and harmony with nature.

Exploiting traditional techniques of forage conservation (hays, silages) will continue to be strategic to alleviating seasonal effects (e.g. drought and winters) and optimizing forage use at the farm level (Nussio and Ribeiro, 2008; Orosz *et al.*, 2008).

Grains and high-energy feeds. Classically, intensive livestock production 'laws' dictate that, 'to maximize production', the livestock producer must use a high-energy ration – that is, a high caloric density and digestibility (e.g. low fibre content). In grain-producing countries (e.g. ICs), a great part of the livestock energy requirement has been traditionally warranted by local cereal production (e.g. maize, wheat, barley, rice, oat and sorghum).

Nevertheless, grain production is becoming highly attractive for the agrofuel industry, shifting the priorities of grain producers in ICs and raising commodity prices, which encourages expansion in the global production of cereals. However, the supply response has been concentrated mostly in ICs and among DCs, in Brazil, China and India (FAO, 2009b).

Rising maize and soyabean prices due to agrofuel production makes it more difficult to use them in animal production from a stable and sustainable perspective. The immediate solution for the livestock sector is to centre attention on the possibilities of becoming less dependent on cereals and oil-seeds in their FeSyst strategies. Livestock keepers are aware, and therefore, strategies such as using energetic by-products, are becoming more important.

In contrast, in the majority of non-cereal-producing countries (e.g. humid tropics, DCs), expensive cereals have to be imported unless they are replaced by the vast amount of energy feed resources that are available locally (e.g. cassava, sweet potato, yam, taro, breadfruit and sugarcane). Therefore, the use of cereals is concentrated in non-ruminant production (e.g. broilers, laying hens and swine). The efficient

utilization of such local resources in the tropics and sub-tropics is a key aspect in which sound and sustainable technologies, which are also feasible from the practical point of view, are imperative (González-García *et al.*, 2009a).

Ruminants (and herbivorous non-ruminants) can also obtain a large proportion of their energy needs through the consumption of forage. The challenge is how to meet production demands (e.g. finishing rations for beef cattle) without replacing dietary forage at such high levels (e.g. $\geq 85\%$ of the concentrate in the feedlot).

The by-products of grain milling, fats, oils, fruits, nuts, roots and specialized feeds such as molasses, often provide excellent alternatives. In the tropics, among the best-known examples are the use of sugarcane molasses and fresh or dehydrated citrus pulp (Preston, 1986).

In the case of roots and tubers (e.g. potatoes, sweet potatoes, chufas, cassava, beets, mangels, carrots and turnips), despite their high-yield nutrient per hectare, the cost of labour needed to harvest these crops has been, in some way, the main disadvantage in using them in a more extensive way. In addition, their high moisture content has contributed to their low use in 'standard technologies' for animal production. Some advances have been made in avoiding these limitations by processing the raw material into flour or dry meal; however, basically, mostly in DCs, there are many technological limitations that do not encourage the use of these important resources.

Fats also enable animals to meet their high-energy requirement with less feed. A small amount of fat is desirable, as fats are carriers of the fat-soluble vitamins in the ration and control dust in feed processing, facilitate pelleting and increase palatability. With the rumen-protected fat system, utilization of fat by the ruminant can also be improved by altering the ratio of the saturated-to-unsaturated fatty acid profile in carcass depot fat. However, factors that limit the utilization of large amounts of fat by ruminants include the inhibitory effects on rumen fermentation, lower intestinal absorption at high intake, low contribution to total oxidation of nutrients and sensitivity to nutrient imbalance, causing reduced energy intake (Kucuk *et al.*, 2004). Recently, there has been some interest in the use of unsaturated sources with positive results (i.e. olive oil; Molina-Alcaide and Yáñez-Ruiz, 2008).

Protein supplements. Among the most recognized protein supplements protein sources coming from plant processing, the corn gluten feed or meal, the pulse grains and other forage legumes can be cited. From processing rich oil-bearing seeds, protein-rich products of great value, such as livestock feeds, are obtained. Among such high-protein feeds are meals from soyabean, coconut, cottonseed, linseed (flax), peanut, canola (rapeseed), safflower, sesame and sunflower seed. Oil is extracted from the seeds by one of the basic processes or modifications, such as solvent extraction, hydraulic extraction or expelled extraction, the feeding value being determined by the method of extraction. The availability and digestibility of amino acids (AA), the concentration of minerals and vitamins

and the level of moisture, fibre and urease can all affect the efficiency of oilseed meal in a livestock ration. These sources of protein feeds are used very often in ICs, where the ideal natural conditions and infrastructure for such processing are available.

Pulses, the seeds of leguminous plants, are used primarily for human consumption, but they can be fed effectively to livestock. Although there are more than 13 000 species within the *Leguminosae* family, only about 20 species are used for food and/or feed. Soyabeans and peanuts are pulses, but they are used almost entirely as oilseed meals in livestock rations. Pulses contain components that possess anti-nutritional properties, like proteases inhibitors, goitrogens, cyanogens, anti-vitamins, metal-binding factors, lathyrogens and phytohemagglutinins. Processing procedures, such as cooking, germination and fermentation can reduce their potentials risks.

In recent years, there has been increased interest in formulating diets to provide a specific array of AA to the small intestine. One of the theoretical advantages is that the amount of crude protein (CP) included in the rations can, potentially, be reduced, resulting in a positive economic and environmental impact (Bach *et al.*, 2000).

Agro-industrial by-products (AIBP) and crop residues. Traditionally, producing and processing animals and plants for food for people and feed for animals result in many by-products and crop residues, which can be utilized as livestock feed (Molina-Alcaide and Yáñez-Ruiz, 2008; Vasta *et al.*, 2008). With the emergence of agrofuel production, another important source of by-products has appeared.

Generally, crop residues are invariably fibrous, of low digestibility and are low in nitrogen. They are often produced on the farm and, therefore, are spread widely geographically. Very often, on small farms in DCs, they form the main feed for the ruminant livestock (Preston, 1986; Ben Salem and Smith, 2008).

