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

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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 (Steinfeld 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...
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 farming 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 in 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 of particular interest.

The six models are:

i. the Agricultural Production Systems Simulator (APSIM) (Holzworth et al., 2014);

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 Reilli, 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-focused 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), PROGRASS (Lazzarotto et al., 2009) and CLASS PGM (Vaze et al., 2009) which operate at the paddock level; and CPFARM (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. 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:

2.1. APSIM — Agricultural Production Systems Simulator

The Agricultural Production Systems Simulator (APSIM; www.apsim.info) (Holzworth et al., 2014) is a flexible modelling
<table>
<thead>
<tr>
<th>Name</th>
<th>Agricultural Production Systems Simulator</th>
<th>DairyMod and the SGS Pasture Model</th>
<th>Discrete Event Simulation Environment</th>
<th>Farm Assessment Tool</th>
<th>GRAZPLAN</th>
<th>Integrated Farm System Model</th>
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<tbody>
<tr>
<td><strong>Software availability</strong></td>
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<tr>
<td><strong>Acronym</strong></td>
<td>APSIM</td>
<td>AgMod</td>
<td>DIESE</td>
<td>FASSET</td>
<td>GRAZPLAN</td>
<td>IPSM</td>
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<td><strong>Developer/Owner</strong></td>
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<td>IMJ Consultants Pty Ltd; University of Melbourne; Meat and Livestock Australia; Dairy Australia</td>
<td>J-P Rellier, R. Martin-Clouaire</td>
<td>Aarhus University, Faculty of Science and Technology, Department of Agroecology</td>
<td>CSIRO</td>
<td>USDA-ARS</td>
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<td><a href="mailto:jpm.djf@agrsci.dk">jpm.djf@agrsci.dk</a></td>
<td><a href="mailto:grazplan@csiro.au">grazplan@csiro.au</a></td>
<td><a href="mailto:arotz@ars.usda.gov">arotz@ars.usda.gov</a></td>
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<tr>
<td><strong>Hardware required</strong></td>
<td>Any recent PC with a minimum of 2 Gb of RAM, 32 or 64 bit</td>
<td>Minimum 4 GB RAM recommended.</td>
<td>Any recent PC</td>
<td>PC with 2 GB RAM, 32 or 64 bit</td>
<td>As for APSIM</td>
<td>Any recent PC, 32 or 64 bit</td>
</tr>
<tr>
<td><strong>Operating system</strong></td>
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<tr>
<td><strong>Language</strong></td>
<td>C#.NET, VB.NET, FORTRAN, C++</td>
<td>Delphi</td>
<td>C++, Java (interface)</td>
<td>C++</td>
<td>Object Pascal</td>
<td>Fortran, C++</td>
</tr>
<tr>
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<td>Free for non-commercial use</td>
<td>Free for non-commercial use</td>
<td>Free for non-commercial use</td>
<td>AUD132 to 1452 depending on the implementation</td>
<td>Free for non-commercial use</td>
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<tr>
<td><strong>Challenge: complex mixtures of forages</strong></td>
<td>Ecotypes</td>
<td>Ecotypes</td>
<td>Individual species</td>
<td>Individual species or cultivars</td>
<td>Depends on user choices</td>
<td>Depends on user choices</td>
</tr>
<tr>
<td><strong>Challenge: Animals – the additional trophic level</strong></td>
<td>A very simple beef cattle component is fully integrated GRAZPLAN stock can be used</td>
<td>Dynamic model, generic for cattle (dairy or beef) and sheep</td>
<td>Detailed model of dairy cow</td>
<td>Dairy cattle and pigs</td>
<td>Beef or dairy cattle, sheep</td>
<td>Dairy or beef cattle</td>
</tr>
<tr>
<td><strong>Challenge: Managing the whole farm</strong></td>
<td>Highly customised for housed &amp; grazed dairy farms, includes a linear program for rations</td>
<td>Capable of simulating very detailed management events/actions</td>
<td>Capable of simulating very detailed management events/actions</td>
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framework in which a defined protocol (Moore et al., 2007) is used to link models of soil processes (water, C, N, P) with one or more plant crops (many annual and perennial species including some tree crops) and the weather and management rules (Moore et al., 2014) needed to describe a paddock or whole farm. Holzworth et al. (2014) gives the range of crop models currently available but where we are more concerned with crops used in grazed farming systems such as temperate perennial pasture species (Li et al., 2011), lucerne (Verburg et al., 2007) and tropical rangeland species (Bell et al., 2008). Soil water processes and solute movement can be modelled using a first-order layered approach (Probert et al., 1998) or a combination of Richards’ equation and the convection–dispersion equation (Verburg et al., 1996; Huth et al., 2012). The model includes a four-pool organic matter model and the major mineral N processes (Probert et al., 1998). Animal production and interaction with forages are described by the very simple Graz model (Owens et al., 2009; Rickert et al., 2000). APSIM’s heritage is in cropping systems simulation so much of the recent development and validation, relevant to grazed systems, has focussed on soil processes important to urine deposition (e.g. Vogeler et al., 2011; Cichota et al., 2013b) and the interaction between cropping and grazing systems (Bell et al., 2008). The management logic needed to simulate pastoral farms is also used under active development as described in Moore et al. (2014). Also under active development is the integration of the GRAZPLAN model (see below) with APSIM. This integration will substantially strengthen APSIM’s capability in pastoral systems.

