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Growth models and their application in precision feeding of monogastric farm animals

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The dichotomy between developed and developing countries was observed not only in asymmetric human population growth, but also in increasing demand for animal products revolving around poultry and pigs in developing World. Modern livestock industry has adopted innovative technologies to improve the biological efficiency of animal production and feeding, and for this purpose different mathematical models have been applied. In this review, the authors summarize the growth models, briefly introduce the principles of precision feeding and provide evidence that models are key elements of these systems. Modelling is an excellent tool to help in understanding and to predict the animal's response to different farm conditions. Models comprise of equations set describing nutrient flows and animal response. They are essential elements of precision livestock farming system being the basis of the decision support tool since, from yesterday's data, they provide today what happens tomorrow. Precision farming adopts real-time monitoring systems collecting serial data about individual or group of animals. However, without a well-defined goal-oriented data process, data by itself are not useful to farmers. Available and newly recorded data can be converted to valuable information for management purposes through models applied in farming systems. Nutritional models are integrated part of those systems; therefore, growth modelling is a key tool to improve the efficiency and sustainability of livestock production systems.

Keywords: precision feeding, mathematical models, pig, broiler, production efficiency

1 Introduction

The meat production and consumption have tripled in developing countries in the last two decades due to their rapid economic growth. It has been mainly attributed to poultry and pig sector since meat production of those species requires relatively short time and they have high feed efficiency compared to other farm animals (OECD-FAO, 2017-2026). It has to be noted, however, that they compete with human nutrition in terms of using grains and protein feeds while producing high biological value and nutritious food products.

In global, animal health and welfare, product quality and security, environmental impact of animal farming, consumer and citizen expectations are crucial in high-quality animal origin food production. Precision livestock farming (PLF) is often referred as the solution to those challenges because it seems promising to provide increasing amount of food with a low environmental impact and waste. Given the society demand for more sustainable productions, there is the need to look for specialized employees and sometimes there is a lack of skilled workers willing to perform even simple tasks. In fact, agriculture production is still the key in rural development. Adoption of PLF systems has increased in the last decade, however compared to precision crop production, it is still in the early phase of its development. The principle of precision agriculture is to use real-time, reliable information to support the transition towards maximizing efficiency and sustainable production. Thus, PLF relies on real-time monitoring and management system that focuses on improving the life and welfare of the animals by warning when problems arise, but also helps in organising on-farm routine (Berckmans,

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2015). Progress in PLF has been made possible by the significant improvements achieved in computer processing power and the availability of different sensor technologies. Precision feeding (PF) has been called information intensive nutrition (Sifri, 1997), since the animals are fed according to their actual requirement that is depending on multiple factors, including the genetic and environmental conditions. The PF relies on feeding techniques to match nutrient supply precisely with the nutrient requirements of individual animals, includes greater economic returns, reduces excretion to the environment, and improves efficiency of resource utilization.

Modern livestock farming has adopted innovative technologies to improve the biological efficiency of animal production and animal feeding, and for that purpose different mathematical models have been applied. In this review the authors summarize the growth models, briefly introduce the principles of precision feeding and provide evidences that models are key elements of these systems. Examples are given on monogastric farm animals, particularly of meat producers as pigs and broilers.

2 Mathematical models to simulate animal grow

Determining the nutrient requirements of different genotypes, particularly of the intensively selected lines, has always been the focus of interest, as feeding costs account for a significant portion of the total breeding costs being nearly 70%. For more sustainable and economic production, the nutrient requirement, particularly the amino acid and phosphorus requirements should be adequately fulfilled. The breeding companies have nutritional recommendations for different genotypes, however for safety reasons they often overestimate the real requirements. This results in a more expensive feed cost that may have a huge impact on the financial returns of the production. Scientific bodies like National Research Council have published their recommendations since decades, however updates do not occur frequently (recent nutrient requirement tables dated 1998 and 2012 for pigs, and 1994 for poultry). Consequently, those reference values are less relevant over time and they represent an average requirement while, as mentioned earlier, in PF systems the feed is continuously adjusted to the actual requirements. Thus, in PF systems the nutrient requirement of the animals in each day has to be known, and the daily allowance is estimated by dynamic growth models.