AIBPs result from the processing of crops, such as oilseeds, sugarcane, citrus, pineapple and bananas, and in those regions in which animal wastes are not prohibited, from the slaughter and processing of livestock and fish. They are restricted geographically to the factory or processing sites. Generally, they are rich in protein (oilseeds and meals of animal origin) or sugar (molasses, citrus and pineapple pulps) and occasionally in starch (reject bananas, cassava peels) and usually are low in fibre. Notable exceptions are sugarcane bagasse, palm-press fibre, coffee pulp and cocoa pods.

These days, there is a large amount of accumulated knowledge on the use of crop residues and AIBPs as part of the diet of growing, gestating or lactating animals. This approach is seen very often in mixed farming due to the benefits of integration between agricultural and livestock systems. Feed cost may be lowered by including such alternative feeds in the ration. However, when determining the economy of AIBPs and crop residues, consideration should be given to the costs of the nutrients supplied, transportation, storage and losses as well as possible variations in nutrient content caused by changing milling and processing procedures, palatability, possible toxicity or contamination

with pesticides or heavy metals, effect on the digestibility and utilization of the total ration, and labour cost in feeding. Hence, reduced animal performance and lesser profit can result from improper feed substitution.

Ruminant nutritionists must be aware that these feed sources will play a very important role in the options of raw materials for livestock feeding in the future and, in that direction, a great job for adapting FeSysts and routines is waiting.

Feed supplements: additives. Along with the production of new feeds, new chemicals, pre- and pro-biotics and growth-promoting factors have been developed and tested extensively for safety and efficacy. The list of feed additives has been growing, with each new product offering ways of improving the rate and/or efficiency of production.

In intensive systems, the successful livestock producer uses supplements, additives and sometimes implants to maximize performance, to improve animal health, to increase feed intake and, hopefully, feed efficiency, and/or to alter some physiological process in the animal that will stimulate production and/or improve the quality of the product. This is very often the case in highly intensive productions in IC settings. However, in DCs, in most of the cases, the use of some of these products normally arrives once they have been evaluated in some research station. There is almost a unanimous ignorance about using additives by farmers from the poorest DCs.

As the symbiosis occurring in the rumen has energy (losses of methane) and protein (losses of ammonia N) inefficiencies, modification of rumen microbial fermentation directed at decreasing losses has become a research priority. One of the main objectives is to evaluate alternative products (e.g. saponins, tannins, essential oils and other plant extracts) as alternatives to the use of antibiotic ionophores as additives in ruminant diets.

Calsamiglia *et al.* (2007) reviewed the research advances in evaluating plant extracts and essential oils as modifiers of ruminal fermentation. Using several plant extracts (whose antimicrobial activity is attributed to a number of secondary plant metabolites) *in vitro* or *in vivo* conditions has resulted in the inhibition of some ruminal bacteria, which depresses the deamination and methanogenesis processes. This results in lower ammonia N, methane and acetate, and in higher concentrations of propionate and butyrate. However, the effects of such products have been shown to be pH and diet-dependent, thus arriving at the conclusion that their benefits may be obtained only under specific well-controlled conditions and RPS. This fact complicates their acceptance at a commercial level, together with other issues of management feasibility, actual commercial prices or mixing filiations with other ingredients.

As this is a promising line of research with both productive and environmental possible impacts, future advances in knowledge, and also in the application of this group of potential products under commercial conditions, are expected. In this regard, Calsamiglia *et al.* (2007) discuss important aspects that need to be taken into account in the future for effective utilization. They include the necessity of continuing to study the optimal *in vivo* dose in units of the

active component, considering the potential adaptation of microbial populations to their activities, examining the presence of residues in milk or meat and demonstrating improvements in animal performance.

Priorities for future ruminant feeding and nutrition researches

First, as mentioned above, from our view, future research in ruminant feeding and nutrition must focus on a broader spectrum of scenarios, thus working with normally 'forgotten' or sub-estimated ruminant species and breeds and enhancing basic research in the tropics and subtropics (i.e. to elucidate complex interactions in grasses and legume associations). In addition, following the integrated, holistic approach of mixed farming systems, future RPS should consider its possible integration with non-ruminants production at farm or regional levels (Figure 1).

Complementarities of multiple crop associations are a priority for the development of new, relevant methodologies for a better understanding of, for example, diet selection in grazing by several types of animals (Niderkorn and Baumont, 2009). The advances in this field, similar to others, have been developed mostly under controlled conditions, both in DCs and ICs and in monoculture grasslands.

In the particular case of understanding rumen functioning, the view of ruminal fermentation as the sum of activities of the dominant rumen microbiota is no longer adequate. A more holistic approach is required in which physiological functions and management must respond to each particular situation in an integral, dynamic and flexible conceptual approach. Thus, farms in the 'North' must differ from the 'South' in their solutions, as their current problems also differ even with similar final production purposes. Concepts generated under highly concentrated use, confinement and genetically 'improved' modified breeds (e.g. feedlot in ICs) cannot be extrapolated anymore to, for example, a bio-diverse forage-based multi-association system (e.g. grasses and legumes) with indigenous 'low potential' genotypes (e.g. tropical agrosilvopastoral system in DCs). In the 'North', emerging concepts of livestock precision farming (e.g. assisted auto-fed animals) offer opportunities to reduce such a gap in a useful iterative manner and could provide novel targets for future strategies and relevant renewed research questions. In the 'South', the scenario is different and probably more complex and diverse in origins. Basic tools (e.g. biotechnology, metagenomics for culturability and body reserve management) actually constitute the connection point of our scientific community at the global level.

Mathematical modelling techniques are important tools that have been applied to the study of various aspects of the ruminant, such as rumen functioning, post-absorptive metabolism and product composition, rumen fermentation and its associated rumen disorders and energy and nutrient utilization and excretion with respect to environmental issues. Models that relate rumen temperature to rumen pH have also been developed and have the potential to aid in the diagnosis of subacute rumen acidosis (Kebreab *et al.*, 2009).

