Feature Article

How can nutrition models increase the production efficiency of sheep and goat operations?

Antonello Cannas,[†] Luis O. Tedeschi,[‡] Alberto S. Atzori,[†] and Mondina F. Lunesu[†]

[†]Department of Agricultural Sciences, University of Sassari, 07100, Sassari, Italy

[‡]Department of Animal Science, Texas A&M University, College Station, TX 77843-2471

Implications

- Improvement of nutrition efficiency in sheep and goats is more challenging than for other species. Because of their nutritional and environmental adaptability, sheep and goats are reared in very diverse farming (from extensive to highly intensive) and feeding (from grazing and browsing to total mixed diets) systems, in wide-ranging geographical areas and by using different breeds, populations, and crosses.
- In the last decades, nutrition models for sheep and goats have greatly evolved, from very simplistic and empirical approaches to more comprehensive and dynamic models, and are able to account for many more variables than in the past.
- Further improvements in the nutritional efficiency of sheep and goats can be obtained with the integration of mechanistic nutrition models and the data derived from sensor technology, especially those that allow monitoring of the movement and environmental effects on grazing and browsing sheep and goats.
- Large data sets made available by sensory technology can be interpreted with artificial intelligence tools and machine learning techniques. However, they were designed to learn from data and provide forecasting, but not as a tool to help us understand the underlying mechanisms.

Keywords: efficiency, goats, nutrition models, sheep

Introduction

Sheep and goat production is an important economic resource in many countries around the world. The industry produces wool (2 million tons/yr), meat (14 million tons/yr, 21% of cattle meat production), and milk (28 million tons/yr, 4.4% of cow milk production). The total world number of small ruminants is growing quickly. As shown in Figure 1, the world population of goats (1.05 billion in 2017) increased by 49% in the last 20 yr, whereas that of sheep (1.20 billion in 2017) and cattle (1.49 billion in 2017) increased more slowly (+15% and +14%, for sheep and cattle, respectively) (FAOSTAT, 2019. http://www.fao.org/faostat/en/#home). Sheep and goats are raised in a wide range of farming (from extensive to highly intensive) and feeding (from grazing diets to total mixed rations) systems, geographical areas, and by using diverse breeds, populations, and crosses, due to their high nutritional and environmental adaptability.

For this reason, the production efficiency of sheep and goats is much more variable and difficult to predict and pursue than for cattle. Although wool production is usually based on extensive systems and does not require large daily amounts of nutrients per animal, meat production and, to a greater extent, milk production require more nutrients per production unit (fattening lamb and milking ewe).

Adequate nutrition requires proper feeding techniques and ration balancing. These, in turn, require estimation of animal nutrient requirements, of feed intake, and of the nutritive value of feed, which accounts for the specific nutritional features of small ruminants and the many management and environmental factors that affect their performances and efficiency.

Sheep and Goats Are Not Just Small Cattle

Recommendations for feeding sheep and goats are often derived from work on cattle, whose nutrition and feeding management have been studied more extensively. Even though sheep, goats, and cattle are all ruminants and have many similarities, they have different feeding strategies and are also different in some physiological functions (e.g., wool growth for sheep). Some of the most important differences between small ruminants (sheep and goats) and cattle (or buffaloes) are related to their body size, where small ruminants are 10 to 12 times smaller than cattle.

The wet fermentation contents of the reticulorumen increase in direct proportion to body weight (BW). However,

---

doi: 10.1093/af/vfz005

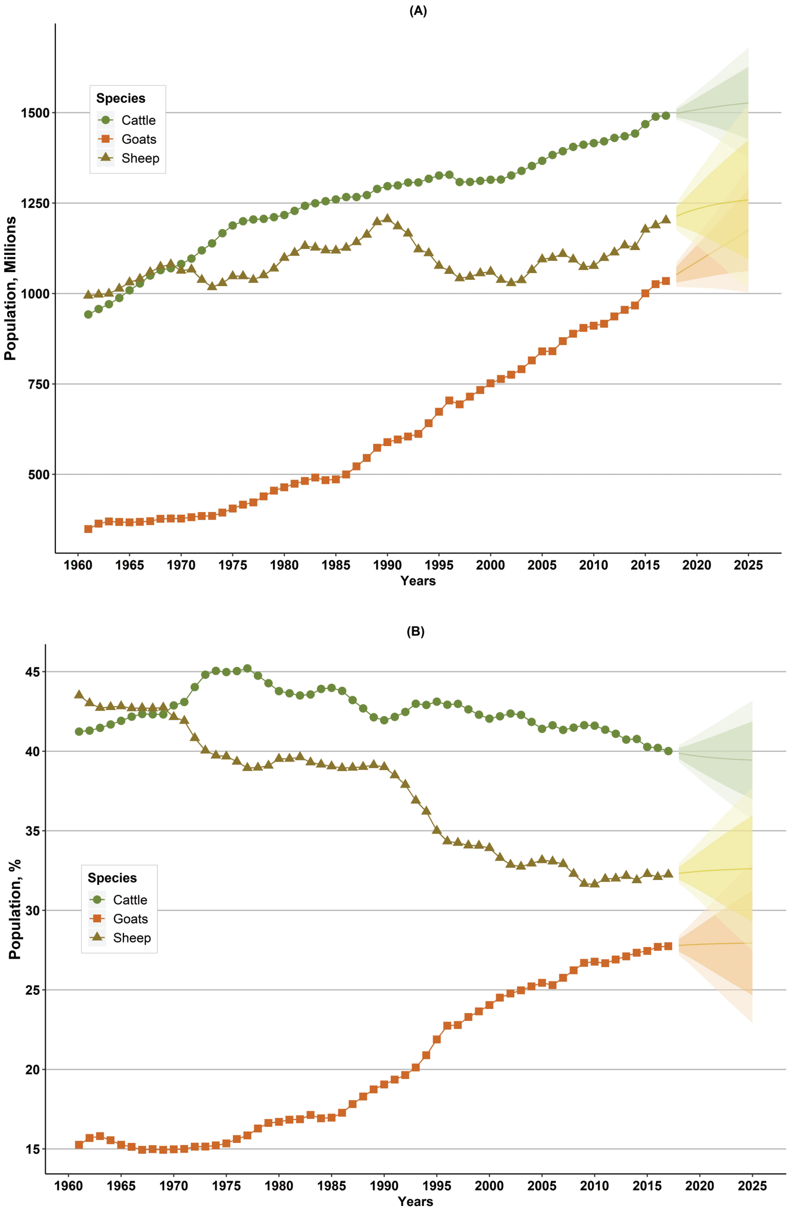

Figure 1. The world population of cattle (green circles), sheep (orange squares), goats (golden triangles) as head numbers (A) and relative percentage (B) from 1961 to 2017. The solid lines after 2017 represent 8-yr forecasts for each species population, and the shaded areas represent their 80% (darker) and 95% (lighter) prediction intervals. Adapted with permission from Tedeschi and Fox (2018).

there is a lower proportional increase in energy requirements, due to their allometric scaling as a function of metabolic BW ($BW^{0.75}$). Thus, per kilogram of BW, small ruminants have higher maintenance requirements and a lower ratio between reticulorumen volume and energy requirements than cattle, i.e., they have less rumen volume available per unit (e.g., Mcal of net energy) of requirements. As summarized by Cannas (2004b), due to these differences, sheep and goats compared with cattle: 1) have to eat more as a percentage of BW to satisfy their maintenance requirements, which results in a higher passage rate of feed and lower feed digestibility (especially fiber). Despite this, the total amount of nutrients digested per day usually increases, due to the higher intake of dry matter. This explains why high-producing dairy sheep and goats may have a level of intake of between 4% and 7% of BW, whereas in high-producing cows this figure does not usually exceed 4%. 2) have a more selective feeding behavior, choosing feeds, or parts of feeds (young stems, leaves, and buds) which are of good quality, which cause lower rumen fill, and whose digestibility is less affected by rumen feed passage rate; 3) are more negatively affected in their intake by the particle size and the fiber content of the forages and have to grind the feed particles more finely to allow them to pass through the rumen and other compartments of the foregut. Consequently, sheep and goats have to spend more time eating, chewing, and ruminating each kilogram of feed to achieve critical particle size to allow feed particles to exit the foregut and ruminate even small size feed particles; thus, 4) ruminate more finely grains and pellets and thus tend to have higher digestibility of these energy-rich feeds.