2.2. DairyMod and the SGS Pasture Model – AgMod

DairyMod (Johnson et al., 2008) and the SGS Model (Johnson et al., 2003) (here collectively referred to as “AgMod”; www.imj.com.au/consultancy) are biophysical pasture simulation models with a common underlying structure but with user interfaces focussed on either dairying or livestock systems. The model includes pasture growth and utilisation by grazing animals, water and nutrient dynamics and animal production. The graphical interface is designed to allow even novice users easy access to a range of options for the management of pasture, irrigation and fertiliser. The farm comprises many paddocks which can each have different soil types, nutrient status, pasture species, fertiliser and irrigation management. All paddocks are subject to the same weather. A full mathematical description of the model is given in Johnson (2013). The pasture growth model is based on Johnson and Thorneley (1983), although it has been extensively revised – for example the treatment of photosynthesis is now that of Johnson et al. (2010) and the animal component is now based on Johnson et al. (2012). The pasture model has been validated against data from disparate geographical locations in Australia and New Zealand (Cullen et al., 2008; Johnson et al., 2008; White et al., 2008) and used to address questions related to climate change impacts (Cullen et al., 2009) and mitigation (Cullen and Eckard, 2011) and the impact of climate variability on farm business risk (Chapman et al., 2008a).

2.3. DIESE – Discrete Event Simulation Environment

The “Discrete Event Simulation Environment” (DIESE; Martin-Cloaïre and Reillier, 2009) (carlit.toulouse.inra.fr/diese) is a generic modelling framework designed for simulating agricultural production systems. DIESE utilises a rich ontology of agricultural production systems to describe farm management decision processes. Each decision process is described in terms of the activities and resources required to realise, or implement, the decision. Each decision process also includes constraints that affect the relevance and feasibility of the activity, the interdependencies between activities and restrictions on the uses of resources. DIESE has been used to build a number of livestock-related models including MELODIE, SEDIVER and SITEL. MELODIE (Chardon et al., 2012) simulates mixed production systems (crop, dairy and pigs) to investigate nutrient flows and greenhouse gas emissions at the farm level. SEDIVER (Martin et al., 2011b) supports the modelling and simulation of a range of pasture-based livestock systems paying particular attention to the dynamic management of the grassland resources and SITEL (Brun-Lafleur, 2011) is an individual-based dairy cow model that enables study of the impact of farmer’s observation practices on herd management.

2.4. FASSET – Farm Assessment Tool

FASSET simulates ruminant livestock, non-ruminant livestock and arable farms. Reflecting the societal concern to maintain a high level of agricultural production whilst reducing losses of N and greenhouse gases to the environment, the model has focussed on the dynamics of C, N and water within highly-managed farming systems. Nitrogen and C are imported to the farm as livestock, fertiliser, manure or feedstuffs with exportation of N in plant or animal products. The production and excretion of cattle are simulated using a model based on Østergaard et al. (1994) and CSIRO (2007). The fate of C and N in livestock excreta is followed after deposition directly to pasture during grazing or through animal housing, manure storage and field application. Emissions from manure management (ammonia, nitrous oxide, methane) and from soils (ammonia, nitrous oxide and nitrate leaching) are described in some detail. A range of crops are available and include wheat, barley, rape, peas, maize, ryegrass and clover (Berntsen et al., 2003, 2005). Crop mixtures such as grass-clover, barley-pea or grass under-sown into a cereal crop are simulated using explicit representations of the individual crops. Since its original release, developments in FASSET have incorporated the effect of spatially heterogeneous return of dung and urine to pasture (Hutchings et al., 2007) and the simulation of greenhouse gases from arable farming systems (Chirinda et al., 2011; Chatskikh et al., 2008).

2.5. GRAZPLAN

The GRAZPLAN suite of models (Donnelly et al., 2002); (www.grazplan.csiro.au) includes a grassland production and water balance model (Moore et al., 1997) and a ruminant dynamics model (Freer et al., 1997). While mainly used in Australia (Donnelly et al., 2002) the models have also been parameterised for livestock systems in Canada (Cohen et al., 2003) and China (Donnelly et al., 2005). The grassland model employs a multi-species, biomass-based state description and includes logic for capture of light, water and nutrients; assimilation, respiration and allocation of assimilate; death, litterfall and litter breakdown; the dynamics of forage quality; and seed banks. The ruminant model covers sheep, beef and dairy cattle. Its sub-model for energy and protein nutrition is mostly drawn from the Australian feeding standard (CSIRO, 2007). These models are implemented in interfaces for tactical (GrazFeed, Freer et al., 1997) and strategic (GrassGro, Moore et al., 1997) decision support, and also in the research-oriented AusFarm package. The latter two pieces of software contain flexible management sub-models and financial calculators that allow the modelling of a wide range of livestock enterprises that occupy multiple paddocks with differing soils and forages. The crop, pasture and ruminant models are capable of simulating N, P and S dynamics but must be coupled to APSIM, as described in Moore et al. (2007), to complete the nutrient cycle.
2.6. IFSM — Integrated Farm System Model

