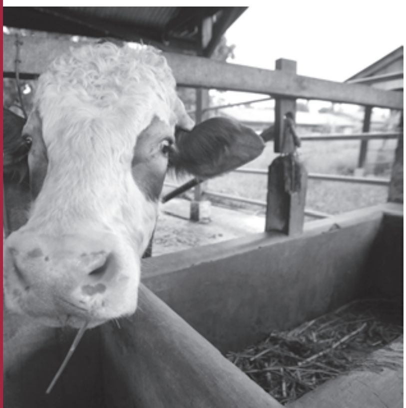
ISSN 1810-0732
16
FAO ANIMAL PRODUCTION AND HEALTH



proceedings

OPTIMIZATION OF FEED USE EFFICIENCY IN RUMINANT PRODUCTION SYSTEMS

FAO Symposium
Bangkok, Thailand
27 November 2012

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16

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Editors
Harinder P.S. Makkar and David Beever

Published by
FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
and
ASIAN-AUSTRALASIAN ASSOCIATION OF ANIMAL PRODUCTION SOCIETIES
Rome, 2013

Editors
Harinder P.S. Makkar
Animal Production Officer
Animal Production and Health Division
FAO, Rome, Italy

David Beever
Richard Keenan & Co
Clonagoose Road
Borris, Co Carlow
Ireland
(Emeritus professor, University of Reading, UK)

Recommended Citation
Makkar, H.P.S. & Beever, D. 2013. *Optimization of feed use efficiency in ruminant production systems.* Proceedings of the FAO Symposium, 27 November 2012, Bangkok, Thailand. FAO Animal Production and Health Proceedings, No. 16. Rome, FAO and Asian-Australasian Association of Animal Production Societies.

E-ISBN 978-92-5-107733-7 (PDF)

Contents

Acknowledgements

The papers in this proceedings have been peer reviewed. All peer reviewers are thanked for their contribution, for taking the time to critically read the manuscripts and for their comments and suggestions. We are also grateful to the members of the Organizing Committee of the Asian-Australasian Association of Animal Production Societies (AAAP) Congress, and in particular to Professor Metha Wanapat and Dr Phongthorn Kongmun, for their excellent support and cooperation in organizing the Symposium.

Welcome address

Berhe G. Tekola
Director
Animal Production and Health Division, FAO

Distinguished delegates, ladies and gentlemen, I welcome you all to this FAO Symposium.

I would like to thank the organizers of the Asian-Australasian Association of Animal Production Societies (AAAP) Congress for inviting FAO to organize a session that could help prepare the livestock industries to effectively address the ongoing and emerging challenges imposed by increasing demand for animal products, increasing human population, decreasing arable land, increasing cost of energy, water shortage, increasing food, fuel and feed competition, increasing risk of exclusion of small-scale producers and ongoing climate change. Feed is in economic terms the single most important element of animal production, since feed cost can form up to 70% of the total cost of production. In addition, animal feeding affects animal productivity, environmental emissions, water pollution, land use and land use change, animal health, product safety and quality and animal welfare. In fact the entire livestock sector, associated services, public goods and services, and animal and human well-being are influenced by animal nutrition. Therefore, we decided to hold this symposium to address an issue of high relevance, i.e. optimization of feed use efficiency in ruminant production systems.

Agriculture has seen some important changes, including the introduction of improved crop and animal germplasm, and improved agronomic and animal husbandry practices. These efforts have contributed to an increased production of food per unit land mass. Efficiency gains in crop production have occurred, whilst in the livestock sector, notable gains have been achieved by the pig and poultry industries. Unlike in the ruminant sector, regular monitoring of feed conversion efficiency in the monogastric sector and selecting animals for higher feed efficiency have contributed substantially to the sector's development. Many of these improvements in efficiency have been driven by the need to maintain farm profits over a sustained period where increases in farm prices for food commodities have failed to match annual rates of inflation. In contrast, efficiency gains in the ruminant livestock industry have been less pronounced, despite having considerable potential to improve the conversion of feed into milk or meat. The ruminant industry is expected to make an ever increasing contribution to the food demands of society. An extended period of low prices encouraged the feeding of cereals to ruminants in many parts of the world. Whilst the use of cereals to feed to livestock to produce human food can be subject to criticism on moral and ethical grounds, this was an opportunity to achieve higher rates of animal production and improved margins. Too little consideration was given to the conflicting demands of society in terms of feeding the world, or indeed to the environmental costs of such practices.

All sectors of livestock production face difficult challenges in the years ahead. Last year, 27% of the world's maize grain production was diverted to the production of biofuels. This alternative use of grain will inevitably have an impact on its availability both for human food and animal feed. Nevertheless, from the increasing production of biofuels, there exists a significant and increasing volume of distillers grains and related co-products considered suitable for feeding to farm livestock, providing an alternative source of protein to soya, and a useful energy feed.

So it is against this background that the ruminant sector will need to operate over the coming years, making better use of home-grown feeds, placing greater emphasis on forage provenance and quality, and employing alternative feeds. But such changes alone will not bring the required gains in overall efficiency of nutrient use that are both possible and desirable. In this respect, current feeding strategies need serious reconsideration. Where a more focused approach to the feeding of ruminant stock has been employed, the evidence of improved performance from the same or a reduced level of feed consumption, better animal health and longevity and improved farm margins are all testimony to the value of the approach. In addition, such an approach has led to reduced environmental emissions: a welcome bonus in mitigating the problems of global warming and a support to farmers seeking to remain profitable and ease current environmental concerns.

The focus of this symposium is on enhancing Feed Conversion Efficiency, through the application of new approaches to feeding ruminants that address both rumen and animal health, and the benefits it holds for farmers, for their livestock and for society

This symposium complements FAO's other activities, including the recently launched Global Agenda of Action in support of Sustainable Livestock Sector Development, which focuses on approaches for enhancing resource use efficiency and for achieving zero discharge nutrients from livestock production systems.

This symposium is also an opportunity to think about the role innovative feeding options could play to offer a better opportunity to small-scale producers to increase their family income.

I wish you all a very productive and successful symposium, and will eagerly look forward to reading its proceedings.

Converting feed into human food: the multiple dimensions of efficiency

Margaret Gill

Aberdeen Centre for Environmental Sustainability, University of Aberdeen, Scotland, UK
E-mail: m.gill@abdn.ac.uk

ABSTRACT

When our ancestors first started to consume animal products their consumption probably helped communities to derive maximum nutritional benefit from local resources while minimizing foraging time. In recent decades the dietary transition towards greater meat consumption is more strongly related to wealth status than nutritional requirements, and meeting the increasing demand does not help to derive maximum nutritional benefit from global resources. The increased consumption of meat in emerging economies, such as China, has highlighted the demand for cereal grains for use in animal feed, at a point in history when both population growth and the impact of climate change are putting pressure on the availability of arable land to supply global needs. Already 35% of crop production is used for feed and 50% of the water from grasslands and crops is used by livestock. Ruminant production is not as dependent as pig and poultry production on the use of grain, but the dilemma is that ruminants fed on high forage diets emit more methane (a potent greenhouse gas) per kg of product than do those on high grain rations. Both food security and the reduction of greenhouse gas emissions are high profile global priorities, and decision-makers need evidence to help achieve optimal use of limiting resources to contribute to these priorities. There is no one ideal solution, and the solutions to achieve optimal feed efficiency will be system- and place-dependent. The paper suggests that five dimensions, in addition to productivity, need to be considered when calculating optimal feed efficiencies, based on the concept of 'planetary boundaries'. These dimensions are: greenhouse gas emissions; land use change and its implications for carbon balance; competition (with humans) for grain; use of water; and impact on the global nitrogen cycle. The paper also recommends that the different communities of policy-makers, the private sector, scientists and farmers need to work together to help to identify ways of ensuring that the best options are economically sustainable.

Keywords: *food security, cereals, greenhouse gas emissions, land use, ruminants*

INTRODUCTION

If we could travel far enough back in time, we would find our ancestors gathering wild plants to provide the energy needed to survive. In recent decades, there has been an active debate in the anthropological literature leading to the development of hypotheses that link the evolution of humans with changes in diet, including the regular consumption of meat (e.g. Kaplan *et al.*, 2000; Milton, 1999). Milton (1999), for example, hypothesized that the supply of essential nutrients for growth through routine inclusion of meat in their diet would have simplified foraging by ancestral humans, allowing them to select plant foods for energy (rather than all essential nutrients). This would have enabled communities to make efficient nutritional use of local resources. Kaplan *et al*. (2000) hypothesized that co-evolution of slow development of the young with expansion of the brain resulted from the introduction of meat into the diet of evolving humans, thus enabling them to occupy the 'skill-intensive feeding niche' that is the basis of farming today. Farming today does not make use of just local resources, however, with global trade in 'feedingstuffs' exceeding US$ 50 billion in 2008 (Niemi and Huan-Niemi, 2012).

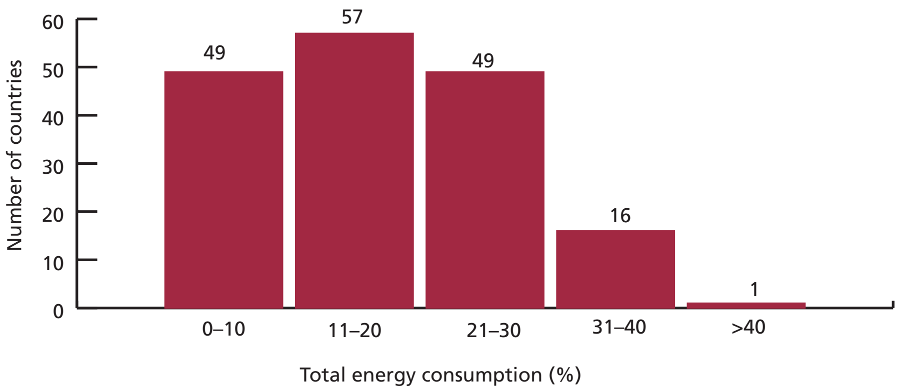
One of the opportunities of global trade is that production is not limited by local resources. One of the challenges of trade is that economic drivers can overlook the overexploitation of resources. The aim of this paper is to provide an overview of trends in livestock production and consumption, with an emphasis on the conversion of feed to food, and by analysing recent trends to identify new ways of working, which might help to optimize the efficiency of feed conversion by ruminants in the context of a growing global population and in an era of climate change. The paper starts by considering trends in consumption and production of livestock products, then examines the consequences on the resources required to feed the world. This identifies a niche for ruminants, but the niche is threatened by climate change and the breaching of other environmental 'boundaries' (Rockstrom *et al*., 2009). The paper goes on to outline a framework with which to consider the impact of different ruminant production systems and management interventions on the collective approach to these boundaries, and suggests how this framework might be used to engage relevant stakeholders. The paper concludes by identifying some strategic knowledge gaps that—if filled—could help to inform policy-makers in their decision-making.

CURRENT DRIVERS OF CONSUMPTION

The contribution of animal products to the human diet in the distant past is not known, but their nutritional contribution would have been important to our ancestors. Today there is a wide variation across the globe in the contribution of animal products to total energy consumed (Figure 1). The global average was 17% in 2005–2007, but the contribution was <5% in 18 countries and over 30% in 17 countries (FAOSTAT, 2012).

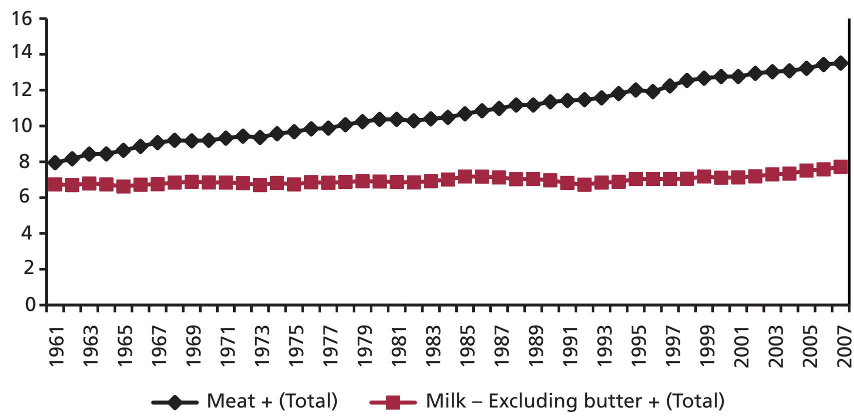
Part of this variation can be explained by long-held cultural practices, no doubt rooted at least in part in the agro-ecology of the locality, but part is also due to the stage of development of the economy of individual countries. FAO (2009) showed a strongly positive relationship between increased per capita income and consumption of livestock products at lower income levels, with a neutral or even negative effect at high levels. Guyomard, Manceron and Peyraud (2013) referred to this as the 'food transition' process, which in developed countries took over a century, but which Popkin (2006) noted now takes place within 20 years in countries deemed to be 'emerging' and 40 years in others. This transition leads to a decrease in the per capita consumption of cereals and vegetables as the intake of sugar, fats, animals and animal products increases (Guyomard, Manceron and Peyraud, 2013). The global impact of this trend is illustrated in Figure 2, which shows the global trend in consumption, based on the FAO statistics on per capita supply of animal products, expressed in terms of protein.

FIGURE 1
Total energy consumptionof animal products by country



Source: FAOSTAT, 2012.

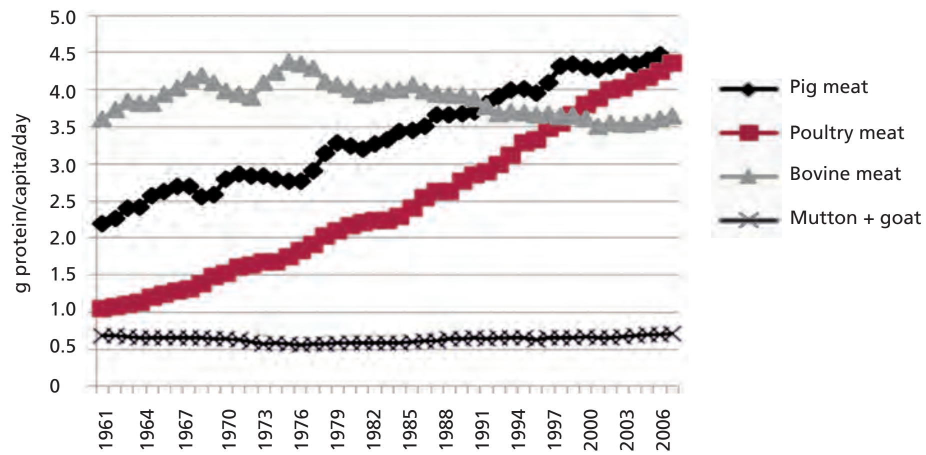
FIGURE 2
Trends in world average supply of meat and milk, 1961–2007



Source: FAOSTAT, 2012.

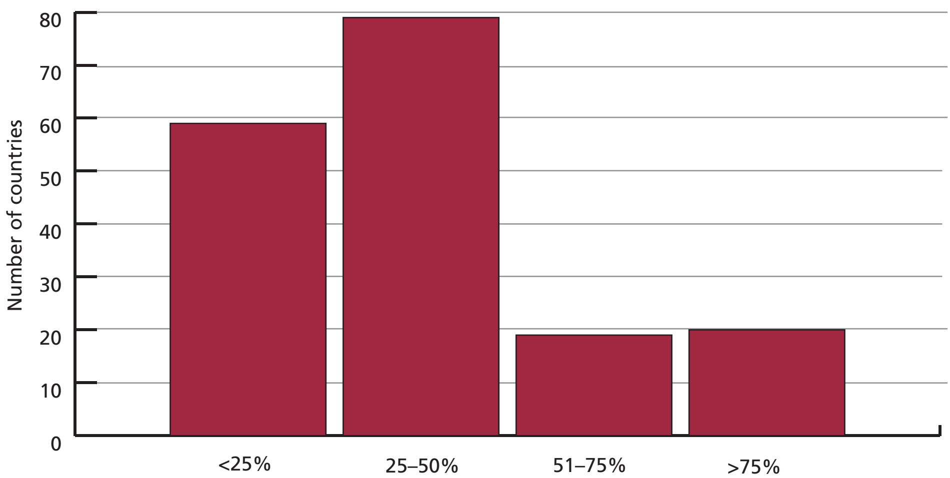
One consequence of the acceleration in this demand-led dietary transition in the human diet has been an increase in demand for animal feed. IAASTD (2009) pointed out that of the over 1 billion additional tonnes (relative to 2000) of grains projected to be required by 2050, ~40% would be used for animal feed. It is projections like this that make this symposium on optimizing feed use efficiency so important. The focus of this symposium is on ruminants though, so before continuing to consider the impact of this growth in livestock productivity on resource use, it is important to set the contribution of ruminant production in context.

FIGURE 3
Trends in global consumption of meat from different species, 1961–2007 7



Source: FAOSTAT, 2012.

FIGURE 4
Global variation in bovine meat as % of total meat (bovine + pig + poultry meat) (all figures compared in units of g protein/capita/day)



Source: FAOSTAT, 2012.

Figure 3 disaggregates by livestock species the world average supply of meat per person over the last 40 years. It illustrates the dominance of pig and poultry meat in driving the increase in global meat consumption per person, with consumption of both pig and poultry meat having overtaken the consumption of bovine meat in the 1990s. Ruminant meat comprised only approximately one-third of total meat consumption in 2007. There is considerable geographical diversity in the contribution of bovine meat, however, as illustrated in Figure 4. It is worth noting that all of the countries in the range of 75–100% of meat consumed being bovine, are either developing or 'in transition', where consumption of bovine meat is <10 g protein/capita/day. Most developed countries consume bovine meat at <50% of the total, and in the United Kingdom the consumption of poultry meat has, until recently, been increasing, having overtaken (in terms of g protein/capita/day) that of bovine meat in the 1990s.

LIVESTOCK SYSTEMS AND USE OF RESOURCES

Concentrate feed

Ruminants, in particular, do not require grain to produce edible products, but inclusion of grain in ruminant diets, as a highly concentrated source of energy, can greatly increase the efficiency of animal production and, at present prices, can help the profitability of livestock enterprises, depending on the availability of alternative feeds. Table 1 illustrates the impact of the human food transition, with a more than doubling in use of feed concentrates in developing countries between 1980 and 2005, with the largest increases occurring in East and Southeast Asia and China, in particular (241 million tonnes in 2005, compared with only 86 million tonnes in 1980). China was the main producer of compound feed in a survey of global feed in 2012 (Alltech, 2012), producing 175.4 million tonnes compared with 164.92 million tonnes in the United States of America. This involved imports of 57 million tonnes of soybean by China in 2010 (FAOSTAT, 2012).

The data in Table 1 illustrate the slight improvement in feed efficiency in developed countries between 1980 and 2007 (production increasing slightly while use of concentrates decreased slightly) and the high dependence of the developing regions on increased use of feed concentrates. For example, the proportion of cereal grain used for animal feed in China increased from 7% in 1960 to 22% in 2007 (FAOSTAT, 2012). This increase in the use of concentrates has seen the total quantity of compound feed being traded globally rise to 873 million tonnes (Alltech, 2012). This does not include forage or concentrate feed

TABLE 1
Trends in use of feed concentrates and production of meat, milk and eggs in different regions

Region	1980		2005	2007
	Concentrate use	Meat, milk and egg production	Concentrate use	Meat, milk and egg production
	million tonnes			
Developed countries	669	457	647	487
Developing countries total	240	172	603	537
East & Southeast Asia	114	28	321	183
Latin America & the Caribbean	64	53	114	115
South Asia	21	47	50	153
Near East & North Africa	26	23	70	49
Sub-Saharan Africa	15	19	48	35

Source: from FAO, 2009.

TABLE 2
Global feed tonnage by species, excluding on-farm feed resources

Region	Ruminants	Pigs and poultry	Other, including aquaculture
North America	45.5	122.3	17.3
Europe	55.8	129.9	9.5
Asia	80.1	197.0	28.5
Near East & Africa	17.0	28.6	1.3
Latin America	22.3	96.0	6.3
Other	3.5	6.6	1.1

Source: from Alltech, 2012.

produced 'on-farm'. Pig and poultry systems are the dominant users of feed tonnage at 580 of the total of the 873 million tonnes, yet ruminants used 224.3 million tonnes, or ~25% of the total.

Land use

The use of grain to feed ruminants has increased markedly in the last 60 or so years, stimulated in part by the development of the barley beef system (Preston *et al*., 1963). There were just over 0.4 ha of arable land per person in the early 1960s, whereas in 2012 there were estimated to be only just over 0.2 ha arable land per person (FAOSTAT, 2012). Since the global population is still growing, this pressure can only increase. Various assessments of land use have targeted livestock as profligate users of grain, with Foley *et al*. (2011), for example, estimating that restricting the use of 16 major crops to direct human consumption would add >1 billion tonne of grain to global food availability.

Ruminants are not, of course, dependent on grain since they evolved with micro-organisms in the rumen capable of digesting fibre. Many ruminant systems therefore produce human-edible food from some of the 3.36 billion ha globally that is in permanent meadows and pasture. For example, Behnke and Ossman (2011) estimated that 90% of the national cattle herd in the Sudan is kept in pastoral systems, with the 2009 off-take being worth US$ 7.7 billion. In terms of global importance, Rass (2006) has estimated that there are 120 million pastoralists and agro-pastoralists worldwide, of which 50 million are in sub-Saharan Africa. There has been a trend of policy initiatives away from pastoralism but as Kratli *et al.* (2013) point out pastoralists are more efficient at producing food per unit area of dryland than other forms of agricultural land-use under the same conditions (e.g. ranching, crops). Pastoralist systems are also efficient users of resources in that the manure produced by the livestock is not seen as 'waste' but as a resource to help increase the yields of crop farmers. Such systems demonstrate resilience to weather fluctuations, from which lessons could be learnt for responding to climate change (Kratli *et al.*, 2013).

Pastoral systems are one type of extensive grazing system, but developed countries such as New Zealand have developed more intensive grazing systems, which on a global basis provide ~17% of global beef and veal and ~17% of sheep and goat meat production (FAO, 2009). The most important type of system for the production of ruminant products is, however, mixed systems, defined as systems in which >10% of dry matter intake comes

TABLE 3
Livestock production (million tonne) by system; average of 2001–2003

	Livestock production system			
	Grazing	Rainfed mixed	Irrigated mixed	Landless/industrial
Beef & mutton	18.4	33.3	16.9	4.0
Pork	0.8	12.5	29.1	52.8
Poultry meat	1.2	8.0	11.7	52.8
Eggs	0.5	5.6	17.1	35.7
Milk	71.5	319.2	203.7	—

Source: Steinfeld *et al.*, 2006.

from crop by-products or stubble, or where >10% of production comes from non-livestock farming activities. FAO (2009) estimated that 86% of global milk production and ~68% of beef production came from such systems (Table 3)

Given the ability of the rumen to use high fibre diets and the decreasing ratio of arable land per person, in terms of efficient use of land, the emphasis should be on making mixed systems more economically efficient.

WATER

Livestock systems are major users of water. The largest proportion (>99%), however, is associated with the production of feed. The amount required per kg of feed grown is, however, highly variable, from 1000–2000 kg water per kg grain in temperate countries such as the Netherlands, to 3000–5000 kg/kg grain in the arid parts of the Near East (Deutsch, Lannerstad and Ran, 2011). Thus Ridoutt *et al.* (2012) estimated a range of 3.3 to 221 litres of H_2O-equivalent per kg live weight at the farmgate when calculating the water footprint of six geographically distinct beef production systems in New South Wales, Australia. Such a range illustrates the potential for error to be introduced when global averages are used.

Indeed, a recent paper by Peden, Taddesse and Haileslassie (2009) proposed that livestock water productivity (the ratio of the net beneficial livestock-related products and services to the water depleted in producing them) compared favourably with crop water productivity in Africa. Peden, Taddesse and Haileslassie (2009) also highlighted the potential for enhancing current levels of water productivity through: "optimal feed sourcing, enhancing animal productivity, conserving water resources, strategic spatial and temporal provisioning of drinking water to livestock".

Thus, while improving animal productivity is an integral part of improving feed efficiency, attention also needs to be paid to the source of the feed when considering resource use efficiency.

CONCENTRATES OTHER THAN GRAIN

The source of feeds is particularly pertinent when considering protein sources. There are only three major producers of soybean in the world: Argentina, Brazil and the United States of America. China is the biggest net importer, but 20% of cows in Europe are dependent on soybean as their major source of protein (Niemi and Huan-Niemi, 2012). Not only does

TABLE 4
Ranking of human edible returns in different livestock systems

Country	System	g product protein per g feed protein
South Korea	Dairy	14.30
South Korea	Beef	6.57
Argentina	Beef	6.12
USA	Dairy	2.08
Argentina	Dairy	1.64
USA	Beef	1.19
South Korea	Poultry meat	1.04
USA & Argentina	Poultry meat	<0.7
All three countries	Pigs	<0.51

Source: from CAST, 1999.

such a high level of dependence on one commodity not produced locally present a risk in terms of continuity and price of supply, but the export of 28.5 million tonnes of a high-nitrogen feed represents a considerable disruption to regional nitrogen cycles.

Other sources of concentrate feed are also at potential risk, due to the increased interest in biomass as a source of energy. Traditionally, crop by-products made a significant contribution to ruminant rations (e.g. Sundstol and Owen, 1984) and this continues in many mixed crop-livestock systems. The inclusion of such by-products reduces the use of grain and the benefits in terms of feed efficiency were highlighted in the Council for Agricultural Science and Technology report (CAST, 1999), which introduced the concept of human-edible returns (calculated as human-edible outputs divided by human-edible inputs). Using this index, they illustrated the potential for relatively high net returns in terms of human-edible products for ruminant systems that are less dependent on grain. Table 4 ranks different livestock systems in South Korea, Argentina and the United States of America in terms of their human-edible returns. All beef and dairy systems in Table 4 showed a net gain in terms of human-edible products, relative to inputs, which illustrates the potential for ruminant systems to be resource efficient, provided such components remain available as feed sources.

THE DILEMMA

This analysis so far has drawn mainly on trends to date, although earlier mention was made of the IAASTD prediction of the need for an additional 1.305 billion tonnes of grain by 2050. Achieving this increase in production of cereals (and indeed the corresponding increase in demand for protein sources) will be further challenged by the likely impact of climate change on the yield of crops. Given the uncertainties over the degree of global warming and the multiple parameters that will have an impact on crop yield (e.g. CO_2 concentration, temperature, rainfall), accurate predictions of the likely impact of climate change on crop yield are not possible, but a range of numerical methods have been applied to the challenge. Wheeler and Reynolds (2013) considered the outcomes of some of these projections for animal feed, and concluded that there will be both opportunities for increased crop productivity and threats in terms of volume, volatility and quality of animal feeds. What is less uncertain, though, is the need for urgent action to decrease anthropogenic greenhouse gas (GHG) emissions.

This then poses a dilemma for ruminant production. Food security challenges would suggest that less grain should be fed to ruminants, but ruminant nutritionists know that higher forage diets lead to higher CO_2 equivalents per kg of livestock product (see e.g. Gill, Smith and Wilkinson, 2010, for discussion of the issue). Thus, while human edible returns is an indicator of efficiency that can indicate net contributions to food security, it does not take account of the contribution of livestock systems to GHG emissions. Nor does it take into account other negative environmental effects of livestock systems.

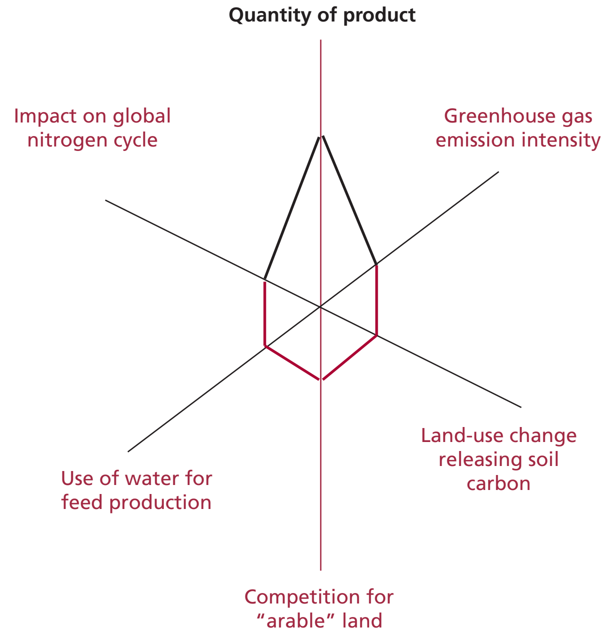
Rockström *et al.* (2009) presented a new way of thinking about the global environment, by identifying nine 'planetary boundaries' – points beyond which further deterioration could 'tip' the planet outside of its current condition. Livestock production currently makes a significant contribution to breaching five of these boundaries (climate change; disruption of nitrogen cycles; global fresh water use; change in land use; and biodiversity loss), yet there is much that could be done at the farm level to reduce the collective impact. Smith *et al*. (2008) estimated the potential of a range of land management practices to mitigate GHG emissions, identifying restoration of organic soils, and management of cropland and grassland as having particularly high potential at a global level, although this differs markedly between countries and among different types of livestock system.

What this means, in effect, is that while there is much that could be done to enhance the contribution of ruminants to poverty reduction and food and nutrition security, there is a high risk of negative unintended consequences on the environment. Many of these are associated with feed production and use. Thus, while in the past it was sufficient to think of feed efficiency in simple terms of unit of food out per unit of feed in, such an approach is no longer sufficient. What is proposed in the next section is a framework (loosely based on the planetary boundary approach) that could be used to assess the impact of changes to feeding systems in multiple dimensions.

FRAMEWORK TO CONSIDER MULTIPLE DIMENSIONS OF FEED EFFICIENCY

The main aim of ruminant production continues to be the production of high quality food for humans, but the earlier analysis emphasized the need not to maximize ruminant products, but rather to achieve a balance that favours *net* food production, i.e. making use of the evolutionary benefits of ruminants to digest fibre. This is depicted in Figure 5 as maximizing the distance from the origin on the axis labelled 'quantity of product' while minimizing the distance from the origin on the axis labelled 'competition for 'arable' land'. It is accepted, however, that different systems and management practices will have different impacts on the other four axes, which represent four of the five 'planetary boundaries', namely GHG emissions; land use change; use of water for feed production; and impact of feed use on nitrogen cycles. (While ruminant systems undoubtedly have an impact on biodiversity, there have been fewer studies in this area, and thus the author judges there to be insufficient knowledge to take this into account at this time.) It is not possible to quantify

FIGURE 5
Framework to compare the impact of systems and management interventions on multiple dimensions of negative environmental impact compared with the net benefit in terms of human edible return (net distance along vertical axis)



the impact of different systems and practice on the four 'boundary' axes, but it is certainly possible to compare qualitative effects and thus estimate the relative size of the negative footprint for different systems and management interventions.

An example of using the framework would be to compare extensive systems that would have a better human edible return than intensive systems, yet a higher greenhouse gas emission intensity, combined with smaller footprints in terms of land use change, water use and impact on nitrogen cycles.

Exploring the combined impact of different systems and interventions could be an interesting academic exercise, but the global impact of ruminant systems will only be influenced if farming practice actually changes. The following section considers how such a framework might help this to be achieved.