Production Efficiency in Sheep and Goats

Production efficiency is always targeted as the maximization of obtained products relative to the amount of input used (e.g., kg of milk or meat per unit of input). The most common indexes used to describe production efficiency consider dry matter, energy, or nutriens intake as the main inputs. Feed efficiency is usually calculated as kilograms of milk produced per kilogram of dry matter intake (higher is more efficient), whereas the feed conversion ratio is computed as kilograms of dry matter intake per kilogram of milk (lower is more efficient). The feed conversion ratio is conventionally the reciprocal of the feed efficiency. Complementary to feed efficiency, it is possible to quantify input losses (inefficiency in terms of the surplus of feed) and the environmental impact of the production process.

Large heterogeneity in small ruminant production systems makes it difficult to define exhaustive indicators and benchmarks for efficiency and optimal feed efficiency levels. In livestock systems, feed efficiency can be measured considering two different reference boundaries: the animal and the farm. At the animal level, nutritional models aim to provide accurate estimates of feed requirements, intake, and production levels. Model outputs should also allow performing adequate calculations and evaluations of production efficiency. The main factor affecting feed efficiency is undoubtedly the production level of the animals. Increases in production levels dilute the incidence of maintenance requirements on total requirements per unit of product, thus increasing feed efficiency.

Feed efficiency values in dairy sheep vary from 0.3 to 1.0 kg of milk/kg of dry matter intake. In meat sheep, feed efficiency can be quite variable depending on the BW, breeds, and gain composition. Oliveira et al. (2014), reviewing performances of dairy goats, reported that average feed efficiency in 17 studies was 1.06 kg of milk/kg of dry matter intake (varying from 1.44 to 0.74), with ranges of daily milk production that varied from 1.1 to 3.5 kg of milk. Under Brazilian conditions, Lima et al. (2017) reviewed key technical efficiency and economic performances of feedlot lambs (ranging from 16 to 52 kg of BW and average daily gain ranging from 0.15 to 0.38 kg of average daily gain/d), observing values of feed efficiency equal to 210 g/kg of dry matter intake (ranging from a minimum of 140 to a maximum of 280) and feed conversion equal to 4.7 (ranging from 3.5 to 6.9).

Feed conversion index can also be indicated regarding residual feed intake, firstly proposed by Koch et al. (1963). It is defined as the difference between the actual feed intake and the predicted intake based on BW and animal performance. A low-residual feed intake corresponds to less feed consumption, for equal weight gain, since animals with low-residual feed intake eat less food than the amount estimated by their BW and weight gain. Residual feed intake is considered a reliable indicator of the differences in feed conversion ratio based on the diverse genetic background of individuals. It is largely used in meat production more than in dairy production, due to the possibility to directly relate residual feed intake with body mass deposition in the former, and the difficulty to attribute residual feed intake to nutrient utilization for milk synthesis or body reserve variation in the latter. The reduction of residual feed intake would allow a reduction of the feed costs and of the environmental impact of the animals by reducing methane and other greenhouse gas emissions (Zhang et al., 2017). Many factors related to individual genetic background and farm conditions affect residual feed intake, such as breeds, age, body composition, nutrient digestion and metabolism, energy output, body activity, thermal regulation processes, and feeding behavior. There are several studies that attempted to use residual feed intake to improve production efficiency in fattening lambs, especially for selection programs (François et al., 2007). However, as reported and reviewed by Lima et al. (2017), there is no way to identify animals with high-feed efficiency and high gains through residual feed intake because this index does not consider the production level (Berry and Crowley, 2012). Indeed, residual feed intake can be low even in animals with low-weight gains, which usually are considered inefficient from a productive point of view, because of the high incidence of their maintenance costs over total nutritional costs. Given the limitations of residual feed intake, it is possible to use the "Residual intake and BW gain index" (called RIG; Berry and Crowley, 2012), which identifies animals, at equal BW, with fast growth and which consume less food than the average intake of the population. Indeed, in feedlot lambs, feed efficiency measures and feed conversion ratio were highly correlated with the "Residual intake and BW gain index" (0.699 and −0.685, respectively) and less correlated with the residual feed intake (−0.462 and 0.443, respectively; Lima et al., 2017). The same authors also observed that both indexes can be used effectively to represent the differences in economic performance among different animals or production systems, being highly associated with returns and profitability.

Nutritional models also allow estimation of environmental consequences of animal production. In small dairy ruminants, as milk production increases, there is a large reduction in the emissions of methane per kilogram of milk due to the dilution effect of methane emitted related to maintenance costs, as shown for dairy sheep in Figure 2A. In 35-kg BW meat lambs, fed on ryegrass-based pasture, with increasing levels of dry matter intake to 0.36, 0.56, 0.70, and 0.87 kg/d, changes in the energy available for gain were −25%, +13%, +47%, and +80% of that required for maintenance, leading to a lower intensity of methane emissions of 25.2, 23.8, 23.1, and 20.8 g/kg of dry matter intake, respectively (Knight et al., 2011). Indeed, methane and carbon dioxide emissions per unit of product can be considered a proxy for animal nutritional efficiency, because decreasing emission of these gases implies a more efficient utilization of nutritional resources.

At the farm level, nutritional efficiency depends on nutritional and managerial factors, and farm or production

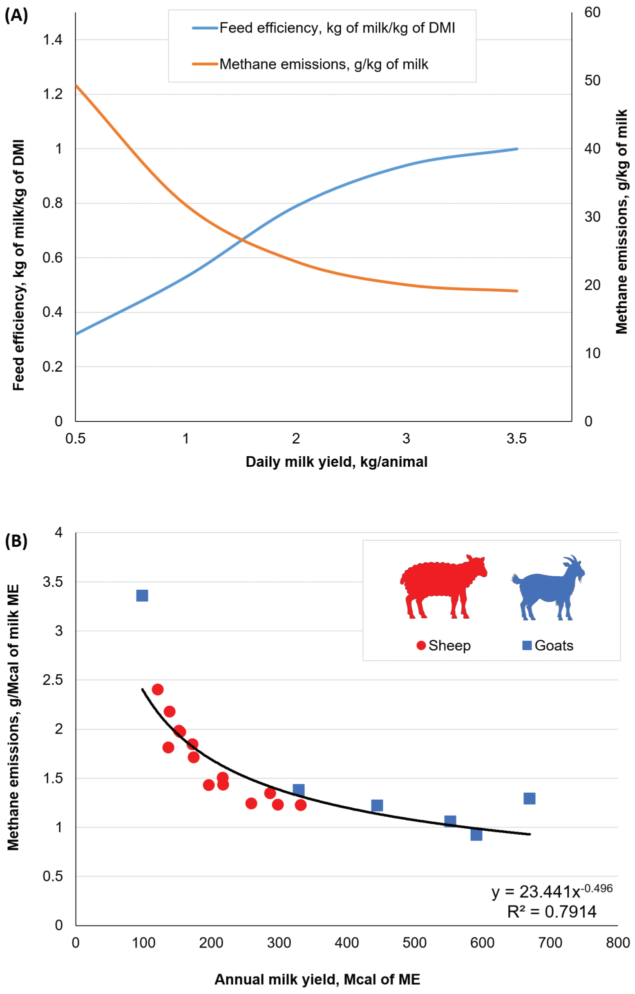

Figure 2. Measurements of production efficiency. (A) Feed efficiency and methane emissions per kilogram of milk of an average dairy sheep (50 kg of body weight), assuming dry matter intake (DMI) intake and energy requirements estimated with the Small Ruminant Nutrition System model (Cannas et al., 2007; Tedeschi et al., 2010). (B) Whole farm emissions of methane per Mcal of milk metabolizable energy (ME) per head from semi-extensive and extensive dairy sheep and dairy goats farms of Sardinia, Italy (Atzori A.S., Lunesu M.F, Cannas A., unpublished data from the project Forage4Climate; EU LIFE+15).