The Integrated Farm System Model, IFSM (www.ars.usda.gov/Main/docs.htm?docid=8519), was created as a research tool to assess and compare the environmental and economic sustainability of farming systems. Crop and pasture production, feed use, and the return of manure nutrients back to the land are simulated for many years of weather on a crop, beef (Rotz et al., 2005), or dairy farm (Rotz et al., 1999, 2013a). Pasture (Corson et al., 2007) is an available feed that is allocated along with other purchased and produced feeds to meet energy and nutrient requirements of animal groups making up the herd. The quantity and nutrient contents of the manure produced are a function of the feeds consumed and herd characteristics. Nutrient flows are tracked through the farm to predict nutrient losses to the environment and potential accumulation in the soil. Environmental losses include gaseous emissions (Rotz et al., 2013b) and leaching losses of N from soil, erosion of sediment across the farm boundaries, and the runoff of sediment-bound and dissolved P. Carbon, energy, water and reactive N footprints are determined using a farm-gate life cycle assessment of the milk or beef produced. Simulated performance is used to determine production costs, incomes, and economic return for each year of weather. Simulations are normally conducted over a 25-year sample of historical weather, so the resulting distribution of annual predictions represents the effects of varying weather.

3. Complex mixtures of forages

3.1. The challenge

Pastoral farms display a complexity of forage mixtures at both the between- and within-paddock scales. Within-paddock complexity arises because few pastures are, or are desired to be, monocultures (Duru et al., 2010; Hector et al., 2010) but rather are mixtures of grasses, legumes and forbs. Intra-specific competition within crops is usually considered in arable models (Zhang et al., 2012) but, increasingly, arable system models also include consideration of the effects of competition between the crop and weeds (Deen et al., 2003; Whish et al., 2014) and intercropping (Ozier-Lafontaine et al., 1998; Brisson et al., 2004) is becoming more important. Nevertheless, the majority of arable crops are modelled as monocultures. This is not the usual case for pasture models. Although highly fertilised pastures can be nearly monocultures (Whitehead, 1995) and are often modelled as such (e.g. McCall and Bishop-Hurley, 2003) most grazed pastures lie somewhere on the spectrum of totally to somewhat reliant (Ledgard, 2001) on the inputs of biologically-fixed N to replace the N lost through animal off-take and gaseous (volatilisation and denitrification) and leaching losses. This dependence necessitates, at the least, modelling pastures as comprising two functional groups — often a grass and a companion legume. When multiple species are grown, it is necessary to consider the interaction and competition between those crops for above- (primarily radiation) and below-ground (water and nutrient) resources. The challenge is further exacerbated when modelling rangeland systems, where a pasture can have in excess of 20 species all contributing to biomass.

Modelling grasslands, or other crops that contain species mixtures, presents a particular challenge. If a uniform spatial distribution is assumed, small competitive advantages to one species over another will lead to the effective extinction of the disadvantaged species. In reality the spatially heterogeneous disruptions caused by grazing and changes in nutrient availability (Schwingham and Parsons, 1995a) lead to a co-existence. Models can only predict long-term stationary mixtures where spatial or temporal heterogeneity mean that the competitive balance between species varies in space and/or time.
senescence). The integration of these parameters into the model makes it possible to predict herbage biomass accumulation rate under different management practices for a wide range of plant communities differing in their PFT composition. Soil nitrogen processes are not dynamically simulated. Nitrogen supply to the pasture is based on an expert assessment of the site status. MELD model (Chardon et al., 2012) uses the growth model in STICS (Brisson et al., 2003) for forage crops. In this model plant growth and nitrogen processes in the soil are dynamically simulated and competition for resources between species (Brisson et al., 2004) can be included.

3.2.4. FASSET

FASSET simulates all crop and pasture species as individual crops, with competition between species for light, water and N. Competition for light occurs on a layered basis in the plant canopy using the green LAI of each species in each layer. Likewise, the competition for water and N occurs on a layer-by-layer basis in the soil and depends on the root density of each species in each layer. In multi-species pastures under constant environmental and management conditions, experience has shown that one species will always tend to become dominant. However, the suppressed species remains present at all times, albeit with a very low biomass. This means they will rapidly reappear if conditions become favourable. It is, therefore, not possible to simulate situations where one or more species becomes extinct in all or part of the pasture.

3.2.5. GRAZPLAN

Pasture swards may have many species but usually up to five. The biomass of each species is divided into cohorts of seedlings and established plants and also into leaf, stem, reproductive structures and roots; each of the above-ground parts can capture light. Light interception is modelled using two vertical strata to accommodate seedlings and all other plants. A simple Beer’s law approach is used within each stratum, with no horizontal heterogeneity or differential absorption of direct and diffuse radiation. For water uptake, a generalization of the Monteith and Greenwood (1986) scheme to the multi-species case has been derived by assuming that interactions between neighbouring roots are confined to a lozenge-shaped prism between them with a zero-water-flux boundary at the edge of each prism. Nutrient uptake is predicted using the equations of de Willigen and van Noordwijk (1994). In environments with distinct temperature- or water-limited growing seasons, modelled compositional dynamics are also influenced by the survival of roots or seeds to the start of a new season.

3.2.6. IFSM

Pasture swards of up to four plant species (Corson et al., 2007) or functional types are modelled with a daily time step growth model based on soil, nutrient and weather conditions. The initial sward in the spring is a pure stand or designated mixture of C3 grass, C4 grass, legume and forb species where various parameters can be used to describe specific species. The species mixture varies throughout the growing season as influenced by competitiveness for soil moisture, soil N and light. Sward fibre and protein levels are predicted using the stem and leaf production of each species. Although root growth and development are not specifically modelled, plant uptake of moisture and N are controlled by stress factors that are functions of their availability in the soil.