THE STAKEHOLDERS WHO INFLUENCE FARMING PRACTICE

The global impact of any agricultural sector is the sum of the impact of millions of individual farm businesses. Livestock make an important contribution to the global economy: they contribute 33% of agricultural GDP at a global scale and their asset value is estimated to be in the order of US$ 1.4 trillion. In poorer countries, livestock directly support the incomes of 600 million small-scale farmers (Thornton, 2010), yet the preceding analysis has illustrated some of the negative impacts of livestock production on the environment. It is therefore important that those taking the decisions at the farm level can understand the impact of those decisions. Farmers are in the business to earn a living, however, and thus regardless of how beneficial a certain course of action might be for the public good (e.g. the environment), they are not likely to implement it unless it is in their economic interest. National governments, in contrast, do have a responsibility for maintaining public goods, but also have an interest in sustaining their livestock industries. In rich countries, livestock may make an important contribution directly or indirectly (e.g. through its contribution to the food industry) to the national economy, or the importance of the livestock sector may lie mainly in maintaining a population in rural areas with poor natural resources. At the same time, there are risks for governments in promoting the livestock sector, associated not only with the negative impacts of livestock on the environment but also with the debate on the impact of excessive consumption of livestock products on human health (e.g. Friel *et al*. 2009). Ideally, governments would use the policy instruments under their control to balance the benefits and the risks, though political pressures often intervene (such as with the European Common Agricultural Policy). What governments need is evidence that illustrates the consequences of different policy interventions, both on the productivity of livestock and the environmental effects.

Researchers should be in a position to provide relevant evidence, but often individual researchers only have fragments of what is required for policy decisions, and often there is a further disconnect between publically funded research and that undertaken by the private sector, in this case particularly by feed companies. The feed industry has important information on sources of supply of different feed sources and their costs, though, as with farmers, they are running businesses and thus not in a position to make choices based on environmental goods.

My contention is, therefore, that the framework proposed could be used to bring together these different communities to help to integrate their complementary pieces of knowledge and thus to deliver a ruminant industry that contributes more to global food security while also minimizing its impact on the environment.

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

For the research community, the framework could be used more specifically to identify where knowledge is lacking with respect to the impact of different systems and management interventions on the multiple dimensions of feed efficiency.

Much research is currently being undertaken on GHG emissions from ruminants, but too much is being conducted at the level of the individual animal in short-term experiments, with less emphasis on the impact at system level, such as taking into account carbon sequestration in different systems (for example, see Pelletier, Pirog and Rasmussen (2010) for the impact of carbon sequestration in beef systems). Estimating the links between land use change and ruminant feed efficiency requires knowledge of the origins of feed components and whether the land was previously used for other purposes. There are currently many assumptions in the literature relating to deforestation to generate pasture for livestock when recent estimates suggest the practice is at least lessening (e.g. http://www.un.org/apps/news/story.asp?NewsID=34195#.UMjjJKyVqSo). In a similar vein, there is a need for a better understanding of the impact of global and regional trade in feed on nitrogen cycles and of the amount of water used in producing feeds under different conditions. There are of course many more knowledge gaps, but as befits an overview paper, I have focused on those priorities to inform policy decisions.

CONCLUSIONS

The extent to which grain is currently used in ruminant feeding systems is not sustainable. There are other options, and optimizing feed efficiency should give serious consideration to how the use of these options can be made to be economic at the farm level, while minimizing negative impacts on the environment, whether locally, regionally or globally.

The simple indicator of feed efficiency as food out vs feed in is no longer sufficient to inform decision-making in the twenty-first century, and additional dimensions need to be considered. Increased efficiency of individual farms then needs to be incentivized in ways that avoid unintended consequences; this will require closer co-operation between the farming, research, private sector and policy communities.

Research needs to focus on answering the big questions, which will help to solve these challenges for the sector as a whole and hence requires more interaction between disciplines.

This is an exciting time to work in animal science, as the challenges are great but scientists have many new tools at their disposal, ranging from new biotechnologies to new numerical applications and advances in data accessibility, which should help to overcome those challenges.

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Forages for ruminants, cereals for human food and fuel

David M. McNeill

The University of Queensland, Australia
E-mail: d.mcneill@uq.edu.au

ABSTRACT

This paper explores opportunities to maintain efficient ruminant feeding systems in the face of increasing world competition for cereal grains. These competitive forces include human population growth, declining availability of arable land, and the more recent phenomenon of biofuel production, especially bio-ethanol, to meet anticipated shortfalls in the global supply of crude oil. Opportunities created for ruminant nutrition by the expansion of the biofuels industry are reviewed in relation to edible by-products, as well as novel 'spin-off' technologies. These are discussed alongside strategies designed to increase the nutritive value of feedstuffs in general, without losing sight of improvements possible through attention to key management issues such as harvesting forage at the correct stage of maturity, the provision of appropriate amounts of feed, correct balance of nutrients at least cost, and strategies to optimize reproductive performance, health and survival. The focus is on opportunities that move us beyond the simplistic past luxury that one needs only to target maximum milk or beef produced per animal. It is better, for example, to consider feed conversion efficiency for an entire reproducing herd than just the individual. To meet maximum production targets, cattle diets have been dominated by high inclusion rates for cereals, with just sufficient plant cell wall added to minimize the risk of ruminal acidosis, and milk-fat depression in dairy cows. This has been the paradigm in developed countries such as Australia and the United States of America where cereals remain relatively cheap. Impressive improvements in the genetic merit of beef and dairy cattle, often on the basis of one trait, such as milk yield, has perpetuated the need to increase the nutrient density of diets with cereals and other nutrient groupings to the extent that the quality of modern ruminant diets can approach that typical of those diets for simple-stomached animals such as the pig. Future market forces should drive a return to research targeting the fundamental comparative advantage of a ruminant – that of an ability to convert plant cell wall to meat or milk. Such a change is discussed in relation to more realistic feed conversion efficiency targets and a realignment of genotype to better match this new 'environment'. How a high-performance paradigm fits in a developing country framework is also explored, using a current Indonesian plan for a rapid expansion in the domestic supply of fresh milk as a case study. To conclude, exciting opportunities exist to offset a decline in the availability of starch-rich cereals for ruminants. These include a more informed utilization of biofuel by-products, forages with the genetics for more easily degraded cellulose, and animal genetics that fit the constraints of the desired system.

Keywords: *biofuel, by-products, cattle, cell wall, dairy, feed efficiency, fibre, starch*

INTRODUCTION

Human need for cereals for food should take priority over needs for biofuel or ruminant protein. However, the resolve behind that imperative is likely to vary, depending on where you are. If cereal production is well in excess of direct human needs such as is the case in wealthier countries like Australia and the United States of America, we continue to see significant diversions of cereals to feed livestock and, especially recently, to provide substrate for the bio-ethanol industry (Alexandratos and Bruinsma, 2012; Cooper and Weber, 2012; Hegarty, 2012; Lywood and Pinkney, 2012). However, prioritizing cereal use becomes a more serious challenge when considered globally. Those countries currently unable to meet self-sufficiency needs for cereals will be increasingly dependent on imports from those countries that can. Dependency in these cereal-deficient countries is not just for human food but to feed animals considered far more efficient than ruminants in converting cereals to animal protein, such as poultry (Vries and Boer, 2010). Consequently, as cereal-rich countries continue to use more cereal, especially for bio-ethanol, ruminant production systems in cereal-poor countries are likely to be those that suffer the most. The world should look to these countries for inspiration on how to meet the challenge of striving for the efficient conversion of feed into affordable ruminant protein in the future. In the following paper, the use of ruminant diets in cereal-rich compared with cereal-poor countries is contrasted according to the basic principles of ruminant nutrition, with a focus on the dairy cow.

GLOBAL BIOFUEL AND ANIMAL PROTEIN TRENDS

Animal protein

The demand trend for animal protein varies considerably depending on where one is in the world and the type of animal. The common view is for increasing per capita demand for animal protein, world-wide, particularly in Asia, compared with more developed countries such as the United States of America (Alexandratos and Bruinsma, 2012). To illustrate these trends, per capita intakes from 2000 to 2012 for common animal proteins in the four most populous countries of the world are presented (Tables 1A to 1F, based on data from www.indexmundi.com). Rates of population growth continue to be more extreme in India and Indonesia compared with China and the United States of America (Table 1A). Intakes of all the animal proteins listed are dramatically lower in India and Indonesia, to the extent that the consumption of beef and veal, swine meat and dairy (fluid milk) is so low as to be unrecorded in Indonesia. Broiler and swine meats are included to highlight the major competition for cereals that these simple-stomached animal systems create. It is difficult to argue that ruminants should take precedence over broilers and swine for cereals when feed conversion efficiency (FCE: kg feed/kg live weight gain) is much better with broilers, ranging between 1 and 2, and swine, between 2 to 3, compared with, at the very best, 5–6 in high cereal- and more likely above 10 in high forage-based ruminant production systems. Per capita consumption of broiler meat in Indonesia, China, and especially India since 2000 is accelerating. Moreover, the more than 20-fold higher average consumption of broiler meat in the United States of America compared with India over the last 12 years indicates that there is massive potential for similar increases in developing countries. In contrast, swine meat consumption, whilst still hugely important in China, where per capita consumption rivals that of the United States of America and continues to grow, is in decline globally, including in the United States of America, and is of little importance in India and Indonesia. Therefore, it is

TABLE 1A
Population and change year-on-year

Year	China		India		USA		Indonesia	
	Pop. (×10^6)	% change	Pop. (×10^6)	% change	Pop. (×10^6)	% change	Pop. (×10^6)	% change
2000	1261.83	NA	1014.00	NA	275.56	NA	224.78	NA
2001	1273.11	0.89	1029.99	1.58	278.06	0.91	228.44	1.63
2002	1284.30	0.88	1045.85	1.54	280.56	0.90	231.33	1.27
2003	1286.98	0.21	1049.70	0.37	290.34	3.49	234.89	1.54
2004	1298.85	0.92	1065.07	1.46	293.03	0.92	238.45	1.52
2005	1306.31	0.57	1080.26	1.43	295.73	0.92	241.97	1.48
2006	1313.97	0.59	1095.35	1.40	298.44	0.92	245.45	1.44
2007	1321.85	0.60	1129.87	3.15	301.14	0.90	234.69	-4.38
2008	1330.05	0.62	1148.00	1.60	303.82	0.89	237.51	1.20
2009	1338.61	0.64	1166.08	1.58	307.21	1.11	240.27	1.16
2010	1330.14	-0.63	1173.11	0.60	310.23	0.98	242.97	1.12
2011	1336.72	0.49	1189.17	1.37	313.23	0.97	245.61	1.09
2012	1343.24	0.49	1205.07	1.34	313.85	0.20	248.65	1.23

Notes: NA = not available or not applicable.
Source: data from www.indexmundi.com

TABLE 1B
Per capita consumption of beef and veal, and change year-on-year

Year	China		India		USA		Indonesia	
	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change
2000	4.04	NA	1.16	NA	45.37	NA	NA	NA
2001	3.97	-1.82	1.25	7.12	44.42	-2.09	NA	NA
2002	4.06	2.31	1.34	7.22	45.40	2.21	NA	NA
2003	4.21	3.64	1.46	8.82	42.50	-6.38	NA	NA
2004	4.29	1.85	1.54	5.65	43.23	1.71	NA	NA
2005	4.30	0.29	1.44	-6.52	42.82	-0.94	NA	NA
2006	4.33	0.80	1.55	7.58	43.00	0.41	NA	NA
2007	4.59	5.92	1.54	-0.71	42.60	-0.92	NA	NA
2008	4.57	-0.37	1.64	6.65	40.82	-4.18	NA	NA
2009	4.29	-6.05	1.63	-0.24	39.84	-2.41	NA	NA
2010	4.20	-2.16	1.64	0.44	38.80	-2.60	NA	NA
2011	4.13	-1.67	1.64	-0.07	37.20	-4.14	NA	NA
2012	4.11	-0.47	1.63	-0.66	37.17	-0.07	NA	NA

Notes: NA = not available or not applicable.
Source: data from www.indexmundi.com

the production of broiler meat that poses overwhelming competition with ruminants for cereals, which leaves the question of which ruminant protein will most likely to be in greatest demand in the future: beef and veal, or dairy?

Beef and veal

Perhaps there is a future upside for beef and veal in Indonesia and India. However, the trend in India and China appears to have reached a plateau, and in the United States of America demand may be in decline (Table 1B). An important area for socio-economic

TABLE 1C
Per capita consumption of broiler meat (poultry) and change year-on-year

Year	China		India		USA		Indonesia	
	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change
2000	7.44	NA	1.07	NA	41.65	NA	3.63	NA
2001	7.26	-2.53	1.22	13.92	41.58	-0.17	3.94	8.28
2002	7.44	2.55	1.34	10.28	43.75	5.22	4.67	18.74
2003	7.74	4.04	1.43	6.45	43.22	-1.20	4.75	1.58
2004	7.65	-1.23	1.55	8.43	44.65	3.31	5.00	5.31
2005	7.72	0.99	1.76	13.61	45.43	1.74	4.67	-6.58
2006	7.89	2.22	1.83	3.87	45.83	0.88	5.15	10.27
2007	8.64	9.41	1.98	8.53	45.13	-1.53	5.54	7.56
2008	8.99	4.08	2.17	9.41	44.22	-2.01	5.70	2.99
2009	9.12	1.49	2.19	0.82	42.14	-4.70	5.88	3.01
2010	9.37	2.67	2.26	3.26	43.42	3.03	6.03	2.60
2011	9.74	3.97	2.43	7.70	43.62	0.47	6.17	2.30
2012	10.08	3.53	2.61	7.56	42.43	-2.72	6.19	0.41

Notes: NA = not available or not applicable.
Source: data from www.indexmundi.com

TABLE 1D
Per capita consumption of swine meat and change year-on-year

Year	China		India		USA		Indonesia	
	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change
2000	31.37	NA	NA	NA	30.68	NA	NA	NA
2001	31.71	1.09	NA	NA	30.20	-1.58	NA	NA
2002	31.94	0.71	NA	NA	30.95	2.51	NA	NA
2003	32.72	2.46	NA	NA	30.37	-1.88	NA	NA
2004	33.11	1.20	NA	NA	30.11	-0.87	NA	NA
2005	34.52	4.26	NA	NA	29.28	-2.73	NA	NA
2006	35.02	1.43	NA	NA	28.96	-1.10	NA	NA
2007	32.31	-7.73	NA	NA	29.77	2.80	NA	NA
2008	35.10	8.65	NA	NA	29.01	-2.56	NA	NA
2009	36.47	3.90	NA	NA	29.34	1.14	NA	NA
2010	38.46	5.45	NA	NA	27.89	-4.93	NA	NA
2011	37.41	-2.73	NA	NA	26.63	-4.54	NA	NA
2012	38.67	3.37	NA	NA	26.95	1.20	NA	NA

Notes: NA = not available or not applicable.
Source: data from www.indexmundi.com

research could be to document the key reasons for such trends. These may range from a lack of suitable land and feed resources in developing countries, through to the success, especially in the developing world, of reducing the retail price of competing meats such as poultry, and more recently the effect of campaigns promoting the consumption of less red meat by extreme animal rights groups such as People for the Ethical Treatment of Animals (PETA), or the more moderate and potentially collaborative organizations such as the World Wildlife Fund (WWF), who emphasize environmental sustainability issues more

TABLE 1E
Per capita consumption of dairy, dry whole milk powder and change year-on-year

Year	China		India		USA		Indonesia	
	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change
2000	0.45	NA	NA	NA	0.14	NA	0.24	NA
2001	0.48	7.04	NA	NA	0.09	-39.01	0.29	18.08
2002	0.49	2.06	NA	NA	0.09	3.24	0.25	-13.22
2003	0.64	30.88	NA	NA	0.08	-7.23	0.27	6.97
2004	0.69	8.38	NA	NA	0.06	-21.56	0.27	1.63
2005	0.73	5.30	NA	NA	0.07	9.51	0.31	13.71
2006	0.82	11.96	NA	NA	0.05	-29.22	0.30	-2.73
2007	0.86	5.53	NA	NA	0.08	51.96	0.32	4.58
2008	0.74	-13.99	NA	NA	0.05	-39.67	0.38	21.51
2009	0.86	16.53	NA	NA	0.12	154.31	0.44	15.15
2010	1.04	20.61	NA	NA	0.09	-20.23	0.46	4.49
2011	1.08	3.68	NA	NA	0.09	-7.79	0.48	4.22
2012	1.11	3.24	NA	NA	0.07	-14.98	0.51	6.31

Notes: NA = not available or not applicable.
Source: data from www.indexmundi.com

TABLE 1F
Per capita consumption of dairy, fluid milk and change year-on-year

Year	China		India		USA		Indonesia	
	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change	Cons. (kg/yr)	% change
2000	7.27	NA	78.16	NA	275.53	NA	NA	NA
2001	8.81	21.10	78.64	0.62	269.70	-2.12	NA	NA
2002	10.89	23.60	78.41	-0.30	274.94	1.94	NA	NA
2003	14.35	31.78	80.02	2.06	266.13	-3.21	NA	NA
2004	18.21	26.96	82.62	3.25	264.44	-0.64	NA	NA
2005	21.91	20.28	84.66	2.46	271.38	2.62	NA	NA
2006	25.11	14.61	87.82	3.74	276.28	1.81	NA	NA
2007	27.46	9.35	90.36	2.89	279.64	1.22	NA	NA
2008	26.63	-3.00	92.33	2.18	283.63	1.43	NA	NA
2009	22.13	-16.92	96.05	4.03	279.55	-1.44	NA	NA
2010	22.95	3.71	99.73	3.83	281.96	0.86	NA	NA
2011	23.94	4.31	102.17	2.44	282.76	0.28	NA	NA
2012	25.11	4.91	105.39	3.15	289.87	2.52	NA	NA

Notes: NA = not available or not applicable.
Source: data from www.indexmundi.com

than animal welfare, and now employ liaison officers to work directly with the beef industry supply chain, including influential agro-political bodies that represent beef producers, such as the Cattle Council of Australia (CCA). Life cycle assessment research has identified beef as having the greatest impact on the use of land and energy, and causes a greater contribution to global warming than swine meat, broiler meat or milk (Vries and Boer, 2010). Beef and veal intakes may be in decline in more developed countries, as public sentiment turns against them.

Milk

Compared with beef and veal, milk in powdered or fluid form is in great demand (Tables 1E and 1F). Whilst people may be eating less red-meat, per capita consumption of milk powder in China and Indonesia has more than doubled in the last 12 years, with an overall growth rate exceeding that for broiler meat. The desire in China and Indonesia for fluid milk may also, in time, eclipse that for milk powder. Consumers in the world's top two producers of fluid milk in 2012, India (127 $\times 10^6$ tonne, equivalent to 16.5 $\times 10^6$ tonne of milk powder assuming an average dry matter content for milk of 13%) and the United States of America (90.97 $\times 10^6$ tonne, equivalent to 11.8 $\times 10^6$ tonne of milk powder) appear to have little interest in milk powder, which could indicate that self-sufficiency needs are close to being met. Fluid milk consumption per capita continues to grow steadily in India, to some extent in the United Sates of America, and especially in China. China recorded growth of nearly 5% in the period 2011/12 in fluid milk production – the fastest rate of change for all animal proteins, with the exception of broiler meat in India, listed in Tables 1B–1D for that period. Despite gaining rapidly in production of fluid milk, which tripled in volume from 2000 to 2012 to become the third-largest fluid milk producer in the world (33.7 $\times 10^6$ tonne in 2012, equivalent to 4.4 $\times 10^6$ tonne of milk powder), China remains by far the world's largest importer of milk powder, with 332 000 tonne in 2012 compared with its nearest rival, Algeria, at 180 000 tonne. Substantial opportunity exists for the production of more fluid milk in China. Similarly, in Indonesia, which is currently an insignificant producer and consumer of fluid milk, but the world's third-largest importer of milk powder in 2012 (57 000 tonne), the government continues to develop plans for self-sufficiency in fluid milk production by 2030 (DGLAHS, 2010).

Therefore, for animal proteins, a key research challenge for ruminant production is to develop feed-base strategies with a low cereal component but of sufficient quality to sustain the profitable production of milk, especially in rapidly developing countries such as China and Indonesia. This must also be done without compromising the development of more efficient animal protein systems, such as broiler meat.

Biofuel

Collaborating with the biofuels imperative

The impact of the developing biofuels industry on ruminant production may not be as severe as that on other animal protein industries, such as broilers. Broilers systems are heavily, albeit not totally, reliant on cereals and by-products that are rich in starch, whereas ruminants are not, so those involved in ruminant production have reason to be optimistic. If we refocus on using ruminants to complement and add value to food production systems rather than to drive them—ruminants should not be driving the production of maize for example—ruminant systems can instead adapt to co-exist and even take advantage of biofuel developments. The obvious advantage is already upon us with ruminants increasingly complementing biofuel production by readily utilizing the growing mountain of by-products such as dried distillers grain with solubles (DDGS) and palm kernel meal (PKM), and adding value by converting them into high-level protein more efficiently than broilers (Hoffman and Baker, 2011). Moreover, as the biofuels industry develops "feedstocks" that are more efficiently converted into fuel, those same feedstocks, which are easily produced in excess of biofuel needs, will advantage ruminants. Future feedstocks include forage maize, and already there is a commercially available maize genetically engineered to express amylase in the grain to speed up saccharification of the starch component for more efficient conversion to ethanol. Also relevant are forage sorghums, potentially more valuable than maize due to their production capabilities in drier environments; and tropically relevant grasses such as King grass (Napier grass, *Pennisetum purpureum*), that could be genetically-modified for improved sugar content and cell wall degradability (Sukumaran *et al.*, 2010; Waltz, 2011; Rao *et al.*, 2012). Ruminant nutritionists should be encouraged to collaborate with the rapidly expanding biofuels industry to ensure such complementarities develop to the advantage of all.

Trends in the biofuel industry

The rapid expansion of biofuel production began around 1980. The major biofuel industry, bio-ethanol, developed from then to plateau in production from 1985 to 2000 at about 300 000 barrels per day, followed by exponential growth from that base to nearly 1 500 000 barrels per day in 2010. The United States of America produces most (867 000 barrels per day) of the world's bio-ethanol, mainly from maize, followed by Brazil, producing mainly from sugar cane (486 000 barrels per day in 2010; www.indexmundi.com). In 2010, the bio-ethanol industry produced about five times more fuel than the other major biofuel industry, biodiesel (1 484 000 barrels per day of bio-ethanol vs 295 000 barrels per day of biodiesel; www.indexmundi.com). Recent projections from FAO suggest the proportion of cereals used for bio-ethanol will more than double between 2005 and 2030, against a background of cereal production needing to triple in that same period to meet the needs of the burgeoning human population, but thereafter cereal use for biofuel may plateau to 2050 at 6–7% of total use (Alexandratos and Bruinsma, 2012). Similar increases in production are predicted for biofuel derived from vegetable oils, with greater increases for fuels derived from sugar (Alexandratos and Bruinsma, 2012).

Bio-ethanol pathways

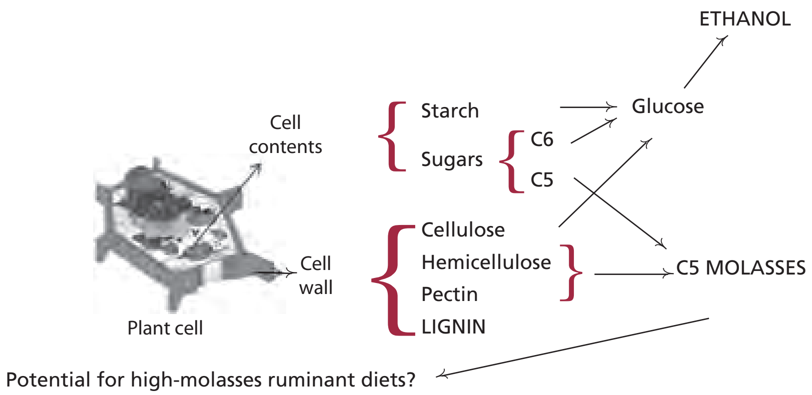
As bio-ethanol technology evolves from the first generation, which targets the conversion of starch to glucose to ethanol, to second generation, which targets the conversion of all glucogenic substrates in plant cells (starch, sucrose and cellulose) to glucose and finally ethanol, more molasses by-product suitable for livestock feeding will become available (Figure 1; Sukumaran *et al*., 2010; Hoffman and Baker, 2011; Henry, 2010, 2012). Second-generation bio-ethanol, otherwise known as cellulosic ethanol, is still at the planning stage globally. However, there are commercial pilot plants in production, such as the Inbicon refinery at Kalundborg in Denmark. Inbicon suggests a potential of more than 2 kg of Carbon 5 (C5) molasses by-product per kilogram of ethanol produced. Interest also exists in cellulosic ethanol in India (Sukumaran *et al*., 2010; http://www.inbicon.com).

Second generation bio-ethanol and ruminants.

In the future, the International Energy Agency (IEA) estimates that more than 80% of biofuel could be produced from cellulosic rather than starch sources. This has been heralded as a means of fully utilizing the growing abundance of crop by-products, such as cereal

FIGURE 1

Second-generation bio-ethanol production technology targets utilization of the glucogenic components of the entire plant, whereas the first generation targets only the conversion of starch to ethanol via glucose



Source: adapted from http://www.illuminatedcell.com/Home.html

straw—feed that could have been used directly for ruminants and as such is thought to present a threat to ruminant feeding systems, especially in developing countries (OECD/ IEA, 2010). However, rather than seeing second-generation production systems as a threat, ruminant industries should view them as an opportunity. Firstly, it is unlikely that the second-generation bio-ethanol industry could ever utilize the total production of crop by-products (Alexandratos and Bruinsma, 2012). Secondly, as mentioned earlier, the C5 molasses will be a by-product with a higher feeding value for ruminants than the cereal straws would have been in the first place. That C5 molasses is a by-product of biofuel production further highlights the excellence of the rumen compared with the industrial fermentation process. Ruminants can potentially degrade all cell wall components (cellulose, hemicelluloses and pectin), except structural lignin, to produce volatile fatty acids and support microbial protein synthesis for the production of high quality protein for human consumption. In contrast, the industrial process can only, easily, convert at best C6 sugars such as glucose and mannose into ethanol, leaving C5 sugars, mainly derived from hemicellulose and pectin, such as xylose and arabinose, for the molasses by-product fraction. Hence the term C5-molasses (Pauly and Keegstra, 2010). Thirdly, just as for ruminants, there is a strong research focus within the cellulosic ethanol industry for the development of feedstocks with more easily degraded cellulose, and this opportunity will be explored in the next section.

Alternatives to cereals-rich diets

Scoping the alternatives

Forages and by-product feeds with more digestible cellulose (a key part of the neutral-detergent fibre fraction (NDF), or cell wall) and non-fibre carbohydrate (NFC) should be the main considerations in the development of ruminant diets that do not rely on cereals.

Several examples of such feeds are also potential outcomes from the developing biofuels industry. The ruminant industries must benefit from these biofuel by-products, if cereal grains are not an option, provided they are fed to optimal advantage. This means a better understanding of such feeds, based on the principles of ruminant nutrition.

The principles of ruminant nutrition

The fundamentals of ruminant nutrition are to optimize the intake of digestible organic matter (DOM, i.e. available energy) and ensure that the correct balance of nutrients in the dry matter (DM) is achieved for the class of stock being fed. To meet the nutrient requirements, one first needs to be sure that there is an abundant supply of feed, that it is easily accessed at farm level, and that the animals are prepared to eat it. Next, it is important to be aware not only of the content but also the availability of key nutrient groupings within feeds. The key focus point in diet formulation at the outset is to correctly estimate the DM percentage of each ingredient so the correct amount of DM is added to the diet. This easily overlooked point is essential to achieving the correct amount of DM on offer and the correct balance of nutrients therein. Next, within DM, it is important to recognize the key nutrient groupings: crude protein (CP) and rumen degradable protein (RDP); neutral-detergent fibre (NDF) less indigestible NDF (iNDF, as calculated from acid-detergent lignin, acid-detergent lignin (ADL) × 2.4); NFC; macro-minerals such as in bone (calcium, phosphorus and magnesium) and electrolytes (sodium, potassium, chloride and sulphate); and micro-minerals, such as zinc, manganese, copper, cobalt, iodine and selenium. Feed additives, that may for example include mycotoxin inhibitors and rumen modifiers, may also prove highly beneficial, but are not discussed here.

Focus on the NFC component

Cereals largely satisfy the need for the NFC component in current 'industrial' diets, NFC being approximately the content of starch plus sugars and pectin. If starch is in excess, the cow becomes susceptible to ruminal acidosis and metabolic diseases such as ketosis and milk fever, whereas if there is too little starch, milk production declines (Goff, 2006; Lean *et al.*, 2006). The NFC component also provides an easy means of diluting the NDF content of the total diet to maximize the intake of DOM. So for inspiration on how to replace starch, the focus should be on feedstuffs that are high in NFC. Such feeds may include immediate by-products from cereal processing that still retain some starch, such as the brans of wheat, maize or rice; cassava by-product (*onggok* in Indonesia); or sugar-rich by-products such as molasses (Table 2).

Focus on the NDF component

A focus on high-NDF feeds should not be restricted to forages. As land availability for forage production declines, as is particularly the case where population growth is rapid, such as in India and Indonesia, high-NDF by-products provide a realistic substitute for forage, provided the limitations of such feedstuffs are realized and taken into account in diet formulation. High-NDF alternatives to cereals include the previously mentioned cereal brans, dried distillers grain with solubles (DDGS) and PKM (Table 2). There is already a strong call for research into the feeding value of DDGS, as recently reviewed, perhaps the result of

TABLE 2
Example nutrient profiles of major by-products relevant to dairy cows in Indonesia

Composition	Dietary components							
	PKM Expeller	Cassava waste (*onggok*)	Wheat bran	DDGS	Corn grain	Molasses, sugar cane	King grass	Corn silage
DM, %	91.2	25.0	87.0	89.0	88.0	73.00	23.70	30.00
CP, % DM	16.7	2.40	17.3	29.4	9.00	5.80	6.60	9.50
ADIP, % CP	2.40	5.00	2.00	14.10	5.00	0.00	0.90	7.00
NFC, % DM	0.00	38.1	27.90	19.80	76.17	82.20	13.30	34.31
Sugar, % DM	2.40	0.00	2.80	1.70	1.54	70.00	7.20	1.43
Starch, % DM	2.10	52.3	23.00	7.00	74.76	0.00	0.60	27.95
aNDF, % DM	73.00	61.00	45.3	34.4	9.00	0.00	71.00	49.00
ADL, % DM	13.40	5.00	4.10	1.10	0.20	0.00	8.00	4.90
Ether extract, %DM	9.20	0.13	3.90	11.00	4.23	1.00	2.30	3.19
Ca, % DM	0.28	0.74	0.60	0.16	0.04	1.00	0.50	0.23
P, % DM	0.60	0.04	1.00	0.79	0.30	0.10	0.30	0.24
Mg, % DM	0.31	0.12	0.31	0.33	0.15	0.42	0.30	0.13
Na, % DM	0.02	NA	0.02	0.24	0.42	0.22	0.00	0.01
K, % DM	0.65	NA	0.65	1.03	0.14	4.01	1.30	0.95
Cl, % DM	0.03	NA	0.10	0.20	0.06	0.75	0.00	0.32
S, % DM	0.63	NA	0.20	0.60	0.14	0.47	0.10	0.12
Zn, ppm	68.00	NA	89.00	62.00	27.0	14.00	NA	25.00
Cu, ppm	28.00	NA	14.00	6.00	5.00	66.00	NA	7.00
Mn, ppm	181.0	NA	113.00	21.00	6.00	59.00	NA	31.00
Se, ppm	0.00	NA	NA	0.40	0.11	0.04	NA	0.03
Co, ppm	1.60	NA	NA	0.00	0.06	1.74	NA	0.06

Notes: Compositional data is sourced from the Cornell Net Carbohydrate and Protein System (CNCPS) feed library and from the INRA/CIRAD/AFZ/FAO Feedipedia Web site (www.feedipedia.org).
Key: King grass (Napier grass) = *Pennisetum purpureum;* PKM = palm kernel meal; DDGS = dried distillers grain with solubles; DM = dry matter; CP = Crude protein; ADIP = acid-detergent indigestible protein; NFC = non-fibre carbohydrate; aNDF = amylase neutral-detergent fibre; ADL = acid-detergent lignin; NA = not available.