conditions. Farm efficiency increases when, assuming a constant level of farm outputs, the inputs used decrease. Important improvements in efficiency are generally reached by reducing mortality and morbidity, and increasing reproduction efficiency. Hygiene, animal welfare and animal comfort, thermoregulation, feed, and water availability, among others, are often fundamental checkpoints to prevent these causes of inefficiency. Differences in efficiency can be highlighted among different farms also considering their methane emissions, which are always reduced as milk production increases, denoting a marked increase in nutrition efficiency that leads to more efficient use of the resources. Figure 2B exemplifies this behavior. From this point of view, environmental indicators can be considered among the most useful proxies to target efficiency of production systems.

Evolution of Nutrition Models for Sheep and Goats

Nutritional models for sheep and goats

There is a vast area of application of models to improve production efficiency of sheep and goats. Probably the most important and explored area is that related to nutrition models, but epidemiological or whole-farm decision support models might also provide some assistance to improve production efficiency. Historically, nutrition models have developed from simple systems, which referred to general feeding situations, to complex systems, with mechanistic components, which aim to account for many variables, including animal, dietary, and environmental factors. Because modern nutritional models are more comprehensive, they require more inputs than the older, simpler systems. They are also subjected to continuous revisions and updates as new research becomes available. Although the nutrition recommendations in the 1970s were mostly based on tabular values, since the 1980s nutrition models have been implemented in nutritional software, making possible more complex predictions in a continuous range of variables and conditions. However, all of these models face the challenge of being able to consider a wide range of feeding and environmental conditions. For this reason, development of nutrition models for sheep and goats is even more challenging than for cattle. Despite this, the available nutrition models for sheep and goats are often more empirical, account for fewer variables, and are updated less frequently than those for cattle (Cannas, 2004a; Cannas et al., 2008).

North American models

The National Research Council (**NRC**) was formed in 1916 by the National Academy of Sciences with a specific mandate by the President of the United States: organize the scientific resource of the country during the First World War (NRC, 1982). Subsequently, the Committee on Animal Nutrition was formed in 1917 under the auspices of the Committee on Food and Nutrition (NRC, 1982), and these days it is under the sponsorship of the Board on Agriculture and Renewable Research. The Committee on Animal Nutrition has published reports of diverse topics, including nutrition (energy and nutrient requirements) and reproduction of farm animals such as poultry, swine, cattle, sheep, goats, horses, and fishes.

For sheep, the Committee on Animal Nutrition released the first attempt of *Recommended Nutrient Allowances for Sheep* in 1945 (NRC, 1945), recognizing the importance of adequate nutrition of gestating ewes to produce vigorous and strong lambs at birth. The protein requirement for maintenance was based on that recommended for cattle in 1945 (i.e., 0.6 g/kg of BW/d) and total digestible nutrients requirement was established at 8 g/kg of BW/d (NRC, 1945). Minor modifications were included in subsequent revisions (NRC, 1949, 1957). The third revision in 1964 (NRC, 1964) discussed the conversion of total digestible nutrients to digestible energy, metabolizable energy, and net energy based on the work of Garrett et al. (1959), but recommendations were still based on the dietary total digestible nutrients (27 g/kg$^{0.75}$ of BW/d). In 1968, the fourth revision (NRC, 1968) marked the beginning of the exponential growth pattern in the content of these publications (Figure 3), including a revised table of feed composition and adoption of the metric system rather than the Imperial system. The fifth revision came in 1975 (NRC, 1975) and included a detailed discussion on nutrient requirements and symptoms of deficiency, significant changes to the protein requirement for lactation and growing lambs, given the changes in the genetic potential of the animals compared with previous publications, and refinement of energy requirements for maintenance and growth. After 10 yr, the sixth revision of nutrition requirements for sheep was released in 1985 (NRC, 1985) and included many modifications to factorize the requirements of energy and nutrients for different physiological stages by providing equations to facilitate the calculations.

In 1981, after 35 yr that the *Recommended Nutrient Allowances for Sheep* was released, the Committee on Animal Nutrition issued the first report on the energy and nutrient requirements for goats, given their increasing economic relevance in the world and accumulated knowledge from national and international symposia (NRC, 1981). Considerable data on energy and protein requirements, from the Raja Balwant Singh College at Bichpuri in India for dairy and meat goats and the Texas A&M Agricultural Experiment Station at San Angelo, TX for Angora goats, were used in construction of this report. In a limited, but significant, chapter on the browsing habit of goats, the committee members indicated key differences between goats and other domesticated ruminants (cattle and sheep) and similarities with wildlife (NRC, 1981). It brought to light many aspects of browsing and grazing and portrayed goats as "mobile pruning machines" of bushy shrubs, being an intrinsic benefit for cattle ranchers (Provenza, 1978).

After 22 yr without revisions, a breakthrough occurred in 2007 with the release of the *Nutrient Requirements of Small Ruminants* for sheep, goats, cervids (e.g., white-tailed deer, red deer, American elk, and caribou/reindeer), and new world camelids (e.g., alpacas and llamas) (NRC, 2007). Until then, the nutritional recommendations for sheep and goats were separate, and cervids and new world camelids never had a nutrient recommendation publication. The 2007 publication contains more than 360 pages and 1900 citations (Figure 3), containing profound departures and many innovative ideas compared with previous small ruminant publications by the National Academy of Sciences. In summary, the NRC's (2007) Committee adopted the deterministic, mechanistic mathematical model developed by Cannas et al. (2004) for sheep and relied almost exclusively on publications from the E (Kika) de la Garza American Institute for Goat Research at Langston University for goats (Sahlu et al., 2004).

The model developed by Cannas et al. (2004) was based on the Cornell Net Carbohydrate and Protein System (**CNCPS**), which was originally developed for beef and dairy cattle (Fox et al., 2004). It was called CNCPS-Sheep and accounted for nutrient requirements of sheep, developed integrating data and equations of Agricultural Research Council (ARC, 1980), Institut National de la Recherche Agronomique (**INRA**, 1988; cited by INRA, 2018), and especially of the Commonwealth Scientific and Industrial Research Organisation (CSIRO, 1990) models. From the latter were taken, with some modifications, the approach of the use of the degree of maturity of growing animals to estimate their requirements, the concept that energy and protein requirements for maintenance increase in proportion to the dietary intake, and the cold stress submodel of maintenance requirements. In the CNCPS-sheep, an original body reserve model and new prediction equations for liquid and solid passage rates were proposed. The model included components, derived from an Italian earlier model (Assis-T; http://www.crpa.it/nqcontent.cfm?a_id=1468&tt=crpa_www&sp=assist-dev), for its utilization with dairy sheep. Compared with the CNCPS for cattle, the fecal endogenous matter prediction was modified, after an extensive evaluation, to avoid double accounting of microbial matter.