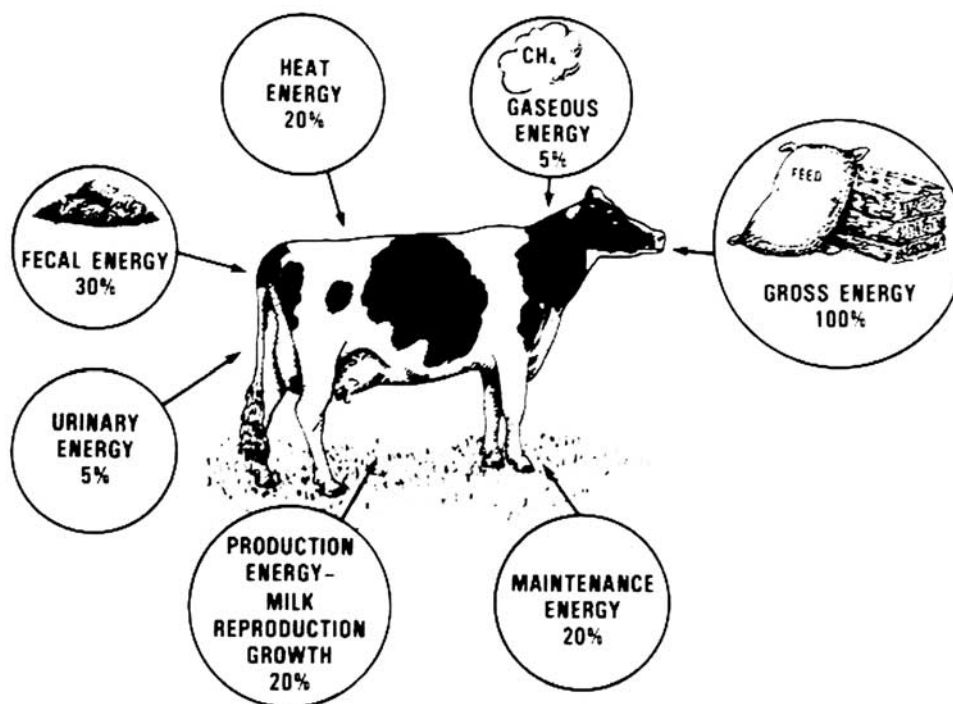


Figure 2 Energy utilization by a lactating cow showing average partition of feed energy by the animal (adapted from Ensminger *et al.*, 1990).

From a nutritional perspective, in our view future research must explore the following major fields:

1. Optimization of ruminal fibre degradation from diversified sources.
2. Adequacy of protein supplementation. Warranting protein by-pass, quality of AA profile. Anti-nutritional factors or secondary compounds in legume-based diets and AIBP use.
3. Methane production mitigation and nutrient excretion reduction and recycling.

Optimizing ruminal fibre degradation. If we propose to focus future ruminant FeSysts research on the more intensive use of fibrous resources, then it seems logical that it will be a priority to continue exploring new ways for optimizing fibre digestion. While much is known about the ways in which ruminants utilize nutrients to convert them into meat and milk, there are, based on several decades of research (e.g. Agricultural Research Council (ARC), 1980; Institut National de Recherche Agronomique (INRA), 1988; National Research Council (NRC), 2001), large gaps in our knowledge of the nutritional value of much of the world's grazing resources, especially from the tropics.

Although conceptual models of diet selection have been developed, in practical terms, it is still difficult to predict the quantity and composition of the grazing animals' diet that will be selected when faced with a complex array of plants. This lack of understanding and predictive ability represents a major limitation to the development of more efficient grazing or forage-based FeSysts. For temperate systems, based on relatively simple monocultures of ryegrass or simple mixtures of a few plant species, some progress has been

made, but for much of the rest of the world's grasslands, such predictive models do not exist.

Despite the advances achieved, the actual conversion of feeds by ruminants to animal products is still known to be somewhat inefficient (Figure 2). Only 10% to 35% of gross energy intake is converted into net energy because 20% to 70% of lignocelluloses may not be digested.

Varga and Kolver (1997) described the four major factors regulating fibre ruminal digestion:

1. Plant structure and composition, determining microbial access to nutrients.
2. Nature of the population densities of the predominant fibre-digesting microorganisms.
3. Microbial factors that control adhesion and hydrolysis by complexes of hydrolytic enzymes of the adherent microbial populations.
4. Animal factors that increase the availability of nutrients through mastication, salivation and digesta kinetics.

Increasing the efficiency with which the rumen microbiota degrades fibre has been the subject of extensive research for at least 100 years. It is known that the optimization of plant cell wall (fibre) digestion may be achieved by two well-defined strategies:

1. Using methods to 'pre-digest' the fibre before being consumed by the animal.
2. 'Helping' the rumen achieve better fibre degradation through manipulation of its environment and fermentation.

The first strategy made significant and recognized advances during the last century (Berger *et al.*, 1994). Several

mechanical (e.g. chopping to reduce particle size), physical (e.g. heating, toasting), chemical (e.g. ammonia, dilute acid hydrolysis) or biological (e.g. application of free-living lignolytic fungi) treatments of forages have been developed more or less successfully from the laboratory to the farms. The challenge still is including these technologies in the normal routine of the farms. In our view, the main disadvantage for these technologies at the farm level is related to the serious failure in the development of efficient extension services. Unfortunately, such kinds of solutions are more due to a lack of efficient politics at any level than to applying technical know-how. However, research institutions are also responsible for a better diffusion.

Furthermore, the notion that the rumen microbiota lacks appropriate fibrolytic activities has persisted. Recently, an excellent review by Krause *et al.* (2003) covered the various attempts and strategies employed for improving fibre degradation in the rumen. These authors emphasize that our understanding of the rumen microbial ecosystem is still superficial in comparison with the complexity it encompasses.