DDGS being largely the product of the United States of America and government policy there driving better utilization of it as an substitute for grain (Hoffman and Baker, 2011; Newkirk, 2011; Kalscheur *et al.*, 2012). Much less information is available on PKM.

Palm kernel meal

PKM has arguably more potential than DDGS to form the basis of diets where the need is greatest for the development of acceptable animal protein industries, such as milk production in Indonesia. Indonesia is by far the world's largest producer of PKM, while DDGS would have to be imported. Yet more than 80% of PKM production was exported from Indonesia in 2012 (3 200 000 from 3 849 000 tonnes produced; http://www.indexmundi.com/agriculture). The vast majority of world PKM exports in 2012 went to the European Union (EU) (2.3×10^6 t) and New Zealand (1.49×10^6 t) (http://www.indexmundi.com/agriculture), both of which are major producers and exporters of milk powder: New Zealand is the largest and the EU the second-largest exporter (www.indexmundi.com/agriculture). So the situation may exist whereby PKM is sent to the other side of the world, fed to cows and converted into milk powder, only then to be returned to Indonesia. Policy-makers could instead consider the efficiencies of retaining sufficient PKM in Indonesia for its developing milk industry. The Indonesian government recently released a blue-print for the development of the Indonesian dairy industry that states production is 25% of that demanded, and that feed supply is a major factor limiting development (DGLAHS, 2010). Indonesian production is currently about 1×10^6 t of fluid milk per year. Assuming a modest FCE of 1 kg milk per kg PKM fed, Indonesia could become self-sufficient in milk production immediately, were the supply of feed the only factor limiting expansion of the industry.

The relative nutritive and feeding value of PKM

Whilst *in vivo* studies on the feeding value of PKM are few, the evidence supports a feeding value well in excess of that predicted by models such as the well-respected ruminant feed-balancing model, the Cornell Net Carbohydrate and Protein System (CNCPS). Challenges to the adoption of PKM by small-scale dairy farmers in Indonesia may include that whereas 99% of the dairy cows in Indonesia are situated on Java, it is produced mainly on other islands, so the PKM producers may find it easier to ship it internationally; and that the dairy industry on Java is so fragmented that the orders are not large or regular enough to warrant the attention of the PKM producers. In terms of nutritive value, PKM is considered to have a number of limitations. These include poor palatability due to grittiness and dustiness; small particle size, resulting in little physically-effective fibre to promote rumination; much of an apparently high CP content being unavailable due to heat damage in processing; a relatively high content of fat that is sufficient to limit feed intake when the PKM is in its most common form – expeller meal rather than solvent-extracted meal; sufficient copper to risk copper toxicity in sheep; and a low ratio of calcium and phosphorus (Jalaludin, 1997; Carvalho *et al*., 2006; Dias, 2010; Wan Zahari, Alimon and Wong, 2012; Table 2). Many of these concerns could easily be addressed. For example, combination of PKM with high nitrogen pastures balances the palatability, nitrogen, fat, and copper limitations, leading to *in vivo* assessments of metabolizable energy (ME) being in the range of 9.8 to 10.3 MJ/kg DM (Dias, 2010). In Indonesia, King grass, well fertilized with urea, could complement PKM similarly (Table 3). Molasses was used by Wan Zahari, Alimon and Wong (2012) to complement 30 to 50% inclusion rates of PKM in the diet of dairy cows producing 10 to 12 litres of milk per day. In contrast, modelling such a diet with the CNCPS predicted a yield of less than 1 litre per day, highlighting the opportunities for research into how to improve the abilities of such models to predict the feeding value of by-products whilst at the same time advertising their true value to nutritionists, who place heavy reliance on such models (Table 3).

Starting point diets for lactating dairy cows in Indonesia that highlight the advantages and deficiencies of by-products, as mentioned above, are given in Table 3. All are suggested at a high inclusion rate of 50% of DMI, and slightly more for molasses. Using the CNCPS, milk production responses from Holstein-Friesian (HF) cows were modelled. The initial diet based on PKM is similar to that suggested by Wan Zahari, Alimon and Wong (2012). Also included is a diet based on maize grain and maize silage, to approximate a diet that corporate-type dairies might target. These are presented, not as balanced diets, but as work in progress, to highlight the deficiencies in our understanding of how to use these

TABLE 3

Milk production estimates from the CNCPS for diets based on the components described in Table 2, starting with a diet based on PKM and then replacing that with a range of relevant by-products in comparison with maize grain, or maize grain plus maize silage replacing King grass

	Diet recipes, kg DM						
Ingredient	**PKM**	**Onggok**	**Wheat bran**	**DDGS**	**Maize grain + King grass**	**Molasses, sugar cane**	**Maize grain + silage**
PKM	7.50	0.00	0.00	0.00	0.00	0.00	0.00
DDGS	0.00	0.00	0.00	7.50	0.00	0.00	0.00
Wheat bran	0.00	0.00	7.50	0.00	0.00	0.00	0.00
Onggok	0.00	7.50	0.00	0.00	0.00	0.00	0.00
Corn grain	0.00	0.00	0.00	0.00	7.50	0.00	7.50
King grass	6.30	6.30	6.30	6.30	6.30	6.30	0.00
Corn silage	0.00	0.00	0.00	0.00	0.00	0.00	6.30
Molasses	0.75	0.75	0.75	0.75	0.75	8.25	0.75
Limestone	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Trace elements	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Salt	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Composition	**Diet compositions**						
CP, % DM	11.4	4.3	11.8	17.9	7.6	6.0	8.9
ADIP, % CP	5.43	1.8	6.63	7.83	2.99	3.51	5.13
NFC, % DM	11.9	36.2	23.9	19.8	48.3	51.3	57.6
Sugar, % DM	7.7	6.6	8.0	7.4	7.4	41.9	4.9
Starch, % DM	1.3	26.7	11.9	3.8	38.0	0.30	49.6
aNDF, % DM	66.3	60.9	53.0	47.5	34.6	30.1	25.3
ADL, % DM	9.21	5.43	4.95	3.03	2.02	1.44	1.36
Ether extract, %DM	5.6	1.1	3.0	6.6	3.2	1.5	3.5
Ca, % DM	0.91	1.15	1.08	0.85	0.79	1.28	0.68
P, % DM	0.44	0.15	0.64	0.53	0.28	0.18	0.26
Mg, % DM	0.34	0.24	0.34	0.35	0.26	0.39	0.18
Na, % DM	0.23	0.22	0.23	0.34	0.23	0.33	0.23
K, % DM	1.08	0.76	1.08	1.28	0.97	2.78	0.82
Cl, % DM	0.38	0.37	0.42	0.47	0.40	0.74	0.53
S, % DM	0.38	0.07	0.17	0.37	0.14	0.30	0.15
Zn, ppm	35.0	52.19	45.63	32.0	14.3	7.77	24.93
Cu, ppm	17.5	3.33	10.4	6.36	5.85	36.64	8.82
Mn, ppm	94	2.98	60.0	13.58	6.01	32.76	19.15
Se, ppm	0.0	0.00	0.00	0.20	0.06	0.02	0.07
Co, ppm	0.9	0.09	0.09	0.09	0.12	0.97	0.14
	Predicted animal responses						
Total DMI	15.01	15.01	15.01	15.01	15.01	15.01	15.01
Allowable milk	0.7 (7.6)	5.5	11.9	15.5	18.3	18.9	23.5
FCE	21.44 (2.0)	2.73	1.26	0.97	0.82	0.79	0.64

Notes: CNCPS = Cornell Net Carbohydrate and Protein System, based on a multiparous mid-lactation Holstein-Friesian, at ambient air temperature 25 °C, RH 70%, 400 kg live weight. Allowable milk = estimated on the basis of metabolizable energy available for milk synthesis in kg of fat corrected milk (FCM)/cow/day. (7.6), (2.0) refer to the estimated allowable milk and feed conversion efficiency (FCE; kg dry matter intake (DMI)/kg FCM) respectively, after correction of the 2.4 factor for iNDF estimation in the CNCPS by lignin % in DM/2.4 factor × 0.6 = 3.35.

by-products, and so scope opportunities for future research. Of the diets based on King grass, the inclusion of molasses shows exceptional potential, ranking similar to maize grain. High-molasses diets for dairy cows in the tropics could be a productive area for research. For example, Hunter (2012) reports live weight gains in excess of 1.4 kg/day in Brahman steers in the tropics of Australia, fed diets containing between 45 and 60% molasses, with no adverse health reports. Replacing King grass with maize silage also highlights a potential advantage, of more than 4 litres of milk per cow per day, if forage quality can be improved. The DDGS rated nearly 3 litres below maize grain, with cassava by-product and PKM having the lowest feeding value and wheat bran ranking between the cassava by-product and DDGS. As mentioned previously, however, the CNCPS may be grossly underestimating the feeding value of PKM, and perhaps also that of cassava by-products. So research opportunities exist to demonstrate the dietary adjustments needed to at least allow PKM to be more correctly represented. Opportunities lie in increasing available CP, reducing ether extract (fat), increasing NFC, and reducing ADL or at least understanding the effect that ADL is having in the PKM.

Under-prediction of the feeding value of PKM by the CNCPS may be due to the way in which the potential ME content is estimated from the NDF fraction. Potential digestibility and therefore ME content of NDF is estimated from the difference between NDF and iNDF content. In turn, iNDF content is estimated from ADL content multiplied by a constant factor of 2.4 (Traxler *et al.*, 1998). This factor derives from ryegrass studies in which indigestible NDF was regressed against ADL, but subsequent studies now indicate substantial variability in the factor. For example, Kramer *et al.* (2012), while confirming a factor close to 2.4 for ryegrass, estimated it to be as low as 0.60 for PKM and advised the generic use of a factor of 1.0 for all by-products. If the CNCPS is modified to accommodate a lower multiplication factor of 0.6, predicted ME increases from 7.5 to 10.9 MJ ME/kg DM, and predicted milk yield increases from 0.67 litres to a more believable 7.6 litres per cow per day (Table 3).

Strategies to improve the digestibility of cellulose in forages

Returning to focus on NDF in forages, both the bio-ethanol and ruminant industries require forages that allow easy access for fibrolytic enzymes to degrade cell wall fibres. Several excellent reviews on strategies to improve ethanol production from plant cell wall offer exciting insights into bio-ethanol 'spin-off' technologies that ruminant nutritionists should be aware of, if not contributors to (Abramson, Shoseyov and Shani, 2010; Henry, 2010, 2012; Pauly and Keegstra, 2010; Xu *et al.*, 2012). Strategies include: (1) genetically engineering di-tyrosine bridges into the lignin framework that normally covers a proportion of cellulose in the cell wall. Thus, lignin that would normally provide a physical barrier to enzymatic attack on a proportion of cell wall could be more easily degraded by proteases, which are abundant in the rumen. This would expose more of the otherwise protected cellulose and hemicelluloses, to improve the extent and rate of cell wall degradation plus allow for a faster reduction in particle size to increase DOM intake; (2) genetically engineering molecular disruptions into the crystalline structure of the otherwise parallel and tightly-packed chains of glucose that comprise cellulose. For example, highly soluble polymers of hyaluronan, a polymer found in the cells walls of bacteria, could be integrated between the chains of glucose, that, once degraded, create sufficient space amongst the cellulose fibres to enable greater access by cellulases; and (3) genetically engineering plants that can express heat-stable bacterial cellulases and xylanases in cellular compartments that are also able to grow normally, and such have been produced. Whether these enzymes maintain an activity in excess of that already offered by the rumen microbial population remains to be seen, but the potential is there.

In addition to genetic-engineering solutions the search continues for genetic combinations and markers thereof that can be applied in conventional breeding programmes to develop plants that have a naturally more open structure to their cellulose or less inhibitory types of lignin (Pauly and Keegstra, 2010; Henry, 2012). Regardless of strategy, the overriding challenge will be to improve cell wall degradability without compromising the ability of the plant to retain normal growth and successfully compete for light with other plants in the pasture sward or crop. Any weakening of the cell wall has the potential to lessen plant vigour. To date, selection for alterations in lignin, mainly in terms of total content, has led to plants that produce less DM/ha, BMR sorghum being a good example.

Matching animal genetics to low-cereal diets

Matching cow genotype to environment should be a major priority in the design of new feeding systems, especially in hot, humid environments (West, 2003; Madalena, 2012). Nutrition is a key part of the animal's environment, and the ability to respond to nutrients presented will be dramatically affected by climate, especially the temperature humidity index (THI). Heat production by animals is tightly and positively related to level of production. To produce more milk, the cow has to eat more, and for each extra unit of feed energy consumed a relatively predictable proportion that is not converted into milk energy has to be released from the body as heat. The cow can only continue to increase intake and therefore body heat production if it can simultaneously release that extra heat from its body to maintain core body temperature within a normal healthy range. The higher the THI, the harder it becomes for the cow to release body heat. In order to return to the healthy range of core body temperature in the face of rising THI, if other cooling options (shade, fans, water sprays) have been exhausted or are unavailable, the major strategy remaining for the cow is to consume less feed, a process that can take several days (West, 2003). Consequently, high-THI environments will place an upper-limit for litres of milk produced per day, as appetite will be constrained. Within this, a key research question becomes whether high-THI environments render genetic rankings for milk production, derived from the performance of related genetics assessed in lower-THI environments, meaningless.

The importance of interactions between dairy cow genetics and the environment are, however, commonly ignored (Madalena, 2012; Madalena, Peixoto and Gibson, 2012). Continuing the Indonesian example, current government advice is that the only genotype of dairy cow allowed to be imported into Indonesia, with importation of pregnant heifers being a cornerstone of the development plans for its dairy industry, is the high genetic merit HF (DGLAHS, 2010). Anecdotally, up to 30% of these imports are prematurely lost from the system, often in their first lactation and most likely due to excessive loss of body condition score (BCS) early in lactation, leading to reproductive failure and increased susceptibility to disease (Moran, 2005; DGLAHS, 2010). It is difficult to find reliable data on the extent of problems with HF cows in Indonesia, highlighting the need for research in this area. Such research needs to be applied with one basic constraint in mind: no calf, no milk. It is well known that as genetics for milk yield advance, especially in hot humid climates, reproduction performance declines (West, 2003; Fulkerson *et al.,* 2008). To clearly define the ideal balance between genotype and environment, studies need to span a minimum of five years (Fulkerson *et al.*, 2008).

The reality that HF genotypes struggle to produce 8 to 12 litres of milk per cow per day in small-scale systems compared to more than 20 litres of milk possible in corporate-type systems in Indonesia is a likely consequence of the inability of small-scale farmers to be able to afford to sufficiently modify the cow's environment and nutrition to match the changed genetics (DGLAHS, 2010). Instead, for small-scale farmers, genetics capable of producing towards 12 litres a day as well as one calf each year for many years should be targeted. The key criterion for the success of such a system should be that it results in more milk per unit of feed invested for the entire herd, over a period of many years, as highlighted by Fulkerson *et al.* (2008). Despite this, dairy genetics research continues to focus on milk yield and FCE or residual feed intake (RFI) using cereal-rich test diets, based on individual animal performance that excludes reproductive ability. However, there is recent and welcome interest in challenging this paradigm, particularly in regard to cattle in high-forage vs high-cereal systems, and the genetic tools now exist to accelerate the process (Meyer, Kerley and Kallenbach, 2008; Clarke, Malcolm and Jacobs, 2012; Lawrence *et al.*, 2012; Pryce and Hayes, 2012; Pryce *et al.*, 2012).

One hypothesis that requires further testing is that the ideal cattle for small-scale farmers should have a much smaller mature-size and possess some *Bos indicus* genetics for tolerance to heat stress and disease, ideally from a milk-oriented breed such as the Gir. Smaller mature-size breeds such as the Jersey are better able to control their body temperatures and show a slower decline in milk yield in response to high THI (West, Mullinix and Bernard, 2003). Smaller cows will also be easier for small-scale farmers to handle. Research is required into the mechanisms that support an ability to maintain core-body temperature, and these may include feeding more processed and mixed diets with a higher ratio of available protein to energy (West, 2003). Excellent Brazilian work reviewed by Madalena, Peixoto and Gibson (2012) indicates the ideal genotype for small-scale farming in a tropical and subtropical climate may be the F_1 hybrid from European dairy breeds, and *Bos indicus* dairy breeds, such as the Gir. However, problems arise with these hybrids when farmers continue to breed from them, leading to loss of hybrid vigour and inconsistent milk performance in subsequent generations.

A novel solution is required to promote a consistent supply of F_1 hybrids to Indonesian small-scale farmers. One option could be for government policy to foster collaborations between small-scale farmers and corporate systems. The corporates could continue to work with HF cows, but mate their heifers to small-mature-weight milk type *Bos indicus* sires. Heifers from this mating could then be reared with the help of either the corporate or government specialist rearing stations and sold to small-scale farmers as pregnant heifers, removing another major risk factor for the development of dairying in Indonesia, namely that few calves are successfully reared to first lactation (Moran, 2011). Male F_1 calves and all male and female offspring from the F_1 cows should be sold to specialist rearers for beef, ensuring F_1 milking cows predominate in small-scale farmer systems. Moreover, these F_1

heifers would be raised in the Indonesian environment and so be better adapted than those currently imported from much cooler climates such as Southern Australia, New Zealand or Canada. The ultimate success of such a system could be based on the long-term measurement of whole-herd feed efficiency, as mentioned earlier, and demonstration that throughout the year, at least 80% of the cows in a given group are able to be kept, using local feed resources, within a target body condition score range of between 2.5 and 3.5 body condition score units (BCS scale: 1 = lean, 5 = obese; Edmonson *et al.*, 1989).

FUTURE CHALLENGES AND OPPORTUNITIES

Specific ideas for future research have been given throughout this paper, but can be summarized as follows:

- optimizing the productivity of high-quality forages per unit of land, especially using forages that have been genetically manipulated for more digestible cell wall components;
- optimizing the substitution of forage, as availability becomes increasingly scarce due to the lack of land, with NDF-rich by-products from the biofuels industry such as DDGS, PKM and cassava by-product fed in carefully balanced partial or total mixed diets; and
- more correctly matching the genetics of ruminants to their environment, diet being a major part of that, with recognition that small-scale farmers will need a very different animal genotype in comparison with corporate animal production systems.

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Key indicators for measuring dairy cow performance

Alex Bach
ICREA Research Professor, Department of Ruminant Production, IRTA, Barcelona, Spain
E-mail: alex.bach@irta.cat

ABSTRACT

Milk is a ubiquitous food for humans that is produced under many different farming systems. Regardless of the production system, it is imperative that a minimum amount of data is recorded to allow objective management decisions to be made. In many situations, cattle are managed by intuition, which may not only lead to uneconomic decisions, but also compromise health, well-being and longevity of cows in the herd. Thus, making management decisions with insufficient information should be avoided. But it is important to differentiate data that are useful for describing herd dynamics, and those that are useful for managing the herd. For example, measures such as average days open and milk production at breeding time would not be considered useful in determining whether to intervene. Indicators that are more pertinent for day-to-day management decisions are those that reflect changes or deviations in a rapid and responsive way. Rather than considering average yearly days open (a descriptive statistic that accumulates fluctuations for the entire past year), determining the proportion of animals open beyond a given day in milk is preferred. This will be more useful to monitor response whenever rapid change is expected or has occurred. Also, management indicators need to be associated with profitability, such as measures of efficiency, including feed efficiency, and, depending on the cost of raw materials, an even more interesting indicator may be efficiency of nutrient utilization (e.g. protein). In addition, producers must bear in mind the future consequences of decisions, nutrition and management applied today: for example, the benefits of improved nutritional management of calves early in life will not be fully realized until those animals have entered the milking herd. Thus, looking at cost and return throughout the entire production system is key. This paper will review some key aspects related to herd profitability, such as feed efficiency and nutrient efficiency and the advantages and importance of looking at costs and return within the long term.

Keywords: *data, feed conversion efficiency, management, profitability*

INTRODUCTION

Managing a dairy herd professionally requires taking decisions based on objective data rather than managing "by feel". A robust animal identification (ID) method is mandatory for any management process based on data and information. The traditional ear tag is an effective ID, although electronic ID systems are much more convenient as they allow more immediate access to the data, require minimal labour and are less prone to error. Once all animals have a unique ID, data from each individual can be collected and stored. The next step is to store all the measurements in a meaningful way that allows fast and easy retrieval of information. To make decisions that account for the global situation of the operation, a versatile database is essential that integrates data from different aspects (feed, reproduction, performance, health, etc.) and sorts them in an intelligible fashion.

To be effective, data should every time be collected reliably and accurately, as there is no value in accumulating unreliable data. This article will assume accurate and reliable data are available and will illustrate the value of data and how they may be used to improve the profitability of dairy herds.

BASIC CONCEPTS

The simplest way of transforming data into information consists of tabulating averages of the target variable over time. Averages may provide reliable information, but the degree of spread around that average should also be considered, which is usually measured as the standard deviation. For example, having an average age at first calving (AFC) of 26 months with a spread from 24 to 28 months might actually be better than an AFC of 24 months with a spread from 18 to 30 months. It is then important to acknowledge the quality of the average being considered. Averages may suffer from lag, momentum and bias (Eicker, Fetrow and Stewart, 2006). The lag of an average refers to the time lapsed between an action being taken and the average reflecting the change. For example, a reproductive problem with cows today will not affect the average calving interval for at least 9 months. The momentum of an average refers to responsiveness of that average to recent changes. For example, average daily gain (ADG) for the entire heifer-growing period (about 24 months) does not reflect small deviations in daily growth at the present time. Finally the bias of an average reflects its deviation from a "more general" average due to exclusion or inclusion of certain data. For example, calculating the reproductive performance (e.g. pregnancy rate) of only those cows that have not suffered any disease will bias the pregnancy rate, making it look better than if all cows (sick and healthy) were included.

TACKLING FEED COSTS

There are many indicators of herd performance. Focusing on feed-related costs and especially feed efficiency is an effective method to manage a dairy herd, because feed costs account for 40 to 60% of total production costs. Feed efficiency is a reflection of nutrition quality, reproductive performance, health and management, and finally it responds relatively quickly, with low lag, low momentum and minimal bias.

Nutrition costs and performance need to be evaluated continuously independently of the evolution of market prices. Over recent years, feed prices have increased considerably whilst milk prices have not kept pace with such changes. In an attempt to maintain economic returns under such conditions, producers and consultants have attempted to reduce costs without compromising performance. However, it is important to differentiate two types of expenses: those considered to be an investment and those that could be actually spared and removed. For example, reducing the amount of bedding may save money in the short term, when it should be considered a credit, improving the health and comfort of cows. If as a result of these apparent savings, cows become lame or mastitis increases, chances are that the costs associated with this management decision will quickly overcome any savings originally captured. Similarly, a reduction in feed costs, if not properly allocated, may impair milk production and thus diminish returns. Therefore, when reducing expenses a careful evaluation of the possible consequences is crucial.

Opportunities for reducing feed costs without hampering production or future health of cows include minimizing feed losses due to forage preservation (especially with silages) and revising mixing order of the ingredients in the total mixed ration (TMR) wagon. Ensiling directly on the ground should be avoided as it increases feed loses. Efficient silage conservation is also important, and in many situations it can be advantageous to use silage preservatives. In terms of mixing order, it is important to avoid feed losses as dust, which can often comprise significant amounts of protein (e.g. alfalfa hay) and adding wet feeds followed by drier components (concentrates, hays) is a suitable strategy.

Another opportunity to reduce costs is to re-evaluate the practice of feeding different rations according to level of milk production. In most situations, dairy herds are managed in two groups, feeding a high-nutrient-dense ration to high producing animals while a lower nutrient density feed being fed to lower producing animals. This is thought to reduce feed costs, but is not always the case. When high-producing animals are moved from a high to a low-nutrient-dense diet there is almost always an inevitable loss of production. The decision to provide two different rations will only be economical if the loss in milk production (in money) plus the labour costs associated with the preparation of the two different rations do not offset the potential savings due to feeding a lower quality ration.

Another important issue is to recognize the costs of the feed ingredients in terms of their nutritional value. The constant increase in feed costs makes it imperative to evaluate the actual value (not the price) of each of them. For example, it is common that maize silage is assigned a bulk price of about € 60/tonne. But in reality, the value of maize silage is dependent upon the level of starch and its digestibility, as not all maize silages are of equal nutritional content. The same applies to many ingredients. For this reason it recommended to value the ingredients based on the most important nutrient for which they have been purchased. For example, alfalfa hay is commonly purchased on the basis of its crude protein (CP) content, but in reality the unit cost of alfalfa CP is much more expensive than the unitary cost of CP in soybean meal. Furthermore, alfalfa is generally included in rations as a source of fibre, not as a source of protein (there are many more cost-effective alternatives) and thus alfalfa should be priced based on its fibre content and not CP.

In terms of feed additives, those where outcomes cannot be measured or noticed (even if those are long term) should be used with caution. Not all feed additives work under all conditions and rations. Producers have to make sure that under their production conditions the feed additives are efficacious and thus they need to have both an objective to attain, and a way of measuring success (or failure).

IMPROVING EFFICIENCY

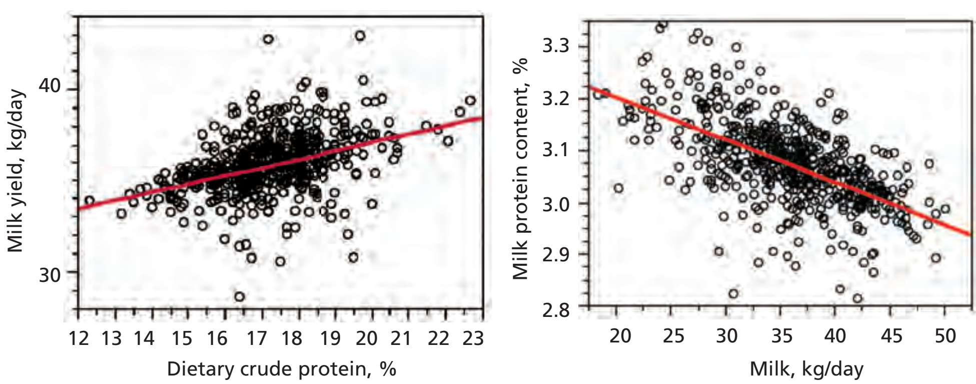
Dairy production is all about efficiency. The ultimate goal is to convert natural resources into healthy and high quality milk at the highest economic return while ensuring proper animal health and well-being and using practices that are respectful of the environment and acceptable to the consumer.

One of the most important parameters to ensure economic returns of dairy herds is milk efficiency (or feed efficiency), a reflection of the efficiency with which nutrients from the diet are converted into milk. Opportunities to improve feed efficiency are large. For example, the levels of P in the diet could be reduced to about 0.3% of the DM without compromising production or reproductive performance. Other alternatives include minimizing weighing errors when mixing ingredients in the TMR, and optimizing ration mix quality to ensure consistent consumption of a more homogenous ration by all cows, and most especially the avoidance of ration sorting.

In general, a ruminant nutritionists' goal is to formulate rations that meet the animals' requirements by providing sufficient quantities of all nutrients. However, this approach can often lead to an excessive supply of some nutrients. Among those likely to be supplied in excess are those amino acids (AA) required in relatively small amounts by the animal, but are relatively abundant in the feeds used to balance rations, such as aspartate. Due to the complexity of factors that contribute to determining the supply of AA to the dairy cow, coupled with the great ability of the mammary gland to modulate blood flow to compensate for AA imbalances (Bequette *et al.*, 2000; Weekes, Luimes and Cant, 2006), there is uncertainty as to the actual supply of AA by any given diet. Thus, it is rather difficult to know whether a change in the protein supply of the diet has corrected or actually induced or exacerbated an AA imbalance. An excess of certain AA may have negative repercussions on performance as energy is diverted from milk production towards the excretion of excess N.

The NRC (2001) acknowledged a modest positive relationship between milk yield and CP content of the diet, with about 12% of the variation observed in milk yield being attributed to CP content. Bach *et al.* (2006) conducted a meta-analysis using a data set with 131 studies from the Journal of Dairy Science (primarily from 2000 to 2006) and found a similar weak positive relationship (R^2 = 0.17; P <0.001) between these two parameters (Figure 1). Also, a similar relationship was found between CP content of the diet and milk protein yield (R^2 = 0.16; P <0.001). The relationship between dietary CP

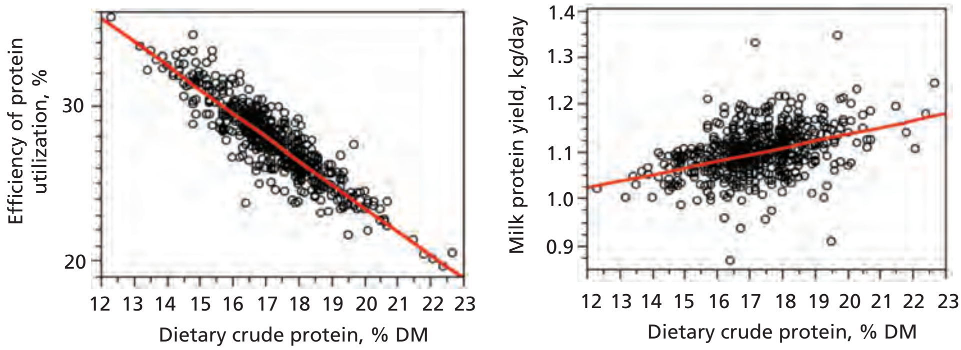
FIGURE 1
Relationship between dietary crude protein concentration and milk yield along with the relationship between milk yield and milk protein content



Source: adapted from Bach *et al.*, 2006.