3.3. Potential solutions

The complexity with which forages in pastures are conceptualised can be disaggregated into the level of detail in the individual species' models, how the model deals with the potential multitude of species in the pasture and then how the model deals with the interactions between species. Within the models reviewed here, there is a moderate degree of diversity in the complexity of the individual species models. APSIM’s GRASP is by far the simplest and does not include N dynamics. Neither APSIM’s AgPasture nor the pasture model in AgMod formally consider reproductive organs in the plant structure while the remaining models (MEDLODIE and SEDIVER within DIESE, GRAZPLAN, IFSM and FASSET) have built their forage models with explicit consideration of reproductive organs and contain approximately the same level of detail. Models without formal inclusion of reproductive stems and seed heads are simpler but are unlikely to capture the negative effects of those plant parts on the pasture nutritive value to the animal and the flow-on effect on animal intake rates (see Section 5).

All of the models consider multiple species as might be expected for pasture simulation. APSIM’s GRASP requires the user to implicitly include all species as a single composite and while this removes the need to model the competition effects it places additional burden on the system understanding of the user. The other models either formally consider pasture species as functional groups (e.g. IFSM, SEDIVER) or leave that decision to the model user. The models differ in their approach to modelling the competition between species, but the variation in the description of competition for light is relatively minor compared to the below-ground processes. AgMod treats the species individually and APSIM with SoilWat uses the same approach but rotates the order of calculation each day. All the other models, including APSIM with the Richards’ equation, treat the competition for water and nutrients explicitly and therefore capture the competitive effects more mechanistically.

For routine uses of simulation modelling of grazed systems, the relatively simple approaches described above are likely to be adequate but it is important to ensure that models retain the flexibility to include multiple approaches that account for different levels of complexity in order to address new questions. For example, the simple approach to below-ground competition in APSIM with SoilWat (Deen et al., 2003) and in AgMod have been shown to be adequate in most cases but raise issues when many different species are included in the simulation (Snow et al., 2013) and under highly resource-limited conditions. The simpler approaches to competition might be adequate for most simulations but also might restrict the flexibility necessary to future-proof models. All the models reviewed would struggle to capture the effects of alternate rows of species with varying height, such as Atriplex sp. (saltbush) and an annual species or agro-forestry systems. The below-ground plant parts and simpler descriptions of water and nutrient competition might not be adequate if we wished to investigate the potential for a novel rhizobia that might fix more N but also require additional assimilate to support the nodules. For these reasons, we need a range of approaches available in the simulation models. Model developers and users need to carefully consider when simpler approaches are satisfactory because many of the more complex approaches, such as those in Schwinning and Parsons (1996b) and Lantinga et al. (1999) are very complex indeed. If the model structure requires these very complex approaches to be used for all simulations, this may compromise our ability to capture other important features of grazing systems.

4. Animals – the additional trophic level

4.1. The challenge

Ruminants, primarily cattle and sheep but also buffalo and goats as well as assorted other species, are a key part of pastoral farm systems. The pasture’s plants convert the key inputs or resources of radiation, water and nutrients into a cellulose-dominant dry matter that is indigestible to humans. However, following fermentation processes in the ruminant digestive system, that dry matter can be
transformed into high-quality, from the human perspective, protein in the form of milk, meat and fibre. Given this ability to transform otherwise human-indigestible dry matter into human-digestible, and that grazing lands occupy almost twice the area of cropping land (FAO, 2013), the estimated 3.5 billion farmed ruminants in the world are important to global food security. However they are associated with significant environmental issues (see for excellent overviews, Steinfeld et al., 2006; Lemaire et al., 2011; Kebrab, 2013) including the emissions of the major agricultural greenhouse gas, methane (Beauchemin et al., 2008; Herrero et al., 2011).

In arable farms, the primary economic production arises is in the form of the mature reproductive structures of an annual plant that is harvested once in the plant’s lifetime. In pastoral farms the plant community is generally perennial rather than annual, and is harvested, either directly by the animals or mechanically harvested for delayed feeding, many times during any year. The economic yield is in the form of the amount of milk, meat and fibre harvested from the animals and so it is necessary to model the additional trophic level in the farm to fully capture the complexities of, and feedbacks in, the system.

4.2. Current approaches

4.2.1. APSIM

GRASP (Rickert et al., 2000) is currently the only fully-integrated APSIM-compliant (Moore et al., 2007) animal growth model in APSIM. Animal performance is simulated using a potential growth rate that is limited by the availability of feed. The effect of pasture quality on animal performance is achieved empirically through user-defined potential growth curves for each pasture type (Owens et al., 2009). Nitrogen processes are not considered at all in GRASP. Additional functionality can be achieved through the on-going integration of APSIM with GRAZPLAN.

4.2.2. AgMod

Animal growth and metabolism is as described in Johnson et al. (2012) and adapted to include pregnancy and lactation as well as responses to mixed rations of forages and concentrates (Johnson, 2013). Body protein, water, and fat are modelled as separate pools and the protein component is subject to turnover that requires reserves for re-synthesis of degraded proteins. Maintenance and energy required for activity takes precedence over growth of new tissue. New growth of fat depends on current protein weight, as well as the maximum potential fat fraction of body mass. Energy dynamics in the animal are affected by the digestibility of the feed and also include costs for excreted urine N and dung (Emmans, 1994, 1997; Bell et al., 2013). Methane emissions are assumed to be a fixed proportion of digestible energy intake at a reference neutral detergent fibre content of the feed.