Many modifications to the original CNCPS sheep model were proposed (e.g., calculation of fecal crude protein, maintenance cost, and efficiency for gain of growing animals) and along with the inclusion of the nutrient requirements for goats, which was largely spearheaded by Cannas et al. (2008), the Small Ruminant Nutrition System (http://nutritionmodels.com/srns.html) and computer model were conceived and evaluated (Cannas et al., 2007; Tedeschi et al., 2010). Further advancements of the Small Ruminant Nutrition System were proposed by Regadas Filho et al. (2014), including a two-compartment model to predict rumen feed passage rate, instead of the original one-compartment model, and testing a new intake prediction for goats, and by Cannas et al. (2016), who proposed reference values for optimal NDF intake in lactating ewes. Recently, the Small Ruminant Nutrition System was integrated into the Ruminant Nutrition System model (http://nutritionmodels.com/rns.html) (Tedeschi and Fox, 2018), with some modifications compared with the original version (e.g., goat

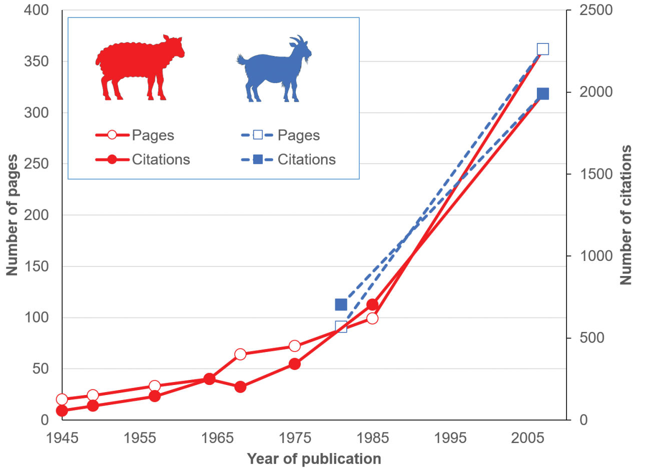

Figure 3. Chronological progress of numbers of pages (open symbols) and citations (closed symbols) of the National Research Council publications on the nutrient requirements of sheep (red circles) and goats (blue squares).

passage rates were based on Seo's et al., 2006, and Tedeschi et al., 2012) and the inclusion of prediction equations for methane production.

European and Australian models

Several nutrition models for sheep and goats have been proposed in Europe and subsequently in Australia. In 1965 the ARC presented a feeding model (ARC, 1965, cited by ARC, 1980), which was markedly improved and expanded in the 1980s (ARC, 1980). The ARC feeding model represented a major advancement in the knowledge of requirements and feed nutritive values for sheep and cattle, whereas goats were not considered. This model explored in detail the composition of the body of sheep from the uterine life to the mature stages, developing specific prediction models for each stage of life, which were largely based on slaughter data. The energy requirements were based on calorimetric studies of Sir Kenneth Blaxter, which also provided data and models for prediction of the efficiency of conversion of metabolizable energy (**ME**) to net energy (**NE**) for various physiological functions, by using dietary metabolizability as a predictor (ratio of dietary or feed ME to gross energy). This efficiency declines as the feeding level increases, but the estimates of feed energy values were measured at maintenance level. Dietary energy was expressed regarding ME and the diets balanced with the same unit, by converting the NE requirements for the various physiological functions (e.g., maintenance, milk production, growth, and pregnancy) to ME values with the efficiencies above mentioned.

Regarding dietary protein utilization, this model overcame the earlier approaches based on crude protein or digestible crude protein, developing, similarly to what was done by North American models, a model in which the energy and nitrogen requirements of rumen bacteria were considered, and the microbial efficiency was estimated. The model predicted rumen degraded and undegraded protein and the supply of metabolizable protein of feed and microbial origin to the intestine. The protein requirements of sheep were calculated by explicitly accounting for endogenous urinary nitrogen excretion, wool nitrogen losses, and the net protein content of the gain or the milk. The rumen degraded and undegraded protein requirements for each category were estimated and reported in tables as a function of the BW of the animals and, depending on the physiological stage, of their average daily gain, milk production, pregnancy, and also of dietary metabolizability. The ARC model has been the base for the development of later sheep models in the United Kingdom (AFRC, 1993, 1998), and in Australia (CSIRO, 1990, 2007), as depicted in Figure 4. Even the French Institut National de la Recherche Agronomique sheep model (**INRA**; 1978, 1988, 1989, 2007, 2018; cited by INRA, 2018) adopted considerable information from the ARC nutrition model.

The CSIRO (1990, 2007) model was developed by integrating the information presented in the ARC and AFRC models with the large body of research carried out on sheep in Australia. It made major advancements in several areas, especially in requirements, introducing many mechanistic components in their prediction. Indeed, for the first time, the degree of maturity was used in a comprehensive feeding system to estimate the composition of the gain and the energy and protein requirements of growing sheep. Thus, instead of using different growth and body composition equations for early and late maturing breeds and for males and females, as done before, the ratio of current to mature weight was used as a general predictor, together with the level of feeding, allowing use of the same equations to estimate composition of gain and the growth requirements for sheep breeds of very different mature size and precocity and for different sexes. The concept of the degree of maturity and standard mature weight was also used in the prediction of dry matter intake. Another major improvement, compared with the existing models, was the fact that energy and protein requirements for maintenance increased not only as a function of metabolic weight, as in the earlier systems, but also in proportion to the level of intake. As intake increases, there is an increase in the size and activity of the visceral organs, the most metabolically active and expensive organs. Thus, at equal BW, slowly growing or adult dry animals would have a substantially lower maintenance cost than fast growing or lactating animals. A mechanistic submodel to estimate the extra maintenance cost due to cold stress cost in sheep was developed and models to estimate the cost of grazing and pasture intake, based on pasture quality, were included. The CSIRO (1990, 2007) model is the only model for small ruminants to estimate the effect of cold stress on requirements. As previously mentioned, the CNCPS for sheep and the Small Ruminant Nutrition System for sheep and goats adopted many of the submodels of the CSIRO (1990, 2007) model, including that for cold stress prediction.

In contrast to the previous models, the Agricultural and Food Research Council (AFRC, 1993, 1998) and the INRA model include all three major ruminant species. The sheep and goat model of the AFRC is based on a modification and simplification of the ARC (1980) model, making it more practical. The goat component was further detailed and improved in 1998 with a specific report (AFRC, 1998), which built on the previous British models by using specific data and models on dairy goats.

The INRA sheep and goat model was first published in 1978 and then evolved with a very recent update (INRA, 1978, 1988, 1989, 2007, 2018; all cited by INRA, 2018). This model is widely used in many European countries (e.g., France, Spain, and Italy) and African countries and made the basis of the Dutch system. The INRA model uses the same feeding units for all species. They are estimated as a ratio between the NE value of a feed and the corresponding value of a reference feed, a kilogram of barley grains (1,760 kcal of NE/kg as fed; INRA, 2018). The corresponding units are called the forage unit for milk, used for all females of dairy animals (cows, ewes, and goats) and the forage unit for meat, used for all males of all breeds and females of meat breeds (cattle and sheep). Although earlier versions (from INRA 1977 to INRA, 2007) estimated the energy and protein value of feeds at a fixed feeding level