FIGURE 2

Relationship between dietary crude protein content and efficiency of protein utilization for milk production and protein yield



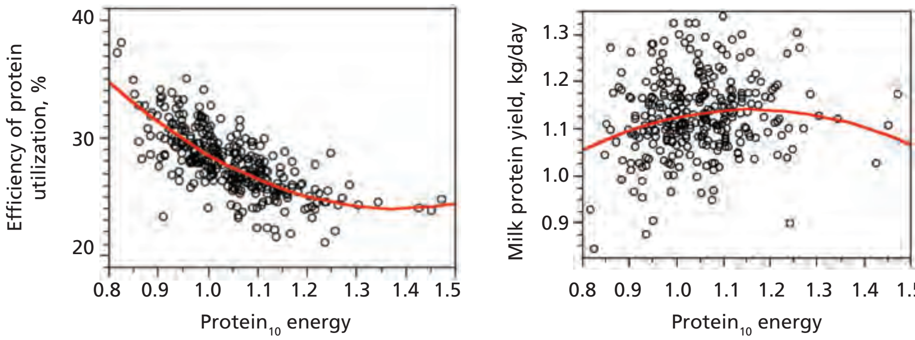
Source: adapted from Bach *et al.*, 2006.

content and milk yield has probably stimulated the use of high-CP rations to improve milk production. However, as milk yield increases (Figure 1), milk protein content decreases (r = -0.61; P <0.001), suggesting that milk protein synthesis may lag behind any increase in milk yield. As a result, efficiency of protein utilization (EPU) is negatively associated (R^2 = 0.81; P <0.001) with dietary CP level (Figure 2). This negative relationship was expected, attributed in part to the mathematical equation used to calculate EPU, where CP intake is the denominator. Nevertheless, when evaluating a mixed-effects model that included CP intake and milk protein yield, dietary CP content was still negatively correlated with EPU and accounted for 13% of variation explained by the model. This observation indicates that as CP content of the diet increases, protein is used less efficiently. Because EPU is positively correlated with milk production (r = 0.65), it would seem possible to produce high amounts of milk with high milk protein efficiencies. Similar to what occurred with level of CP in the diet, this positive relationship was expected due to the fact that milk yield enters into the numerator in the equation to calculate CP efficiency.

A common approach used to meet the protein needs of dairy cows is to supply large amounts of CP in the diet. Bach *et al.* (2006) reported a strong relationship between dietary protein:energy ratio (where protein is a percentage of CP divided by 10 to transform its units close to those of net energy of lactation (NE_L), and energy is expressed as Mcal of NE_L/kg of DM) and EPU (R^2 = 0.85; P <0.001). Again, this relationship was inflated by the fact that dietary CP content is mathematically linked to EPU. To remove this mathematical dependence, a model including dietary CP consumption (kg/day) and the linear and quadratic effects of protein:energy ratio was considered (Figure 3). The relationship found (R^2 = 0.44; P <0.001) that to maximize EPU, the ratio should be as close to 0.8 as possible. In other words, for a diet with an energy density of 1.7 Mcal/kg, the optimum CP content to maximize EPU should be about 13.6%.

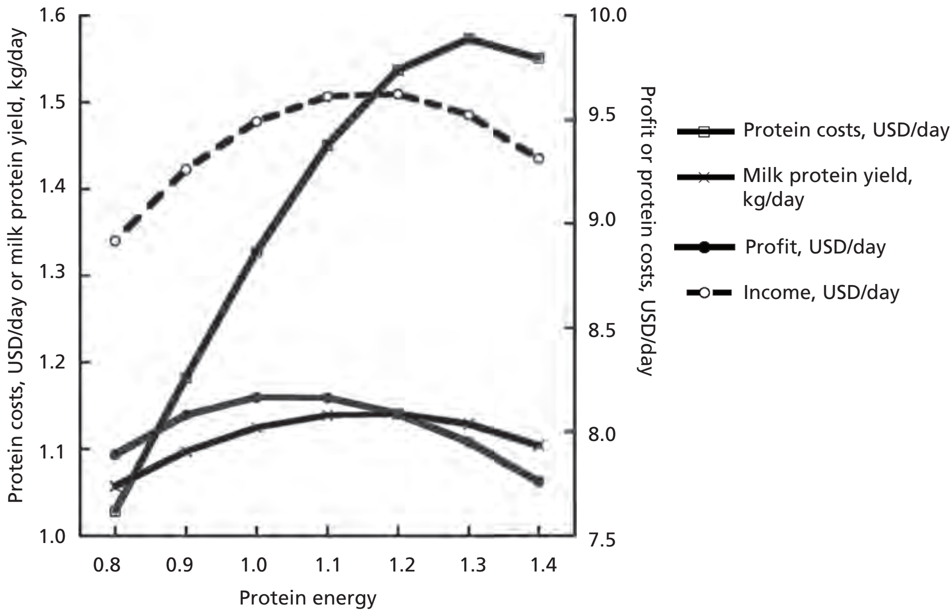
Figure 3 shows that to maximize milk protein yield the optimum protein:energy ratio should be about 1.1, which for a ration containing 1.7 Mcal/kg should contain 18.7% CP. However, this optimum may not coincide with the maximum profit. Figure 4 shows

FIGURE 3
Relationship between the ratio of protein to energy intake and efficiency of milk protein synthesis and milk protein yield



Source: adapted from Bach *et al.*, 2006.

FIGURE 4
Expected evolution of milk protein yield, gross income from milk, protein costs associated with the level of milk protein yield, and net profit (considering only protein costs) as affected by the protein to energy ratio



the evolution of milk protein yield, gross income from milk, protein costs associated with yield of milk protein and net profit (considering only protein costs) as affected by the protein:energy ratio. From this analysis, it can be concluded that the optimum dietary protein:energy ratio to maximize profit, not yield, would be about 1.0, and provides an illustrative example of how, in some contexts, maximum milk yield does not coincide with maximum economic returns.

Last, important savings in feed costs and management resources can be achieved by addressing the nutritional programme of the dry cows. Nutrition around calving is crucial to minimize metabolic upsets and ensure good milking and reproductive performance. Back in the late 1990s, it was believed that providing high-energy diets to cows before calving would minimize mobilization of body reserves and minimize metabolic upsets post-calving (Minor *et al.*, 1998). However, Janovick, Boisclair and Drackley (2011) found that high-energy density (>1.54 Mcal of NE_L/kg) rations offered pre-partum predisposed cows to compromised feed intakes and ketosis post-calving. Thus, the increased feed costs associated with high-energy rations fed pre-calving are not justified. In fact, it is now recommended to feed rations around 1.32 Mcal of NE_L/kg throughout the whole dry period, thus negating the need to feed two separate groups of dry cows.

LOOKING BEYOND THE CURRENT STAGE

Often, economic and management decisions are based on short-term returns. However, there are situations in dairy production systems where considering a broader time span to evaluate returns may substantially increase profitability.

For example, raising a dairy replacement is a long and expensive process necessary to ensure the future of the dairy operation. Surprisingly, in most situations heifers are raised by "feel" rather than by objective assessment (e.g. measured body weight, feed intake, height), which makes it difficult to ensure that heifers will fully express their genetic potential. Furthermore, raising dairy replacements correctly may provide additional economic savings and a reduced environmental impact for the dairy enterprise. The number of heifers required to maintain cow numbers in a dairy operation can be calculated with the following equation:

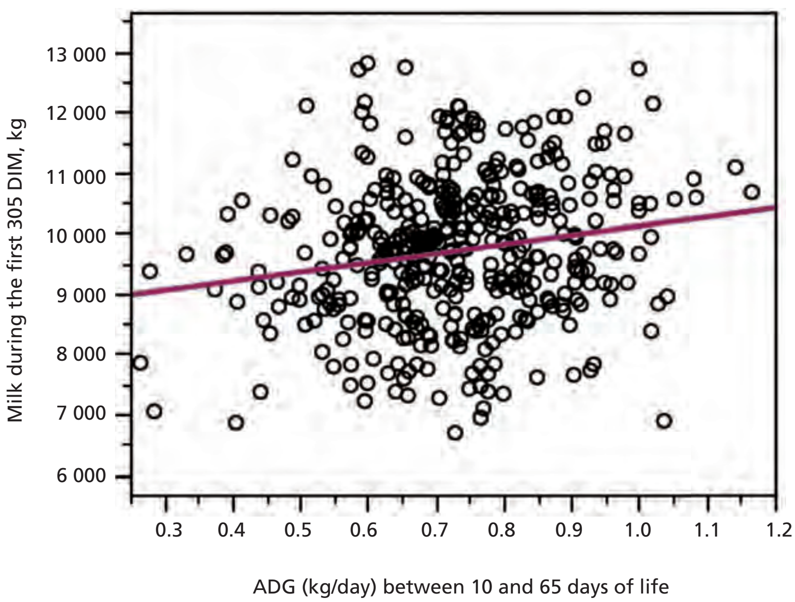
$$\text{No. of cows} \times \text{replacement rate} / [(1\text{-mortality}) \times (1\text{-cull rate})] \times 2 \times (\text{age at first calving}/24)$$

Assuming a 100 dairy cow herd with 30% replacement rate, 3% mortality and a 1% culling rate, it can be determined that at AFCs of 22, 24 or 28 months, the number of heifers required will be 57, 63 and 73, respectively. At an average feeding cost per heifer of € 2/day, producers with an AFC of 22 months would save about € 10 000/year compared with those with an AFC at 28 months. This relatively large saving is due to a combination of both the fewer heifers reared and the fact that they are fed for a shorter period (22 vs 28 months), and these are both considered good for the environment.

It is important to recognize that some management decisions taken today may not have their full impact until 2 or 3 years later. It is recognized that nutrient supply and hormonal signals at specific windows during development (both pre- and early post-natal) can exert permanent changes in the metabolism of humans (Fall, 2011), as well as changes in performance, body composition and metabolic function of the offspring of livestock (Wu, 2006) through processes generically referred to as foetal programming and metabolic imprinting. Thus, it follows that today's cow, with high milk yields but significant reproductive and metabolic challenges, is not only a consequence of genetic selection, but the result of the way her dam was fed, the way she was fed early after birth and the way the cow was reared as a calf and to a lesser extend as a heifer (Bach, 2012).

The analysis of a dataset including 900 heifers raised in a contract heifer operation in Spain and followed into 3 different dairy herds revealed a significant positive relationship between ADG during the first 65 days of growth (with ADG ranging from 0.37 to 1.12 kg/day) and future milk yield (Bach and Ahedo, 2008). From Figure 5, it can be concluded that despite the large (R^2 = 0.05) scatter (it could not be otherwise as there needs to be room for the unaccounted effects of disease, environment, nutrition, management, etc.), on average, calves gaining about 1 kg ADG could be expected to produce about 1000 kg more milk during their first lactation than calves reared on a traditional system and gaining about 0.5 kg/day. A recent study (Soberon *et al.,* 2012) evaluating the relationship between ADG and future milk yield of 792 heifers reported results coherent with those of Bach and Ahedo (2008), although Soberon *et al*. (2012) found ADG accounted for a significantly greater proportion of the observed variation in future milk yield than the current study (25% vs 5%, respectively). A simple meta-analysis, including 7 studies, concluded that for every 100 g of ADG during the first 2 months of life, an additional 225 kg milk could be expected in the first lactation (Bach, 2012). Furthermore, two recent prospective studies indicate that growth rate is positively correlated with survivability to second lactation (Bach, 2011; Heinrichs and Heinrichs, 2011). Therefore, providing the necessary nutrition

FIGURE 5
Relationship between average daily gain (ADG) during the first two months of life and milk production during the first 305 days in milk of the first lactation

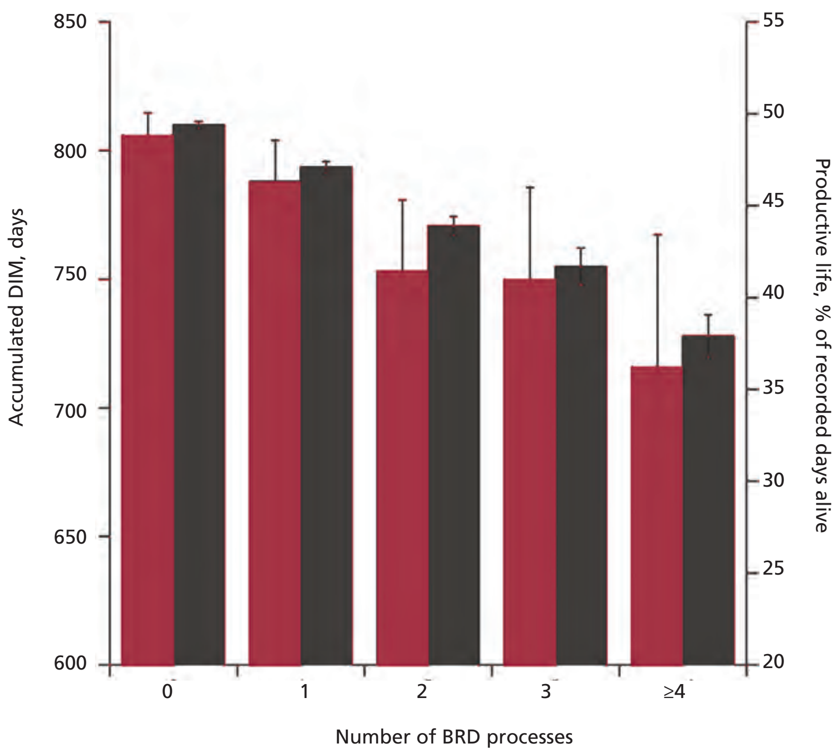


Source: adapted from Bach and Ahedo, 2008.

to sustain rapid growth rates (>0.75 kg/day) during the first 2 months, should result in more efficient (economically) and more effective (greater milk performance) heifer rearing. Improved growth rates can be achieved by implementing enhanced-growth feeding programmes, including supplying relatively large amounts of milk replacer.

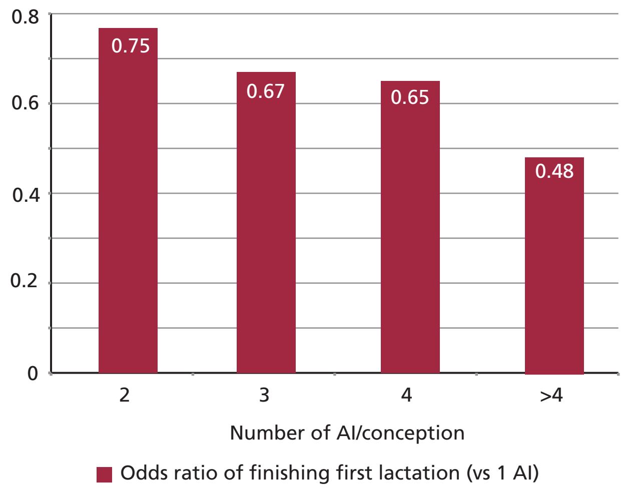
Infectious diseases (mainly diarrhoea and respiratory upsets) are the most important illnesses affecting calves around weaning, and respiratory problems may have profound consequences on calf performance and life-time productivity. Stanton *et al.* (2010) reported that calves with clinical bovine respiratory disease (BRD) in the 60 days after being grouped had significantly lower ADG than calves without BRD after grouping. Moreover, data (n = 7 768) from our research group (Bach, 2011) show that heifers that incurred 4 or more BRD problems during the rearing period had 1.9 greater chances of not finishing the first lactation than those that had no BRD incidence. Furthermore, total productive days (accumulated days in milk) and the proportion of productive days with respect to recorded days of life of cows, decreased linearly as the number of BRD cases increased (Figure 6). With such data, producers should both attempt to minimize BRD, and implement early culling (diverting

FIGURE 6
Accumulated days in milk (DIM; red bars) and productive life (as a proportion of productive days out of those recorded as alive; black bars) of cows as affected by the number of bovine respiratory disease (BRD) processes experienced before first calving



Source: adapted from Bach, 2011.

FIGURE 7
Odds ratios of finishing first lactation in terms of number of services (AI) required per pregnancy with respect to heifers with a 100% conception rate



Source: adapted from Bach, 2011.

animals to meat production to recover the investment) of calves that experience repeated BRD cases. The possibility of forecasting future survival rate of a heifer early in life may spare unprofitable investment in a particular animal and allow recovery of part of the expenses when sold for meat rather than retained for milk production. The cost of rearing heifers typically represents about 20% of total milk production costs, and the return on the investment allocated from birth to first lactation is commonly not fully recovered until at least the end of the first lactation. Therefore, the future productive life span of heifers is an important factor in determining dairy enterprise profitability. Voluntary culling decisions based on profit consist of substituting a cow with a replacement on the assumption that the latter will be more profitable, not because the cow being replaced was unprofitable. Congleton (1988) indicated that allocating an individual predicted milk performance to each replacement would improve the economic outcome of culling decisions. However, if the expected longevity of a replacement is not attained, then clearly the forecast milk performance would not be fulfilled, rendering a culling decision either unprofitable or less profitable than initially expected.

Another example of using data to make pro-active management decisions and cull heifers early in life involves considering the number of inseminations per heifer. The number of artificial inseminations needed to conceive as a heifer has been recently correlated with odds of finishing the first lactation (Bach, 2011). In that study (involving more than 7000 animals), nulliparous heifers requiring 1 service had the greatest chance of completing first lactation, and as conception rate decreased, chances of leaving the herd before completing first lactation increased (Figure 7). Cows that completed their first lactation had a greater conception rate at first service as heifers (60.3 ±1.8%) than those that did not (50.7 ±2.6%).

CONCLUSIONS

When evaluating herd performance, there is a need to focus on objective data and values that are sensitive, such that small deviations from the target can be detected relatively rapidly and easily overcome. Thus, figures such as longevity and calving interval are not really relevant, and it is much preferable to consider feed efficiency, and other short-term indicators such as conception rate in the last 30 days, cases of metritis in the last 50 calvings, or somatic cell count in the last 30 days.

Using data to monitor feed efficiency has a direct repercussion on profitability, and ensures adequate animal well-being and optimum utilization of natural resources. Also, considering the entire productive life of the animal, and using predictions about future productivity and longevity, may prove useful in order to cull animals that would not contribute to profits.

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Optimizing maternal cow, grower and finisher performance in beef production systems

Alan W. Bell[1] *and Paul L. Greenwood*[2]

[1] Cornell University, United States of America

[2] NSW Department of Primary Industries, Australia

E-mail: alanwilliambell@gmail.com

ABSTRACT

This review identifies and evaluates aspects of biological efficiency that underpin productive performance of beef cattle and the profitability of the enterprises in which they are managed. Maternal cow performance up to weaning is considered separately from post-weaning performance of progeny destined for slaughter because of the different biological functions underpinning reproduction and lactation versus post-weaning growth, and the widespread industry segmentation of cow-calf, grower and finisher operations. Efficiency of feed utilization is emphasized because of the importance of feed costs in the overall production system. Maternal efficiency is defined as weaned calf weight per total feed intake of the dam from mating exposure to weaning plus that of her offspring from birth to weaning. In most beef industries the production of weaned calves accounts for 60–70% of overall production costs to slaughter. The most important maternal traits are reproductive performance, including age at puberty, fertility and fecundity, and lactation potential, mature size and related growth potential, all of which exhibit at least moderate genetic variation within and between breeds and can be significantly influenced by nutrition. Poor nutrition has a greater negative effect on the productive efficiency of cows with a high genetic potential for calf production, mainly through a decrease in fertility, whereas such cows exhibit superior performance on a high plane of nutrition. Non-maternal traits that influence maternal performance include paternal genetic influence on pre- and post-natal growth potential of offspring, which is considerably greater than the direct influence of maternal genotype. There is a strong positive genetic correlation between birth weight and weaning weight, but a negative correlation between birth weight and calving ease. Intriguingly, individual bulls exist that sire calves that are lighter than average at birth but heavier than average at weaning. Timing of weaning and subsequent management of weaned cattle until slaughter varies widely according to industry structure and opportunity. Overall efficiency of growth, expressed as feed conversion ratio or residual feed intake, is positively influenced by genetic capacity for lean deposition in carcass tissues, nutrition and, where available, treatment with metabolic modifiers such as steroid implants or inclusion of β-adrenergic agonists in the finishing diet. Preparation of growers after weaning can take advantage of the biological capacity of young cattle for compensatory growth when fed a high quality diet *ad libitum* after a period of moderate feed restriction. Performance during the finishing phase is strongly influenced by the target specifications for carcass composition which, in turn, dictate desired genotype, diet quality and length of the finishing phase. Feeding of high grain diets to finishing cattle markedly improves feed efficiency, but acceptable growth performance can be achieved with a combination of high quality forages and co- or by-product feedstuffs.

Keywords: *beef cattle, maternal nutrition, reproductive performance, growth phase, compensatory growth, carcass composition*

INTRODUCTION

The objective of this review is to identify and evaluate aspects of biological efficiency that underpin productive performance of beef cattle and the profitability of the enterprises in which they are managed. The biological functions underpinning maternal performance up to weaning, including reproduction, lactation and pre- and post-natal calf growth, differ from those that determine post-weaning growth and performance of progeny destined for slaughter. Also, there is widespread industry segmentation of the management between cow-calf operations and those devoted to post-weaning growth and finishing. Therefore, maternal, grower and finisher performance are considered separately, acknowledging the importance of biological carryover effects among these phases and the fact that all phases may be integrated in single enterprises, especially in smaller operating systems.

We have adopted the definition of biological efficiency proposed by Notter (2002) as: "the capacity to convert physical inputs (feed) into marketable product (beef) under prevailing production systems." This can be applied to the individual animal as well as to the herd, enterprise or industry, and enables separate evaluation of maternal and post-weaning growth performance. Efficiency of feed utilization by individual animals is emphasized because of the importance of grazed and harvested feed costs in the overall production system. However, other biological indices, such as reproductive performance, must be considered because they have powerful effects on efficiency at the herd, enterprise and industry level.

MATERNAL PERFORMANCE

Definition of maternal efficiency

Maternal biological efficiency can be expressed as the total calf weight as a function of maternal dry matter intake from first mating exposure to weaning (Jenkins and Ferrell, 2002). This index is preferred to the commonly used ratio of calf weight to cow weight because of inherent flaws in this ratio, including the assumption that cow feed requirements are solely a function of body weight (Johnson, Dunn and Radakovich, 2010). The importance of maternal efficiency is highlighted by observations that the cow-calf phase of production generally accounts for at least 60% of the total cost of beef production (Ferrell and Jenkins, 1984).

Management priorities

Cow survival. Breeder cow mortality should not be an important concern in relatively intensive and environmentally favoured management systems. However, in harsh environments such as those found in parts of northern Australia, mortality of extensively managed cows during pregnancy and lactation can have a major negative impact on herd productivity, with average annual losses of up to 15%, and levels of 30–40% reached in poor seasons (Holroyd and O'Rourke, 1989). Management options to reduce cow mortality under these conditions include more conservative stocking rates, nutritional supplementation, planned weaning of calves and culling of older cows, with genetic improvement of environmental adaptability as a long-term objective (see below).

Environmental adaptability. The need for beef cows to survive and produce calves in harsh environments has largely been addressed by adoption or development, or both, of breeds that are relatively well-adapted to such environments. This approach led to the almost complete replacement of pure *Bos taurus* genotypes by pure or part *Bos indicus* genotypes in tropical Australia during the mid-twentieth century (Burrow *et al.,* 2003), taking advantage of the heat tolerance, parasite resistance and foraging ability of indicine cattle. Development of tools for genomic selection (Goddard, 2012) offers the opportunity to overcome barriers to conventional approaches to genetic improvement for adaptive traits such as heat tolerance and tick resistance, provided appropriate phenotypes are available against which to conduct whole-genome association studies (Pollak *et al.*, 2012). Most importantly, there are few negative genetic associations among tropically adaptive traits and production traits in Brahman and Tropical Composite cattle, suggesting that continued selection for productive performance will have little negative effect on adaptive traits (Prayaga *et al.*, 2009).

Reproductive performance. Optimizing reproductive efficiency should be a management priority because reproductive rate is a primary determinant of overall beef production efficiency (Jenkins and Ferrell, 1994). Low pregnancy rates, especially in second-calf heifers, are a major limitation to overall productivity of predominantly Brahman herds in regions such as parts of northern Australia, where uncertain feed supply and heat stress are ongoing challenges (Burns, Fordyce and Holroyd, 2010). Other aspects of reproductive performance also can contribute to maternal efficiency. Reducing age at puberty is a desirable objective because it lowers the non-productive feed costs of rearing replacement heifers (Abeygunawardena and Dematawewa, 2004). Increased incidence of twinning offers a potential avenue for substantially increasing maternal productivity in more intensive production systems, but gains may be partly offset by increased incidences of dystocia and neonatal mortality, and decreased growth rates from birth to weaning (Gregory, Echternkamp and Cundiff, 1996).

Cow maintenance costs. The overhead cost of feeding a cow herd throughout the annual production cycle is a substantial fraction of overall beef production costs, with cow maintenance energy requirements estimated to account for as much as 70% of the total feed energy requirements of a cow-calf operation and 50% of overall feed costs from conception to slaughter of progeny (Ferrell and Jenkins, 1984). Much of the variance in cow maintenance requirement among and within breeds can be attributed directly to mature size expressed as metabolic body weight ($kg^{0.75}$); however, capacity for production, particularly lactation, has an additional influence on maintenance energy utilization per $kg^{0.75}$

(Ferrell and Jenkins, 1984). The practical implications of maternal maintenance requirements and body size for productivity and profitability of cow-calf operations will depend on income and cost factors related to herd size (Johnson, Dunn and Radakovich, 2010).

Weaning weight. Calf weaning weight is the ultimate expression of maternal productive output and the numerator in ratio expressions of cow efficiency. In addition to its direct contribution to maternal, and thence overall, efficiency of beef production, weaning weight may influence efficiency of post-weaning performance through its positive correlation with post-weaning growth (Garrick *et al.*, 1989; Meyer, 1994). Also, relatively rapid growth of calves before weaning offers producers the option of early weaning with positive implications for recovery of maternal body condition and subsequent reproductive performance (Houghton *et al*., 1990).

Biological traits underpinning maternal efficiency

The biological components of maternal efficiency include various reproductive traits such as age at puberty, fertility and fecundity, and, as identified by Jenkins and Ferrell (2002), lactation potential, mature weight and post-weaning gain, and capacity for deposition of lean and fat. All of these traits are at least moderately heritable and can be influenced by nutrition and other environmental factors. Therefore, the following discussion focuses on the influence of genetics, nutrition and their interactions on phenotypic outcomes for maternal traits.

Reproductive traits. Traits such as age at puberty and length of the postpartum anoestrus interval are moderately to highly heritable (Johnston *et al.*, 2009; 2010) and strongly influenced by nutrition (Savage, 2005) in tropically adapted cattle. As with adaptability traits, it is anticipated that the development of commercial tools for genomic selection soon will be applied to genetic improvement of reproductive performance in beef cattle (Hawken *et al.*, 2012), with special opportunity for applications to tropically adapted cattle managed under extensive conditions.

Inadequate nutrition due to reduced feed availability or quality, or both, can have negative effects on subsequent pregnancy and weaning rates that are considerably more damaging to profit than more immediate effects on the growth, carcass yield and beef quality of current progeny (Alford *et al.*, 2009). More specifically, seasonal deficiencies in energy, protein or phosphorus are a major cause of decreased pregnancy rates and increased duration of anoestrus in extensively managed herds grazing native pastures in northern Australia (Savage, 2005). These effects are mediated more by the body weight and condition (fatness) of breeding cows than by short-term changes in energy or nutrient balance. Timing of feed restriction during pregnancy also may be important, since there is evidence that moderate losses of body weight and condition can be incurred during the second trimester without penalty on subsequent pregnancy rates in mature cows (Freetly, Ferrell and Jenkins, 2000) and first- and second-calf heifers (Freetly, Ferrell and Jenkins, 2005), provided cows are re-alimented during late pregnancy or early lactation.

In a five-year study of maternal production efficiency involving nine taurine breeds each fed at four different levels, Jenkins and Ferrell (1994) found significant interactions between genetic potential for mature size and plane of nutrition, such that larger breeds had reduced reproductive rates at lower feed intakes, but higher calving rates on higher feed intakes relative to moderate-sized breeds. More specifically, the reduced calving rate of the underfed large-framed cows was primarily due to extended periods of postpartum anoestrus (Nugent *et al.*, 1993).

Plane of nutrition of pre-pubertal heifers may affect efficiency of cow-calf operations that breed their own replacements by influencing age at puberty and first calving, and thence the overhead cost of feeding replacement heifers. Protein supplementation of heifers grazing subtropical native pasture also has increased their long-term productivity by increasing the number and individual growth performance of calves born over a 5-year period (Hennessy and Williamson, 1988). However, Funston *et al.* (2012) recently concluded that, at least within production systems typical of the US Great Plains, heifers can be first mated at 50–57% of mature body weight compared with traditional guidelines of 60–65% mature body weight, without impairing reproduction or subsequent calf production, and with significant savings in feed costs.

Lactation. Lactation potential in beef cows is moderately heritable and not genetically correlated with direct effects of maternal genotype on calf weaning weight, offering opportunities to select dams for milk yield as well as calf growth potential (Meyer, Carrick and Donnelly, 1994). Milk yield is also influenced by maternal body condition at calving and post-partum plane of nutrition (Arthur *et al.*, 1997; Lake *et al.*, 2005). However, despite the undoubted positive association between lactation performance and weaning weight (e.g. Arthur *et al.*, 1997), the effects of milk yield on efficiency of cow-calf production are complex. For example, benefits for calf growth to weaning may be offset by the additional feed costs imposed by the higher maintenance requirements of high-yielding cows, as well as negative effects on fertility (Jenkins and Ferrell, 2002). Notwithstanding the biological validity of these observations, Miller, Wilton and Pfeiffer (1999) reported a positive association between milk yield and profitability of beef production from birth to slaughter in an intensively managed herd fed to requirements throughout the production cycle.

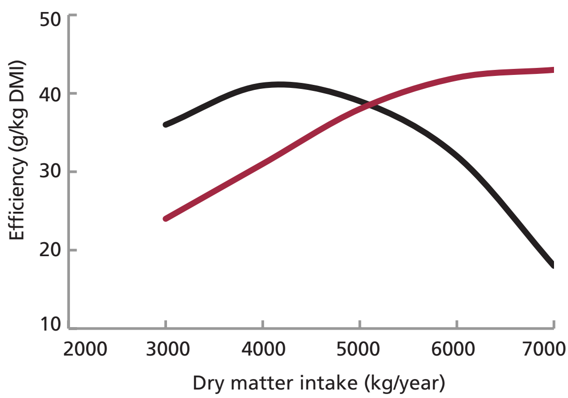
Mature weight and calf growth. The direct genetic effect of maternal size contributes to pre- and post-natal growth potential of progeny, albeit to a lesser degree than paternal genotype (Garrick *et al.*, 1989). The size and uterine capacity of the dam also influence foetal growth independently of the direct effect of maternal genotype, especially during late gestation (Ferrell, 1991). The positive genetic correlation between birth weight and mature weight can have a negative effect on maternal efficiency when heavy birth weights are associated with increased incidence of dystocia, especially in heifers (Cundiff *et al.*, 1986). Although there are generally strong genetic and phenotypic correlations between birth weight and subsequent post-natal growth rates (Garrick *et al.*, 1989), multiple-trait selection models have been used to produce so-called "curve bender" bulls which combine superior breeding values for birth weight and calving ease with acceptable or superior values for weaning weight (e.g. Bennett, 2008).

We have observed that severe maternal feed restriction during pregnancy or lactation, or both, resulted in pre- or post-natal, or both, growth retardation, from which progeny were unable to fully compensate after weaning, leading to lighter weights at any age up to slaughter (Greenwood and Cafe, 2007; Robinson, Cafe and Greenwood, 2013). However, despite this substantial penalty, no effects on post-weaning feed efficiency were found, nor were carcass composition or retail beef yield adversely affected when adjusted for carcass weight. Modest economic benefits of adequate maternal nutrition, especially during pregnancy, were observed due to advantages in carcass weight and retail beef yield at a given age, and reduced feed costs to reach a target market weight. However, as noted earlier, these benefits were considerably smaller than those due to improved reproduction rates (Alford *et al.*, 2009).