4.2.3. DIESE

SITEL (Brun-Lafleur, 2011; Brun-Lafleur et al., 2013) concentrates on a detailed representation of the reproductive process composed of stochastic processes: ovulation, insemination, conception, calving and sometimes embryo loss or abortion. In the language of DIESE, each process predicts the occurrence of the next based on actions (e.g. insemination) and observation (including the effects of errors in observations) of the current states in the model. SITEL is concerned with herd reproductive performance and so places emphasis on calving-to-first ovulation interval, return intervals, oestrus expression and pregnancy. The model is driven by changes in body condition score as an input – it does not simulate the processes leading to changes in condition score and so is designed to fit into an animal simulation model. MELODIE (Chardon, 2008; Chardon et al., 2012) uses a demography model that simulates the dynamics of the dairy herd split into 21 animal classes, including heifers. This model is able to represent the wide variety of breeding strategies encountered in most French dairy farms. Its main parameters include age at first calving, replacement rate of dairy cows, natural death and distribution of calving period.

4.2.4. FASSET

Dairy cattle in FASSET are modelled using a rumen fill approach following the Danish feed recommendation system (Møller et al., 2000) using values supplied by Østergaard et al. (1994), Madsen et al. (1995) and Poulsen et al. (2000). Energy and protein partitioning is based on Hutchings et al. (2007) and CSIRO (2007). The cattle are simulated in age and lactation categories and can be modelled as a range of variable individuals or as a number of uniform animals. Methane emissions from the rumen are calculated as a function of the animal’s diet, those from dung by the IPCC (2006) method and those the manure systems are calculated dynamically.

Note that FASSET also includes a detailed model of a breeding pig herd that includes production, nutrients and greenhouse gas emissions but the pigs are considered to be housed year-round.

4.2.5. GRAZPLAN

The animal model in GRAZPLAN was originally published by Freer et al. (1997) but has evolved along with the Australian feeding standard (CSIRO, 2007). The model is designed for ruminants grazing or being fed pasture-based diets or concentrates but is not suitable for browse-based diets. The state of a flock or herd is maintained in a list of physiologically-distinct groups of animals, which may be of different genotypes. Daily calculations are based on flows of metabolisable energy, rumen-degradable and rumen-undegradable protein on a daily time step and have the flexibility to model a range of sheep and cattle breeds by scaling against the animal’s mature weight. Energy and protein use to support maintenance (including maintenance of body temperature), foetal growth, lactation, wool production and body weight change are considered. Vital rates (conception and mortality) are modelled explicitly as stochastic functions of animal genotype, age, weight and time of year. Methane production is calculated from Baxter and Clapperton (1965). Nitrogen, P and S excretion and their partition between urine, organic forms in dung and inorganic forms in dung are included.

4.2.6. IFSM

Animal energy and nutrient requirements are determined for each month as a function of the number, age, growth rate and milk production level of each animal group making up the herd (Rotz et al., 1999, 2005, 2013a) using the Cornell Net Carbohydrate and Protein System, Level 1 (Fox et al., 2004). Feed is allocated to each group individually and can include grazed and conserved forages as well as concentrates. Based upon the diet consumed, the quantity and nutrient content (N, P and S) of the manure produced is determined.

4.3. Possible solutions

Animal growth and metabolism is an important component of a pastoral simulation model. Animal processes can be modelled at different levels of complexity, ranging from detailed ruminant nutrition models (Baldwin, 1995; Hanigan et al., 2009) to simple growth curve responses (see Thornley and France, 2007 for a discussion). There are several approaches that occupy a middle-ground using established national standards, e.g. CSIRO (2007) and Freer et al. (1997). Detailed models of rumen metabolism,
while offering an understanding of processes (Gregorini et al., 2013a) may be too complex to be readily parameterised for different animal types and breeds. These rumen-based models also demand detailed information about forage characteristics that are not readily provided by most forage models. These issues make the detailed rumen models difficult to use routinely in biophysical simulation models. Similarly, describing animal growth with simple functions may reproduce experimental data, but cannot be applied directly to conditions of variable available pasture. For a whole-system biophysical model, striking a balance among complexity, realism, and versatility allows the model to be applied quite readily to different animal breeds and respond dynamically to pasture availability and quality.

The models outlined above span a considerable range of complexity of solutions to modelling the animal component of a grazed system. Models with more detailed representations of physiology than those above do exist (e.g. Baldwin, 1993; Hanigan et al., 2009) and can be linked to grazing system models (Beukes et al., 2008). Inclusion of a very complex sub-model may make it necessary to introduce simplifications elsewhere that limit the system feedbacks (e.g. Beukes et al., 2011). Such simplifications require considerable knowledge and judgement on the part of the model user to understand the impact when feedbacks in the system have been excluded through assumptions or simplifications. Understanding the implications when some feedbacks are excluded can also be challenging for those needing to review model applications.

At the other end of the spectrum, the simplest models can require the user to insert a considerable amount of highly context-specific information. In the case of GRASP, that information is the potential growth rate of the animal on each pasture type. While the concept itself might be easy to explain and to understand, it is difficult to extend it to other locations or farm types because it is highly dependent on the local knowledge of the user. This latter feature also makes independent review of modelled results difficult.