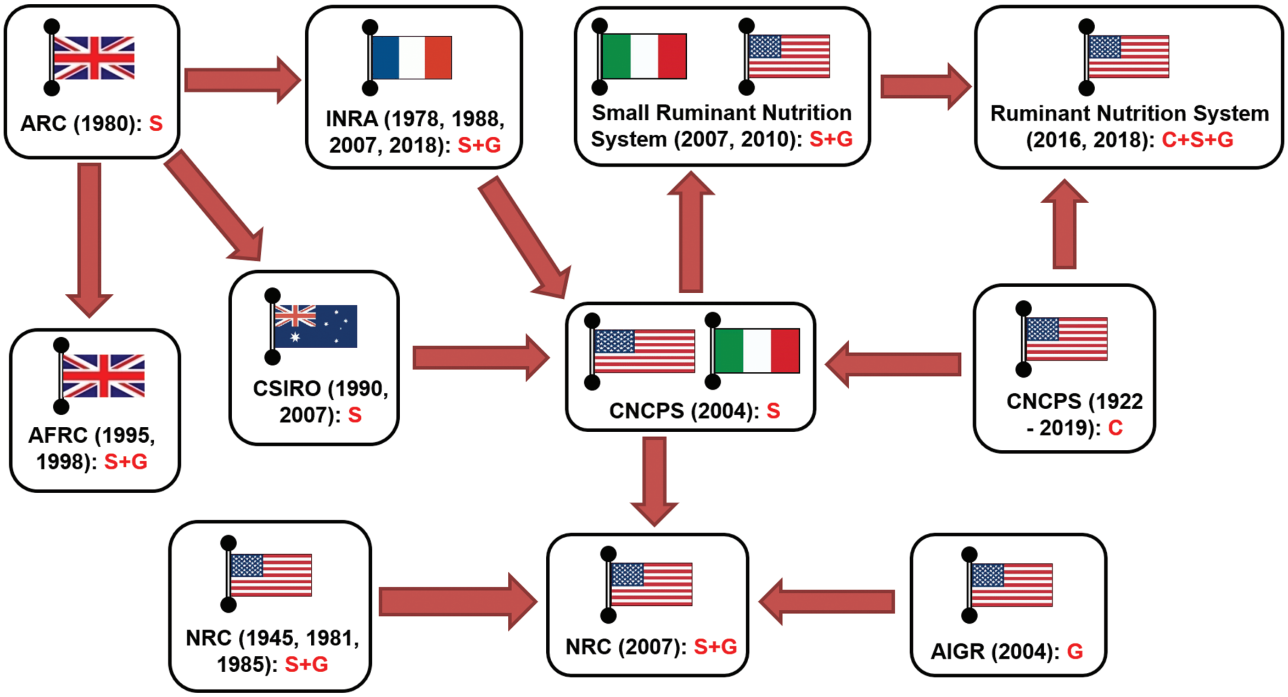

Figure 4. Evolution and interconnection of the main sheep and goat nutrition models. C = cattle; S = sheep; G = goats; AIGR = American Institute for Goat Research, Langston University; ARC = Agricultural Research Council; AFRC = Agricultural and Food Research Council; INRA = Institut National de la Recherche Agronomique; CSIRO = Commonwealth Scientific and Industrial Research Organization; NRC = National Research Council; CNCPS = Cornell Net Carbohydrate and Protein System.

(near or at maintenance feeding level for energy, fixed at 6% rumen passage rate for proteins), the latest version (INRA, 2018) developed equations to account for the reduction in digestibility and the increase in rumen escape of nutrients as the level of intake increases. The energy values are also corrected for negative associative effects due to high concentrate intake, considered as a probe of low rumen pH, and for rumen nitrogen balance, reducing the values in case of rumen nitrogen shortage. Regarding requirements, the INRA sheep submodel is fully empirical, accounted for few variables and evolved very little since it was first published. It does not consider environmental factors in the estimation of requirements, has a simplified body reserve model, and estimates the cost of grazing by increasing the energy maintenance cost by fixed coefficients, based on the quality of the pasture, defined in three main classes. Despite this, it has the merit of being the first nutrition model to consider the requirements of dairy sheep and not those of meat or wool sheep only.

The INRA goat model is also empirical and does not account for environmental factors, but it evolved markedly over time, with much new information and predictions included in the latest version (INRA, 2018). It is focused on specialized dairy goat breeds, namely, Saanen and Alpine. It includes models to predict the lactation curve based on parity, genetic potential and days in milk, and the corresponding milk fat and protein concentrations, separately for the two breeds mentioned above. In addition, for the same breeds prediction equations of the kinetics of energy reserves and live weight changes, which accounts for the homeorhetic control of milk production and body reserve variations, have been developed. Eventually, based on previous predictions, empirical modeling of the energy balance driven by homeorhesis and potential milk yield was proposed. These are major advances in the direction of improving the production efficiency of goats, since they allow an accurate prediction of the expected body reserve evolution and thus a close monitoring of the animals that do not follow the expected patterns, with potential positive implications on the production level of the animals and also on their health. Indeed, too fast body reserve losses are considered one of the main causes of nutritional disorders and goat culling.

The Future of Sheep and Goat Nutrition Models

The scientific community has surmounted many obstacles since the mid-1940s in collecting data and acquiring knowledge to develop recommendations on nutrient requirements for domesticated ruminants, including sheep and goats. This effort resulted in a huge leap forward, obtained building upon previous models (Figure 4), with the release of the CNCPS-Sheep (Cannas et al., 2004), the goat model of the American Institute for Goat Research of Langston University (Sahlu et al., 2004), the NRC (2007), the Small Ruminant Nutrition System (Cannas et al., 2007; Tedeschi et al. 2010), and eventually the INRA (2018).

An extensive comparison of many sheep and goat models was carried out by Cannas (2004) for sheep and Cannas et al. (2008) for goats. The comparisons highlighted that although the total cumulated prediction for maintenance and milk production in thermoneutral conditions did not differ much among feeding systems, there were large differences in the variables considered to estimate the maintenance requirements besides the basal metabolic rate, in the prediction of movement, in those for pregnancy requirements, and, above all, for growth. An example of these large numerical and methodological differences is illustrated in Figure 5 for growing goats.

Thus, considerable work is still required to improve the predictions of energy and nutrients for sheep and goats (and other wildlife and small ruminants), given the diverse environment and management practices in which they are raised around the globe. New hurdles exist (e.g., environmental pollution, climate change, and water scarcity) and they must be defeated to provide high-quality protein to an astounding human population that continues to grow. Sahlu et al. (2004) discussed some elements in the scientific literature on goat nutrient requirements that require further investigation. Although some of these elements have been addressed in the Ruminant Nutrition System model (Tedeschi and Fox, 2018), others persist (e.g., ruminal recycled nitrogen, browsing and pasture forage intake, the efficiency of use of amino acids for maintenance and growth, the effectiveness of fiber, the prediction of rumen pH, and the effects of heat stress).

Further improvements in the nutritional efficiency of small ruminants could be based on the integration of nutrition models with the data derived from sensor technology, which can markedly increase the amount of information available by continuously monitoring the animals, their environment, and their performances. Many systems at research and market level are already available for small ruminants (Fogarty et al., 2018), and many others will be soon ready, for identifying, tracking and weighing animals, monitoring their body temperature and heart rate, and assessing body condition score, among many others. Utilization of this information would require a change in the approach taken when developing nutrition models, by increasing the few and mostly static inputs (e.g., intake, BW, yield, and composition of milk) used so far. Great improvements could be achieved especially for sheep and goats on pasture, e.g., to assess their actual movement or the direct effects of climatic conditions, and thus the corresponding requirements. This could produce a great improvement in prediction accuracy and thus in nutritional efficiency of small ruminants.

Using Predictive Analytics to Improve Nutritional Modeling

The media publicity about artificial intelligence and other data technology breakthroughs can be daunting at times. It may even catch savvy experts unprepared about the evolution that these technologies have to go through before reaching their state-of-the-art reputation.

Our education in science is grounded on the Platonic thinking that knowledge is not simply a collection of beliefs; rather, it reflects a systematic and natural way the universe works. The word “science” derives from the Latin “*scientia*,” which in turn translates the Greek “*episteme*,” from which English derives “epistemology,” the study of what knowledge is and how to acquire it. Consequently, learning is needed to develop ideas to gain knowledge. Much of the Platonic thinking on knowledge was incorporated into the data–information–knowledge–wisdom hierarchy (Figure 6), which acts as a lighthouse that has guided much scientific research.