Maternal efficiency – putting it all together

The overriding importance of reproduction to maternal efficiency has been highlighted by three comprehensive, multi-breed studies in which pregnancy rate was the major contributor to genotype × nutrition interactions for maternal efficiency (Morris *et al.*, 1993; Barlow *et al.*, 1994; Jenkins and Ferrell, 1994). Thus, breeds with moderate frame size and genetic potential for milk production and growth (e.g. Red Poll, Angus, Hereford) were relatively efficient because of higher pregnancy rates when on lower energy intakes. However, larger Continental breeds (e.g. Charolais, Simmental, Limousin) became more efficient at higher intakes when available energy was sufficient to support reproduction and allow expression of their greater genetic capacity for lactation and calf growth (Figure 1). An analogous study of body size and maternal efficiency in Brahman cattle showed that, over three calvings, small- and medium-framed cows were more efficient for the first two calvings, but large-framed cows became more efficient by the third, when they had achieved their full growth potential (Vargas *et al.*, 1999). Thus, as noted by others (Jenkins and Ferrell, 2002;

FIGURE 1
Predicted maternal biological efficiency (g calf weaned/kg dry matter intake per cow exposed) at varying dry matter intakes



Note: The black line gives values for cows that are composite means for equal numbers (n = 20) of Angus, Hereford and Red Poll cows; red line gives values for cows that are composite means for equal numbers (n = 20) of Charolais, Limousin and Simmental cows.

Source: adapted from the data of Jenkins and Ferrell, 1994.

Johnson, Dunn and Radakovich, 2010), matching maternal capacity for milk production and growth to available feed resources is key to optimizing maternal efficiency.

Choice of cow genotype also should be influenced by environmental adaptability where efficiency and productivity of cow-calf operations may be constrained by extremes of cold (e.g. northern United States of America, Canada) or heat (e.g. Brazil, northern Australia). For example, even in temperate conditions, maternal efficiency of crossbred cows with *Bos indicus* (Brahman or Boran) sires was superior to that of cows with tropically adapted (Tuli) or unadapted (Angus, Hereford) *Bos taurus* sires (Jenkins and Ferrell, 2004). Conversely, crossbreeding of Brazilian *Bos indicus* (Nellore) cattle with *Bos taurus* breeds produced dams that were more efficient at calf rearing than straightbred Nellore cows in a tropical environment (Calegare *et al*., 2009).

Bottom line recommendations for improving efficiency of cow-calf operations are:

- to optimize reproductive performance;
- to use cow genotypes that are adapted to the environment and production system in which they are expected to produce; and
- to consider the effect of cow size and maintenance requirements on the number of cows that can be supported by available feed resources, with particular implications for small-scale farmers to whom loss of even a single animal is a major imposition.

POST-WEANING PERFORMANCE

The period between weaning and slaughter of beef cattle offers a great diversity of management options depending upon weight and condition of calves at weaning, relative availability and cost of forage and concentrate feeds, and market opportunities and specifications for the finished beef product. In contrast to the multiple biological traits contributing to maternal efficiency, discussed in the previous section, the main focus of the present section is feed efficiency, expressed as feed conversion ratio (FCR) or residual feed intake (RFI).

Growth biology, body composition and feed efficiency

Regulation of lean and fat deposition. The principles of allometric growth dictate that in cattle as in other animals, relative rates of lean and fat deposition are determined largely by empty body weight within a given genotype (Greenwood and Dunshea, 2009). Thus, lean tissue growth predominates in smaller immature animals but as the growth asymptote approaches, lean growth rate slows and fat accumulation in adipose tissue accelerates. This pattern can, to some extent, be modified independently of body weight by nutrition, metabolic modifiers and other environmental influences; however, effects of nutrient supply are due mostly to concomitant effects on rate of body growth and physiological maturity.

Composition of growth and feed efficiency. Feed efficiency of growing animals expressed as FCR is simply the ratio of dry matter intake to average daily gain. Unlike the numerator in this ratio, the denominator includes water, which comprises over 70% of lean tissue weight but less than 10% of replete adipose tissue weight. Also, protein, the predominant organic constituent of lean tissues, contains little more than half the energy of triacylglycerol, the major constituent of fat tissue. Thus, FCR is strongly and directly related to the fat:lean ratio of body growth and accordingly is influenced by stage of maturity and other factors that affect the composition of growth.

Residual feed intake is an alternative index of feed efficiency that is calculated as the deviation of an individual animal's actual feed intake from that predicted by its level of production, i.e. body weight and rate of growth for a beef animal. This index is also genetically and phenotypically correlated with body fatness in growing and finishing beef cattle, especially in subcutaneous depots, with much stronger correlations observed in older finishing steers and heifers (Robinson and Oddy, 2004) than in younger yearling cattle (Richardson *et al.*, 2001; Schenkel, Miller and Wilton, 2004).

Genetic selection for feed efficiency. Both FCR and RFI are sufficiently heritable to enable creation of divergent selection lines for these traits in beef cattle (Bishop *et al.*, 1991; Arthur *et al.*, 2001) and, not surprisingly, the two traits are genetically and phenotypically correlated (Arthur *et al.*, 2001; Schenkel, Miller and Wilton, 2004; Smith, Davis and Loerch, 2010). However, both efficiency phenotypes require the expensive measurement of individual feed intake, and selection for each can have undesirable consequences for other traits. Thus selection for FCR may increase mature body size while selection for low RFI may constrain growth potential and female reproductive ability. Also, the magnitude of feed efficiency responses to direct selection for these derived traits can be less than responses to selection for more easily measured biological traits that underpin feed efficiency. For example, the strong genetic correlation between body fatness and RFI in finishing cattle, together with the high heritability of fatness, suggests that selection against fatness would result in improved (lower) RFI while directly addressing a primary aspect of carcass quality (Robinson and Oddy, 2004). The question of whether inclusion of RFI in multivariate selection strategies for genetic improvement of feed efficiency is superior to simply selecting for desired growth rate and composition should be addressed. Furthermore, the relationship between RFI measured intensively and at pasture (using alkanes) on the same animals is poor (Lawrence *et al.*, 2012) and warrants further investigation.

Weaning

Age at weaning. Reduction of age at weaning can have a major, positive influence on subsequent maternal reproductive performance in first-calf heifers (Arthington and Kalmbacher, 2003) as well as mature cows (Houghton *et al.*, 1990), and thence productive efficiency of cow-calf operations. Also, several studies have suggested that early weaning of calves onto high energy rations results in increased feed efficiency during feedlot finishing (Myers *et al.*, 1999; Barker-Neef *et al.*, 2001; Wertz *et al.*, 2001). However, the early-weaned animals in these studies were finished and slaughtered at lighter weights and, presumably, an earlier stage of physiological maturity than conventionally weaned cattle. In contrast, when early-weaned and conventionally weaned animals were slaughtered at comparable weights, no differences in efficiency were observed at feedlot entry or during finishing (Arthington, Spears and Miller, 2005). A recent Australian study of early weaning of Shorthorn calves found a similar result, even though the early-weaned animals remained lighter throughout the growing and finishing phases (Wolcott, Graser and Johnston, 2010).

Weaning practice. In beef production systems, weaning generally is performed from about 6 months of age and at live weights from 200 kg, unless early weaning is practised. Weaning is typically abrupt, and the extent to which calf growth is affected by weaning depends on factors such as live weight and energy reserves, the amount of solid feed consumed by the calf prior to weaning, and the availability and quality of the diet onto which the calf is weaned.

Weaning is stressful for the calf, and systems that minimize social and environmental stressors have been reviewed recently (Enriques, Hötzel and Ungerfeld, 2011). Weaning systems such as yard weaning and training have also been developed, which involve training to feed from bunks or troughs and close association with humans during the weaning period, with benefits due to improved temperament and feedlot performance later in life (Walker *et al*., 2007).

Grower phase. The grower phase of beef production encompasses the period between weaning and entry to the feedlot or intensive finishing system of steers and heifers destined for slaughter. The term “backgrounding” denotes the feeding and management practices used to prepare grower cattle, including health and behavioural management. These practices vary widely according to industry structure, feed type and availability, and market opportunity, but most often involve grazing on rangeland pastures. Regardless of this variation, the primary objective of backgrounding is to optimize growth and development of muscle and frame (skeleton) of the weaned calf, while avoiding excess fat deposition. The rest of this section considers factors affecting growth performance and subsequent productivity of cattle during the grower phase.

Genetics. As discussed above, growth rate and fatness are moderately to highly heritable traits, enabling relatively rapid responses to genetic selection for lean growth rate within breeds and herds. Consequent improvement in efficiency of feed utilization may be partly offset by increased maintenance requirements, associated with increased mass of visceral tissues (Ferrell, 1988), but the net response should lead to both improved use of feed resources and timely achievement of product specification goals.

In crossbreeding calf production systems, choice of terminal sire genotype is an important consideration. Calves sired by large-framed, late-maturing Continental breed bulls will be leaner than those sired by bulls from breeds of more moderate frame size at any weight below mature size (Fox and Black, 1984). However, this attribute must be weighed against the additional time needed to reach market specifications for carcass quality during finishing of later maturing animals, as well as the possibility of an undesirable increase in carcass weight.

Selection for docile temperament also may have a positive influence on growth performance during backgrounding. Various indices of temperament, including flight speed and crush score, are moderately heritable (Burrow, 1997), persistent throughout the post-weaning period and are positively associated with growth rate, FCR and carcass and meat quality (Cafe *et al*., 2011). These associations were stronger in Brahman than in Angus cattle, reflecting the greater and more uniform docility of the Angus animals in the latter study.

Nutrition. Requirements for energy, protein and other nutrients of grower cattle are dictated by genetic capacity for rate and composition of growth, with mature size an important determinant. This and other animal factors such as age, sex and initial body weight and condition score, together with a range of environmental factors, have been incorporated into models that predict growth performance from known nutritional inputs or nutrient requirements from measured rates of growth (e.g. NRC, 2000; Tedeschi, Fox and Guiroy, 2004). Obviously, such models and associated feeding recommendations are of most use in confinement systems where growing cattle are fed rations of known composition. However, expansion of databases with detailed information on the nutrient composition of temperate and tropical forages has allowed some application to the more commonly used grazing systems used to background cattle before finishing (e.g. Tedeschi *et al*., 2002).

Weaned calves that are raised mostly or exclusively on rangeland pastures often experience nutrient restriction and growth checks due to seasonal variation in forage quality and availability during cold winters in regions such as the Great Plains of North America or extended dry seasons in the tropics of South America and northern Australia. Depending on their physiological maturity and the length and severity of feed restriction, calves can exhibit a substantial degree of compensatory growth, especially during the early period of the finishing phase, with possible implications for feed efficiency during the overall post-weaning period as well as during finishing alone.

To address questions about the relative contributions of changes in feed intake, gut fill, energy expenditures and composition of gain to the compensatory growth phenomenon, Sainz, de la Torre and Oltjen (1995) compared the performance during finishing of medium-framed British breed steers fed three different dietary regimens during the growing phase (237–327 kg): high forage *ad libitum* (FA), high concentrate limit fed to match the weight gains of the FA group (CL), or high concentrate *ad libitum* (CA). When fed the high concentrate ration *ad libitum* during finishing, both the FA and CL groups displayed substantial compensatory growth relative to the CA group, associated with clear and relatively similar increases in dry matter intake (Table 1). However, the improvement in feed efficiency was significantly greater in the CL (30%) than in the FA (10%) group, related to observations of a 17% decrease in the maintenance requirement of the CL steers compared with a 21% increase in the FA group. Neither gut fill nor composition of gain was an important contributor to the compensatory gain response. The effect of diet quality during the growing phase on maintenance requirement is consistent with observations of increased visceral tissue mass in forage-fed versus concentrate-fed steers (McCurdy *et al.*, 2010).

The relative lack of association of grower nutrition and subsequent compensatory growth with composition of gain during finishing has been extended to observations that feed restriction during backgrounding had little effect on carcass quality or yield at slaughter when treatment groups were compared at similar levels of fatness (Klopfenstein *et al*., 2000). In contrast, when steers of diverse breeds were slowly or rapidly grown to the same live weight, the rapidly grown animals were clearly fatter at feedlot entry, to a degree associated with breed propensity for fattening (Wilkins *et al.*, 2009). This difference was less evident at slaughter because compensatory growth in the slowly grown steers was associated with a faster rate of fattening during finishing, also to a degree affected by

TABLE 1
Growth performance and maintenance energy requirement of steers fed at different levels during the growing phase and *ad libitum* during the finishing phase

Nutrition during growing phase	High concentrate *ad libitum*	High concentrate restricted	High forage *ad libitum*	SEM
		Growing phase		
Days	57	112	112	–
DMI (kg/day)	8.41^{d}	4.55^{e}	8.41^{d}	0.19
Daily EBW gain (kg/day)	1.96^{d}	0.69^{e}	0.77^{e}	0.04
EBW gain:feed	0.237^{d}	0.152^{e}	0.092^{f}	0.007
		Finishing phase		
Days	96	89	111	–
DMI (kg/day)	9.04^{d}	10.98^{e}	11.73^{e}	0.33
Daily EBW gain (kg/day)	1.22^{d}	1.92^{e}	1.74^{f}	0.05
EBW gain:feed	0.134^{d}	0.175^{e}	0.147^{f}	0.005
Maintenance requirement	515^{d}	427^{e}	623^{f}	22
		Overall		
EBW gain:feed	0.173^{d}	0.176^{d}	0.118^{e}	0.004

Notes: DMI = Dry matter intake; EBW = Empty body weight; SEM = Standard error of the mean; Maintenance requirement is in kJ/kg $EBW^{0.75}$/day; Means within a row lacking a common superscript letter differ significantly (P <0.05).
Source: from Sainz, de la Torre and Oltjen, 1995.

genotype. Net consequences for carcass fatness and other quality traits were accordingly modest (McKiernan *et al.*, 2009).

Ionophores and metabolic modifiers. The ionophores monensin (Rumensin®) and lasalocid (Bovatec®) are widely used as feed additives or pasture supplements for growing cattle. These selectively antimicrobial compounds act in the rumen to promote the production of propionate, decrease feed protein breakdown and increase efficiency of nitrogen utilization, and decrease methanogenesis (Callaway *et al.*, 2003). They also are efficacious in reducing grain and legume bloat and rumen acidosis. Production responses include improvements in average daily gain and FCR in forage-fed growing cattle (e.g. Duffield, Merrill and Bagg, 2012).

Several classes of metabolic modifiers have been demonstrated to improve the growth and feed efficiency of beef cattle in the post-weaning period. These include the steroid and steroid-like hormonal growth promotants (HGP); the β-adrenergic agonists such as ractopamine and zilpaterol; and rbGH. Of these, only the HGP will be discussed here because ractopamine and zilpaterol are approved for use in the United States of America only in the late finishing period (28–42 day before slaughter) and rbGH has not been commercialized for treatment of growing or finishing cattle in any major beef-producing country.

HGPs have been used in the beef cattle industries of North America, Australasia and parts of South America, Asia and Africa for at least several decades. The chemical nature, treatment methods and schedules, metabolic mode of action and efficacy of these compounds for improving growth performance and feed efficiency of growing and finishing cattle have been comprehensively reviewed elsewhere (Preston, 1999; Hunter, 2010).

Briefly, compounds used in HGP formulations include oestradiol-17β, zeranol (a steroid-like lactone), progesterone, testosterone and trenbolone acetate (TBA; a synthetic androgen). The most commonly used formulations for pasture-fed growing cattle are oestradiol-17β (Compudose®) at various dose levels for steers and spayed heifers; various combinations of oestradiol plus TBA (Compudose G®; Revalor G®) for steers and heifers; and zeranol (Ralgro®) for steers. Their use in pastoral systems is facilitated by their modes of administration (ear implantation) and delivery (slow release into the bloodstream over many weeks). In general, these compounds act by promoting protein deposition in skeletal muscle, leading to a 10–30% increase in growth rate, a 5–15% improvement in feed efficiency and a 5–8% decrease in carcass fat content (Preston, 1999). Most notably, summary of a large number of commercial trials on immature, pasture-fed *Bos taurus* and *B. indicus* cattle in northern and southern Australia showed that the growth promoting efficacy of HGP implantation was retained across widely different cattle genotypes, planes of nutrition and basal growth rates (Hunter, 2010).

Health, behavioural management and transport. Backgrounded cattle are susceptible to a range of infectious diseases during and soon after consignment to the feedlot, exacerbated by the stress of transport and being grouped with unfamiliar animals. Among these, the bovine respiratory disease (BRD) complex, caused by a range of viral and bacterial pathogens, is by far the most common and damaging to feedlot performance. This disease, which usually manifests soon after arrival at the feedlot, has been estimated to cost the United States of America beef industry between US$ 800 million and US$ 900 million annually due to mortality, treatment costs and decreased feed efficiency and carcass merit (Brooks *et al.*, 2011). Management practices designed to reduce stress and increase resistance to BRD include yard weaning and socialization of weaned calves (Walker *et al.*, 2007) together with assembly into feedlot groupings, familiarization with bunk feeding, and vaccination against BRD of backgrounded cattle several weeks before consignment to the feedlot (Duff and Galyean, 2007). In addition, the stress of transport should be minimized by limiting distance travelled and adoption of a range of recommended practices (Fisher *et al.*, 2009).

Finishing phase

Systems for finishing beef cattle vary widely according to market demand and specifications for degree of fatness, including marbling, tenderness and other attributes of the finished meat product, and, increasingly, to consumer perceptions of environmental impacts and animal welfare practices of the beef industry. The relative contribution of these factors to product value has implications for the biological efficiency of finishing systems, as does the cost of inputs, especially feed ingredients in intensive feeding enterprises. Consistent with the central theme of this review, the present section focuses on factors affecting biological efficiency of finishing cattle while acknowledging that there are circumstances where optimization of economic efficiency may not coincide with optimal biological efficiency.

Market factors. Market specifications for beef quality range from the very heavily marbled product demanded by sectors of Japanese and Korean consumers, through various

United States of America quality grades based mostly on degree of marbling, to the much leaner beef preferred by sectors of the European market, and to the freshly-killed product favoured by many Asian consumers. Premiums paid for fat content have a major influence on choice of cattle genotype (early- versus late-maturing), feeding system (high grain versus pasture) and length of the finishing period. Meat Standards Australia (MSA) is a recently developed quality assurance system that employs a database compiled from the sensory analysis of over 603 000 beef samples by 86 000 consumers to predict an eating score for each part of the carcass, depending on cooking method. The prediction model relies on numerous other factors, mostly recorded at MSA-approved abattoirs, including sex, tropical breed (*Bos indicus*) content, carcass weight, hanging method, use of HGP, ossification, marbling, rib fat, meat pH, temperature and colour, and hanging time (Polkinghorne *et al.*, 2008). Penetration of the MSA system into the Australian domestic market recently has accelerated, with a 43% annual increase to over 2 million carcasses graded in 2011–12, fuelled in large part by the system's adoption in 2011 by the nation's largest supermarket group.

Genetics. Research at the United States of America MARC (Meat Animal Research Center) confirmed the ability of large-framed Belgian Blue or Piedmontese bulls to sire steers that were significantly leaner and more feed efficient than Angus- or Hereford-sired steers at similar slaughter weight (Ferrell and Jenkins, 1998a). This study also found that for many traits, effects of dam breed and interactions between sire or dam genotype and plane of nutrition were as important as sire breed effects.

Further comparisons of the steer progeny of tropically adapted Brahman, Boran and Tuli sires with those of Angus and Hereford sires showed that when fed a high concentrate diet *ad libitum*, crossbred steers sired by tropically adapted breeds (especially Boran and Tuli) consumed less, grew more slowly and had similar FCR compared with steers sired by British-breed bulls (Ferrell and Jenkins, 1998b). Sire breed effects on carcass weight, 12th rib fat thickness and yield grade were consistent with growth performance, while steers sired by the two British breeds had quality grades that were significantly higher than those of steers sired by tropically adapted bulls. No breed effects on heat production beyond those explained by feed intake were found, contrary to earlier reports that tropically adapted breeds have lower maintenance energy requirements than those adapted to temperate environments (e.g. Frisch and Vercoe, 1982). However, these studies were conducted in a favourable nutritional environment under cool-temperate conditions and do not necessarily refute the hypothesis that under more challenging nutritional and environmental conditions, *Bos indicus* and other tropically adapted types of cattle have lower maintenance requirements that allow them to perform as well or better than taurine breeds.

Nutrition. The biological efficiency of feeding high grain diets, appropriately balanced for protein and other nutrients, to finish beef cattle is amply documented (NRC, 2000). A recent review of the effect of dietary energy density on performance of feedlot cattle concluded that the upper limits of metabolizable energy content for maximizing growth rate and feed efficiency were 13.2 and 14.4 MJ/kg DM, respectively (Krehbiel, Cranston and McCurdy, 2006). However, these fairly extreme levels may not achieve optimal productivity, partly because to achieve maximal feed efficiency, at least, grains would need to be processed and(or) fed in high moisture form, thereby adding to feed cost, and partly because there may be undesirable consequences for carcass quality. Recent research on optimizing efficiency of nitrogen utilization by feedlot cattle has focused on dietary protein level, source and feeding strategies to achieve desired growth performance with reduced environmental impact through lower emissions of ammonia (Cole, 2006) and, presumably, nitrous oxide.

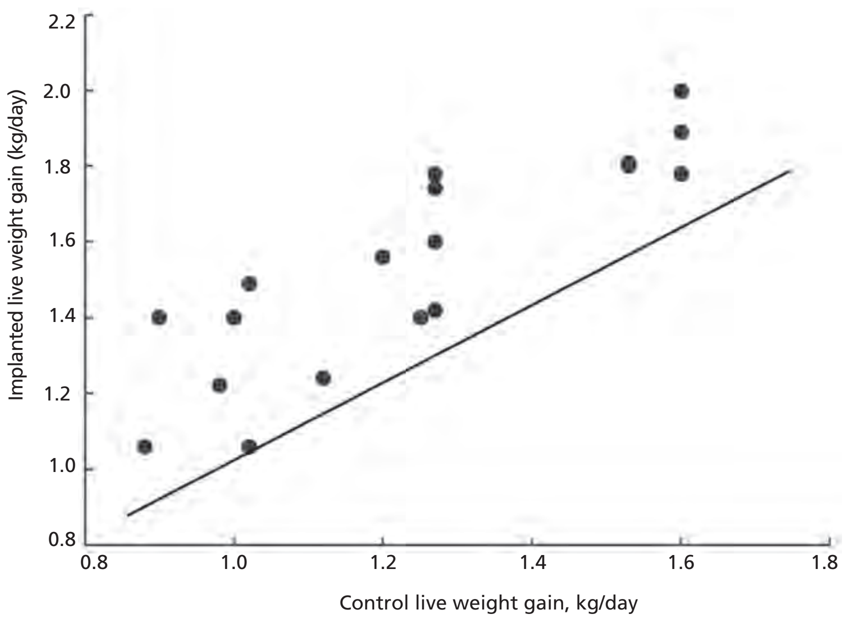
The economic rationale for grain-finishing is clear where premiums are paid for well-marbled beef and feed grain is relatively accessible and cheap, notwithstanding costs associated with feedlot-specific diseases such as BRD and acidosis, and with maintenance of feedlot infrastructure. However, research into alternative sources of energy and protein for feedlot rations continues, driven by factors such as price elasticity in the global feed grain market and availability of relatively cheap co-product and by-product feedstuffs. Examples include generally positive evaluations of the use of distillers by-products in United States of America feedlot diets (Klopfenstein, Erickson and Bremer, 2008) and of molasses for finishing Brahman steers in northern Australia (Hunter, 2012). Price-cost margins also are affected by the ability of cattle feeders to meet market specifications for product quality, especially marbling, with genotype and time on feed being the major determinant of intramuscular fat accumulation according to previously discussed principles of allometric growth (Greenwood and Dunshea, 2009). The price benefit of longer finishing periods must be clearly understood and calibrated against additional feed costs imposed by extra days on feed and the waning feed efficiency associated with acceleration of fat deposition relative to declining deposition rates of lean carcass tissues.

In many parts of the world, cattle continue to be finished on pasture for reasons of economy, practicability and resource availability. The growth performance and feed efficiency of pasture-finished cattle are inferior to those of grain-fed animals due to limitation of dry matter and energy intakes by ruminal fibre digestion rate and extent, and gastrointestinal rate of passage of digesta (Van Soest, 1994). Productivity and profitability of pasture finishing operations are determined by the degree to which these biological constraints can be offset by nutritional supplementation or improving pasture quality, or both, as well as by external factors such as value-added pricing and reduced cost of inputs.

Metabolic modifiers. Hormonal growth promotants are widely used to improve growth rate and feed efficiency in finishing cattle. It is estimated that at least 90% of cattle entering United States of America feedlots are implanted (Johnson and Hanrahan, 2010), while a slightly lower incidence of 80% has been estimated for Australian feedlots (Hunter, 2010). The latter author also reported an average increase in ADG of approximately 20% in implanted versus untreated steers and heifers across 18 independent feedlot trials in Australia (Figure 2) and cited evidence for improved performance of pasture-finished cattle. In United States of America studies, similar increases in growth rate of feedlot cattle were associated with an 8% improvement in feed efficiency, increased carcass leanness and reduced time to slaughter (Duckett *et al.*, 1996).

Use of the β-adrenergic agonists, ractopamine (Optaflexx®) and zilpaterol (Zilmax®) in United States of America feedlots has grown steadily since their commercial release in

FIGURE 2
Live weight response in individual studies (n = 18) of feedlot steers and heifers implanted with one of the following hormonal growth promotants: Revalor S®, Revalor H®, Synovex S®, Compudose 100® or Ralgro®



Notes: The straight line represents equality of live weight gain between implanted and unimplanted (control) cattle. For further details, see Hunter (2010) at http://www.publish.csiro.au/nid/72/paper/AN09120.htm from which this figure is reproduced with permission of the author and CSIRO Publishing.

2004 and 2007, respectively, for use during the final 28–42 days of finishing. Impressive increases in weight gain and feed efficiency were optimal when ractopamine was fed at 200 mg/steer/day for 35 days, with no further response when fed at this dose for an additional 7 days (Abney *et al.*, 2007). Carcass characteristics were unaffected, except for an increase in longissimus muscle diameter and a modest decrease in carcass yield grade (USDA scoring system).

Bottom-line recommendations for improving efficiency of post-weaning production:

- moderate feed restriction during the growing phase can have positive effects on growth performance during finishing and the overall post-weaning period;
- finishing rations based largely on by- and co-product feedstuffs can give acceptable growth performance;
- use of ionophores and metabolic modifiers should be considered when permitted by regulatory and market requirements; and
- during finishing, the goal should be optimal economic performance, which may not always align with optimal biological efficiency, depending on prevailing market conditions.

FUTURE CHALLENGES AND OPPORTUNITIES

The future for global beef production into the twenty-first century was assessed recently in a series of reviews published in a single issue of *Animal Frontiers*, in terms of challenges and opportunities for most of the major beef-producing regions of the world, including Australasia (Bell *et al*., 2011), Europe (Hocquette and Chatellier, 2011), North America (Galyean, Ponce and Schutz, 2011) and South America (Arelovich, Bravo and Martinez, 2011; Millen *et al.*, 2011). All sectors recognized the opportunity presented by accelerating global demand for animal protein, including beef, especially in East and Southeast Asia and in Latin America. This trend has obvious short- and medium-term implications for major beef exporting countries such as Brazil and Australia, but also will affect domestic markets in North America and Europe where per capita consumption of beef has been steadily declining for several decades.

There was broad agreement on four major challenges facing the global beef industry.

- Mitigation of the environmental impact of beef production should be a priority, especially effects on air and water quality, and on the stability and biodiversity of relatively fragile pastoral ecosystems.
- Growing public concerns about animal welfare issues must be addressed, including currently used management, slaughter and transport practices, for practical (government regulation, market impacts) as well as ethical reasons.
- Food safety and the need for total traceability from individual animal source to retail outlet will continue to be issues, influenced by the increased scale, intensification and complexity of both on-farm operations and the post-farm processing and distribution chain, including international trade.
- Substantially increased research investment and effort will be needed to address the above challenges as well as to improve the performance of individual animals and the productivity and resilience of production systems, especially pastoral systems that do not compete directly with human food availability.

Finally, the grand challenge of the twenty-first century will be to meet the nutritional needs and dietary preferences of a growing and increasingly affluent global population without irreparably harming the environment. Considering the major theme of this review, it is notable that in many cases, gains in biological efficiency and productivity can be linked to improvement in environmental performance. For example, it is estimated that between 1977 and 2007, improved productivity in the United States of America beef industry resulted in substantial decreases in animal numbers (30%), feed (19%) and water (12%) utilization, and land used (33%) per billion kg of beef produced (Capper, 2011). Waste outputs were similarly reduced for manure (18%), methane (18%) and nitrous oxide (12%) per unit of beef produced.

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Towards sustainable animal diets

Harinder P.S. Makkar

Animal Production and Health Division, FAO, Rome, Italy
E-mail: Harinder.Makkar@fao.org

ABSTRACT

Animal feed and feeding is the foundation of livestock systems. It directly or indirectly affects the entire livestock sector, associated services, public goods and services, including animal productivity, health and welfare, product quality and safety, land use and land use change, and green house gas emission. Current livestock production systems need transformation since they demand high energy, land, chemicals and water, which are increasingly becoming scarce. The proposed concept for sustainable animal diets integrates the importance of efficient use of natural resources, protection of the environment, socio-cultural benefits, and ethical integrity and sensitivity in addition to currently recognized nutrition-based criteria of delivering economically viable safe animal products by producing safe feed. The main constituent elements of the concept are presented with the aim to arrive at a common understanding on these elements and then to prioritize them. Such an understanding and participation of all stakeholders are vital for integrating this concept into sound management practices to contribute to sustainable livestock production.

Keywords: *animal diet, ethics, environment, feed, feeding, natural resource use, social equity, sustainability*

INTRODUCTION

Availability, in a sustained manner, of desired types and quantity of animal feed and its feeding is the foundation of successful animal production. Feed is financially the single most important element of animal production, irrespective of species and production system. The choice of feed constituents (diet) and their consumption affect animal productivity (including reproductive efficiency), greenhouse gas emissions (GHG), animal health, product safety and quality and animal welfare. The production of those dietary constituents has an impact on water quality, GHG and land use. The entire livestock sector, associated services, public goods and services, and animal well-being (and possibly human well-being) may be influenced by animal nutrition.

Before discussing the concept of sustainable animal diets, there is a need to consider what proper nutrition is. It may be defined as the feeding of a diet balanced in all nutrients and free from deleterious components, at a level that meets the production objectives considering the animal's physiological state, and which generates animal products that are safe for human consumption. These traits should be at the core of sustainable animal diets. However, sustainable animal diets, in addition to having the conventional traits of a diet that provides proper nutrition, should also have additional elements, as discussed below.

The term 'sustainable' has in recent times been one of the most widely used and discussed terms in agriculture and in development fields as a whole. Three Ps that stand for profit, people and planet have, *inter alia*, been used to describe the term, implying economic growth, social equity and ecological soundness (IUCN, 2005). Using the three-P definition of sustainability, an approach or a technology is considered to be sustainable if it is profitable; socioculturally acceptable and beneficial to people; and protects the environment and natural resource base (the planet).