Varga and Kolver (1997) also stated some priorities for research to enhance fibre digestion in ruminants. In some of them, advances have been made. However, others will need further effort. For example, even when fungi exert a significant role in fibre digestion, there is still a lack of information about the interaction and synergisms between the bacteria and fungi populations during the attachment, adhesion, penetration and consortia formation in the digestion process. More information is also needed on the microbial fermentation rate *v.* growth rate as affected by the nutrient requirements of ruminal microorganisms. Genetic management of ruminal flora will need further advances and greater detail in the understanding of the processes, as well as the enzymatic and adhering capabilities of microorganisms that attack the most refractory sources involving the lignin–carbohydrate bonds.

The reader should refer to Krause *et al.* (2003) and other extensive lists of studies for further information on chemical and mechanical treatments, plants genetically modified for plant cell wall composition (e.g. lignin synthesis – changes to the components of lignin result in improvements in digestibility – or cellulose synthesis; e.g. Cherney *et al.*, 1991; Sewalt *et al.*, 1997; Turner *et al.*, 2001), lignolytic fungi (e.g. Akin *et al.*, 1995; Mayer and Staples, 2002; Sun and Cheng, 2002) and exogenous enzymes (McAllister *et al.*, 2001; Beauchemin *et al.*, 2004; González-García *et al.*, 2009b).

Yeasts (Chaucheyras-Durand *et al.*, 2008), fibrolytic enzymes and other feed additives (Horton, 1980) have been widely evaluated in recent years with a lack of consistency in the results that have been obtained. The complexity of the rumen and the great diversity of situations at the farm level contribute to such inconsistency. However, these are also valuable resources on which nutritionists must continue to work with standard methodologies of evaluation.

Adequacy of protein supplementation. For more than a century, protein supplements and AA have been studied and recognized as essential dietary constituents. However, before 1890, no one was concerned about adding protein

supplements to livestock rations. As an anecdote, in the United States, the flour mills in Minneapolis dumped wheat bran into the Mississippi River because nobody wanted to buy it, cottonseed meal was used as fertilizer, if used at all, while soyabean was little known outside the Orient (Ensminger *et al.*, 1990). Many of the by-products that once were pollutants are now in unprecedented demand.

In the current scenario and the imminent competition for cereals with the agrofuel sector, future sustainable RPS will have to consider more seriously the use of forage legumes and safe protein AIBPs. We have to harvest or graze our forage till the optimum maturity stage point (Archimède *et al.*, 2000; Boval *et al.*, 2007), and we have to profit more from those high-protein forages by establishing and managing them at the farm level. We have to plant and manage legumes others than soyabean (for grain production). We have to exploit the vast forage germplasm existing worldwide in several latitudes (see the CIAT-CGIAR website available at <http://isa.ciat.cgiar.org/urg/language.do;jsessionid=96938AECC788127301C75D4179F0ECE4>). This approach is particularly important in DCs.

Legumes have good levels of CP and are used in grazing (e.g. association of grasses and legumes) or cut-and-carry systems generally for use as protein supplements. Because of their content in secondary compounds, they are able to 'protect' CP from rumen degradation. The development of agrosilvopastoral and agroforestry systems for animal production (see Maurício *et al.*, 2008) relies on the essential role of such plants as a cheap and valuable source of protein at the farm level in a biodiverse, iterative and dynamic context. These systems have caught the attention of farmers, specialists, researchers and extensionists in recent decades, mostly in the tropics and the subtropics. Without doubt, advances in such fields have contributed during the last times to the poverty alleviation in the poorest regions of DCs through an improvement of animal production indicators.

There is also a group of plants that are not legumes and have been included successfully in such strategies (e.g. mulberry *Morus* spp., *Trichantera gigantea*). A good collection of applied and basic research results is available in the *Agroforestry Systems* and *Livestock Research for Rural Development* (LRRD) journals or on the websites of important institutions such as CATIE, CIPAV and ILRI.

However, the presence of secondary compounds in legumes may affect voluntary intake, digestibility, animal health and final product quality. A lot of research has been devoted to this subject in recent years. As an example, the lower intake of tannin-rich feeds is attributed generally to their astringent taste. In addition to this unpleasant taste, the lower rate of digestion (higher rumen fill) in the presence of tannins could also be responsible for the lower feed intake. The effect of bound tannins on digestion is not necessarily related in any way to that of free tannins.

It will be important to conduct studies on the relationship between tannin structure and activity. Although research on tannins has a long history, considerable additional research

is required to exploit the benefits of fully incorporating legumes and AIBPs in livestock feed (Reed, 1995; Makkar, 2003).

In addition, very little is known in the area of 'anti-nutrient–antinutrient' interactions (e.g. tannins–saponins) from the perspective of different feed sources, which should be explored further. They as are likely to have immense nutritional and ecological significance. This area of research will need continuous effort in the near future.

Moreover, extensive research has shown that global protein efficiency can be increased by protecting some proteins (or AA) from ruminal degradation.

Methane production mitigation, nutrient excretion reduction and recycling of farm waste. The root cause of the past and projected climate change is now recognized to be the warming potential of a number of GHG. Like all other human activities, development and use of intensive animal production systems, including those with ruminants, contribute to environmental pollution due to the waste output (Tamminga, 1996).

Anthropogenic processes are responsible for between 55% and 70% of the estimated 600 T_g of methane that is released annually into the atmosphere (Intergovernmental Panel on Climate Change (IPCC), 2001), with studies suggesting that ruminant eructation is one, if not the main, anthropogenic source (Table 2). Enteric fermentation is a major contributor to emissions in a number of countries (Thorpe, 2009).

Around 90% of methane is produced in the rumen and 98% of the enterically produced methane is released through the nose and mouth (Johnson *et al.*, 2000). Johnson and Johnson (1995) and Johnson *et al.* (2000) have suggested that methane yields in cattle may vary from 2% to 3% (if fed a high-concentrate diet) to 10% (when fed a very poor quality diet), with most diets at most feeding levels producing methane yields in the range 6% to 7% of the gross energy intake.