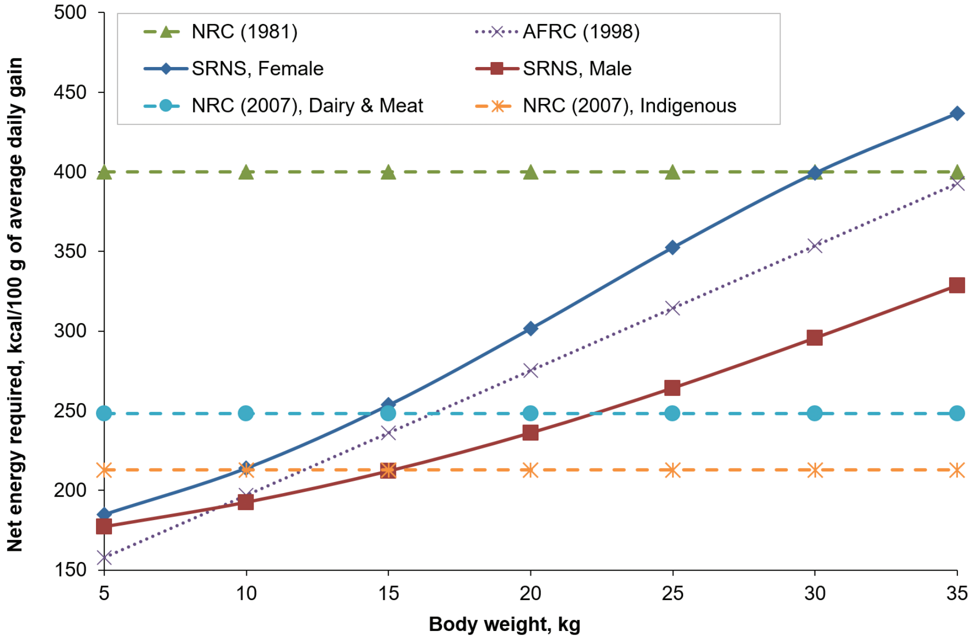

Figure 5. The relationship between BW and net energy requirements for 100 g/d of average daily gain of growing goats, as predicted by different feeding systems (Cannas et al., 2008, modified), assuming a mature weight of 55 kg for females and 85 kg for males for the Small Ruminant Nutrition System model (SRNS). The different approaches taken bring to very different estimations of the energy requirements for growth. AFRC = Agricultural and Food Research Council; NRC = National Research Council.

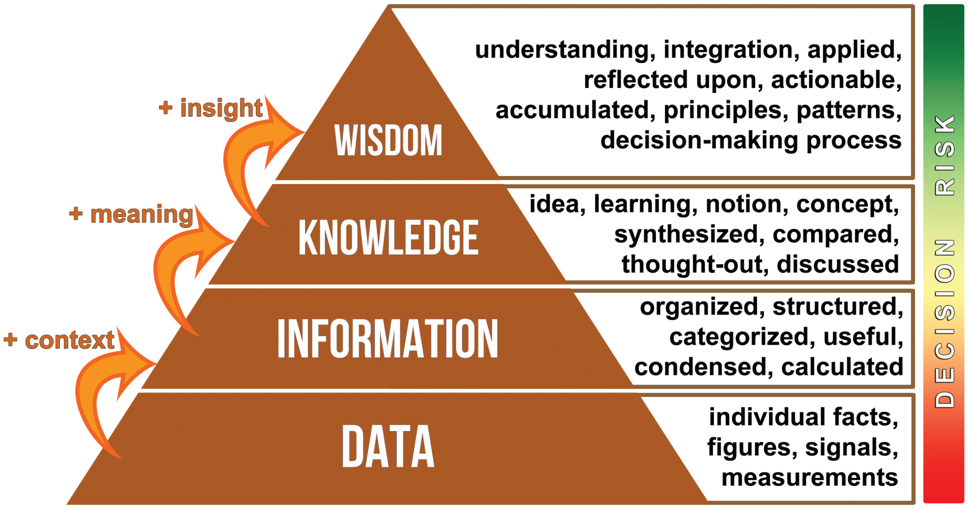

Figure 6. The data–information–knowledge–wisdom (DIKW) hierarchy as a pyramid to manage knowledge. Reproduced with permission from Tedeschi (2019).

At the beginning of research endeavors in any science field, scientists lacked data and frequently blamed that lack on our inability to make adequate predictions or forecasts. In the Animal Science field, circa the 1960s data started to become abundant as governmental and commercial experimental research stations were built around the world. Not until recently, circa the 2000s, remote sensing, and many other electronic devices were developed and made broadly available to ease the collection and storage of data (e.g., the Internet). Then, we generated data but lacked ways to analyze large data sets. Statistical methods have been used to compress the data (e.g., principal component analysis and partial least squares) and to make sense of the vast amount of data. However, the arrival of the big-data era necessitated more powerful data analytics methods. Artificial intelligence has evolved to make sense of the big data, but it has some flaws: although it may represent the data structure, it does not explicitly explain the underlying assumptions of the data and the selective combination of specific inputs that it used to reach the result. Artificial intelligence misses the *wisdom* in the data–information–knowledge–wisdom hierarchy because wisdom requires judgments that are unique to individuals who assimilate information and knowledge simultaneously to make intelligent decisions and novelty creations. The scientific road we have traveled since the 1940s has had its ups and downs (Tedeschi, 2019), reflecting our appetite for scientific data, the need to understand the unknown, and the desire to make rational decisions to improve our livelihoods, assuming that greater knowledge and wisdom would reduce the risks of being wrong (Figure 6). Despite our ignorance of how artificial intelligence works its way through data in developing its sets of neural network weights for the inputs—what some call learning—it is a powerful advancement in predictive analytics. The artificial intelligence technique is a fantastic data-driven technology that was originally developed in the 1950s with the goal of automating human intelligence through computational programming. As depicted in Figure 7, the programming codes for artificial intelligence (i.e., rules of logic and calculations) were initially hardcoded, like most computer programming tasks. Then, with the boom of expert systems in the 1980s, the "learning" era began to take shape (Chollet, 2018). The question has

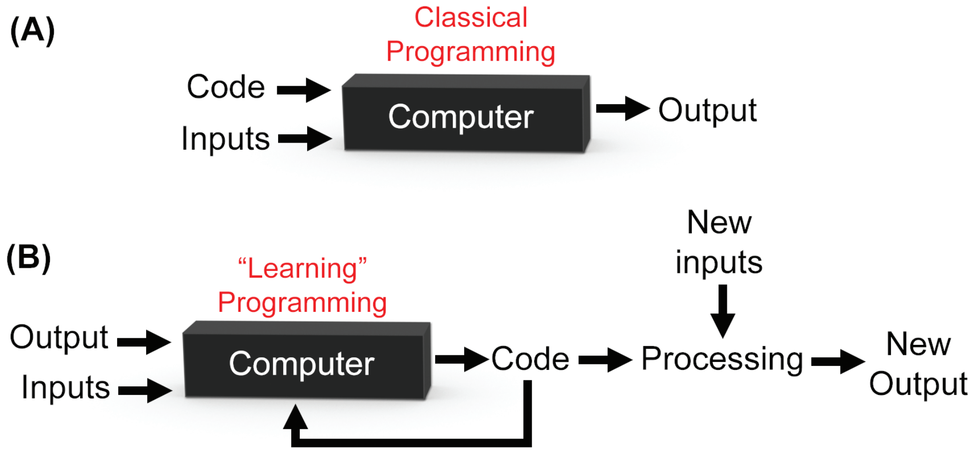

Figure 7. A schematic representation of how (A) classical programming and (B) "learning" programming paradigms use inputs, outputs, and codes (i.e., rules) for predictions. The arrow from code to "learning" programming indicates back propagation frequently used in deep learning. Adapted from Chollet (2018).

always been: can computers create a code given the inputs and the outputs rather than create outputs from inputs and codes? Artificial intelligence comprises different highly sophisticated, data-driven technologies that are based on neural network programming.