The concept of sustainable animal diets discussed in this paper is pertinent only for domesticated animals. This concept is being presented with the objective of arriving at a common understanding on its main constituent elements. Such an understanding is vital for integrating this concept into sound management practices (while using research and technology advances) in support of sustainable livestock production systems. Sustainable intensification of livestock production systems is fundamental to meeting the large demand, both current and future, for livestock products, the drivers of which are the increasing human population, growing developing economies, urbanization and associated changes in dietary habits, leading to increasing consumption of animal products. The sustainable intensification of livestock production systems cannot be achieved without the use of sustainable animal diets.

The present day animal-based human food production systems need re-defining and re-structuring if present and future human population needs are to be met in a sustainable manner, since they often rely heavily on one or more of the elements of energy, chemicals, minerals (phosphorus), water and land, all of which are becoming increasingly scarce. During the last three decades, inexpensive grain, energy and protein enabled the economic development of intensive meat and milk production systems based on feeding grains and other ingredients sourced from distant places. In parallel poultry and pig intensive production systems became highly capital intensive, and they have posed many environmental challenges. It is unlikely that the growth rates of the past could be sustained in the future due to increasing costs of energy, grain and other inputs. The growth rates may even decline if the price of grain rises above a critical level, and might even become economically unviable. Furthermore, the issues may become magnified due to increasing competition for arable land for food, feed and biofuel production (Devendra and Leng, 2011). So far, in many situations, feeds have been produced and feeding has been designed to achieve maximum yield, giving high economic benefits; however, this approach, especially when animal manure is not properly managed, is considered to contribute to ecosystem degradation (deforestation, chemical contamination, decreased biodiversity, water shortage, and water and air pollution) and global warming through the emission of methane and nitrous oxide (Flachowsky, 2002; Niemann, Kuhla and Flachowsky, 2011). Moreover, the current systems of livestock production incur high energy consumption at every step, more so the intensive systems. Large feed units producing compounded feeds or complete feeds consume energy, not only in processing but also in transporting the feed. These situations demand attention to examine the profligate use of resources and to consider ways of adopting more efficient processes and systems, and hence the need for re-definition of animal diets.

WHAT SHOULD A SUSTAINABLE ANIMAL DIET ENTAIL?

The 'three-P' dimensions of sustainability from the perspective of animal diets should embrace a number of elements.

Profitability (the profit dimension)

- Cost:benefit ratio of feeding needs to be defined in terms of the benefits over the long term, remebering that costs are involved in repairing the damage done to ecosystem health during production and feeding. Pertinent issues include "Who should bear this cost?" and "Which cost should be included in the cost:benefit calculation?" One option could be to systematically account for the costs of key negative externalities. The concept of sustainable animal diets attempts to minimize this cost, as illustrated in the next section. Covering environmental and social cost accounting systems (Boyd and Banzhaf, 2007; Petcharat and Mula, 2012) could also be adopted for undertaking cost:benefit analysis.
- Procurement or cultivation of feed ingredients for sustainable animal diets to be affordable for livestock producers.

Socio-cultural benefits (the people dimension)

Sustainable animal diets should:

- consider social aspects of rearing livestock;
- avoid being culturally offensive to producers and consumers of the animal products;
- respect perceptions, beliefs, values and taboos (i.e. be socially acceptable);
- break social barriers and promote social harmony;
- avoid exacerbation of unfavourable legal processes (e.g. 'land grab');
- promote corporate social responsibility;
- promote and preserve local knowledge (e.g. in biodiversity management);
- empower women;
- minimize competition with human food, both in terms of use of material that can be used as human food as well as diversion of land producing human food to animal feed and fodder production; and
- result in animal products that are safe and affordable to consumers.

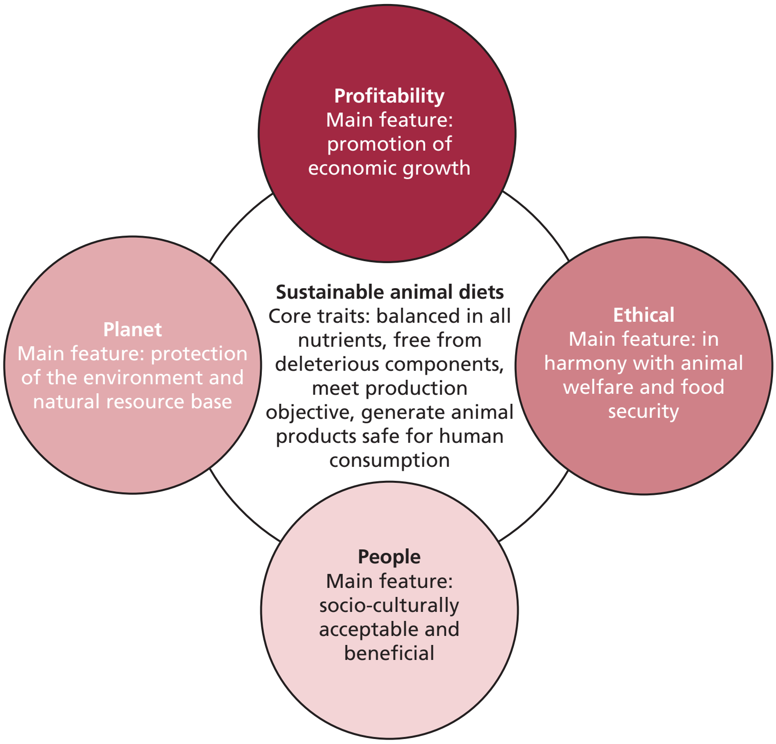
Environment and natural resource base protection (the planet dimension)

Sustainable animal diets should:

- minimize use of chemical additives;
- preferably use locally available feed resources;
- minimize use of water and energy;
- minimize the carbon footprint of feedstuff production, processing and distribution;
- minimize water and air pollution;
- enhance resilience within the different livestock production systems;
- not lead to de-forestation and land degradation;
- enhance, or at least not lead to a decrease in, biodiversity; and
- respect landscape diversity and aesthetic values.

The three-P principle of sustainability described above needs to be complemented by a further vital aspect of animal nutrition, namely the ethics of using a particular feed, particularly where there are associated animal welfare issues. The rumen is not physiologically designed to cope with high grain rations and it would therefore appear

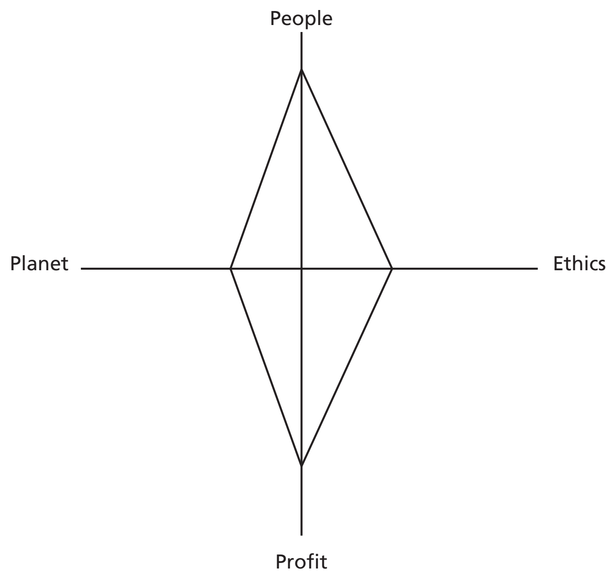
FIGURE 1
Conceptual framework of sustainable animal diets



questionable whether feeding a diet containing high amounts of grain to ruminants can be considered ethical, either from a (scarce) resource use perspective or from an animal welfare perspective, as such a diet may result in acidosis, lameness and other associated problems affecting the well-being of animals (FAO, 2012a).

Feeding grains to animals competes with their use in human food and nutrition. At a time when over one billion people are hungry and suitable land for growing crops is becoming increasingly scarce, the use of food-grade grains in the diets of ruminants is certain to face increased questioning on both resource use efficiency and ethical grounds. For ruminants, a sustainable diet should not only meet the core traits of a feed listed in the definition of proper nutrition and the three-P criteria, but also the relevant ethical dimensions (Figure 1). A sustainable diet for monogastric animals involves grains (preferably non-food grade), but the amount of grain use requires careful assessment and possibly reduction (a key parameter suggested here is the comparative assessment of the emission of GHG as calculated using the Life Cycle Analysis approach). Increasing fibre content in rations during specific production stages of non-ruminant animals (especially sows) is also considered to enhance animal welfare, health and productivity (FAO, 2012a). Sustainable diets need to reflect these issues.

FIGURE 2
Balancing different dimensions of the sustainable animal diet concept



Sustainable animal diets are expected to be beneficial for the animal, the environment and society, and are likely to generate socio-economic benefits, furthering poverty alleviation and food security efforts.

The elements of and criteria for the sustainable animal diets discussed above may need to be prioritized, and then indicators developed for ranking diets as to their sustainability. Since the concept of sustainable animal diets has the three P dimensions (profit, people and planet) and the ethical dimension, the weight given to the indicators of sustainable animal diets is expected to differ between regions. The prioritization of the indicators in different regions may assist in balancing the objectives of the sustainable diets. A situation as shown in Figure 2 could emerge for a region, and there will always be trade-offs. It is impossible to define a standard or an ideal 'sustainable animal diet' and this also is not the objective of this concept. It is important to note that realization of sustainable animal diets is a journey and not an end, and the aim should be to move towards these diets based on the agreed indicators of sustainability.

POLICY DIMENSIONS AND DECISION TOOLS

Proper policies need to be formulated and applied to stimulate the use of the concept of sustainable animal diets. Currently, policies tend to prioritize the maximization of yields rather than addressing sustainability with its three-P dimensions. The 'Pressure Phenomenon' seen to affect policy decisions in various sectors affects the livestock sector as well: there is pull of market demand and economic benefits, and push of the technologies that promise rapid growth. Rapid increase in demand and prices of livestock products is resulting in pressures to take steps that would increase production rapidly. The first component that is affected in this cascade of events is the animal diet, since it has a major impact on performance of animals and decisions are made at the cost of sustainability. Therefore there is a need for policies that address various components of the sustainable animal diets concept as presented above, and this would require involvement of all stakeholders, including public ministries of agriculture, finance, environment and culture; small- and large-scale private industries, including feed industries; producers; and civil society organizations, NGOs and national and international institutions.

Comparison of diets based on sustainability criteria will be easier than arriving at a decision as to whether a diet is sustainable or not, since fulfilling the criteria listed under the three Ps requires fundamental decisions, such as on the acceptable levels of agrochemicals, energy and water use, and on how to measure biodiversity and resilience of production systems, amongst many others. Decision tools need to be developed, including for assessing the carbon footprint of production and use of feeds and associated environmental costs, to measure the resilience of production systems and to assess their impacts on biodiversity.

WHAT IS NEW IN THE CONCEPT AND WHAT DIFFERENCE CAN ITS IMPLEMENTATION MAKE?

The concept has: (a) a thematic focus on meeting production objectives by improving feed (nutrient) use efficiency; (b) multi-dimensional scope, embracing socio-cultural, ethical and environmental dimensions in addition to economic; (c) an action-oriented holistic approach, targeting change of practices; and (d) a multi-stakeholder involvement approach, harnessing synergies and complementarities.

For example, the concept, when put in practice, might enhance economic viability, reduce food-feed competition and enhance food security by promoting the use of unconventional feed ingredients in place of expensive ones such as grains. Feeding of locally available feed resources, including those that avoid land degradation, energy efficient feed production, and targeted smart feeding which the concept advocates, is expected to enhance biodiversity and protect the environment. The use of animal diets that empower women and further social equity will enhance social health. All these will increase people's understanding, appreciation and tolerance of farming practices. In advanced stages of the implementation of the sustainable animal diet concept, it is possible that a model could be developed to compare diets against the indicators of sustainable animal diets. A decision tool based on this concept could also be integrated into other models, enabling comparison of animal products from different animal species and assisting consumers to choose one animal product over another. Similarly, animal products originating from different livestock production systems could be compared. The concept and its likely outcomes also hold potential for integration into the 'Global Agenda of Action in Support of Sustainable Livestock Development' (FAO, 2012b).

Society expects agriculture to provide safe and affordable animal products while maintaining environmental quality and biodiversity. The further development of a sustainable animal diets concept and its translation into concrete action would be an important step towards achieving this. This requires participation of researchers, extension workers, science managers, policy-makers, industry and farmers.

CONCLUSIONS

The concept of sustainable animal diets acknowledges the importance of environment, natural resource protection, socio-cultural benefits and ethical integrity and sensitivity in addition to the hitherto nutrition-oriented criterion of producing safe feed to obtain safe animal products for human consumption at a level that is economically viable. In a majority of cases the emphasis so far has been on the quantity of the product produced and its economic viability, rather than on its sustainability in a holistic context. In the present-day context, where we are faced with tremendous challenges imposed by resource scarcity, climate change, land degradation, water shortage, high energy prices and loss of biodiversity, there is an urgent need to act swiftly and embed these additional dimensions in defining sustainable animal diets and subsequently producing and using them. Criteria and processes presented in this concept paper are intended to help move in that direction.

The old paradigm that considers technologies as tools, the application of which, in a framework that provides capital and other resources to generate an output merely to provide financial gains, appears insufficient to address the challenges faced. The environmental and sociocultural and ethical dimensions must be integrated to take account of substantial externalities and social inequalities and to promote animal welfare and fair practices.

International and national agencies, including donors, could consider including sustainable animal diets as one of the basic elements of their projects and programmes, integrated with, and contributing to, other multi-faceted goals of a project or programme. Research is required to assist in the development of sustainable animal diets and in supporting their use at the field level. It is essential that sustainability is measured using robust, but simple, methods, in clear and consistent language and with reliable metrics. This report represents a starting point in the process to develop a robust set of indicators, so that the concept can be translated into sound management practices.

ACKNOWLEDGEMENTS

Thanks are due to Drs Samuel Jutzi, Philippe Ankers, Emyr Owen and D.V. Rangnekar for their valuable inputs.

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Feeding for optimal rumen and animal health and optimal feed conversion efficiency: the importance of physical nutrition

David E. Beever[1] *and James K Drackley*[2]

[1]. R Keenan & Co, Ireland

[2]. University of Illinois, United States of America

E-mail: dbeever@keenansystem.com

ABSTRACT

This paper examines opportunities to improve the conversion of feed by ruminant livestock into milk or meat. Whilst focusing principally on livestock systems in the developed world, it demonstrates considerable gains are possible irrespective of system type, and suggests that the world's current level of milk production could be achieved with a net feed saving of over 270 million tonne, or 20% of current usage, if improved feeding strategies were adopted.

Feed represents the major cost of producing milk or meat from ruminant livestock. Many dairy and beef farms could markedly improve the efficiency of feed use (Feed Conversion Efficiency – FCE) and secure significant production, health, financial and environmental benefits. Compared with non-ruminants, systems of ruminant production are less efficient, due to the lower nutrient density of many of the feeds used and the processes by which feeds are digested and utilized. Losses as methane, faeces, urine and heat can account for over 70% of energy intake, and whilst such losses are unavoidable, they need to be controlled.

The rumen is the principal site of feed digestion and central to optimizing the conversion of feed into milk or meat. Whilst most ruminant rations are balanced for chemical entities including energy and protein, optimizing the physical characteristics of the ration is often overlooked. The digesta mass in the rumen requires constant gentle mixing to optimize the processes of digestion and microbial growth. Optimal structural architecture of the ration promotes rumen mixing and rumination and supports the conversion of feed into food for humans. Sub-optimal rumen conditions can lead to animal health issues, including sub-acute acidosis and lameness. Avoiding such conditions results in more milk or meat/kg feed consumed.

An integrated feeding system to optimize ration chemical and physical characteristics is considered. A survey of 1086 dairy farms in France and UK reported an additional 1.84 litre/cow/day within 12 months of system adoption, whilst feed consumption fell by 0.74 kg dry matter (DM)/cow/day, with a 12% improvement in FCE (1.276 v 1.141 litres energy corrected milk (ECM)/kg feed DM). Many dairy farms have suitable genetics to achieve annual FCEs of 1.5 litre/kg DM, but current levels are much lower. A similar pattern exists on beef farms. By improving FCE, methane output per litre ECM or per kg weight gain is reduced, possibly by as much as 20% of current levels. Adoption of the system for dry cows showed improved animal health, with the incidence of health issues around calving reduced from 45 to 16 cases per 100 cows calved.

For those farms in developed countries, this unique system for feeding ruminant livestock is easy to operate and has important feedback mechanisms to ensure consistency of ration presentation and constant monitoring of FCE. With minimal adoption it also has the potential to bring important gains for small-scale farms. Overall, the gains in animal health, resource use, environmental pollution and margins can be considerable, with benefits in feeding such rations to milking cows, growing stock and dry cows.

Keywords: *animal health, beef cattle, dairy cows, feed conversion efficiency, methane production, physical nutrition, rumen function*

INTRODUCTION

For systems of milk and meat production to be efficient, healthy animals, feeds of high quality and provenance and first class management are required. Feed represents over half of the variable costs of milk or meat production (Colman *et al.*, 2011), and whilst non-ruminant systems rely extensively on cereal grains and protein-rich feeds, ruminant rations generally contain significant amounts of fodder. This might be grazed and comprise >75% of total ration DM intake, or fed as silage or hay and typically comprise 50 to 60% of total ration dry matter (DM). However, the nutritional value of forages can be highly variable, according to forage type, environment, season and stage of growth when harvested (Beever, Offer and Gill, 2000). When increased levels of production are targeted, or where issues of fodder supply or quality exist, many farmers provide supplementary feeds. Frequently these are sourced off-farm, adding to production costs and reducing margins per unit of animal product, despite their use to maintain total enterprise margins.

Livestock farmers everywhere need to control total feed costs, especially now when record feed prices are being reported, but providing lower priced feeds to control costs invariably results in lower quality products, with associated effects on animal performance and margins. The non-ruminant sector has long recognized the importance of the efficiency with which animals covert feed into animal product as a key indicator of technical and financial success, with the concept of feed conversion efficiency (FCE; product output/feed input) well embedded in these industries. In contrast, the ruminant sector has been slow to harness the value of the FCE concept and only recently has this concept begun to receive some recognition.

This paper will consider the principal factors affecting the efficiency of converting feed into milk or meat by ruminant livestock, with a brief summary of the concept of FCE. Issues affecting overall ration utilization will be discussed, highlighting the importance of rumen health and physical nutrition. The importance of animal health and how it may be affected by nutrition will be considered, before describing the benefits of an integrated nutritional solution designed to optimize rumen and animal health to improve FCE and margins, supported by extensive farm and research evidence. The environmental benefits accruing from improved FCE will be considered, and finally the paper will examine the applicability of this system for feeding ruminant livestock in both the developed and developing worlds.

FEED CONVERSION EFFICIENCY

In most dairy herds, daily milk production will be known, along with some estimates of feed usage. This should allow FCE to be determined (milk output/feed input), but milk yield is affected by stage of lactation, which inevitably confounds interpretation of any measures of FCE. In early lactation, cows lose body tissue to support milk production, which inevitably increases FCE, with the reverse in later lactation, when part of the consumed feed is used for body tissue repletion, which reduces FCE. Once total milk production, feed intake and some estimate of body tissue depletion or repletion (i.e. body condition change) are known, meaningful assessments of FCE can be obtained, although the importance of milk composition also needs to be recognized.

Producing beef is a longer process than poultry or pig-meat production, often with disparate feeding periods (e.g. extensive grazing vs intensive feeding) according to the animal's physiological growth stage. Added to which, few beef farmers routinely weigh cattle, making measurement of FCE and interpretation of the data a more challenging task.

Dairying

For dairying the definition of FCE, as provided by Colman *et al.* (2011), which appears to have most universal acceptance, is described as:

$$\text{FCE} = \text{ECM Yield/Total feed DM consumed}$$

where FCE = litres ECM/kg feed DM, and ECM = Energy corrected milk yield standardized to 4% fat and 3.3% crude protein.

The equation of Tyrell and Reid (1965) allows milk energy content and the yield of ECM to be determined. Where only milk fat content is known, other equations are available, but for meaningful within- or between-herd comparisons of FCE, ECM yield rather than observed milk yield must be used to account for any differences in milk composition. Attempts to adjust FCE according to distance walked by cows, heat stress and other such factors are to be avoided. FCE for dairy cows is, in its simplest form, the output of standardized milk per unit feed DM input.

Based on established principles of energy metabolism (Alderman and Cottrill, 1993), the energy costs of cow maintenance and milk production can be determined, along with the energy costs or gains of body condition gain or loss. After allowance for cow maintenance, higher feed intakes should improve FCE, but the response may be attenuated if overall feed digestibility is impaired under such conditions. A maximum FCE approaching 1.75 litre ECM/kg DM can be assumed, after discounting possible contributions from mobilized body tissue, with Drackley and Beever (unpublished) suggesting most herds, with no obvious feed or animal health issues, should be able to achieve an annual FCE of 1.5 litre ECM/kg feed DM. In contrast, Colman *et al.* (2011) and others have indicated that few herds routinely achieve such levels, with many in the developed world operating below 1.2 litre/kg, and below 1.0 litre/kg in other situations where feed and animal constraints exist. This can represent a significant loss of milk for each kg feed consumed. Once FCE is known, its impact on margin over total feed costs can be determined by:

$$\text{Margin} = \text{Milk price minus (Feed cost/FCE)}$$

where Margin and Milk price are cents (or pence) per litre and feed cost is cents (or pence) per kg DM.

Within their own specific environment, few farmers have any real control over milk or feed price, leaving FCE as the only element by which they could improve margin per litre. At a milk:feed price ratio of 1.5, a 10% gain in FCE improves margin per litre by around 12%, and improves further to 17% with a 15% gain in FCE.

Beef

Conventional practice when expressing FCE for beef cattle has been the amount of feed DM used to produce each unit of weight gain. With growing acceptance of FCE for dairying being a function of output per unit feed input, it is contended a similar function would be a more meaningful measure for meat producing animals, as below:

FCE = Total weight gain/Total feed DM consumed

with total weight gain and total feed DM intake = kg/day and FCE = g/kg feed DM.

Frequent weighing of animals, with a suggested interval between a minimum of 3 and a maximum 6 weeks, is indicated, with achieved weight gains compared with total feed consumption over that period to determine FCE. Growing animals have a higher propensity for lean tissue growth and, given its lower energy cost than fat deposition (Alderman and Cottrill, 1993), FCEs approaching 200 g/kg (kg/tonne) feed DM should be targeted. In contrast, finishing stock depositing increased amounts of fat should be targeted to achieve an FCE of 140–150 g/kg feed DM. In practice, many farms are operating substantially below such levels.

The calculations above relate only to animals producing either milk or meat, and take no account of other stock on the farm supporting the production of milk or meat whilst making no direct contribution to herd output. These include heifer replacements and dry cows in dairying, and the maternal dam in cow-calf operations. In both sectors, poor management practices with reduced young stock survival rates, high herd cull rates, extended dry periods and poor fertility increase the amount of feed consumed by 'non-productive' stock and significantly affect annual herd FCE (i.e. total herd output/total herd feed input). The implications of such will be considered in a later section.

RATION ISSUES

Comparison of current FCE with theoretical expectations allows any underperformance to be identified and suitable remedial strategies developed. Many reasons for underperformance can be advanced (Beever and Doyle, 2007). Feed quality or provenance, especially of the fodder component, may be less than expected and further analysis of the principal feeds may be advisable. Achieved levels of feed DM consumption may be less than expected and, as most ruminant rations contain significant amounts of moist feeds, further determination of the DM content of the offered ration or its principal components may be appropriate. With grazed forages, measurement of forage intake is always challenging but worthy of reconsideration when underperformance is suspected. Added to these, animals suffering physical injury, metabolic disease or infection are less likely to consume and utilize feed to the expected level. In this respect, the importance of rumen health as a key driver of FCE is recognized, with its potential impact on overall ration digestibility and nutrient supply, and associative effects on animal health, such as sub-clinical rumen acidosis. Many farmers fail to recognize the possible impact of compromised digestion on animal performance, and often misjudge the limits of conventional nutritional recommendations. When a ration of computed metabolizable or net energy content is fed, farmers expect delivery of the targeted outcome, provided the desired levels of feed intake are achieved. This however is rarely the case and a modest decline in ration digestibility can lead to a significant reduction in daily milk yield.

OPTIMIZING RUMEN HEALTH

As the principal site of digestion in ruminants, the rumen requires an active microbial population to secure optimal digestion of the dietary fibre (Beever, 1993). It is also the major site of dietary sugar and starch digestion, whilst significant amounts of dietary protein are degraded to support growth of the rumen microflora. After dissolution of the dietary carbohydrates to smaller molecules, extensive microbial fermentation results in the production of volatile fatty acids (VFA), CO_2 and hydrogen. Extensive plant lipid bio-hydrogenation also occurs in the rumen (Bauman *et al.*, 2003). Energy (as ATP) released during fermentation supports microbial growth, whilst most of the VFA are absorbed from the rumen and used by the animal for energy or the synthesis of milk or body fat (acetate and butyrate) and glucose (propionate). The small intestine is the site of digestion of rumen microbial protein and undigested feed protein (Beever and Siddons, 1986), plant and microbial lipids (Bauman *et al.*, 2003) and any unfermented feed starch (Nocek and Tamminga, 1991), following passage from the rumen. Collectively, these processes of digestion affect both feed intake and the yield of milk or meat. Methane is produced in the rumen, with a critical role in maintaining oxidation-reduction potential of the rumen by the removal of hydrogen associated with the fermentation of plant carbohydrates (Kirchgessner, Windisch and Muller, 1995). The amount of methane produced is affected by feed intake (Reynolds, Compton and Mills, 2011) and ration fibre content (Blaxter and Clapperton, 1965), with Mills *et al.* (2001) reporting a less pronounced difference at higher dietary starch inclusions. Methane can account for as much as 8 to 10% of total digestible energy intake, with data from Kebreab *et al.* (2003) indicating a mean output of 21.8 g/kg feed DM intake, with between 250 and 500 g methane/cow/day according to cow body size and feed intake.

Fibre-degrading bacteria operate most efficiently when rumen pH is above 6.0 (Mould, Orskov and Mann, 1983). Below this, accumulating acid levels affect their functionality and growth, allowing other bacteria that are less efficient fibre digesters to dominate, as seen when high-starch feeds are provided, especially in discrete meals (Krause and Oetzel, 2005). Under such conditions, rumen lactic acid levels generally increase, and being a stronger acid than VFA, results in a more pronounced decline in rumen pH and ultimately may lead to sub-clinical or even clinical lactic acidosis (Bramley *et al*., 2006). Rumen acidosis also occurs in pasture-fed cattle, especially with spring grass containing high levels of water soluble carbohydrate, as noted by O'Grady, Doherty and Mulligan (2008) in Ireland, Williams *et al*. (2005) in Australia and Gibbs *et al.* (2007) in New Zealand. However, low rumen pH levels in grass-fed cattle are more likely to be due to increased levels of rumen VFA than to lactic acid, and should be easier to reverse, with VFA being weaker acids than lactic acid. Nonetheless, the evidence of considerable diurnal variation in rumen pH in grazing cattle, presumably affected by grazing behaviour, is concerning, and whilst the distribution of microbial species does not appear to be affected, there could be consequential effects of the unstable rumen environment on their functionality.

Whilst control of rumen pH and avoidance of large diurnal fluctuations is important, other factors need to be recognized. The rumen needs to be operating to maximal efficiency in terms of mixing, rumination and emptying. Continuous mixing of rumen contents improves the intimacy between ingested feed particles and the microbial population, essential for optimal fibre digestion. The historic notion of the importance of a rumen mat is challenged as this does not appear conducive to optimal mixing and there is minimal evidence of its existence in productive animals. Active bouts of rumination support feed breakdown and promote saliva secretion, which assists the control of rumen pH. But rumen mixing, with coordinated contractions of the rumen wall, and rumination require the presence of suitable physical particles within the rumen mass, which need to be provided in the ration, and collectively termed physically effective fibre.

THE IMPORTANCE OF PHYSICAL NUTRITION

Against the indicated need for physical nutrition, many current feeding practices appear to have adopted a juxtaposition, driven by factors such as forage type, feeding management practices and the urge to optimize feed intake. The importance of providing highly digestible forages influences the choice of forage grown and when it is harvested, either grazed or by mechanical means. But forages ‘harvested’ at earlier stages of maturity contain lower amounts of physically effective fibre. Pasture-based cows graze short stubble height swards to optimize feed quality, pasture re-growth and overall pasture utilization. The ensiling of forage encourages increased mechanical processing during harvesting to reduce forage length for improved silo compaction and waste minimization. Added to this, most supplementary feeds are extensively processed, which eliminates any physically effective fibre they may contain. Collectively, many ruminant rations contain insufficient physically effective fibre for optimal rumen mixing and rumination. Under such conditions, both rate and extent of fibre digestion may be reduced (Beauchemin, 2007), inevitably affecting nutrient supply per unit feed provided. Reduced particle size increases rumen emptying rate and will promote feed intake, with possible negative effects on feed utilization. As sub-optimal conditions persist, rumen contractions will be reduced, resulting in a slower rate of emptying leading to erratic, and in many cases lower, levels of feed intake. There are many examples where sub-optimal rumen conditions are adversely affecting animal performance.

Adoption of the Penn State separator was a means by which the level of physically effective fibre in the ration, and thus in the rumen, could be optimized, and in this respect there have been genuine claims about its utility. But using only particle length as a measure of physically effective fibre is open to question, as this provides no description of the structure of that particle and its behavior in the rumen. All physically effective fibre in the ration needs to be fully dispersed within the rumen mass, with sufficient residence time to be effective, whilst avoiding any notable accumulation. This led to the concepts of specific gravity, compressibility and water holding capacity being proposed as an extended description of the physical characteristics of the final ration and the principal feed ingredients (Beever, unpublished observations).

After a suitable source of physically effective fibre has been identified, there remains the issue of ensuring adequate consumption of that feed together with the other ration components. Long forage provided as mature hay or cereal straw for free-choice consumption does not guarantee adequate intake of that feed, when other more desirable feeds are available. The sources of physically effective fibre need to be processed to a defined length and structure and fully incorporated with the other feed ingredients, if rejection of such feeds (e.g. cereal straws and mature hays) is to be avoided and optimal rumen function achieved.

Research evidence supports the concept of physically effective fibre and its importance in rumen function. Beauchemin *et al.* (2008) fed small amounts of cereal straw (<0.5 kg/day) as a source of structural fibre and when straw of suitable length (4 to 8 cm) and structure was fully incorporated into mixed rations, encouraging animal performance results were noted. In contrast, providing ryegrass straw as a ground pelleted or coarse chopped cubed feed to cows grazing high quality pasture showed no positive effects on milk production, milk composition, rumen pH, or time spent ruminating per unit DM intake (Wales, Williams and Doyle, 2001). These results confirm the importance of the method of fodder inclusion in the ration to achieve optimal rumen function. When suitable forages, such as straw or mature hay, are correctly processed and incorporated into well mixed rations, minimization of sorting ensures more consistent ration consumption, with Humphries, Reynolds and Beever (2010) reporting positive benefits in milk yield, eating behaviour and time rumen pH was below 6.0, when the ration, including the forage, was processed in a more controlled manner using a horizontal paddle mixer rather than a vertical auger mixer.

