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The challenges – and some solutions – to process-based modelling of grazed agricultural systems☆

V.O. Snow [a,*], C.A. Rotz [b], A.D. Moore [c], R. Martin-Clouaire [d], I.R. Johnson [e], N.J. Hutchings [f], R.J. Eckard [e]

[a] AgResearch – Lincoln, Private Bag 4749, Christchurch, Lincoln 8140, New Zealand
[b] USDA-Agricultural Research Service, University Park, PA 16802, USA
[c] CSIRO Sustainable Agriculture Flagship, GPO Box 1600, Canberra, ACT 2061, Australia
[d] INRA, UR 875, MIAT, 31326 Castanet Tolosan, France
[e] School of Land and Environment, University of Melbourne, Vic. 3010, Australia
[f] Aarhus University, Department of Agroecology and Environment, Tjele, Denmark

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A B S T R A C T

Pastoral systems are characterised by a number of features that are absent in arable cropping systems. These features include: (i) pastures are biologically diverse so interactions between plant species must be considered; (ii) economic return requires the inclusion of the animal as an additional trophic level; (iii) interaction between the grazing animal and the pasture is complex, influenced by the environment, plant species and animal behaviour and this creates feedbacks that can result in vicious cycles; (iv) animals spatially transfer substantial amounts of nutrients both randomly and systematically and this creates or exacerbates soil variability; and (v) whole farm management is both more complex and more important to system function in grazed compared to arable systems and it is harder to capture in simulation models. These challenges complicate the process-based modelling of pastoral systems and present significant obstacles to model developers and users.

Here we discuss these challenges, describe the range of solutions used by different models and discuss the strengths and weaknesses of these solutions. We have placed particular emphasis on the analysis of a range of possible solutions with the point of view that diversity between and within models is important to provide the flexibility needed for future uses.

We find that for most challenges there is a diversity of solutions incorporated into the models and that there is the potential to capture additional diversity, if needed, from other models. We note an apparent lack of development in the modelling of extreme events such as very high temperatures, systematic animal-mediated nutrient transfers, pests, weeds and gene-environment interactions in pastoral simulation models and suggest that these subject areas should receive more attention.

1. Introduction

Grasslands occupy 25% of the terrestrial surface (Lemaire et al., 2011) or about 70% of the world agricultural area (FAO, 2013). They contribute to the livelihoods of over 800 million people (Reynolds et al., 2005) and so have an important role to play in satisfying the increasing demand for high-quality protein (Steinfield et al., 2006). Given their extent, grasslands are a crucial system to consider when evaluating local or global issues related to sustainable management, especially in the face of on-going land-use changes and climatic uncertainty. At the scale of the individual farmer, efficient usage of the home-grown pasture resource is also important. For example, Dillon et al. (2008) summarised data from several countries and showed that the costs of milk production decreased as the proportion of grazed pasture in the diet increased. Also Peyraud (2011) and Rotz et al. (2009) found that increasing the use of grazed pastures on dairy farms could improve their environmental sustainability by reducing leaching or gaseous emissions and energy use.

Although grazing-based farming systems are often considered to be relatively environmentally benign compared to many other farming types, they have been following the general trend of

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* Corresponding author.
E-mail address: Val.Snow@agresearch.co.nz (V.O. Snow).

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agricultural activities with increasing usage of imported nutrients. This importation of nutrients results in an intensification of the farm system, usually through increased stocking rate, and causes increased nutrient losses (Ledgard et al., 1999; Tilman et al., 2002). Thus it is important to consider the environmental performance of pastoral faming systems as well as the ecosystem services that they provide (Lemaire et al., 2011). Environmental pressures on farming systems coincide with continuing cost-price pressures and this places additional demand on the ability of research and extension to evaluate and promote new technologies to improve the financial and environmental performance of pastoral agricultural systems. Simulation modelling has an important role to play in understanding and quantifying the relationships, or trade-offs, between farm inputs, farm management and the production and environmental outputs from the farm but robust simulation models are needed for that endeavour.