Growth models have been developed since decades by researchers working in the field of animal nutrition. They are a set of equations to describe nutrient metabolism through nutrient flow mechanisms resulting in the growth process. Thus, nutritional models, which include growth models, represent the animal's response to a given feed or certain feeding strategy, as well as show their usefulness for feed evaluation in terms of net energy yielding potential in different species and physiological status of farm animals. The input parameters are related to the animals (such as rate and dynamics of protein deposition), to the feed (content of digestible nutrients), and in some cases to the environmental conditions such as ambient temperature, humidity and stocking density. Outputs are usually the protein and fat deposition, the body gain, the body weight and composition at each day of the simulation, as well as feed conversion ratio. Depending on the objective of the model, specific traits such as fatty acid composition (Lizardo et al., 2002), anatomical body composition (Halas et al., 2004), or the nitrogen and phosphorus excretion can also be predicted (Kebreab et al., 2009; Halas et al., 2017; Dukhta et al., 2019).

There are different approaches to represent the transformation of the feed to animal product, but all of them differentiate between the efficiency of nutrient transactions and whether the nutrients are used for maintenance or deposition. The level of aggregation of the different models are variable, they are combination of nutritional-physiological-biochemical theory representations and conceptual equations (France and Thornley, 2007; Dumas, 2008; Black, 2014; Halas et al., 2018). The more detailed and lower level of aggregation is represented (e.g. biochemical pathways or homeostatic-homeorhetic regulation represented by Sauvant, 1994) the more mechanistic the model is. Those models are generally aimed to improve our understanding of the behaviour of a biological system. The first model on biochemical basis for nutrient partitioning and metabolism in monogastric animals was developed by Schulz (1978). This approach has been later adopted in models for ruminants (young sheep by Gill et al., 1984; beef cattle by France et al., 1987; lactating cows by Baldwin and Gill, 1987), as well as for pre-ruminant calves (Gerrits et al., 1997), sows (Pettigrew et al., 1992), growing pigs (Halas et al., 2004), and humans (Coles et al., 2013). Biochemical based nutritional models compound metabolite pools and tissue pools, often called compartmental models. The transactions between different pools are defined by rate:state formalism and the mass of a pool is calculated by differential equation. The partitioning of nutrients between different pathways is usually expressed by assuming first-order or saturable enzyme kinetics. In this way, priorities for nutrient partitioning are set by the relative values of maximum velocity parameters and affinity or inhibition constants. Not all biochemical pathways can be represented, simplifications are needed focussing on the most relevant nutrient pathways, referred to as “pivots” (van Milgen, 2002). Though, biochemical based compartmental approach is very detailed and explanatory, it is difficult to adopt to real-time environment. It is often acknowledged that although a certain approach is biologically more appropriate, the difficulty in obtaining relevant and accurate information to quantify these processes even compromise its application. Likely this is the reason – at least partly – why in precision feeding systems the factorial, bioenergetic-based nutrient partitioning models are used (for pigs: Black et al., 1986; Moughan et al., 1987; Whittemore, 1987; De Lange et al., 2001; Milgen et al., 2006; for poultry: Emmans 1981; Emmans and Fisher, 1986; Emmans, 1989; Johnston and Gous, 2006). Those are principally based on the first pig model developed by Whittemore and Fawcet (1974 and 1976). In this type of models, the dietary energy and amino acids are used for maintenance and retention with nutrient specific efficiency. The protein deposition (PD) depends on the genetic potential often represented by Gompertz function, and the available amino acid and energy supply. Those models use linear-plateau function to describe the relationship between PD and energy intake. The PD is always simulated as an independent phenomenon, lipid deposition (LD) derived from the nutrients not used for maintenance and PD. In the model of de Lange et al. (2001) a minimum LD to PD ratio is applied that differs in various genotypes, therefore not only the PD, but also the minimum LD is defined as a trait of the animal. In other models the LD is independent of the genotype, but the voluntary feed intake (FI) is an animal trait. In many models (Whittemore and Fawcett, 1976; Moughan et al., 1987; de Lange et al., 2001; van Milgen et al., 2008; NRC, 2012) the FI is an input variable calculated by an algorithm based on the body weight. In these models all energy not used for PD or for maintenance will accumulate in body lipids. In other models the FI is regulated by the concept of “desire to eat”, and thus it is determined by the genetically determined (desired) PD and LD (Black et al., 1986; Emmans, 1981; Emmans and Fisher, 1986; Emmans, 1989; Johnston and Gous, 2006). Thus the body composition has an impact on daily FI in those referred models. However, it seems neither of the approaches gives a proper estimation, since as discussed by Black (2014) the prediction of FI is one of the gaps in which the models should be improved.