THE IMPORTANCE OF ANIMAL HEALTH AND FERTILITY

Providing optimal rations also improves animal health and fertility. Issues such as the supply of adequate protein, minerals or vitamins can be easily corrected, but one area where inappropriate nutrition can have long-term implications on animal performance is dry cow feeding, notably the provision of optimal energy and physical nutrition in the ration. In dairy cows, the dry period provides an opportunity for metabolic recovery from the demands of the previous lactation. Whilst foetal growth rate will be increasing exponentially at this time, the cow's overall nutrient requirements, principally energy and protein, will remain relatively modest. Failure to take due regard of these, and most especially to avoid periods of excessive energy consumption, will have an impact on animal health during the periparturient and subsequent lactation and breeding periods. Suckler cows have longer dry periods than dairy cows, but, if not managed correctly, can easily become over-conditioned, leading to dystocia issues, followed by impaired fertility during the subsequent breeding period.

Whilst the importance of the dry period can not be over emphasized, many farmers view it as an opportunity to reduce management inputs, giving less attention to the cow's nutritional and welfare needs, particularly during the first part ('Far Off period'). Then follows the 'Close Up' period, and here most farmers increase ration nutrient density and feeding rate, based on recommendations by their nutritionist or historical practice, to "steam-up" the cow in anticipation of increased nutrient demands after calving. Despite extensive adoption, little research evidence exists to support the efficacy of this approach

(Drackley and Dann, 2008), with many herds continuing to experience high incidence rates of peri-parturient issues, poor feed intakes and increased loss of body condition score (BCS) after calving, and impaired fertility, all having welfare or longevity implications. A survey of more than 600 000 cows removed from almost 6000 herds through culling or death over a five-year period (Fetrow, Nordlund and Norman, 2006) found 25% of the cows left the herd within the first 60 days after calving. Undoubtedly these were principally involuntary culls, or deaths of cows that had not remained in the herd long enough after calving to reach their milk income potential, but nevertheless had all the accrued costs of breeding, feeding and management during the gestation period and calving.

Recently, Drackley and Dann (2008) challenged the theory of providing additional nutrients before calving in pursuit of higher peak milk yields and avoidance of the consequences of impaired feed intakes after calving as advanced by Boutflour (1928), Grummer (1995) and others. They showed that increased energy intake prior to calving, even in cows of low to average BCS, increased the incidence of health problems around calving and the early post-calving period, including dystocia, fatty liver and ketosis (Dann *et al*., 2006; Douglas *et al*., 2006; Janovick and Drackley, 2010). Based on earlier farm experience, supported by subsequent scientific research, Beever (2007) and Drackley and Dann (2008) considered an alternative feeding strategy to control feed intake during the dry period, ensuring all nutrient requirements were met whilst avoiding excess intake, especially of energy. A mixed ration with 40 to 50% cereal straw, 30% lactation forage and 20% lactation concentrates (of ration DM), with a suitable dry cow mineral, was proposed, the cereal straw having an important role in energy dilution, reduced sodium and potassium levels and the provision of physically effective fibre in the final ration. It was proposed the ration should be fed *ad libitum* during the whole dry period. Richards *et al*. (2009) examined the concept, and when compared with a typical dry cow feeding programme, noted a more controlled intake of feed during the early dry period with more stable intakes through to calving, and only a minimal decline during the last 1–2 weeks. Intakes were improved after calving, with a significant reduction in BCS loss, and reduced plasma non-esterified fatty acid and β-hydroxy butyrate levels prior to and after the calving event. The Controlled Energy-Hi Fibre (CEHF) system has been adopted on many farms across the world, with substantial improvements in cow health. A study of almost 300 dairy farms in four EU countries reported an average of 16 health issues per 100 cows calved after adoption of the CEHF system, compared with 45 cases per 100 cows before adoption (Colman *et al.*, 2011), indicating significant welfare and financial benefits. Richards *et al.* (2009) also noted evidence of an increased incidence of insulin resistance in the overfed cows. Providing rations with up to 50% (DM) as cereal straw and avoidance of feed selection can be challenging and requires a suitable feed mixer to correctly process and incorporate the straw into the final ration.

One benefit of the proposed approach noted by Richards *et al.* (2009) was the significant reduction in BCS loss after calving. As expected, conventionally-fed cows gained BCS during the dry period and at calving were over 0.3 BCS units higher than CEHF fed cows, despite both groups having similar BCS at study commencement. By 9 weeks post-calving, however, both groups again had similar BCS, indicating significantly greater loss of BCS for conventionally-fed cows. Cows losing increased amounts of BCS after calving are frequently more difficult to get back in calf, with Butler and Smith, (1989) noting a mean pregnancy rate of 53% to 1st service in cows losing between 0.5 and 1.0 BCS units between calving and service, compared with 17% for cows losing over 1.0 BCS at this time. Subsequently, Beam and Butler (1999) reported reduced pulse frequency of luteinizing hormone, which affects the fate of the developing follicle, in cows with increased BCS loss after calving. The phenomenon of increased BCS loss after calving and impaired fertility also occurs in lower yielding cows, with Mee (2004) reporting a 1% unit per year decline in 1st service conception rate and a 10-day increase in mean calving interval over a seven-year period in pasture-fed cows in Ireland. Added to which, the number of cows with abnormal reproductive cycles was increased (13% to 26%), despite no overall increase in annual milk production, along with less overt oestrus behaviour in many cows. Mee (2004) concluded that 'strategies are required to improve or halt the decline in reproductive performance (and that) these must include feeding systems to reduce negative energy balance and maintain body condition'. This supported Buckley *et al*. (2003), who, with similar cows in Ireland, concluded that 'reproductive performance, especially the probability of conception, may be negatively associated with the magnitude and duration of negative energy balance in early lactation'. Although no direct evidence exists, it is contended a system of feeding during the dry period which significantly reduces BCS loss during early lactation, as reported by Richards *et al.* (2009), has the potential to bring sustained improvements in fertility, with shorter calving intervals and reduced culling of cows that fail to re-breed.

DELIVERING IMPROVED ANIMAL PERFORMANCE THROUGH IMPROVED FEED CONVERSION EFFICIENCY

Dairy cows

The essence of the proposed system is the provision of consistent rations for housed and pasture-based cows, suitably balanced for chemical and physical nutrition, to optimize rumen function and animal health and deliver improved FCE. Crucial to the system is a dedicated software programme to control feed ingredient loading order and mixing time of the ration, with an important feedback of mixing protocols together with feed usage for the routine estimation of FCE. No additional feed is provided at milking, as this can impair rumen function. The system must be applied consistently, with sufficient feeding space to encourage cows to consume according to their individual milk yields and minimize cows becoming over- or under-conditioned. Ration processing and mixing is achieved by slow rotating horizontal paddles with a series of fixed knives to promote a gentle chopping action. This preserves feed structure and delivers rations containing the requisite amount of physical nutrition. The widespread view of farmers and their advisors that ration structure is unaffected by mixer type or its operation (Buckmaster, 2010), was recently challenged by Ploetz *et al.* (2011), who fed three identical rations, with increased levels of distillers grain (DG), produced using either a vertical mixer, with its more aggressive chopping and mixing action, or a horizontal mixer of the type described above. Cows fed rations prepared with the vertical mixer consumed more feed but failed to produce more milk, with a pronounced progressive decline in FCE and milk fat content at higher levels of DG. Lower milk fats are frequently reported when increased DG is fed, and often limits its use in dairy cow rations. In contrast, cows fed rations prepared with the horizontal mixer showed an improved FCE at the first increment of DG followed by a small decline, but most noticeably, there was

TABLE 1
Impact of system adoption on feed intake, production of energy corrected milk and feed conversion efficiency on 1086 dairy farms in France and UK

	Total feed DM intake (kg/day)	ECM yield (litre/day)	FCE (litre ECM/kg feed DM)
Start	20.71	23.64	1.141
Finish	19.97	25.48	1.276
Change	-0.74	+1.84	+0.135

Source: from Colman *et al*., 2011.

only minimal evidence of any reduction in milk fat content. Analysis of the fatty acid composition of milk fat for the various treatments revealed changes attributable to a significant improvement in microbial metabolism in cows fed with the horizontal mixer.

Over four years, Colman *et al.* (2011) compared the performance of 1086 dairy farms in France and UK in the year before and following system adoption, with the cohort of producers changing each year. Average ECM yield increased by 1.84 litre/cow/day (Table 1) whilst average feed DM intake declined by 0.74 kg/cow/day, with a 12% improvement in average FCE. Notably the responses were greatest in France, where there was increased system compliance, but all yearly comparisons for both countries were statistically significant. Based on average milk and feed price for the four years, annual margin over total feed costs improved by € 200 per cow, with a positive relationship between FCE and margin described by:

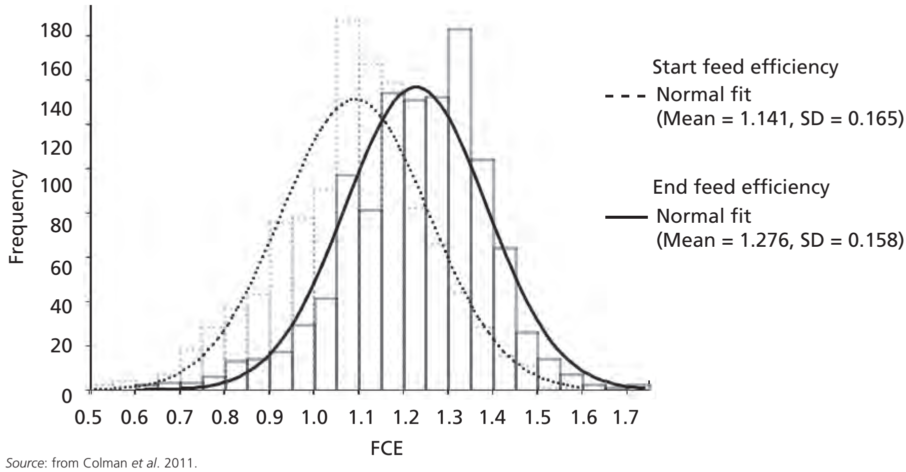
$$\text{Margin gain (€/cow/day)} = 5.24*\text{FCE gain} + 0.003 \ (r^2 = 0.770)$$

a gain of € 0.52/day per 0.1 FCE gain.

Figure 1 presents the fitted distribution of FCE for all herds in the study and reveals two interesting aspects. From the start position, a significant spread in FCE was noted, with substantial between-herd differences. Clearly some herds were performing well, with little opportunity to improve, against which many were operating at suboptimal FCE levels, with 59% of herds below 1.1 litre/kg DM. Whilst there may have been extenuating circumstances for some of these outcomes, the data suggest considerable scope for improvement exists on many farms. After 12 months of system adoption, whilst the pattern of distribution was similar, there was a pronounced shift towards higher levels, with fewer herds operating below FCE 1.1 litre/kg DM, several over 1.5 litre/kg DM, and a mean value of 1.28 litre/kg DM. This is convincing evidence that many farms have the potential to improve FCE and that the proposed system is capable of delivering such benefits to a large number of farms.

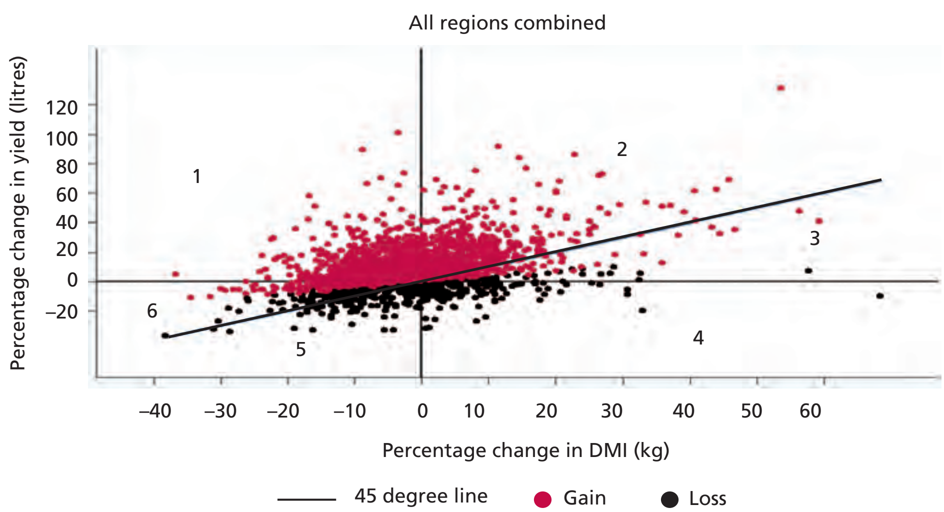
Both increased milk from the same (or possibly less) consumed feed or the same amount of milk from less feed will improve FCE, but the manner in which such gains are achieved will have an impact on overall margins according to the prevailing milk:feed price ratio. Jolly and Beever (unpublished observations) examined how changes in FCE after 12 months of system adoption had occurred in a cohort of 2098 farms in Ireland, UK, France, Australasia and Northern Europe, by expressing changes in milk yield (Y axis) against changes in feed DM intake (X axis) for each farm (Figure 2). The 45-degree line represents no change in FCE, herds above and below having improved or reduced FCEs respectively. Overall, FCE was improved in 84% of herds, as indicated in sectors 1, 2 and 6, achieved by additional milk

FIGURE 1
Fitted distribution of feed conversion efficiency (FCE) for 1086 dairy farms before (start) and 12 months following adoption (end) of a novel dairy feeding system



Source: from Colman *et al*. 2011.

FIGURE 2
Relationship between % change in feed intake and % change in ECM yield following system adoption



Source: from Colman *et al*. 2011.

from less feed (sector 1), additional milk despite some increase in feed intake (sector 2) or lower milk yields and feed intakes (sector 6). Herds in sectors 3, 4 and 5 had reduced FCEs, with changes in milk yield and feed intake in sectors 3 and 5 being in the same direction as sectors 2 and 6, respectively, but with the differential between these increases being insufficient to prevent a reduction in FCE, whilst those in sector 4 simply produced less milk but used more feed with a consequential decline in FCE. Obviously sector 1 is the most desirable outcome, whilst sector 2 carries more risk, with the additional feed use increasing farm exposure to feed price volatility. In sector 6, the reduction in milk yield and thus total income would not be desirable, despite the noted FCE gain. Overall, 90% of herds with improved FCEs showed improved daily margins (Red) based on standardized start and end milk and feed prices for each farm.

Beef cattle

Similarly, with beef cattle the focus is on improved rumen and animal health, emphasizing the importance of consistent, well balanced rations in respect to both chemical and physical nutrition. Unlike the situation with dairy cows, however, minimal field data exists to fully demonstrate the benefits of the system for beef cattle, in part due to the lack of reliable weight gain data on many farms, added to which few research studies have focused on the impact of rumen and animal health in beef cattle on overall performance and FCE.

Rations containing significant amounts of grain generally have higher nutrient densities and intakes than forage-based rations, and in theory should be utilized with a higher efficiency, leading to higher daily weight gains. There are indications, however, that feeding high levels of grain can increase the incidence of sub-acute rumen acidosis, affecting both animal performance and FCE. A field study in Australia (Hollier, unpublished observations) compared a high grain ration with one of reduced grain and increased forage, with adequate physically effective fibre. When fed to growing and finishing cattle, higher feed intakes and weight gains were noted for the high-grain-fed cattle. However, the difference in weight gain was much less than expected (1.69 vs 1.57 kg/day) and only a modest (4 kg) increase in carcass weight was noted. Most notably, FCE was similar for both rations (168.2 vs 169.7 g/kg feed DM), most probably due to impaired performance on the high grain ration.

With increased biofuel production from cereals and the ever-increasing demand for human food, the long-term prospects for feeding high grain rations to beef cattle looks bleak. Inevitably, more forages will be fed to beef cattle, but the increased use of cereals for biofuels is increasing the availability of DG and associated co-product feeds. Whilst the use of such feeds by dairy farmers is frequently limited by concerns over milk fat levels, beef cattle can be fed much higher levels to achieve high weight gains and FCEs, with Beever (unpublished observations) noting an average FCE in excess of 170 g/kg feed DM per day for grower and finisher cattle over a 150-day period. However when high levels of DG are fed, rations need to be optimized for physical nutrition if optimal rumen function is to be achieved, as indicated by Schingoethe *et al.* (2009), and highlighted by Galyean *et al.* (2012), who reported satisfactory weight gains and FCE with rations containing increased levels of DG.

HERD IMPLICATIONS

The obvious outcome of improved FCE is the production of more milk or meat per unit feed consumed. This improves margin over total feed, provided there are no significant cost implications of the new strategy, and represents a significant saving in feed, suitable for feeding to other livestock, or the diversion of land to other uses. But only accounting for the annual feed use of those animals producing milk or meat fails to recognize the total feed costs of maintaining the herd.

In dairying, dry cows and replacement heifers consume significant amounts of feed, with the numbers of these affected by overall herd efficiency. Considerable variation exists in the management skills and nutritional practices of heifer rearing between farms and affects both heifer survival rates and average age at first calving (Wathes *et al.*, 2008). Heifers failing to achieve a successful first calving, or calving after 2 years of age, add an unnecessary feed cost. Further to this, annual cow cull rate affects the number of replacement heifers required to retain herd size, and whilst a replacement rate of 20% should be possible, many herds are operating closer to 30%. It is also noted that whilst most herds target a 305-day lactation period, 60-day dry period and a 365 day calving interval, in many the calving interval will often exceed 400 days, principally due to failure of the cows to re-breed at the appropriate time. Extended dry periods and increased herd replacement all add significantly to the total amount of feed used annually by the whole herd.

The implications of sub-optimal management are presented below (Table 2) for assumed herds of 100 adult cows plus followers operating at 'below average' or 'target' levels of efficiency. The herds had assumed lactation milk yields of 6250 and 7000 litre/cow, at lactation FCEs of 1.05 and 1.21 litre/kg DM (15% gain), respectively. At any one time, the below-average herd was assumed to have 72 cows in milk compared with 80 for the target herd. After allowance for differences in annual cull rate, longer dry periods and additional heifers to be reared to retain herd size, the herds had estimated annual feed usages of 838 and 823 tonne respectively. However, on target farms, 66% of this was fed to milking stock (539 tonne), compared with only 56% for the below-average herd (469 tonne). With more cows in milk consuming more feed, the target herd produced an additional 160 tonne ECM (+32%) at an average annual herd FCE of 0.793 litre/kg DM, compared with 0.587 litre/kg DM for the below-average herd. The production of 0.79 tonne milk per tonne total feed by the target herd is a useful measure of herd technical efficiency, albeit one that is rarely used. More importantly, improved herd efficiency, principally due to improved nutrition management, resulted in an extra 0.206 tonne milk produced per tonne feed. Currently, global milk production is 700 million tonne per annum, produced under many different

TABLE 2

Impact of improved heifer rearing, herd fertility with improved dry periods and reduced herd cull rate on average annual feed use, annual energy corrected milk (ECM) production and annualized feed conversion efficiency (FCE) for a herd of 100 cows plus followers

Herd efficiency	Below average	Target
% milking cows in adult herd	72	80
Annual herd cull rate (%/average lactation no.)	28.5/3.5	22.2/4.5
Heifer feed use (tonne/year/heifer)	2.27	2.10
Total annual herd feed use (tonne)	838.2	823.1
Total ECM production (tonne)	492.0	652.5
Annual herd FCE (AFCE: litre/kg total feed DM)	0.587	0.793

conditions and levels of overall efficiency. Adoption of nutritional and management strategies to improve both lactation FCE and herd efficiency has the potential to reduce current feed use for the present global level of milk production by more than 270 million tonne, equivalent to over 20% of current usage.

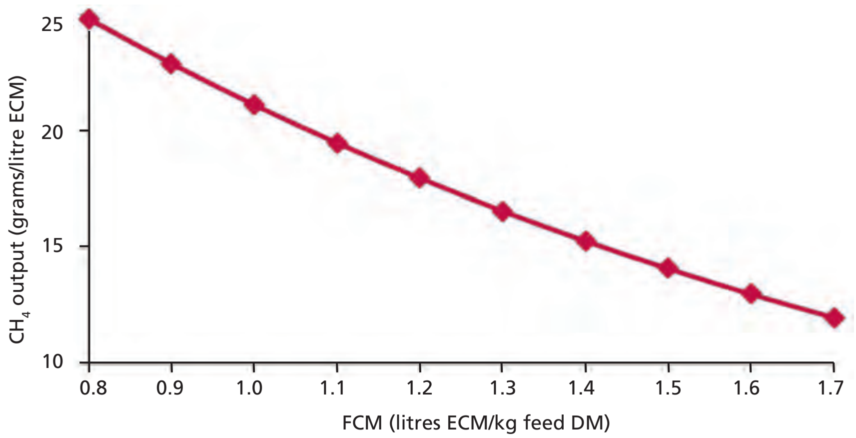
In cow-calf operations, a more accurate assessment of FCE needs to take account of the feed consumed by suckler cows, often in excess of 4 tonne DM/cow/year. Ideally, beef cows should calve within a 9 week window, equivalent to 3 oestrus cycles, and achieve 95 weaned calves per 100 cows bred. However, many cow-calf operations, after excluding those operating in harsher climates, fail to achieve such levels, with recent UK data indicating an average calving spread of 18 weeks with fewer than 90 weaned calves per 100 bred cows. After due allowance for maternal cow feed costs, herds achieving average daily weight gains of 1.25 kg (growing and finishing) at an average FCE of 160 g/kg feed DM would have an annual herd FCE of 53 kg weight gain per tonne feed DM. In contrast, herds where fewer weaned stock, lower weaning weights, lower post-weaning weight gains (1.0 kg/day) and reduced FCE (125 g/kg feed DM) are seen, would require an additional 1.5 tonne feed DM per finished animal, at an annual FCE of 49 kg/tonne DM. Such levels of efficiency challenge the current profligate use of feed resources for the production of beef and the financial security of such systems. Improving FCE through improved nutrition and management provides opportunity to improve resource use against a background of continued use of grains becoming more questionable.

ENVIRONMENTAL CONSIDERATIONS

Improving FCE inevitably results in more feed nutrients being converted into animal products, with an associated reduction in nutrients lost to the environment. The principal environmental pollutants in systems of ruminant production are nitrogen (Castillo *et al.*, 2001), phosphorus (Wu *et al.*, 2001), both being excreted in solid and liquid waste, and carbon, as methane and CO_2 (Reynolds, Compton and Mills, 2011) excreted in gaseous wastes. Colman *et al.* (2011) considered the impact of improving FCE on methane emissions, employing almost 200 estimates of methane production by lactating dairy cows (Kebreab *et al.*, 2003) and presented a negative curvilinear relationship between methane emissions and lactation FCE. Recently this analysis was extended by Reynolds and Mills (unpublished observations), confirming the earlier analysis of Colman *et al.* (2011) with a progressive decline from 24.8 to 13.0 g/litre ECM as FCE doubled from 0.8 to 1.6 litre/kg feed DM intake (Figure 3).

It follows that the annual production of 1 million litres of milk at an FCE of 1.05 litre/kg would have a methane output from milking cows alone of 20.3 tonne compared with 17.8 tonne at an FCE of 1.21 litre/kg DM, with further gains thereafter as higher FCEs are achieved. But these represent minimal estimates of methane production, taking no account of replacement stock or dry cows. Based on the performance of contrasting herds included in Table 3, annual methane output from milking cows alone was estimated at 10.0 tonne, increasing to 18.2 tonne for all stock, these contributing almost 45% of total herd emissions. In contrast, milking cows in the target herd had an estimated methane output of 11.6 tonne, along with the noted increase in total milk production, but a similar higher summated annual herd output of 17.9 tonne methane, with non-milk producing stock

FIGURE 3
Relationship between feed conversion efficiency (litre ECM per kg feed DM) and methane output expressed as grams/litre ECM



accounting for 35% of total output. For below average herds, this equated to a methane burden of 36.9 g/litre ECM, compared with 27.5 g/litre for the target herd, a reduction of over 25%. Whilst based on best estimates of methane production, opportunities to improve both herd performance and FCE as a consequence of adopting the novel feeding system suggest that many herds are capable of achieving substantial reductions in the environmental costs of dairying.

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

This paper has focused on the importance of optimizing rumen and animal health to improve the conversion of animal feeds into human food by ruminant livestock, bringing substantial gains for farmers, society and the environment. Supported by extensive field evidence, with scientific research and interpretation, the importance of physical nutrition in feeding the rumen and the animal is highlighted. Significant progress to date has been made, but more comprehensive descriptors of physical nutrition are required, which will

TABLE 3
Impact of improved heifer rearing, herd fertility with improved dry periods and reduced herd cull rate on the estimated annual output of methane and the burden of methane per litre energy corrected milk (ECM) production for a herd of 100 cows plus followers

Herd efficiency	Below average	Target
Methane production (tonne/year)		
Milking cows	9.98	11.63
Non-productive stock	8.18	6.28
Total	18.16	17.91
Methane production (g/litre ECM)	36.9	27.5

involve further research. The system can be easily implemented on most farms where dairying is reasonably well developed, and specifically where mixed rations are produced on site using home grown forages. It is recognized that smaller operations are not be able to meet the investment costs of mixed ration feeding, but many of the scientific principles described here will be equally valid for smaller operations. Further to this, the possibility of establishing centralized facilities to produce optimal rations for all livestock classes suitable for farm delivery is worthy of further consideration and is already under trial in Asia.

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A new future for ruminant production

P.C. Thomas

Artilus Consultancy and Research, Edinburgh, Scotland, UK
E-mail: phil.thomas@artilus.co.uk

ABSTRACT

The principles of market economics first propounded by Adam Smith have been widely adopted to meet the prevailing socio-political environments and trading policies of countries throughout the world. This has led to an increasingly interconnected and interdependent world, where there is a shared reliance on limited resources and a shared burden-of-consequences from their overexploitation. This is clearly illustrated in current national and international discussions of food security, sustainable development and climate change. This paper considers the future of ruminant production in that context, highlighting the factors that will influence the direction and pattern of development. It concludes that increasing global population and increasing global affluence will continue to drive the development of the ruminant production industry. However, production technologies and systems will reflect the need to respond to reduce the carbon footprint of ruminant production and to adapt to the consequences of climate-change on the ruminant industries. In these objectives the key underlying concept is efficiency of resource use, and particularly feed efficiency, since that drives up resource-performance and reduces the animals' environmental footprint, including greenhouse gas emissions. It is argued that future technology development requires: a refocusing of publicly-funded ruminant R&D; a greater use of the 'global science village' to maximize benefits of scientific capabilities; and greater synergy between public and private R&D investment, which would benefit developing countries where private R&D investment is low.

Keywords: *climate change, efficiency of feed utilization, food security, ruminant production, sustainable development*

INTRODUCTION

It is a salutary fact that, whoever you are and wherever you live in the world, your future and the future of your local community will be significantly determined by global factors beyond your control. In an increasingly interconnected and interdependent world, events and developments in one global region have an impact on another; there is a shared dependence on limited resources and a shared burden arising from the consequences of their overexploitation.

Two centuries ago things were very different. Nations, and even communities within nations, could significantly isolate themselves from what was happening elsewhere in the world. Countries considered wealth in terms of their stock of gold and silver, and whilst they were happy to export goods for sale, imports were seen as wealth eroding. This led to protectionism not only at national borders but also internally between regions: taxes on imports, levies on the movement of goods, and strictly controlled access to markets were common.

In his book *An Inquiry into the Nature and Causes of the Wealth of Nations* (1776), Adam Smith, the Scottish economist and philosopher, condemned this thinking and approach. He reasoned that a nation's wealth did not depend on its gold or silver but on its production and commerce (what we would now call the gross domestic product). He argued that if trade and commerce operated in an open and competitive market, resources and human effort would be drawn automatically towards the ends and purposes that people valued most – as if guided by an 'invisible hand'.

Over two hundred years later, Adam Smith might be impressed by the ways in which his concepts of market economics have been adopted to meet the particular needs of countries throughout the world. However, as a social reformer, he would also understand the challenges of today's global conditions, and note developments that he would not have anticipated, nor welcomed.

PERSPECTIVES OF ECONOMIC GROWTH

Philosophically, humans' essential requirements for a fruitful and rewarding life have not changed fundamentally since Adam Smith's days. The core elements remain the need for food, water and shelter; fuel for heating; health protection; motive power for tasks and travel; and the means for intellectual fulfilment. However, quantitatively, the demands on the world's resources have ballooned. Population has increased from approximately 1 billion to the current 7.2 billion, with a further increase to 9–10 billion projected by 2050. Additionally, average global prosperity has grown substantially and, whilst huge disparities of affluence exist, the human race in aggregate is consuming hugely increased levels of finite resources.

That the demands of a growing population were beginning to challenge the global environment and the limits of natural resources was first highlighted by the World Commission on Environment and Development (The Brundtland Commission). Its report *Our Common Future* (UN, 1987) firmly established the terminology of 'sustainability', notably through defining sustainable development as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'.

This concept quickly began to influence public policy thinking, although it was not until it was expressed in a three-pillar social, economic and environmental context (see Adams, 2006) that it gained academic and policy utility, and laid the foundations for the development of a 'green economy' industry. Market forces have in fact played a massive role in driving 'sustainable practices' forward, although not until 'sustainability' could be expressed in recognizable market terms of goods, services and corporate responsibilities. In a recent evolution, sustainability concepts have been expressed in 'ecosystems services' frameworks (Box 1). These are finding a role in supporting national and international policy thinking about human use of natural resources. However, as yet, they lack effective links with the real economy or with markets, so limiting their usefulness (Defra, 2011).

The most important current global issues relate to understanding climate change and how we might address it. The need for long-term climate change mitigation is now widely acknowledged and accepted, but it is also apparent that mitigation alone will not be

BOX 1

The conceptual framework of ecosystems services
(UK National Ecosystem Assessment, 2011)

The Concept

'Ecosystem services' are the benefits provided by ecosystems that contribute to making life both possible and worthwhile. The terms 'services' is used to encompass the tangible and intangible benefits that humans obtain from ecosystems, which can sometimes be separated into 'goods' and 'services'. The 'ecosystems services' framework allows economic values to be attributed to ecosystem provisions.

The Approach

Typically ecosystem services are subdivided into different categories:

- Provisioning services: the products obtained from ecosystems. For example: food; fibre; fresh water; genetic resources.
- Regulating services: the benefits obtained from the regulation of ecosystems processes. For example: climate regulation; hazard regulation; pollination; disease and pest regulation; regulation of water, air and soil quality.
- Supporting services: ecosystem services that are necessary for the production of all other ecosystems services. For example: soil formation; nutrient recycling; water recycling; primary food production.
- Cultural services: the non-material benefits people obtain from ecosystems. For example: spiritual or religious enrichment; cultural heritage; recreation and tourism; aesthetic experience.

enough. Additionally, there must be a focus on adaptation to deal with the impacts of the climate change that are already becoming evident. The projections of population growth over the next 40 years and the continuing growth in global affluence must be regarded as 'givens'; the focus must therefore be on managing the consequences, whilst addressing both mitigation and adaptation objectives. In an early attempt to express global human impact mathematically, Ehrlich and Holden (1974) used the equation $I = P \times A \times T$, where I is the impact, P is the population, A is consumption (expressed as Affluence) and T is the impact per unit of resource use (expressed as Technology, because the impact depends on the technology used). In contemporary terms, we are now in a period where the trajectory of P and A are largely predetermined, so there is a massive need to focus on innovations in T, to counteract the impacts that will otherwise occur.