Several of the models used national feeding standards as the basis for their animal models. These systems have the advantage of being well-documented and having some level of national acceptance. In general, they provide a middle-ground in terms of complexity, require less context-specific information but may not be able to capture some processes, e.g. methane production, as emergent properties of the model. The latter can be important where the objective of the simulation is to explore a new technology that is intended to disrupt the usual relationships and this is where a more complex model can be very useful.

In our opinion it is important that we maintain a diversity of animal models so as to give developers and users the flexibility to choose or adapt the most appropriate model for the task at hand. For some applications (e.g. McGechan and Topp, 2004), it has been possible to gain informative answers without including the animal in the simulation at all. However in most cases we are concerned with the relationships or trade-offs between inputs (fertilisers, feeds, management effort) and outputs (farm production) or between two types of outputs (production and losses to the environment) and in the feedbacks in the farming system. In these cases some representation of the animal is essential.

5. Animals – interactions with forages

5.1. The challenge

The economic yield (usually grain) in cropping systems is influenced by the interaction of soil, weather and management factors. The same principles apply in pastoral systems except that the relationship between inputs/resources and the final product is mediated (and therefore also complicated) through the additional trophic level of the animal. Unlike the single harvest usually implemented for most annual crops, a pasture should be harvested several (perhaps four to 20 depending on growth conditions) times a year to maintain digestibility at an acceptable level and to prevent the biomass reaching a ceiling level where gains through assimilation are matched by losses through senescence.

To maximise utilisation, the pasture must be harvested (by machinery or animal) at a critical biomass. If this harvesting is done by grazing rather than through some harvest-storage system, it will be the more economically-efficient (Dillon et al., 2008) at a whole-farm scale. However there are biological limits on the rate at which ruminants can consume pasture and this limits the ability of the farmer to use animals for this harvest. The rate at which animals can consume pasture declines as the standing biomass increases and quality of the pasture declines. This can lead to a vicious feedback cycle where a pasture growth rate that is slightly higher than the maximum intake rate of the animals leads to a high biomass of pasture that is of such a low quality that the animals cannot consume enough pasture to achieve acceptable live weight gains. This cycle is difficult to break and is a primary pasture management concern for farmers (Gray et al., 2003). This feedback process challenges both the farm manager and the simulation model because a relatively small error, positive or negative, in pasture growth rate or animal intake rate can balloon to very large errors in pasture mass and livestock performance (Noy-Meir, 1975).

Ruminants are selective grazers – they will preferentially graze the parts of the pasture they prefer such as low-fibre/high-leaf patches, clovers and other legumes, patches with a preferred height and other factors. Not all animals have the same ability to select between herbage components when grazing. Those with small mouths, such as lambs, can select individual clover leaves while those with larger mouths, e.g. a dairy cow, can only select at a larger scale. The importance of selectivity by the animal on animal performance, and subsequent herbage growth and composition, is undoubted at low and continuous grazing pressures (Parsons et al., 2000). However the effects are less important with rotational grazing to a low residual biomass or when there is mechanical harvesting during the year as these events tend to reset the pasture system to some extent.

Ruminants will reject patches of pasture associated with dung patches and this may reduce the utilisation of herbage by cattle in particular. The rejection may continue for long periods and the absence of defoliation may mean that the pasture becomes rank (a high proportion of stem and many senescent leaves) which adds to the original reason for the stock rejecting the pasture. Cattle have a greater ability to preferentially reject areas of pasture in systems with low grazing intensity and these systems also tend to have lower pasture quality and so result in a larger proportion of ingested N being excreted to the paddock as dung.

5.2. Current approaches

5.2.1. APSIM

The relationships that result in poor quality of large standing biomasses are captured in the AgPasture model (Li et al., 2011) which is based on an earlier version of the pasture model in AgMod. However, that model does not include the very low quality effects of reproductive stems and seed heads. The pasture model AgPasture allows for selective or preferential grazing animal but at present there is no animal model available within the simulation platform that can use that mechanism. There is no explicit representation of selective grazing in GRASP.

5.2.2. AgMod

Animal intake of pasture and supplement responds to availability, quantity, quality and substitution effect (where the offer of a
supplement acts to reduce pasture intake). Selective grazing of different species is included. Protein composition of pasture is calculated dynamically but is specified for each supplement. Digestibility of the neutral detergent fibre is given for each feed source but that of neutral detergent solubles and protein is assumed constant.

5.2.3. DIESE

In SEDIVER, pasture digestibility is provided by the model following Duru et al. (2010). No selectivity in grazing is modelled with rotational grazing. In SEDIVER and MELODIE, a “Fill Unit” system (Jarrige et al., 1986) is used to predict forage intake and net energy requirements on a daily time step.

5.2.4. FASSET

Pasture digestibility is calculated from the grass N content using standard relationships between N content, crude protein and digestibility from the Denmark feed tables as described in Møller et al. (2000). When cattle have access to a number of paddocks or to pasture containing areas with herbage of differing digestibility, the areas are selected for grazing in order of decreasing digestibility, until either the intake capacity of the cattle is reached or all areas available are selected for grazing. The availability of the herbage in each area is made dependent on the contribution that the mass makes to the total herbage on offer. This means for example that a small area of high-digestibility herbage might be included in the diet first but that the intake from that area would be small.