Research findings recognize that both management practices and feeding schemes could have substantive impacts on mitigating methane emissions. Reducing herd sizes and adjusting livestock FeSysts have been among the main strategies that have been proposed. The propensity of certain additives to reduce ruminal methane production (Calsamiglia *et al.*, 2007) and emissions effectively is also a possible tool in which research has to make further advances.

As using more fibrous diets is a target in the current situation, this will drive the shift towards lower energy density and, therefore, increasing the risks for more methane production and emissions, which means a challenge for ruminant physiologists.

A large number of compounds can reduce methane production (i.e. halogenated methane analogues, oils, essential oils, organic acids, fructan and even antibiotics such as monensin). However, halogenated compounds are unlikely to be approved for administration to animals, and responses to oils can be variable, especially in the long term, while organic acids and fructans are prohibitively expensive

Table 2 Enteric emissions of CH₄ from the main domesticated ruminant species by world region and its changes during the last two decades

Specie	Annual CH ₄ emissions (T _g)	
	1984	2004
World region		
Cattle		
Developing	32.43	39.82
Developed	23.77	17.67
Total	56.2	57.49
Buffaloes		
Developing	6.64	8.60
Developed	0.03	0.04
Total	6.67	8.64
Sheep		
Developing	2.93	3.46
Developed	3.85	2.49
Total	6.78	5.95
Goats		
Developing	2.28	3.74
Developed	0.14	0.16
Total	2.42	3.90
Camels		
Developing	1.03	1.08
Developed	0.02	0.02
Total	1.05	1.10

Source: FAOSTAT, 2009.

(Waghorn and Clark, 2006) and the use of antibiotics is banned in some regions, like the EU.

In the short term, in extensive grazing systems, there are no cost-effective methods able to achieve substantial reductions in GHG emissions from grazing systems. More opportunities for intensive grasslands exist because high-input systems are more amenable to improvements in pasture, fertilizer and animal management.

A combination of pasture improvement, management and animal selection will, for sure, reduce GHG/unit production but not necessarily absolute GHG emissions. A multifaceted approach towards mitigation, with lower forage nitrogen concentrations and use of lifecycle analysis to integrate all inputs, will identify the best opportunities for immediate application (Waghorn and Clark, 2006).

On the other hand, much of the effort expended on nutrient management has focused on the post-excretion product. It is important to keep in mind that the management of the diet can have an important impact on the quantitative and qualitative aspects of the excreted nutrient (critically N and P). This is another environmental challenge for future ruminant sustainability. It is easier to control potential pollutants by managing their release into the environment than to recover or confine them once they have been released.

High-forage diets also contribute to the absorption of NH₃ N from the rumen because of the higher ruminal pH associated with these diets. Nitrogen losses may also impair animal performance. Energy supplementation of diets based on fresh forage has been shown to increase non-ammonia

nitrogen flow to the duodenum, reduce ruminal NH_3 N concentrations and improve animal performance.

Balancing rumen undegradable and degradable proteins, and use of protected methionine along with the strategic selection of protein supplements that are relatively rich in lysine, may permit a 10% to 15% reduction in total N excretion, with most of the reduction occurring in urinary N. Urinary urea, following conversion to NH_3 , is the N excretion product most vulnerable to loss to the environment. More accurate formulation of diets for protein provides an opportunity for reducing N excretion. This would translate into a reduction in N excretion and NH_3 volatilization in open-dirt pens.

Importantly, manure recycling at the farm (and regional) level is an ideal solution to 'close the cycle' in a more holistic manner (Figure 1). Returning limiting nutrients to the soil (i.e. organic fertilization) and producing energy (i.e. through biogas) are among the best-known benefits (Preston, 2009). This solution of integration between agriculture and livestock systems would be ideal for applying to all scales.

Biological adaptive capacities of ruminants in situations of feed supply variation

Classically it has been considered that nutrient requirements include maintenance and the costs of productive functions (ARC, 1980; INRA, 1988; NRC, 2001). Although not fully exact, the immediate consequence of such an assumption is that the aim of breeders is to limit the length of unproductive periods (e.g. ensuring the success of reproduction).

Feeding practices of ruminants at maintenance

Even at maintenance, there are possibilities of saving dietary energy and nutrients thanks to the capability of the animal to reduce its whole metabolism under conditions of limited feed supply. This adaptive capacity involves several phases of sparing mechanisms avoiding the use of classical limiting substrates in the ruminant (glucose, essential AA) and mobilizing endogenous tissue substrates to fulfil the energy expenditure (Chilliard *et al.*, 1998). In this case, homeostatic regulations operate to warrant the longest individual survival (Atti and Bocquier, 1999; Bonnet *et al.*, 2000). Inversely, for a given animal, it has been shown that maintenance requirements are increased in fat animals (cows: Agabriel and Petit, 1987; ewes: Bonnet *et al.*, 2000). As another regulatory process linked with leptin secretion from adipose tissue, voluntary feed intake is reduced in fat animals (sheep: Tolkamp *et al.*, 2006; dairy cows: Favardin and Bareille, 1999) and stimulated in lean animals (Delaud *et al.*, 2002; González-García *et al.*, 2009c). This latter situation allows the achievement of a high level of intake when they are refed. After a long period of energy restriction, when dry mature females of ruminants are refed, a rebound in the evolution of body weight (BW) change, lipid re-deposition and a protein recovery is observed (Atti and Bocquier, 1999).

Effects of feeding practices in producing animals

Homeostatic regulations that only operate in non-productive ruminants to maintain physiological parameters within the range of normal values are not always successful, especially in productive animals. This, together with other physiological arguments, has led to the concept of teleophoresis (Chilliard, 1986), also called homeohoresis (Bauman and Currie, 1980; Bauman and Vernon, 1993). This phenomenon, whose biological significance is to ensure the species' survival (e.g. during pregnancy – foetus survival, lactation, feeding the offspring or growth reaching mature size for reproduction), is an upper regulatory level. It allows explaining how the integrity of the organism is maintained while supporting the metabolic orientations towards production and establishing saving and recycling mechanisms. It could be considered as a driving force of nutrients partitioning exerting a ranking of priority of biological functions at a given physiological stage. For example, milk production in early lactation and replenishment of body reserves at the end of lactation (Chilliard, 1992; Kharrat and Bocquier, 2010).