As mentioned above, models can be used to improve our understanding on the animal response and to evaluate different scenarios. However, in general, mathematical models are not easily accessible for end-users. Although described and published in scientific journals, these models are typically written in specific programming languages and the source code of the model is not always made public with the publication. Only some models have been integrated into software (AUSPig, InraPorc, EFG, Avinesp, INAVI, FeedUtiliGene), thus are available for the practitioner.

Nutrient curves of dynamic growth models are proper for determination of the actual nutrient requirement of the animals. However, it has to be noted that response of animal to the nutrient supply is curvilinear and feeding the animals to the requirement may not be the optimum economical solution (Morris, 2006). Therefore, knowledge of the animals’ response to a limiting nutrient supply is as important as knowledge of the requirement itself. Growth models can be used effectively to identify an appropriate strategy for grower-finisher pigs and broilers, by evaluating different management and feeding strategies and comparing observed performance to the predicted outcomes. However, the optimal feeding strategy may depend on local market conditions (e.g. target live weight or carcass weight, carcass quality), farm rotation system, as well as feed and labour costs. Based on input and output data, economic analyses of alternative feeding strategies can be assessed, which are essential in decision-making (de Lange and Schreurs, 1995). Even in the 1970s and 1980s, the available growth models were adapted to simulate animal performance and through that to assist decision making on farms (Black, 2014). At that time there were no monitoring systems available to integrate the growth models to the day-by-day farm management, therefore those models and software were used for long almost exclusively in strategic decision making.

3 Growth models in precision livestock feeding

The concept of PF is clear to feed the animals according to their actual requirement, but it is quite challenging to adopt the concept to farm situation. There are at least three components which are crucial and need to be considered: (i) to determine frequently the nutritive value of the feed with high precision, (ii) to estimate the nutrient requirement of the animals, and (iii) to adjust the feed to fulfil the actual nutrient requirements based on the actual FI.

Mathematical models developed for PF have been designed to operate in real-time using actual measure (Pomar and Remus, 2019). In order to fit the diet to the actual requirements, an integration of three main steps is needed: (i) automatic data collection, (ii) data processing and analysis, and (iii) actions concerning control of the system (Banhazi et al., 2012). Modelling is an essential mid-step, thus it plays an important role into connection of the observed data and may influence further actions to undertake. The minimum required measures are the body weight and the FI in each day. Based on these data, the FI and the nutrient requirement for anticipated gain can be predicted. Several attempts have been made to precisely estimate the FI for the next day, however, it appears to be a multifactorial trait and the individual variation in day-by-day FI is high. Therefore, up to now empirical algorithms have been applied to estimate the expected individual body weight, FI and weight gain in PF systems (Hauschild et al., 2010; Meda et al., 2015). Whereas a mechanistic model component uses these three estimated variables to calculate the optimal concentration of nutrients, particularly the daily lysine content in pigs or broilers diet (Hauschild et al., 2010; Dusart and Meda, 2017). There are individual PF systems in pigs that can handle the individual variance within the herd. The system recognizes the animal's radio frequency identification when pig enters the feeder. Through precise estimation of the dynamic nutrient requirement of a pig, it is possible to formulate diets with day-by-day adjustments to the actual requirements, but this requires specific feeding systems. The feed is mixed according to the feeding history and body weigh records of that pig and offered in small portions (the portions are different in different feeders, but it can be even 15-25 g; Pomar et al., 2011). The pig receives the feed as long as it desires to eat the meal. The number of blended feeds determines how many of nutrients can be adjusted. If two feeds are blended than Lysine to net energy ratio can be optimized in time. The more nutrients are ought to be adjusted the more routine calculation is complicated. At least two (pre)mixed feeds are blended, one that is desired at the beginning of the phase for the best animal (high nutrient density), and the other that covers the nutrient needs at the end of the feeding phase for the least grower (low nutrient density feed; Pomar et al., 2011). In this way, not only the change in nutrient requirement over time can be controlled, but also the variation between animals can be handled and thus the efficiency of nutrient utilization can be maximized in each animal, and therefore in the herd.