Artificial intelligence has seen limited use in agriculture production (Liakos et al., 2018), and even less in animal science. Different artificial intelligence technologies have been featured in cattle studies: animal welfare, genome-wide predictions, breed classification, expected progeny differences, anatomical biometrics for cattle identification and recognition, growth patterns, and rumen functioning in lactating dairy cows (Tedeschi, 2019). In studies of small ruminants, artificial intelligence applications have been incipient and restricted to milk production, including the relationship between profitability and production systems of sheep and goats (Magdalena et al., 2009) and weekly prediction of milk yield in goats (Fernández et al., 2007). Some recent exploratory, sporadic applications of artificial intelligence in the sheep industry have been publicized for wool production (https://www.sheepcentral.com/does-artificial-intelligence-have-a-role-in-the-wool-industry/) and animal distress (https://www.dailymail.co.uk/sciencetech/article-4559216/Scientists-use-AI-sheep-pain.html).

In conclusion, artificial intelligence technologies were designed to learn from data and provide forecasting, but not as a tool to help us understand the underlying mechanisms. Little is known about the reasoning behind each prediction by an artificial intelligence algorithm, so as Knight (2017) asked, can we trust artificial intelligence predictions if we cannot reasonably explain them? This might be an important bottleneck for combining artificial intelligence technologies with nutrition models, a bottleneck that needs to be transcended to further improve ruminant nutrition systems (Cannas et al., 2004; Tedeschi et al., 2010; Tedeschi and Fox, 2018). It feels like we have traveled far and developed powerful advancements in data and predictive analytics and digital computing, only to relive the black-box era. Inexplicability is a known limitation of artificial intelligence, but it was not developed to provide explanations. However, the question still stands: how can we benefit from artificial intelligence, or its variants, to further advance our mathematical modeling efforts in animal production, more specifically ruminant nutrition?

About the Authors

Antonello Cannas is a professor of Animal Nutrition in the Department of Agricultural Sciences (Dipartimento di Agraria), and Director of the PhD School at the University of Sassari, Sardinia, Italy. He holds a Bachelor's degree in Agricultural Sciences from the University of Sassari, and MSc and PhD in Animal Science from Cornell University, Ithaca, NY. His main areas of research are on the nutrition and feeding of small ruminants, with focus on the development of mechanistic nutrition models, estimation of energy and protein requirements, prediction of rumen function and turnover, utilization of nutritional indicators (such as milk and blood urea), study of the relationship between nutrition and milk yield and composition, the factors affecting feed palatability, and prediction of the environmental impact of sheep and goat production systems. He led the development of the *Cornell Net Carbohydrate and Protein System for Sheep* and its evolution into the *Small Ruminant Nutrition System,* jointly with D.G. Fox, Cornell University, USA and L.O. Tedeschi, Texas A & M University, USA.

Corresponding author: cannas@uniss.it

Luis Tedeschi is a professor and fellow in the Department of Animal Science at Texas A&M University, College Station, TX. He holds a Bachelor of Science degree in Agronomy Engineering and Master of Science degree in Animal and Forage Sciences from the University of São Paulo, Brazil, and Doctor of Philosophy degree in Animal Science from the Cornell University, Ithaca, NY. His research focuses on the integration of accumulated scientific knowledge of ruminant nutrition into applied mathematical models to solve contemporary problems. His areas of interest are energy and nutrient requirements of grazing and feedlot animals, growth biology and bioenergetics, chemical composition and kinetics of fermentation of feeds, and modeling, simulation, and evaluation of decision support systems. In 2013, he was awarded the distinguished J. William Fulbright Scholarship to develop models to understand the ruminant production impact on the global warming effect through the emission of methane. He has served on a committee at the 2016 National Research Council of The National Academies of Sciences, Engineering, and Medicine to revise the 1996 nutrient requirements for beef cattle.

Funding

The data reported in Figure 2 have been developed in the project Forage4Climate (LIFE15CCM/00039), funded by the EU LIFE+15 program on Climate Change Mitigation.

Literature Cited

AFRC. 1993. Energy and protein requirements of ruminants. Wallingford (Oxon, UK): CAB International.

AFRC. 1998. The nutrition of goats. Wallingford (UK): CABI Publishing.

ARC. 1980. The nutrient requirements of ruminant livestock. London (UK): Agricultural Research Council. The Gresham Press.

Berry, D. P., and J. J. Crowley. 2012. Residual intake and body weight gain: a new measure of efficiency in growing cattle. J. Anim. Sci. 90:109–115. doi:10.2527/jas.2011-4245.

Cannas, A. 2004a. Energy and protein requirements. In: Pulina, G, editor. Dairy sheep nutrition. Wallingford (Oxon, United Kingdom): CAB International; pp. 31–49.

Cannas, A. 2004b. Feeding of lactating ewes. In: Pulina, G., editor. Dairy sheep nutrition. Wallingford (Oxon, United Kingdom): CAB International; pp. 79–108.

Cannas, A., A. S. Atzori, F. Boe, and I. A. M. A. Teixeira. 2008. Energy and protein requirements of goats. In: A. Cannas, and G. Pulina, editor. Dairy Goats, Feeding and Nutrition. Cambridge (MA): CABI Publishing; Pp. 118–146.

Alberto Stanislao Atzori is an Assistant Professor in Animal Nutrition at the University of Sassari. He holds a degree in Agricultural Science and a PhD in Animal Science from the University of Sassari (Italy). He spent 6 mo as visiting scholar at Texas A&M University (USA) studying system dynamics modeling. His education background is in ruminant nutrition and dairy farm management. His current research focuses on the relationship among ruminant nutrition and environmental impact of farms, to enhance production efficiency and profitability of farming systems. In his research activity, he also uses system dynamics and life cycle assessment techniques applied to livestock systems.

Mondina Francesca Lunesu is a Post-Doctoral Fellow in Animal Science at the University of Sassari. She holds a degree in Agricultural Science and a PhD in Animal Science from the University of Sassari (Italy), with a dissertation on the effect of type of carbohydrates on dietary energy partitioning in lactating ewes and goats. She spent 3 mo in South Africa (Pretoria University) and 4 mo at the Department of Animal Science at Texas A&M University, College Station, TX, studying the digestibility and characteristics of dietary carbohydrates. Her current research focus is on quantifying greenhouse gas emissions of sheep and goats and on mitigation strategies based on the improvement of nutrition and management techniques.

Cannas, A., L. O. Tedeschi, A. S. Atzori, and D. G. Fox. 2007. The Small Ruminant Nutrition System: development and evaluation of a goat submodel. Ital. J. Anim. Sci. 6 (Suppl. 1):609–611. doi:10.4081/ijas.2007.1s.609

Cannas, A., L. O. Tedeschi, D. G. Fox, A. N. Pell, and P. J. Van Soest. 2004. A mechanistic model for predicting the nutrient requirements and feed biological values for sheep. J. Anim. Sci. 82:149–169. doi:10.2527/2004.821149x

Cannas, A., L. O. Tedeschi, G. Molle, A. S. Atzori, C. Dimauro, and M. F. Lunesu. 2016. Prediction of optimal NDF intake in sheep. Can. J. Anim. Sci. 96: 628–629. doi:10.1139/cjas-2016-0149

Chollet, F. 2018. Deep learning with Python. Shelter Island (NY): Manning Publications.

CSIRO. 1990. Feeding standards for Australian livestock. Melbourne (Australia): Ruminants. Commonwealth Scientific and Industrial Research Organization.

CSIRO. 2007. Nutrient requirements of domesticated ruminants. Collingwood (VIC): Commonwealth Scientific and Industrial Research Organization.