Such ability to cope with variations of nutrient balance allows development of original feeding strategies as ruminants are able to support transient periods of underfeeding while producing. Conversely, they can store body reserves when feed supply is above total energy requirements. This has already been put into practice in dairy cows that can deposit body energy with high efficiency ($\text{NE}/\text{ME} = \text{KI} = 0.60$) at the end of lactation and can further mobilize this body energy into milk with an even higher efficiency ($\text{Krl} = 0.80$, INRA, 1988). Even if the whole process is less efficient (0.48) than direct milk production ($\text{KI} = 0.60$), it may avoid the use of large amounts of concentrate. Another classical feeding strategy that is used in beef cattle production, relies on the ability of winter underfed animals to regain BW (compensatory growth) when refed with low-cost feeds (spring grazing). Digestive and metabolic adaptations in this rebound period are effective within few days (Hoch *et al.*, 2003), showing the reactivity of the organism to benefit from an improvement in its nutritional conditions. Such a strategy can be successfully applied to dairy heifers (Ford and Park, 2001).

Feeding costs reduction related to specific production system

The cost of energy for thermoregulation (Thatcher, 1974; West, 2003) and for walking activities (Coulon *et al.*, 1998) has often been an argument to place animals in confinement (Blake *et al.*, 1982). This could not be avoided in more extensive farming systems, but this cost has to be re-evaluated because there are conflicting results in the literature.

Coordinated biological responses of ruminants: opportunities for achieving the system plasticity

Effects of genetic potential on response laws

An increment in the performance of ruminant specialized breeds in ICs is well documented, with only slightly differing objectives among countries (Miglior *et al.*, 2005; Hayes *et al.*, 2009). In contrast, productive results of local breeds in

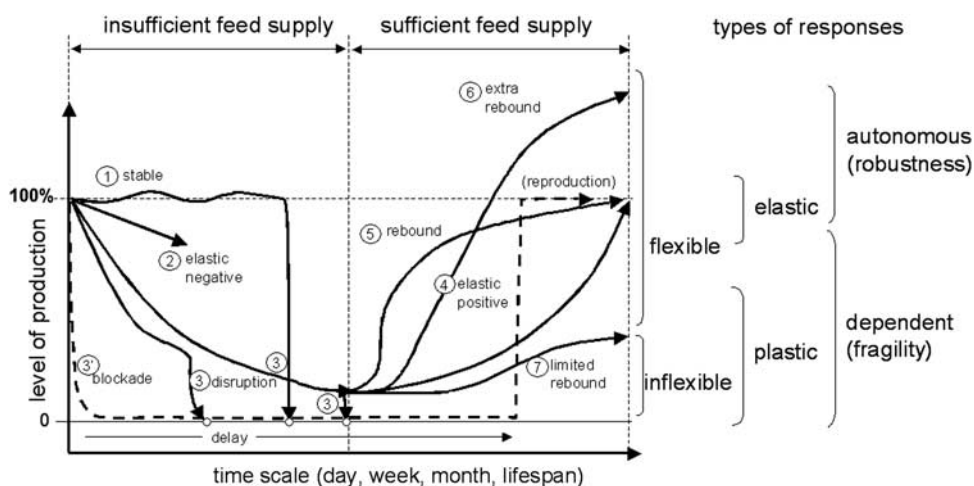


Figure 3 Schematic representation of response curves of a productive function (milk production, growth or reproduction) in domestic ruminants subjected to severe feed supply changes. Interpretations of numbered steps are inserted in the text.

DCs are considerably less documented and, consequently, less reliable. In addition, numerous transfers of improved dairy cattle from temperate zones to harsh environments revealed that performance were considerably lower due to the recognized effects of genotype–environment interactions (Hammami *et al.*, 2008). The approach to analysing the exact causes of difficulties encountered with highly selected ruminants, even in ICs, is now questioned (see Blanc *et al.*, 2006; Friggens and Newbold, 2007; Friggens *et al.*, 2010).

For reducing the length of the unproductive periods, the success of reproduction is crucial. Considering the reproductive rhythm of the species in the temperate climate, reproduction rates are often close to the theoretical biological limits of the species: calving interval being close to 1 year in cows and three lambings in 2 years in sheep (Robinson *et al.*, 2006). In the sub-tropical climate the N’Dama cows have a much longer average breeding interval (e.g. 2.3 years) and age at first calving is around 5 years (Ezanno *et al.*, 2003). As the constraints in the sub-tropical climate are higher than in temperate zones there is a natural separation between pregnancy and lactation. Reproduction occurs when cows have dried off for almost 1 year so that they can slowly replenish their body reserves and then, only when feeding conditions are improved (rainy season), they become able to support a new productive cycle (Ezanno *et al.*, 2003). Furthermore, contrary to the intensively bred cattle of temperate climates the decision to cull a cow does not depend on its fertility.

Another biological strategy can be observed in the dual-purpose Lebanon Balady goats fed in rangelands (Kharrat and Bocquier, 2010). Each time the feed supply is improved milk yield rebounds. When reaching the end of lactation milk rebounds cease and dietary energy surplus is clearly oriented towards the full recovery of body fat reserves. It seems that this breed has maintained a high trade-off capability between lactation and reproduction.

General framework of adaptive processes under innovative feeding practices

When considering innovative feeding practices, the individual adaptive capacity becomes central because the biological response must be predictable and eventually controlled, the type of responses being dependent on the genetic potential defined at least by breed characteristics. Several functional responses of ruminants to underfeeding constraints have been described and classified according to the shape of the response curves (Blanc *et al.*, 2006; Friggens and Newbold, 2007). In the case of domestic ruminants their adaptive response cannot be assessed only by the individual capacity of survival or even by the species perennity but, importantly, by the ability to sustain a given productive function.