It has been confirmed that individually tailor-made diets reduce the feeding cost by more than 8% due to the smooth curve of lysine intake, as well as nitrogen and phosphorus excretion by nearly 40% and greenhouse gases emission by 6% in pigs, while there is no difference in final body weight (Pomar and Remus, 2019). Another benefit of the individual feeding is that the animals are slaughtered at the optimal weight, and with predictive models the timing of transport to slaughterhouse can be well managed. In poultry, individual care has not been applied in the practice and it seemed as a faraway system in commercial broiler farming routine. However, recently precision feeding tool prototypes that can measure and record individual FI and body weight of identified birds using implanted radio frequency identification chip has been developed for broiler breeders (Zuidhof et al., 2018) and meat producing birds (Berger et al., 2019). The system recognizes the individuals with radio frequency identification reader for each visit to the feed station. Unlike commercial broilers, which have access to the feed ad libitum, breeder birds are restrictedly fed. Obviously, those individual feeder prototypes for broilers still have to be improved for the highest technological readiness level as well as reach an affordable price suitable for commercial poultry farms. Nowadays, PF system for broilers operates on the flock/barn level by integrating models predicting FI, future daily gain, and the requested dietary nutrient requirement (Meda et al., 2015). However, the feeds are blended in different ways to be proportionally combined for each day of a specific phase (Dusart and Meda, 2017). The premixes are the one that fits the requirement of the flock at the beginning of the first phase (premix A) and the one that is demanded at the end of the same phase (premix B). In the coming phase premix B is blended with a premix C that is formulated according to the requirements at the end of the next phase. According to the principle in pigs, the feed that contains the nutrient needs of the flock is suitable for some birds, yet the majority of the flock is oversupplied while a minority is undersupplied. In this way, the birds at a lower growth rate cannot achieve maximum efficiency. Compared to pigs, the individual vs. flock based tailor-made feeding probably makes less improvement in farm efficiency, since a broiler flock due to its shorter lifetime has lower heterogeneity. Nevertheless, a next-generation system for providing a variety of nutrient specifications to tailor both the amount and composition of the feed to each bird's needs is being manufactured (Zuidhof, 2020).

4 Further model applications

By its nature growth models are essential and integral parts of PLF systems. They are the basis of the decision support tool, since from yesterday's data they provide today what happens tomorrow.

Therefore, application of mathematical models improves the safety and flexibility of the production in terms of economy (Halas et al., 2018). They are helpful if certain condition changes, for instance during heat stress when FI reduces. At high environmental temperature, the animals refuse to eat due to their heat imbalance. Therefore, it is feasible to offer more concentrated diets to compensate the negative effect of high temperature on the performance. Comparison of simulated and observed performance gives the possibility to check if there is any health, management, or other problem. Thus, growth models can be integrated into early warning systems. According to Pomar et al. (2019), animal models must be further developed and integrated with new and existing smart machines designed to deliver precisely the right amount of the right feed to the right animal at the right time. The implemented models can be permanently refined as new data emerge, due to the fact that datasets from more frequent sampling protocols are available (such as data collection on growth, behaviour and production performance) in a continuous and automated way (Oviedo-Rondón, 2015). Continuous collection of more datasets and development of more reliable models might help to achieve the goals of global food security.

5 Conclusions

Precision farming adopts real-time monitoring systems collecting serial data about individual or groups of animals. However, without a well-defined goal-oriented data process, data by itself are not useful to farmers. Available and newly recorded data can be converted to valuable information for management purposes through reliable models applied in farming systems. Growth models are integrated part of the PLF systems and through them the nutrient supply of farm animals can be optimized. Therefore, modelling is a key tool to improve the efficiency and sustainability of livestock production systems.

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