FOOD SECURITY AND FOOD SYSTEMS

Public perceptions of food security often focus on crises in the hunger hotspots of the world but in fact the food security concept is much more widely embracing. The World Food Summit (see FAO, 2006a) defined food security as the condition that prevails when '*all people, at all times, have physical, social and economic access to sufficient, safe and* *nutritious food to meet their dietary needs and food preferences for an active life*'. Food security issues therefore arise both where economic hardship is widespread and where average affluence is high, but there are wide disparities of income distribution. In either case, the economically disadvantaged are always most at risk and first to suffer, and this is a growing concern as global food costs continue to rise (World Bank, 2012a).

Food security is considered to have four main dimensions (FAO, 2006a) which can be briefly stated as:

- *Food availability*: The availability of sufficient quantities of appropriate quality food through domestic production or imports.
- *Food access*: Access by individuals to adequate resources for acquiring appropriate foods for a nutritious diet.
- *Utilization:* Utilization of food through adequate diet, clean water, sanitation and health care to reach a state of nutritional well-being, where all physiological needs are met.
- *Stability*: To be food secure, a population, household or individual must have access to adequate food at all times. They should not be at risk of losing access to food as a consequence of sudden perturbations in economic, climatic or other events.

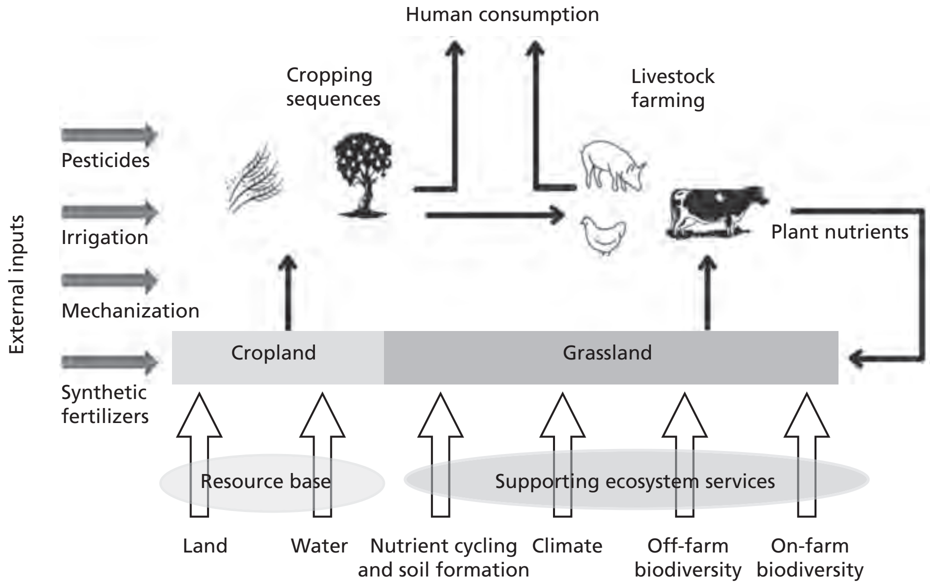
It is fundamental to these four dimensions that the global food system must provide sufficiency in terms of volume and variety of economically affordable food, otherwise food security will be unachievable. The global food systems are complex (see below) but they rely on agriculture, i.e. the production of crops and animals from the land, and aquaculture and fisheries, i.e. the production systems through which fish and other seafood are derived from fish farming and wild fish stocks. In quantitative terms, agriculture is hugely dominant in food supply. It provides some 90% of human calorie intake, as against 10% from aquaculture and fisheries. At the same time, globally, aquaculture and fisheries account for about 16% of human protein supply, and in some regions and communities it is the main animal protein in the diet.

CLIMATE CHANGE AND ECOSYSTEMS

That the food system could be influenced by long-term climatic and ecosystem changes has long been appreciated and agricultural production methods have been progressively adjusted as a consequence. However, in 2008 the UN's Intergovernmental Panel on Climate Change (IPCC) began highlighting that the speed and potential impact of global climate change had been underestimated, and tangible concerns about the near-term impacts of climate change on food security began to emerge. In Europe these were dramatically highlighted by the UK Government's Chief Scientist John Beddington in a paper entitled: *Food, Energy, Water and the Climate: A Perfect Storm of Global Events?* (Beddington, 2009). What had, until then, been academic discussions amongst scientists began to become clear to the policy-makers and also to the general public.

A number of substantive reviews of the climate change and ecosystem impacts on the food system have followed but for the present purpose reference to two will suffice. The first is the UK foresight report on the *Future of Food and Farming* (GOS, 2011), the second is *Avoiding Future Famines* (UNEP, 2012). These two reports, although significantly different in their approach, have many findings and conclusions in common. However, they also highlight some subtle differences, reflecting the perspectives from which they were written.

FIGURE 1
Principal resource flows and ecosystem services supporting agricultural systems



Source: adapted from UNEP, 2012.

Both reports are clear that there is an urgent global challenge to produce more food sustainably, and that this will require spreading best practice and new scientific innovations. Both reports seek: a reduction in food waste at all levels; a reduction in the most resource-intensive methods of food production; and improved policy governance for the food system. Both reports envisage food system policies working hand in hand with climate change and ecosystem policies, so that they become two sides of the same coin, complementary and supportive rather than in conflict. However, the reports tend to diverge in their approach to food consumption: both recognize that as economic affluence in developing countries increases there tends to be shift towards a 'Western diet', characterized by a higher consumption of meat, dairy products and refined processed foods. The UNEP report advocates seeking to moderate this through using 'sustainable diet' and 'sustainable consumption' policies, whereas the GOS report is more *laissez faire*, whilst recognizing broad 'healthy diet' objectives. Finally, the GOS report favours globalization of the market as a way of addressing food security, whereas the UNEP report puts much more emphasis on the roles of small-scale farmers and local food production. It builds its approach around strengthening the ecological foundation of food security using an ecosystems services approach (Figure 1).

FOOD SYSTEMS STRUCTURES AND ECONOMIC DYNAMICS

Documents like the GOS and UNEP reports are extremely helpful in providing a background for policy-makers, but they have a number of limitations. In particular, it is difficult for them to capture the changing dynamics of the global food market, to reflect the underlying geo-economic and socio-economic shifts that influence patterns and levels of global investment, or to allow for the differences in the structure of food systems in different regions of the world. Drilling down to evaluate the implications of climate change or ecosystem changes on the operation of the food systems in different global regions therefore presents a significant challenge, in which a number of separate factors need to be considered.

Firstly, climate change impacts will differ substantially between different regions, with increased temperatures and water shortages tending to have their largest adverse impacts on agricultural productivity in areas around the equator (Gornall *et al.*, 2010). However, even in those regions there may be scope to adapt food systems to reduce impacts (Rosegrant *et al.*, 2008). In other regions, climate change will actually have compensating positive effects on agricultural productivity. Thus, we are facing global impacts that will have negative effects on crop and animal production in some regions, but counterbalancing increases in production in others. Global temperature is currently estimated to be +0.8 °C above pre-industrial levels, but, if climate mitigation targets are not reached, temperatures could potentially increase above +4 °C by 2060 (World Bank, 2012b). At those extremes, the impacts on water availability, agriculture, ecosystems and human health could lead to large-scale displacement of population and consequences for human security, global economics and trade going beyond anything that has been considered so far. Even with lesser temperature rises, temperature impacts and exacerbated water scarcity in Eastern Africa, Near East and South Asia could be substantial; dry conditions could also be experienced in parts of southern Europe, Africa (except north-east Africa), North America, South America and southern Australia (World Bank, 2012b).

Secondly, there are no convincing indications that policies based on 'sustainable diet' or 'sustainable consumption' concepts will have significant impact on patterns of change in human food consumption. Whilst many countries have seen enormous changes in people's dietary habits and choices of foods over the past three decades, policy-driven attempts to create significant changes in diet generally have had only a small impact. Therefore, for realistic planning purposes, the global trend for increased meat, fish and dairy consumption should be accepted as a given factor, because it will be driven by consumer demand.

Thirdly, at the economic and structural levels, food systems will continue to evolve, reflecting both their current levels of development and the underlying (and difficult to constrain) socio-economic forces that reflect the evolution of consumer markets. This will not necessarily mean that there will be exactly the same food systems in all regions of the world—because of cultural diversify that may never be the case—but it does mean that the underlying forces that shape and re-shape the food systems will have a substantial degree of trans-regional commonality.

In situations representative of developed countries. primary production has already been incorporated in food systems operating from 'farm to fork'. This has brought huge benefits to consumers in providing assured supplies of a huge range of foodstuffs: safe to eat, of high sanitary standards, quality-assured and offered at affordable prices. At the same time it has also been associated with a consolidation of primary production businesses. Farms have grown larger, capital investment in equipment has escalated, numbers employed in primary production and unit labour costs have plummeted, and farm management has become increasingly market focused, technologically advanced and professional.

These farm-to-fork food systems have achieved a great deal, although they are characterized by significant food losses and waste as a result of out-of-specification discarding in processing, retailing and, notably, in the homes of consumers (Gustavsson, Cederberg and Sonesson, 2011). The systems are responsive to consumer demands and market forces, but in some countries there is a growing concern that the economic benefits of increased efficiencies in primary production are simply benefiting processors, retailers and end consumers, rather than rewarding the primary producers themselves. This is leading to new kind of 'fair trade' debate and to strategic alliances between farmers, processors and retailers to ensure a more equitable distribution of economic rewards. A new market force—the tightening world food supply—is, in effect, leading to a re-balancing of power between those involved in primary production and those further along the food chain.

By comparison, the food systems representative of developing countries generally reflect a substantial presence of 'traditional' small-scale farmers who grow food for their own families and also supply local markets with staple commodities, root crops, vegetables and animal products. The farms are generally small, limited in their use of technology, chemicals and equipment, and with high labour input, although low labour cost. They are widely, and properly, regarded as important in achieving local food security, particularly in countries where food supply is limited and transport infrastructure is poor.

Because of their low inputs, these food systems are often regarded as being in tune with ecological objectives. Nevertheless they are also vulnerable because of their limited capability to respond to increased population pressure, increased demands on food supply, adverse climate changes or economic circumstances. They are also impacted by forces which create a 'drift from the land', including industrialization, urbanization and factors that provide better 'life chances' for people in non-farming occupations. Generally the systems are rudimentary in terms of formal consumer assurance and they suffer significant on-farm and post-harvest food losses, although consumer wastage is much lower than that found in the European systems (Gustavsson, Cederberg and Sonesson, 2011). For these food systems, change is challenging because farm size limits the scope for mechanization. Economic, technical and cultural factors also act as constraints on farm expansion and food system improvements. Such constraints may be overcome by inward investments in farming, but the benefits of this are not without controversy (Grain, 2012a, b). Nonetheless, increasing demands by more affluent consumers, price increases as a result of global food shortages and the burgeoning growth of supermarket retailing (Reardon, Timmer and Minten, 2012), will all act to create farming changes in developing countries. The effects of Adam Smith's 'invisible hand' will come into play. The public policy challenge is to ensure that corporate investments deliver the desired public benefit as well as investor profit, and that indigenous primary producers are not excluded from the economic benefits of development.

Public policy intervention to offset or modify the effects of market forces can be made in a variety of ways, including trade restrictions, intervention buying, taxation allowances, agrarian policies and direct public investment in farming. However, such interventions are fraught with risks of unintended consequences, particularly if they result in national market prices moving out of line with their international equivalents, or if they affect land ownership and land use. Examples of this can be found in many countries where intervention buying has been used as a means of raising agricultural commodity prices, or where there have been strategic public-sector schemes to promote the use of agricultural crops for bio-fuel production or the use of farmland for forestry, as a means of climate change mitigation.

MARKET DEMAND AND ANIMAL PRODUCTION

In simple terms, future consumer demand for increased fish, meat and dairy products can be expected to fuel growth of production in these sectors. Fish is a special case since although there is no likely growth in wild catch fisheries, the capacity for expansion of aquaculture, marine aquaculture in particular, is enormous. As a result, aquaculture will continue to be a rapidly growing food sector for the foreseeable future (FAO, 2010). Projected expansion in poultry, pig and ruminant sectors is more complex and brings both global and regional considerations into play.

Animal production and feed use

Policy-makers and campaign groups have pointed out that there is a potential competition between the use of arable crops, such as cereals and oilseeds, in the human food chain and in animal production. Moreover, the recent increased use of arable crops in biofuel production has re-ignited this discussion in a slightly different context. The papers by Margaret Gill, Harinder Makkar and David McNeill earlier in this symposium considered aspects of these topics and highlighted the substantial synergies between the use of arable products in the human food chain and use of their by-products as animal feeds. Additionally, Wilkinson (2011) used a classification of 'human-edible' and 'non-edible' feeds as a way of exploring the relative efficiencies of different types of animal production, and has again highlighted the substantial synergies in use that can be identified. Setting aside the political and policy dilemmas that might be posed by adopting cereal-based biofuel production in a cereals-restricted world, it is apparent that there is considerable scope to optimize the use of raw materials for both human food and animal feed purposes, and that optimization will be a priority area for the future.

In practice, of course, the balance of use of arable products for human food production, for animal feeding or for biofuel will be determined by market forces, taking account of national or international market-intervention policies, where they apply. When prices of arable products increase beyond the point where their use in animal feeding can be economically justified alternative feed sources will automatically come into consideration, and the balance of animal production will alter between species, reflecting the availability of feed resources. Thus, it is consumers' relative readiness to pay the prevailing market prices for crop-based foods, animal products and biofuels that will ultimately determine the global balance of raw material use.

Environmental impact

Since the publication of *Livestock's Long Shadow* (FAO, 2006b) animal production generally, and methane-producing ruminant production in particular, has been under policy scrutiny. The litany of problems that the report linked with the animal production sector—land degradation, atmospheric and climate impact, use of water resources, water pollution, deforestation and threats to biodiversity—provided a jolt to policy-makers and industry. Since its publication the document has been criticised for wrong assumptions, incorrect calculations and for overly simplistic generalizations from specific examples. Because of this criticism and its more controversial claims, some key messages in the report have tended to be 'lost'. Statements relating to the suggested scale of the environmental impact of animal production have largely been rejected, but unfortunately statements indicating that the impacts could be substantially reduced at modest cost were also disregarded. Some campaigners have regarded the report as an argument for reducing global levels of animal production, but that was never advocated. The case set out, even if the figures and analysis were open to debate, was that the animal production industries 'could do better', and few people in industry would reject the idea that there is always scope to improve.

Carbon footprint and life-cycle analysis

During the past five years, work on carbon footprint assessments and product life-cycle analysis (LCA) has blossomed at the R&D level, in national inventory calculations, in commercial food operations and on Web sites designed to assist consumers in making 'low-carbon' food choices. The many evaluations and reports published give useful insights into the greenhouse gas and carbon footprints of different production processes and food system operations; relevant examples for dairy and beef production have been published by Capper, Cady and Bauman (2009) and Capper (2011). Because of variations in methodology it is often difficult to make precise and accurate comparisons between assessments of different animal production systems, or similar systems in different geographical areas, but in sectors such as dairying, standardized methodologies are now being promoted (IDF, 2010).

Comparisons of animal protein sources indicate that, in ascending order, C-footprints increase from farmed shellfish through to cattle and sheep (Table 1). The high values for beef and lamb reflect the ruminants' lower intensity of growth, lower efficiency of feed utilization and distinctive production of methane from rumen fermentation. However, these figures should be interpreted with caution since they are estimates based on animal-production isolated from the production environment.

TABLE 1
Some estimates of emissions as CO_2-equivalents associated with the production of farmed foods for human consumption

Food	Emissions expressed as CO_2 equivalents (kg/kg product)
Mussels	0.25
Milk	1.0
Oysters	1.3
Salmon	3.3
Chicken	3.5
Eggs	3.8
Pork	4.7
Beef	14.7
Lamb	15.8

Note: Results taken from: Torrissen *et al.* (2011); Fry (2012); Waghorn and Hegarty (2011). Methodology is not identical for all estimates, but that does not invalidate the comparisons. Values are representative of the production systems assessed; other production systems may differ slightly.

In almost all countries of the world ruminant production depends substantially on grassland or pasture-based feeding systems. In the long term, soil is the most important terrestrial carbon store and grassland is a net carbon sink. Indeed, the rate of sequestration of carbon into soil per unit of land area has been estimated as potentially three to four times as great in grasslands as in forests (EC, 2009; Ciais *et al*., 2012). Thus, until there is a much better understanding of the relationships between grassland management for ruminant feeding and carbon sequestration in the pasture soils, it is difficult to be certain about the C-footprint of the 'complete' ruminant production system. Recent studies on a sample of 21 beef and sheep farms in Scotland suggest carbon sequestration by grassland may be sufficient to offset substantially or completely the carbon footprint of the livestock, meaning that many beef and lamb production systems may be either carbon neutral or carbon sinks (QMS, 2012).

In response to the Kyoto Protocol, the UK has set ambitious targets for reducing GHG emissions against the 1990 baseline. This has served to focus minds in the R&D community and in all sectors of industry, including agri-food production. The information that has resulted from initial field studies has helped to identified early-win opportunities for GHG reductions, since it has identified substantial variations in emissions and feed efficiency between farms operating at similar levels of animal production (for example, see DairyCo, 2012).

A NEW FUTURE FOR RUMINANT PRODUCTION

In defining a 'new future' for animal production some soothsayers start from a position of regarding animals and people as being in competition for water, land and available food resources. However, that stance cannot be sustained except in extreme situations. In arid, drought-stricken areas competition for water is a concern that will intensify if rainfall is reduced by climate change. But in large parts of the globe water supply is not limiting, and rainfall will increase as a result of climate change. Livestock, especially ruminants, can eat a much wider range of foodstuffs than humans; they can sustain themselves on land that is poorly suited for human food production; and they thrive on by-products and waste food from the human food chain. Thus, as a starting point for 'new future' thinking, animals and humans should be regarded as complementary. An interesting approach to the analysis of the complementary features of animals and humans in food use has been put forward by Wilkinson (2011), and has already been raised earlier in this symposium.

Drivers of change

Nonetheless, there is no doubt that the ruminant production will change significantly over the coming decades, and this will be influenced by the degree to which global warming can be mitigated (World Bank, 2012b). On the basis of what is already apparent changes will be driven by three underlying forces.

- Population increases and growing affluence will drive demand for more, high quality ruminant products, at affordable prices.
- Public policy *and* market forces will drive industry to reduce production impacts to meet climate-change and ecosystem targets.
- Climate and ecosystem changes arising from general anthropogenic impacts on the global environment will mean industry will have to adopt improved methods of

ruminant production to deal with new production challenges, whilst also meeting the two other objectives.

These three drivers might seem disparate at first sight. However, they are in fact closely linked with the central concept of the 'new future' vision, namely efficiency of resource use and particularly of feed use.

In the 'new future' the positive contributions offered by ruminant animal production must be re-asserted and re-assessed as part of a coherent whole-system approach, reflecting a 'new model' of agriculture. Around the world, ruminant producers must be armed with regionally-relevant fit-for-purpose technologies and management tools to allow them fully to use and manage the natural resources at their disposal, to minimize waste and climate impact, and to achieve economic and social prosperity. Efficiency of resource use, and particularly feed efficiency, must be the major objective, since that drives up resource performance and reduces the animals' environmental footprint, including GHG emissions. This emphasis on efficiency of feed utilization will be recognized as a theme in the papers by David McNeill; Alan Bell and Paul Greenwood; and David Beever and James Drackley given earlier in this symposium, and it provides the overarching 'take-home message' from the meeting.

In practice, the efficiency of feed utilization can be described using a variety of different metrics depending on the purpose of the application. These metrics may vary from simple descriptors, e.g. live weight gain (LWG) per kg dry matter intake (DMI), or fat corrected milk (FCM) yield per kg DMI intake (Colman *et al*., 2011), to more complex measures such as residual feed intake (RFI) (Archer, Richardson and Herd, 1999), methane yield/kg DMI or measures relating to emissions intensity (see Waghorn and Hegarty, 2011). They also may embrace genetic characteristics for body composition (Gomes *et al*., 2012) or milking characteristics (Veerkamp *et al.*, 1995). However, many of the simple descriptors can readily be used on farm, and they fit well into systems of farm management in which key parameters are benchmarked and monitored as a basis for determining progress towards efficiency goals. This performance benchmarking approach will in most instances provide a key aid to achieving continuous improvement in efficiency; it is both a knowledge exchange tool and a hands-on farm management aid.

With regard to C-footprint, virtually everything that will improve livestock production efficiency will reduce the C-footprint of the production process (see earlier papers). There are a number of ways of reducing methane production through forage selection and chemical and physical formulation of the diet (Martin, Morgavi and Doreau, 2010; Kebreab *et al*., 2012). Additionally, there are substantial opportunities to reduce 'feed waste' through better genetic selection of animals, optimizing production systems and reducing the 'impact cost' of too many unproductive stock, resulting from slippage in calving patterns or over-generous reserves of replacement stock (see Garnsworthy, 2004). Benchmark standards for electricity, fuel and water use on farms are already available in several countries, and they can readily be adopted at low investment cost, with a rapid pay-back through reduced operating costs. There are also guidance schemes and benchmarking schemes for biodiversity impact (for example, see www.leafuk.org). As yet, these have not 'caught up' with the 'ecosystem services' approach, although that is a priority. From a European perspective, there are many situations where cattle and sheep contribute positively to biodiversity management, both in upland and in lowland grazing situations (Rook, 2006; Pakeman, 2011) and that should be fully recognized.

What emerges from all this is the scenario of 'balanced scorecard' systems of ruminant production, where sustainable intensification through climate-smart approaches allows increased production and lower climate and ecosystems impact to go hand in hand. Thus food security objectives and climate-change and environmental goals will all be achieved simultaneously.

R&D and knowledge exchange

From the late 1940s to the early 1980s, agricultural development in most high-income countries was driven by technological innovation focused on the need to produce greater amounts of food at affordable prices. All forms of agricultural production were transformed, but none more so than ruminant production. The growth in productivity was underpinned by public investments in R&D and extension work, which provided the knowledge exchange between the R&D base and industry (Table 2). In the early 1980s, things began to change: global food supplies were assumed to be assured and agricultural R&D funding in many high-income countries was reduced (Table 3). Additionally, research was refocused on underpinning science, and the responsibility for technology development was transferred to industry: in several countries extension services became charged or were privatized. By the 1990s, developing countries, where R&D effort had continued to grow, were responsible for more than half the global public-sector R&D investment, although total investment remained greater in the high-income countries because of the private sector investment (Tables 2 and 3).

Ruminant production is now facing a period of accelerated change, with new challenges and goals. Policy-makers are beginning to recognize the need for a more integrated scientific, environmental and socio-economic approach to ruminant production; even within the constraints of the present global economic downturn there are indications of renewed public-sector interest in short-term impact, practitioner-relevant R&D. However, during the

TABLE 2
Estimated global public and private agricultural R&D investments for developing and high-income countries

Group or Country	Investment (million 2000 international dollars)			Share of global (percent)		
	1981	1991	2000	1981	1991	2000
Public funding						
Developing countries, public	6 904	9 459	12 819	45.4	47.3	55.7
High-income countries, public	8 293	10 534	10 191	54.6	52.7	44.3
Total public	15 197	19 992	23 010	100	100	100
Private funding						
Developing countries, private	NA	NA	862			
High-income countries, private	NA	NA	12 086			

Notes: An international dollar is a hypothetical unit of currency that has the same purchasing power parity that the US dollar has in the United States of America at any given point in time. NA = data not available.
Source: Pardy *et al*., 2006.

TABLE 3
Private investment share of total investment for selected OECD countries and average growth rates from 1981 to 1991 and 1991 to 2000

OECD Country	Private share of total funding (percent)			Average annual growth rate (percent per year)	
	1981	1991	2000	1981–1991	1991–2000
Australia	5.9	22.0	24.8	15.3	4.0
Canada	17.3	21.5	34.0	2.5	5.5
USA	49.3	51.0	51.5	3.6	2.4
Japan	36.6	48.4	58.6	7.5	1.8
France	44.1	52.0	74.7	8.2	2.7
Germany	56.2	43.6	53.6	2.4	0.7
Netherlands	44.8	56.1	57.7	9.3	1.1
United Kingdom	55.9	66.8	71.5	6.0	1.7

Source: Pardy *et al*., 2006.

'lean years', applied scientific disciplines in the public sector have been eroded and they will take time to become fully restored. Given the circumstances, there are national and international arguments for adopting a strategic R&D approach, which might logically focus on three strands of action:

- Refocus some present publicly-funded research effort into more applied work: many current scientists are well trained and innovative, and would relish the challenge of making their work more closely applicable to urgent problems.
- Make fuller use of the 'global science village' to maximize use of available scientific capabilities.
- Increase synergy between public-sector and private-sector R&D investment, including new partnership approaches, which would benefit developing countries where regional private-sector R&D investment is low.

CONCLUSIONS

The challenge is to adapt, deploy and integrate modern knowledge to address the new circumstances and the approaching food security and climate change challenges. Scientifically, there are key developments needed in: crop and animal genetics; improved protection of animal health and treatment of disease; smart engineering and computerized technologies; and enhanced animal nutrition and production-management. However, the crucial underlying focus must be efficiency of resource use, and particularly feed efficiency, since that drives up resource performance and reduces the animals' environmental footprint, including GHG emissions. The goals of delivering economically profitable, socially supportive and ecologically resilient systems of ruminant production to allow communities to thrive under the prevailing conditions in their region of the world will need global cooperation, although such systems are within the reach of human endeavour.

Significantly, successful pursuit of these goals will need to harness the strengths, skills and investment capabilities of both the public and private sectors. Intellectually engaging conceptual frameworks of how man and environment can seek to live in long-term harmony are important in shaping how we think about our future and in assisting the development of underlying public policies. However, the short timescale of the present food security and climate change challenges is such that urgent and concerted action is a priority. Most of what will need to be done to address the challenges of the future will be delivered by *livestock practitioners* working in agriculture, and by the market-economic influences of Adam Smith's 'invisible hand', but both the practitioners and the markets will require the knowledge and tools to do the job.

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Contributing authors

Alex Bach obtained a veterinary degree from the University Autonomous of Barcelona. Then moved to the United States of America to pursue a Master and a PhD in Dairy Science at the University of Minnesota. After graduating, he returned to Spain to work in the research department of a multinational feed company, where he built nutritional models for ruminants across Europe. After a few years in the industry, Dr Bach returned to academia as ICREA Research Professor and Director of the Department of Ruminant Production of IRTA (Institut de Recerca i Tecnologia Agroalimentàries) devoted to study of ruminant production systems (nutrition, management and development). He conducts research on ruminant nutrition and metabolism, and dairy cow and replacement management.

Dr Bach has received several awards in recognition of his research activity, has spoken at more than 80 international congresses, is author or co-author of more than 75 peer-reviewed publications, more than 80 extension articles and 10 books or book chapters. He is section editor and member of the editorial boards of several scientific journals, member of several scientific committees, and serves as a scientific expert for the European Food Safety Authority (EFSA).

David Beever is Nutrition Director and Scientific Advisor to Richard Keenan & Co since 2004. He grew up on a small livestock farm in Yorkshire, before receiving his PhD from The University of Newcastle upon Tyne in 1969. Then spent 22 years at the Grassland Research Institute, Hurley, before becoming Professor of Animal Production at the University of Reading and Director of the Centre for Dairy Research (CEDAR) in 1992. He holds Emeritus Professorship at the University.

Alan Bell was educated at the University of New England (B.Rur.Sc (Hons), 1969) and the University of Glasgow (PhD, 1976) and has held research and teaching positions in Australia, Scotland and the United States of America. He was Chairman of the Department of Animal Science at Cornell University from 1997 to 2007, with responsibilities for teaching, research and extension in livestock biology and management. From 2007 until his retirement in 2012 he was Chief of CSIRO Livestock Industries, Australia, with responsibility for research operations in Queensland, NSW, Victoria and Western Australia. Alan is internationally known for his research on the nutritional physiology of pregnancy, lactation and growth in ruminants. He has published more than 150 peer-reviewed original papers and reviews and has edited two books.

Jim Drackley is Professor of Animal Sciences and Nutritional Sciences at the University of Illinois at Urbana-Champaign, United States of America. Dr Drackley grew up on a small dairy farm in southwestern Minnesota, and received his BS in Dairy Production and his MS in Dairy Science from South Dakota State University. He received his PhD in Nutritional

Physiology from Iowa State University in 1989, and joined the faculty of the University of Illinois in 1989.

Maggie Gill has a degree in agricultural science and a PhD in sheep nutrition. She is currently a professor in Integrated Land Use at the University of Aberdeen and a Senior Research Fellow in the UK Government's Department for International Development (both part-time), where she works on agriculture and food security, with an emphasis on livestock. She is also a member of the CGIAR Independent Science and Partnership Council and has worked in research and research management in both developed and developing countries for over 30 years.

Paul Greenwood has a PhD in Animal Science from Cornell University, having completed Bachelor and Masters Degrees in Agricultural Science at The University of Sydney. He is a Principal Research Scientist in NSW Department of Primary Industries Livestock Systems branch, and an Adjunct Professor in the School of Environment and Rural Science at the University of New England. He also has an appointment with CSIRO Animal, Food and Health Sciences as Project Leader for a new programme on development and application of real-time sensors for enhanced efficiency and productivity at pasture, including use in automated phenotyping of ruminant livestock in their commercial grazing environments.
Much of Dr Greenwood's research has focused on long-term consequences of foetal and neonatal growth and development in ruminants, and on various other factors affecting productivity, efficiency, body and carcass composition, meat quality and cellular development of muscle. He has published nearly 400 scientific and extension articles, including 100 refereed scientific journal and conference papers or book chapters.

Harinder P.S. Makkar obtained his MSc degree from the National Dairy Research Institute, India, PhD from University of Nottingham, UK, and Dr Habilitation from University of Hohenheim, Germany. Before joining FAO in 2010, he was Mercator Professor and International Project Coordinator of a Sino-German Project on 'Fuel and Feed for Tomorrow' at University of Hohenheim, Stuttgart, Germany. He worked for the International Atomic Energy Agency, Vienna, for 7 years and the Indian Veterinary Research Institute for 10 years. He has published over 250 research papers and 10 books, in the areas of bio-active compounds and their interactions with livestock, soil, plant and environment; biotechnologies in animal agriculture; use of unconventional feed resources as livestock feed; strategies for enhancing nutrient use efficiency in animal food chains; and generation of value-added products from co-products of the biofuel industry. He has acted as a consultant for a number of international organizations. He has been honored with Honorary Professorships by Universities in China and Mongolia. He has been a fellow of the Commonwealth Association, UK; Humboldt Foundation, Germany; and Japanese Society for the Promotion of Science, Japan.

David McNeill graduated from the University of New England in 1985, then completed a PhD at the University of Western Australia, before a postdoctoral year at Cornell University. He began an academic career in 1996 at the University of Queensland and University of

Sydney, then became a ruminant production and nutrition systems consultant for several years. He returned to academia in 2010, as a Senior Lecturer in Ruminant Health and Production, School of Veterinary Science, University of Queensland, Gatton. Current research includes improvement of forage cell wall digestibility, and macro-mineral nutrition of ruminants for improved bone and metabolic health.

Phil Thomas held several university and research institute posts before serving as inaugural Chief Executive of the Scottish Agricultural College in the 1990s. He now works as an independent consultant and researcher, as well as holding a number of public and industry appointments. His interests are in food supply and socio-environmental economics, and particularly in livestock agriculture and aquaculture. He is a Fellow of the Royal Society of Edinburgh, Society of Biology, and Royal Agricultural Societies.

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