It could be considered that biological adaptation is the ability of the whole organism to cope with environmental changes either through resistance (e.g. the production is apparently maintained in a stable condition) or through deformations that could be considered as flexible (high probability of returning to the initial point without any damage; Figure 3). This includes strong elastic marginal responses to underfeeding (if the breaking point is not reached) but also to overfeeding (when the mechanism induces a rebound-like compensatory growth). The response law is described by the integration of the marginal coefficients of elasticity. In some cases, the animal may not be able to reach its initial status because of limited rebound; the system is then considered to be inflexible, but as it attempts to adapt it can be considered to be plastic (Figure 3). With plastic responses some carry-over effects may persist. In all inflexible situations, the breaking point is reached and a dramatic production turn-off occurs. Of course, at a sub-level of organization, within the organism, several biological functions may be successively activated in order to sustain the productive function (Chilliard *et al.*, 1998) in a non-visible manner, thus complicating the assessment of a disruption (Tillard *et al.*, 2007

and 2008). When a biological sub-system has reached its breaking point some other metabolic pathways may be activated, and the global response is still elastic within a given range of intensity of perturbation or within a range of duration of this perturbation. With regard to reproduction, it has also been underlined (Blanc *et al.*, 2006) that the introduction of a delay in the response is also a way of adapting to inadequate nutrition. This is particularly the case in species such as the bovines, whose reproduction should occur during lactation at a stage when the females are in strong negative energy balance (see Friggens *et al.*, 2010).

As the ovulation process *per se* does not require high fluxes of energy, there is no real competition in the energy partition between the mammary gland and the ovary; with only a passive subordination of reproduction to the dominating process occurring. Nevertheless, we can consider that teleophoretic regulations that operate at this stage (lipid mobilization, mammary drain of nutrients) introduce perturbations in the functioning of the ovary whose response is to postpone the occurrence of ovulation. Such a situation, recognized by the breeder as a failure, may be interpreted as the direct result of an adaptive process that ensures the survival of the individual (the lactating female) at the expense of the survival of the species (giving birth to a newborn). This could be considered as an anticipative adaptation (summarized by Friggens, 2003). Inversely, the effect of flushing, which is a short-term positive effect of nutrition on ovulation rates (Robinson *et al.*, 2006), overcomes the negative effect of poor body fatness.

From the physiological point of view, it can be considered that the regulatory systems that should prevent multi-ovulations in lean ewes are temporarily misled and an unexpected positive response is obtained. More recently, this idea to mislead the regulatory systems has been extended to other biological functions and to other feeds or compounds with the aim of eliciting a specific biological response such as controlling the anoestrus duration (Somchit *et al.*, 2007; Violesca *et al.*, 2009). Even if one of the main interest could be to save expensive feeds, this feeding practice, which was called 'focus feeding', may not be convenient for all renewed FeSysts and may be at risk for some biological functions. The applied objectives of 'focus feeding' are sound and ambitious, but one must keep in mind that reasoning *a priori* the reaction of regulatory systems may be risky. For instance, in early lactating dairy cows it was expected that providing high-energy content feeds, such as dietary fat, would help in reducing body lipid mobilization through direct fat supply. Surprisingly, a meta-analysis of the data revealed that under this focus feeding practice cows mobilized more body lipids than unsupplemented ones (Chilliard, 1993).

Transferring innovative strategies to farming conditions

Under the farming conditions, ruminant FeSysts mostly cannot be individualized and diets are normally formulated for large groups of animals. Numerous studies has been conducted with the objective of grouping animals into homogenous groups

expecting that their adaptive response (and the resulting performances) would also be homogenous. Unfortunately, the large variety of individual responses, even inside a class of similar animals, mostly leads to unpredictable group responses. Another important factor that alters the prediction is the social behaviour and interactions (i.e. competition for feed). Thus, to maintain homogeneity within the groups it would be necessary to reallocate the animals. This procedure is, however, delicate as re-compositions of groups reinforce behavioural problems. Nevertheless, some conclusions can be drawn with animals often fed as a unique flock. From studies on dairy ewes (diversity of milk production levels) a common feeding caused disruptive situations in some sensitive individuals (Bocquier *et al.*, 1995), precisely those that often have higher nutritional requirements. The proportion of sensitive animals not only depends on the variability of nutritional requirements (physiological stage, production level) but also on diet characteristics (bulk, nutritional value). However, appropriate feeding strategies for bulk diet do exist. It has been shown that a common diet avoids problem occurrence when it is warranted to fulfil the requirements of at least 80% of the individuals in the flock (Bocquier *et al.*, 1995 and 2002). According to the often-observed variability in milk yield, this leads to formulation of diets that fulfil energy and protein requirements at 120% and 140%, respectively. In all situations, whatever the adjustment of feeding practices, there is feed wastage due to the inadequacy of feed allowances to individual animal requirements.

Finally, the grouping of individuals with similar characteristics is convenient for production planning, for work simplification and to design feasible feeding strategies leading to increased feed efficiency. But in situations of large uncertainty about the availability of feed supply, this synchronization clearly exposes some classes of animals to common risks. Therefore, as a paradoxical effect, it seems that for livestock systems in which reproduction periods are not well controlled and where the physiological stages of the animals are widespread, the adaptive capacity of the herd considered as a whole may be greater than that of a cohort of individuals with a narrow range of nutritional requirements. Such a strategy is often adopted in DCs (sheep: Atti *et al.*, 2004; cattle: Ezanno *et al.*, 2003).

One should not forget that farming systems that strongly rely on adaptive responses may have consequences on animal welfare. As adaptive responses are also mediated by behavioural troubles they may not be acceptable (see Martin *et al.*, 2004). This important point related to the acceptability of stress according to the cultural environment, is not in the scope of this paper.