5.2.5. GRAZPLAN

Herbage mass is classified by digestibility class (Moore et al., 1997) and the senescence of forage is modelled dynamically as a function of tissue age, frost and phenology. The digestibility of dry forage is modelled assuming that digestible and indigestible material decomposes differentially. Animal intake across these classes is modelled for the whole sward using a relative preference curve (Freer et al., 1997) that embodies a fill unit concept; this approach permits selection of leaf over stem and a more-digestible over a less-digestible species as well as different levels of substitution of supplementary feed for forage intake. Effects of stocking density, animal species and size on selective capacity are accounted for.

5.2.6. IFSM

Pasture and animal interactions in the IFSM include the effect of feed quality on animal intake, and the influence of N excretion of the animals on pasture productivity (Rotz et al., 2013a). Sward fibre and protein levels are predicted using the stem and leaf production of each species during daily growth. Fibre content and digestibility convert to a fill unit. A fill intake constraint limits the amount of forage consumed, so increasing fibre levels in pasture limit animal production. Grass growth is limited by N available for uptake, so the quantity and distribution of N influences pasture productivity. The interaction between plant height, bite size and intake is not specifically modelled nor is an interaction such as trampling effect on plant growth and productivity.

5.3. Possible solutions

All the models reviewed used similar, relatively simple, approaches to modelling the interaction between the animal and the pasture. The principles of animal interaction with pasture attributes, see for example Gordon et al. (1996), are relatively well-known. At an individual animal level: instantaneous intake rate is controlled by the combination of mouth characteristics (size and shape) with sward architecture to determine the bite size; the physical attributes of the forage such as dry matter density and shear strength influence the bite and mastication time; and chemical composition of the pasture influences the passage time and animal preference. There are a number of models of that bite-based interaction with pasture, e.g. Blackburn and Kothmann (1991) and Baumont et al. (2004) and Gregorini et al. (2013b) that have utilised such an intake model within a more complete farm system model. An earlier version of AgMod included a bite-based approach to modelling pasture intake. The approach was abandoned because the complexity that it introduced made other features, that were considered more important for the purposes of the model, unrealistically difficult to implement and use.

Most simulation models use simpler approaches to describe animal intake and the interaction of intake with pasture attributes. In our opinion, there are two likely (and related) reasons for this. The first is that if the pasture to be grazed is other than a monoculture then the bite-approach to modelling intake is dependent on a realistic representation of not only the pasture composition but also on how that composition changes with depth into the pasture. Although the general principles controlling pasture architecture are well understood, e.g. Griffiths et al. (2003), the detailed requirements of the bite-approach to modelling intake are somewhat beyond our current abilities to realistically model. For example, an earlier version of DairyMod included a bite model of animal intake along with a representation of the avoidance of longer patches of pasture but this approach was abandoned as being too complicated for the purposes of the model. And this relates to the second reason – the relative importance of the animal’s ability to selectively graze in the systems being modelled. As the grazing pressure is managed towards fast rotations with low residuals there is a declining capacity for the animal to selectively graze so the importance of the process declines. We do not know of any simulation models that currently account for the animal’s rejection of the pasture surrounding dung patches. While this may be an unnecessary complication under many circumstances, it may limit our ability to explore the dynamics involved with internal parasites and potential farm system and animal management methods of parasite control.

There is a greater need for the complicated models of animal intake interaction with pasture when either grazing pressure is very low or where the voluntary intake process is important to understanding rumen processes, as in Gregorini et al. (2013b). Most of the models included in this review (SEDIVER is an exception but is more concerned with the whole-farm management than grazing pressure per se) are not focussed on such detailed processes so a simpler approach is justified. Nevertheless there are substantial research questions in which a more detailed approach might be required and here we require the flexibility to incorporate that detail when needed.

6. Animal-mediated nitrogen transfers

6.1. The challenge

Animals are well known to be important in lateral transfer of nutrients within the farm boundary (Haynes and Williams, 1993; Cichota and Snow, 2009). While all nutrients are affected, here we concentrate on the transfers of N within the farm system that are mediated through the animal as they convert forage into dung and urine. We categorise these N transfers into those that are: (a) the primarily random, small-scale dung and urine patches within a grazed paddock, (b) larger-scale (but still within-paddock) systematic transfers resulting from preferred grazing and resting areas and (c) those that are additionally mediated by management actions such as manure management from housing systems and feed pads.
Nitrogen cycling in farm systems that are based on in-situ grazing of permanent pastures is driven by the deposition of urinary-N (Haynes and Williams, 1993; Whitehead, 1995). Urine patch areas can receive instantaneous N depositions of 30–1200 kg N/ha. This creates a heterogeneous soil and pasture because the inter-patch areas might hold mineral-N amounts in the range of <20 kg N/ha (Haynes and Williams, 1993; Ball and Ryden, 1984). Moir et al. (2011) found that, on an annual basis, about 23% of the area of an extensively grazed dairy pasture was affected by urine and that this affected area accumulated through repeated grazing events from individual urine patches of 0.34–0.40 m² each. The small size of the urine patches adds considerable uncertainty to the measurement of leaching (and therefore also to the validation of modelling systems) from grazed pastures as outlined by Lilburne et al. (2012). This heterogeneity has far reaching effects (Whitehead, 1995) and should be considered in the simulation of nitrification, volatilisation, denitrification (de Klein and Eckard, 2008), leaching and pasture growth.