Fernández, C., E. Soria, P. Sánchez-Seiquer, L. Gómez-Chova, R. Magdalena, J. D. Martín-Guerrero, M. J. Navarro, and A. J. Serrano. 2007. Weekly milk prediction on dairy goats using neural networks. Neural Comput. Appl. 16 (4):373–381. doi:10.1007/s00521-006-0061-y

Fogarty, E. S., D. L. Swain, G. Cronin, and M. Trotter. 2018. Autonomous on-animal sensors in sheep research: A systematic review. Comput. Electron. Agric. 150:245–256. doi:10.1016/j.compag.2018.04.017

Fox, D. G., L. O. Tedeschi, T. P. Tylutki, J. B. Russell, M. E. Van Amburgh, L. E. Chase, A. N. Pell, and T. R. Overton. 2004. The Cornell Net Carbohydrate and Protein System model for evaluating herd nutrition and nutrient excretion. Anim. Feed Sci. Technol. 112 (1):29–78. doi:10.1016/j.anifeedsci.2003.10.006

François, D., J. C. Brunel, E. Ricard, J. L. Weisbecker, J. Bouix, Y. Bourdillon, and B. Bibé. 2007. Use in selection of the measurements of feed intake and feeding behaviour parameters in sheep. In: Priolo, A., L. Biondi, H. Ben Salem, and P. Morand-Fehr, editors. Advanced nutrition and feeding strategies to improve sheep and goat. Options Méditerranéennes: Série A. Séminaires Méditerranéens. vol. 74. Zaragoza (Spain): CIHEAM; p. 441–447.

Garrett, W. N., J. H. Meyer, and G. P. Lofgreen. 1959. The comparative energy requirements of sheep and cattle for maintenance and gain. J. Anim. Sci. 18 (2):528–547. doi:10.2527/jas1959.182528x

INRA. 2018. INRA feeding system for ruminants. Wageningen (The Netherlands): Wageningen Academic Publishers.

Knight, W. 2017. The dark secret at the heart of AI. MIT Technology Review. 120 (3):54–65.

Knight, T. W., H. Clark, G. Molano, S. V. Maclean, and D. S. Villacorta. 2011. Methane emissions from sheep fed different intakes of high quality pasture. MAF Technical Paper No: 2011/84. pp. 16.

Koch, R. M., L. A. Swiger, D. Chambers, and K. E. Gregory. 1963. Efficiency of feed use in beef cattle. J. Anim. Sci. 22:486–494. doi:10.2527/jas1963.222486x

Liakos, G. K., P. Busato, D. Moshou, S. Pearson, and D. Bochtis. 2018. Machine learning in agriculture: a review. Sensors. 18 (8):1–29. doi:10.3390/s18082674

Lima, N. L. L., C. R. de F. Ribeiro, H. C. Menezes de Sá, I. Leopoldino-Júnior, L. F. L. Cavalcanti, R. A. V. Santana, I. F. Furusho-Garcia, and I. G. Pereira. 2017. Economic analysis, performance, and feed efficiency in feedlot lambs. R. Bras. Zootec. 46(10):821–829. doi:10.1590/s1806-92902017001000005

Magdalena, R., C. Fernández, J. D. Martín, E. Soria, M. Martínez, M. J. Navarro, and C. Mata. 2009. Qualitative analysis of goat and sheep production data using self-organizing maps. Expert Syst. 26 (2):191–201. doi:10.1111/j.1468-0394.2009.00477.x

NRC. 1945. Recommended nutrient allowances for sheep. Recommended nutrient allowances for domestic animals. Washington (DC): National Academy Press. doi: 10.17226/21454

NRC. 1949. Recommended nutrient allowances for sheep. (1st ed.). Recommended nutrient allowances for domestic animals. Washington (DC): National Academy Press. doi: 10.17226/21454

NRC. 1957. Nutrient requirements of sheep. (2nd ed.). Nutrient requirements of domestic animals. Washington (DC): National Academy Press.

NRC. 1964. Nutrient requirements of sheep. (3rd ed.). Nutrient requirements of domestic animals. Washington (DC): National Academy Press.

NRC. 1968. Nutrient requirements of sheep. (4th ed.). Nutrient requirements of domestic animals. Washington (DC): National Academy Press.

NRC. 1975. Nutrient requirements of sheep. (5th ed.). Nutrient requirements of domestic animals. Washington (DC): National Academy Press. doi: 10.17226/20671

NRC. 1981. Nutrient requirements of goats: angora, dairy, and meat goats in temperate and tropical countries. Nutrient requirements of domestic animals. Washington (DC): National Academy Press. doi: 10.17226/30

NRC. 1982. Brief history of agriculture in the National Academy of Sciences/National Research Council. Washington (DC): National Academy Press. doi: 10.17226/18487

NRC. 1985. Nutrient requirements of sheep. (6th ed.). Nutrient requirements of domestic animals. National Academy Press, Washington, DC.

NRC. 2007. Nutrient requirements of small auminants: sheep, goats, cervids, and New World Camelids. (7th ed.). Animal nutrition series. Washington (DC): National Academy Press. doi: 10.17226/11654

Oliveira, T. S., F. P. Leonel, C. J. Silva, D. F. Baffa, J. C. Pereira, and J. T. Zervoudakis. 2014. Factors affecting feed efficiency in dairy goats. R. Bras. Zootec. 43(10): 524–529. doi:10.1590/S1516-35982014001000003

Provenza, F. D. 1978. Getting the most out of blackbrush. Utah Sci. 39 (4):144–146.

Regadas Filho, J. G., L. O. Tedeschi, A. Cannas, R. A. Vieira, and M. T. Rodrigues. 2014. Using the small ruminant nutrition system to develop and evaluate an alternative approach to estimating the dry matter intake of goats when accounting for ruminal fiber stratification. J. Dairy Sci. 97:7185–7196. doi:10.3168/jds.2014-8632.

Sahlu, T., A. L. Goetsch, J. Luo, I. V. Nsahlai, J. E. Moore, M. L. Galyean, F. N. Owens, C. L. Ferrell, and Z. B. Johnson. 2004. Nutrient requirements of goats: developed equations, other considerations and future research to improve them. Small Rumin. Res. 53 (3):191–219. doi:10.1016/j.smallrumres.2004.04.001

Seo, S., L. O. Tedeschi, C. G. Schwab, and D. G. Fox. 2006. Development and evaluation of empirical equations to predict feed passage rate in cattle. Anim. Feed Sci. Technol. 128 (1–2):67–83. doi:10.1016/j.anifeedsci.2005.09.014

Tedeschi, L. O. 2019. Mathematical modeling in ruminant nutrition: approaches and paradigms, extant models, and thoughts for upcoming predictive analytics. J. Anim. Sci.:(Submitted).

Tedeschi, L. O., A. Cannas, and D. G. Fox. 2010. A nutrition mathematical model to account for dietary supply and requirements of energy and nutrients for domesticated small ruminants: the development and evaluation of the Small Ruminant Nutrition System. Small Rumin. Res. 89 (2–3):174–184. doi:10.1016/j.smallrumres.2009.12.041

Tedeschi, L. O., A. Cannas, S.G. Solaiman, R. A. M. Vieira, and N. K. Gurung. 2012. Development and evaluation of empirical equations to predict ruminal fractional passage rate of forages in goats. J. Agric. Sci. 150: 95–107. doi:10.1017/S0021859611000591

Tedeschi, L. O., and D. G. Fox. 2018. The ruminant nutrition system: an applied model for predicting nutrient requirements and feed utilization in ruminants. (2nd ed.). Acton (MA): XanEdu.

Zhang, X., W. Wang, F. Mo, Y. La, C. Li, and F. Li. 2017. Association of residual feed intake with growth and slaughtering performance, blood metabolism, and body composition in growing lambs. Sci. Rep. 7:12681. doi:10.1038/s41598-017-13042-7