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A model of milk production in lactating dairy cows in relation to energy and nitrogen dynamics

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ABSTRACT

A generic daily time-step model of a dairy cow, designed to be included in whole-system pasture simulation models, is described that includes growth, milk production, and lactation in relation to energy and nitrogen dynamics. It is a development of a previously described animal growth and metabolism model that describes animal body composition in terms of protein, water, and fat, and energy dynamics in relation to growth requirements, resynthesis of degraded protein, and animal activity. This is further developed to include lactation and fetal growth. Intake is calculated in relation to stage of lactation, pasture availability, supplementary feed, and feed quality. Energy costs associated with urine N excretion and methane fermentation are accounted for. Milk production and fetal growth are then calculated in relation to the overall energy and nitrogen dynamics. The general behavior of the model is consistent with expected characteristics. Simulations using the model as part of a whole-system pasture simulation model (DairyMod) are compared with experimental data where good agreement between pasture, concentrate and forage intake, as well as milk production over 3 consecutive lactation cycles, is observed. The model is shown to be well suited for inclusion in large-scale system simulation models.
Key words: dairy cow, model, lactation, energy dynamics

INTRODUCTION

Milk production in dairy cows has been modeled at various levels of complexity, from detailed biophysical processes to empirical lactation response curves. The widely used and detailed Californian model of the lactating dairy cow Molly (Baldwin et al., 1987a,b,c; Baldwin, 1995) has 2 main modules that describe rumen processes and postabsorptive metabolism, providing insight into the metabolic processes fundamental to milk production. At a more fundamental level, individual models of rumen and mammary gland function can provide insight into the behavior of the underlying biochemical function relating to milk production (Neal and Thornley, 1983; Hanigan et al., 2001, 2002). At the other end of the spectrum, descriptive empirical curves are used to describe the lactation response following calving. These curves can be used for analysis of the time-course of milk production or for assessing feed requirement throughout the lactation cycle, although they contain little or no underlying mechanistic processes (Rook et al., 1993). Perhaps the most widely used lactation curve is the Wood equation (Wood, 1967), which uses the gamma function, although other equations are reviewed in Thornley and France (2007), which also provides a detailed discussion of dairy models in general.

A dairy farm typically represents a complex system with different interacting components. Generally, whole-farm approaches distinguish at least an animal component and a soil-crop component, and the models constructed are designed to give accurate representation of animal production, internal cycling of materials, and exchange between the farm and the environment (Schils et al., 2007b). Several whole-farm models exist to simulate milk production and related aspects such as grazing behavior and greenhouse gas emissions from dairy farms [e.g., DairyWise (Schils et al., 2007a), FarmGHG (Olesen et al., 2006), MINDY (Gregorini and Hanigan, 2012), and $\mathrm{SIMS_{DAIRY}}$ (Del Prado and Scholefield, 2006)]. Proponents of these models demonstrate the ability to simulate a range of conditions and predict well. However, it is difficult to reproduce and verify their findings independently as concise mathematical descriptions are generally not readily accessible from mainstream literature.

Our focus is not only on milk production, but the interactions between the grazing animal and whole-system dynamics, including pasture production and utilization, N dynamics, and system management. This

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requires a model that has appropriate mechanistic detail to describe the necessary biophysical processes, while being sufficiently tractable to allow inclusion in whole-system models. We describe an energy-driven model of lactation and N dynamics in dairy cows that includes both lactation and pregnancy. The model is an extension of the animal growth model of Johnson et al. (2012). It has been developed as an integral part of DairyMod (Johnson et al., 2008), which is a biophysical whole-farm simulation model of dairy pasture systems incorporating pasture growth and utilization, water dynamics, soil organic matter and N dynamics, animal growth, and metabolism, as well as milk production. The model has flexible multi-paddock management options, feeding regimens incorporating pasture, concentrate, forage, and TMR. The model, along with the SGS Pasture Model (Johnson et al., 2003), which is a livestock production model with the same underlying biophysical core, has been applied extensively in Australia and New Zealand, and other locations, to address a range of research questions such as the effects of climate variability, drought, business risk, and climate change on pasture production (e.g., Cullen et al., 2008). A primary objective in developing the model has been to ensure that each module has been constructed at a similar level of complexity, which allows us to explore the behavior of each component in the system and their interactions in a consistent manner. Although the model described here for milk production and N dynamics in dairy cows has been developed as an integral part of DairyMod, it will be suited to any whole-system dairy simulation model.

We first describe the model structure, with full mathematical description of the underlying processes, and then look at the general model behavior, including pregnancy, lactation, and N dynamics including partitioning between dung and urine to demonstrate the structural consistency in model behavior. This is followed by an analysis of a 3-yr period of a whole-farm dairy system that has been previously published (Chapman et al., 2014a,b; Hill et al., 2014; Tharmaraj et al., 2014).

METHODS

Animal Care and Use Committee approval was not obtained for this study because no animal experimentation was conducted.

Model Overview

The model is an extension of the animal growth model described by Johnson et al. (2012), which describes animal growth and energy dynamics in sheep and cattle in relation to available energy. Animal mass comprises protein (W_P), water (W_H), and fat (W_F), with protein being the primary indicator of metabolic state, whereas fat is a potential source of energy for metabolic processes. Model variables are defined in Table 1, and parameters, with default values, are defined in Table 2. Parameter values will vary between different animal types and species, and our default values are the values we use for illustrations and analysis, unless we specifically mention otherwise. The total body weight is W, and all body components have units in kilograms, so that

$$W = W_P + W_H + W_F, \tag{1}$$

Protein and water are assumed to be in fixed proportion, with

$$W_H = \lambda W_P, \tag{2}$$

where λ is a dimensionless constant with default value 3. Thus, W can be written

$$W = (1 + \lambda)W_P + W_F. \tag{3}$$

The growth of protein is defined using a Gompertz equation in its derivative form, so that it defines growth rate, not actual BW (for a discussion, see Thornley and France, 2007), with actual protein growth dependent on protein mass and available energy. Fat growth is secondary and depends on the current protein mass and is constrained to a maximum potential fat fraction of total BW. Protein degradation occurs so that energy is required for protein resynthesis (that is, the maintenance of existing protein). Energy is also required for activity, which, combined with that for protein resynthesis, defines the total maintenance energy requirement. This approach to defining energy required for activity is also assumed to include any significant costs associated with thermoregulation. A normal fat proportion is defined, which increases during growth. If the energy is not sufficient for protein and fat growth, after accounting for maintenance, then fat growth will be reduced. Conversely, if the energy available exceeds maintenance and normal protein and fat growth requirements, then excess growth occurs solely in the fat component. The model was demonstrated to give realistic growth dynamics for animal BW and components under a range of available energy conditions (Johnson et al., 2012).

Central to the model structure is the relationship between available energy and growth of body compo-

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