Agricultural systems that include grazing ruminants are characterised by a number of features that are not present in arable cropping systems and which present challenges to the experimentation, understanding and simulation modelling of these systems. We consider the major challenges to include:

i. biologically diverse vegetation is usually the desired state of affairs (Duru et al., 2013) and so interactions between plant species must be understood and managed;
ii. economic returns are largely derived from animals rather than directly from plant production and there are multiple economic yields (milk, meat, fibre and cash crops) with trade-offs between them (Harrison et al., 2011);
iii animals interact with the pastures through their grazing behaviour and selective harvesting of the pasture on offer and this causes a feedback on pasture processes and performance (Schulte et al., 2003; Noy-Meir, 1976);
iv. animals are mobile and so substantial quantities of nutrients can be transferred across space (Whitehead, 1995) and these transfers substantially affect soil and plant processes (Haynes and Williams, 1993); and
v. because of the interactions created by the points above, it is important to consider the management of the grazed system at the whole-farm (compared to single-paddock) level.

These challenges add complexity to the process-based modelling of grazed forage systems compared to annual cropping systems, and thus present significant challenges to model developers and users.

Here we discuss these challenges, describe a range of solutions used by different models and the strengths and weaknesses of these solutions. The models reviewed are necessarily a subset of published grassland models but have been specifically selected, considering their origins from different farming systems and perspectives, to encompass a wide range of solutions to the challenges of modelling pastoral systems. This review forms a basis to discuss the available solutions as well as the major challenges not covered adequately and that require further attention. The review is structured by: first describing the models and the model selection process (Section 2); next (Sections 3–7) outlining each of the challenges identified above, how the models address these challenges and possible solutions to the challenges; and concluding (Section 8) with a discussion of the future prospects for process-based modelling of grazed systems.

2. Description of the models

We consider six process-based simulation models that are able to simulate pastoral farming systems (Table 1). The models are all process-based, dynamic and deterministic (although some contain some stochastic descriptions of some processes) and they all include some aspect of spatial heterogeneity. The models have arisen from a range of approaches to simulate farming systems and thus have a variety of development histories. The six models are:

i. the Agricultural Production Systems Simulator (APSIM) (Holzworth et al., in this issue);
ii. DairyMod and the SGS Pasture Model (here considered as a single model and labelled AgMod) (Johnson, 2013);
iii the Discrete Event Simulation Environment (DIESE) (Martin-Clouaire and Rellier, 2009);
iv. the Farm Assessment Tool (FASSET) (Berntsen et al., 2003);
v. GRAZPLAN (Donnelly et al., 2002); and the
vi. Integrated Farm System Model (IFSM) (Rotz et al., 2013a).

Our purpose is to deliberately sample a diversity of approaches taken in order to understand and learn from the range of solutions that these models have adopted to overcome the challenges. Of the models surveyed:

- GRAZPLAN and AgMod arise from the grazing-focussed farming systems of the Southern Hemisphere while DIESE, FASSET and IFSM arise from the Northern Hemisphere farming systems with a strong component of animal housing, APSIM comes from Southern Hemisphere cropping systems;
- DIESE is a very generic, and APSIM a somewhat generic, simulation platform while the others are more purpose-specific;
- FASSET considers pigs as well as ruminants, IFSM and AgMod have particular strength in dairy systems, GRAZPLAN has greatest strength in mixed crop-livestock systems and APSIM is only recently moving into the pastoral systems space; and
- APSIM has an international user base while most of the others have a national or regional focus.

Some of the notable models not included above include: the DairyNZ Whole Farm Model (Beukes et al., 2008) which is largely constructed by drawing together elements of existing models; PaSim (Graux et al., 2011; Ma et al., in this issue), PROGRASS (Lazzarotto et al., 2009) and CLASS PGM (Vaze et al., 2009) which operate at the paddock level; and GPFARM (Ascough et al., 2010; Qi et al., 2012) which focuses on the dryland range and cropping systems of the USA. Readers are also referred to a recent review by Del Prado et al. (2013) focussing on models for greenhouse gas issues in pastoral systems. We consider that, for the most part, these models employ solutions within the range of those used in the six models upon which we will focus. We will note, however, other models where they present solutions of particular interest.

The six models included in this review are in active development and use and this activity can result in a temporal fluidity of model descriptions. The information below and in the “Current approaches” parts of Section 3 is based on the authors' knowledge of the current state of the models as well as on both unpublished and published material and so supersedes previously-published information. One example of that fluidity is that since the development of the Common Modelling Protocol (Moore et al., 2007) there has been a move towards integrating the Agricultural Production Systems Simulator and GRAZPLAN (Moore, 2009). That integration is not yet complete and here they are treated as separate models.

The sections below give a brief description of each of the six models and Table 1 summarises each model.

2.1. APSIM – Agricultural Production Systems Simulator

The Agricultural Production Systems Simulator (APSIM; www.apsim.info) (Holzworth et al., in this issue) is a flexible modelling