Conclusions on adaptive capacities of ruminants to renewed feeding systems

If ruminants of ICs are performing in this manner, it is both because of genetic selection and to an artificial change in their direct environment. This has been an iteratively successful process in terms of individual animal performance for determined production (i.e. meat and milk) with an accelerated co-evolution of their immediate environment. No doubt

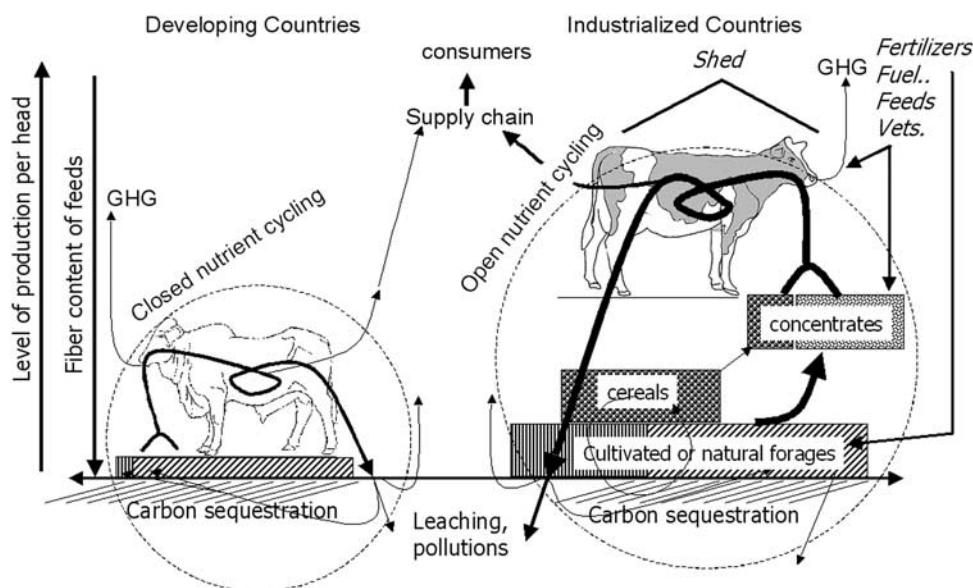


Figure 4 A vision of the ecological position of ruminants from developing countries (DCs, mostly corresponding to extensive and low input systems) to developed countries (industrialized countries (ICs), mostly highly intensified systems). Emphasis is made on nutrients cycles that may be nearly close in DCs and widely opened in ICs.

that this general scheme gave very efficient animals from the point of view of gross energy and protein conversion into goods for humans. Simply considering feeds used by animals in ICs, however, one could notice a great difference from those consumed by ruminants in DCs, which are also far different from their wild counterparts. Although hazardous (e.g. ruminal disorders – acidosis – due to reduction of fibre content of diets), these substitutions of feeds made selected ruminants evolve from their initial trophic level of strict forage eaters to nearly omnivorous status, thus becoming less dependent on primary lignocellulosic resources. However, from the ecological point of view (Figure 4), this rising up along the food chain imposed the use of artificial and standardized resources such as cultivated forages and grains (selected, fertilized, harvested, treated and often transported to very long distances). This food chain position should be holistically reevaluated through multi-criteria methods. For instance, life-cycle analysis may allow judging their interest not solely from the economic but also from the eco-systemic point of view (nutrient cycles; Figure 4).

If this is not done, a clear danger is that these selected ruminants that appear to be in direct competition with nutritional needs of human populations, could be excluded from the local food chain. Paradoxically, the less efficient the ruminants are, because of their capacity of high fibre diets consumption, the higher they are of ecological interest. The message is that all ruminants should be kept in a proper definite vital cycle, whatever its magnitude, which can be far larger than a classical ecological niche. This is the central condition for making a community of living organisms stable and self-perpetuating. The main issue, from a technical point of view, would be to select more robust ruminants in ICs and to move forward more productive ruminants in DCs without

removing their natural adaptive capacity to harsh environments. Thus, look for the 'ideal balance' between productive capacity and adaptability. Altogether it is necessary to better control the expression of adaptive traits that are required in each productive system.

Perspectives

This general review could not deal with several key issues (i.e. health) that have, however, to be kept in mind (Figure 1). Surely, ruminants will continue being essential in future food security and poverty alleviation programmes; however, some strategies (i.e. feeding and genetic programmes) are asking for new ways to breed them, given the current global challenges. Whatever the country or region, the sustainability of ruminant production will be largely determined by the management of environmental issues, which also depend on public institutional initiatives and decision makers' support.

More emphasis on animal welfare will direct some ruminant farming systems in regions like EU. Integration of 'omics' technologies (functional genomics, proteomics and metabolomics) is a particularly exciting opportunity for the understanding of ruminant future potentialities.

Other promissory fields on which applied research must continue focusing from a multidisciplinary expertise include, in our view:

1. To better know the metabolic processes and intermediary metabolism while enhancing microbial protein synthesis under several scenarios from dietary material to final product.
2. Helping to find alternatives for digestive limitations in legume FeSysts related to secondary compounds content and their bioactivity in some lesser-known plants.

3. To actively include a broader spectrum of domestic ruminant species and breeds in future research programmes.

There is no 'recipe,' as so many different solutions and diverse situations that exist at the farm level; in addition, there are a multitude of different socio-economic and edaphoclimatic contexts. As we have seen above, with rare exceptions (e.g. new biotechnological findings), the feed resource base will continue to be almost the same in the future. A great amount of accumulated knowledge in feed processing and utilization exists, with a large gap between such volume of knowledge and actual farming practices. Even less is applied from the already demonstrated biological adaptability of animals to environmental constraints.

Furthermore, there is no 'renewable' alternative that can supply energy at the same level of usage as presently occurs with oil. Thus, economy in energy use must be a major factor governing the choice of future farming systems. This puts major emphasis on farm-grown inputs where external energy costs are minimized.

The world has changed and will never be the same as when oil was cheap and abundant. The role of livestock will almost certainly become more important and our approach to the development of production systems must also change. Smaller farms with fully integrated crop-livestock systems could be more appropriate than industrialized monocultures in a world where exogenous energy sources are becoming increasingly more expensive. Changes of this nature will impact strongly on future FeSyst for all livestock, not just ruminants.

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