Systematic transfers of N are also important. Haynes and Williams (1993) and Ledgard (2001) reviewed literature that suggested annual accumulations on the camping areas of hill country of up to 210 kg N/ha/yr and these transfers have significant effects on pasture growth, pasture composition and N fixation inputs. Any structure or feature that attracts animals, such as the borders on flood irrigated land, shearing sheds, water troughs or the gate end of the paddock (Haynes and Williams, 1999; White et al., 2001), will result in a systematic transfer of nutrients. The animal type also seems to be important in this as Betteridge et al. (2010), using sheep and cattle fitted with GPS and urination sensors, found greater transfer of nutrients to low-slope areas by the cattle than sheep.

Systems to handle manure from housed animals are very important in European (EUROSTAT, 2010) and North American production systems and are of increasing importance in other areas. By feeding optimal diets to meet their nutrient needs, maximum production can be maintained from fewer animals, which can have economic and environmental benefit in some regions. Collecting of manure, see for examples Menzi (2002), enables more control over the distribution and use of the nutrients but the increased routes for nutrient flows creates a new challenge for the modelling of these systems (Dämmgen and Hutchings, 2008). As large concentrated feeding facilities have developed, more reliance has been placed upon purchased feeds that are sometimes shipped long distances. This leads to a surplus of manure nutrients at the feed facility and proper distribution and use of those nutrients becomes a problem.

6.2. Current approaches

6.2.1. APSIM

The currently-released version of APSIM does not have an automated approach to model urine patches within a paddock (a system to do this is in development and should be released in late 2014) and much of the development work to date in this topic has focussed on improving the modelling of the important processes within patch itself (e.g. Cichota et al., 2013a, 2013b; Vogeler et al., 2013b). There is no in-built system in APSIM to model the systemic or managerially-mediated nutrient transfers but the flexible Manager scripting system in APSIM (Moore et al., 2014) allows users to implement these processes if they wish.

6.2.2. AgMod

AgMod has implemented an implicit approach for modelling the impact of urine patch dynamics in which the paddock is divided into ‘patch’ and ‘bulk’ portions which are simulated separately with the area of the patch proportion increased by grazing activities and decreased using a time-based decay approach. Paddock area, and the associated N, is transferred between these categories to implicitly simulate the effect of the urine patches. This implicit approach has been tested against the explicit description (Snow et al., 2009) and this testing has indicated that it is a pragmatic approach for many uses. While the implicit approach might not be suitable for detailed studies, it captures the larger effects and the computational requirements are only double that of a homogenous paddock and so places no practical limitation in whole-system studies. AgMod uses a loss factor for lanes and does not consider systematic transfers. Housing systems and manure/effluent handling are not considered.

6.2.3. DIESE

The models that have been built to date in DIESE have not considered either random or systematic nutrient transfers but instead have placed considerable greater emphasis on the managerially-mediated transfers. MELODIE (Chardon, 2008; Chardon et al., 2012) combines a very detailed biotechnical system mixing animal and crop production with a DIESE-based management system that enables the study of multi-year dynamics at farm scale. MELODIE can simulate nutrient flows over several decades in pig and/or dairy farms. The nutrient flows are calculated at a daily time step by the biotechnical system, which is a set of connected sub-models. In the biotechnical system, four main nutrient pools are considered: animals, agricultural wastes (storage and treatment), soils and crops and feedstuffs. Internal flows between and within these pools are simulated, as well as nutrient losses to air and water, such as nitrate leaching. For example, animals are grouped in batches, and the nutrient flows are calculated separately for each batch. The model simulates dynamically animal, manure and crop production, the emissions of greenhouse gas (CH₄, N₂O), ammonia (NH₃), nitrate leaching and organic matter in soils. MELODIE has been coupled with two planners that yearly allocate crops to fields and wastes to fields respectively.

6.2.4. FASSET

Explicit consideration of the bulk and patch area of a grazed paddock is included in FASSET as described by Hutchings et al. (2007). Because FASSET is coded using object-oriented techniques, it is possible to clone the grass and soil models, add the appropriate amount of nutrients and then model these new areas individually. This system presents both scientific and technical challenges. The scientific challenge was to model the grazing and pasture off-take from the areas individually – i.e. model how the livestock selected where and how much to graze. The technical challenge was to devise a method for incorporating areas back into the part of the model used to describe the area unaffected by excreta when the effect of the excreta was no longer of practical significance. This reincorporation was never satisfactorily achieved and this limited the run length of the model. Systematic transfers of nutrients are not considered. FASSET includes a detailed representation of the managerially-mediated nutrient transfers through housing systems, manure storage and spreading onto land.

6.2.5. GRAZPLAN

GRAZPLAN does not consider random transfers of nutrients but instead returns urine uniformly to the soil after removing volatilization losses; a version of the model that followed urine patches (Simpson et al., 2001) was not pursued. The systematic transfer of nutrients is considered though a conceptual transfer to stock camps but at that point the nutrients are considered to have been lost from the system. Managerial transfers are considered only as the nutrients enter (purchases) and leave (sales) the farm system. The pasture model is capable of handling nutrient uptake from patches...
with different nutrient concentrations. Future applications of GRAZPLAN involving nutrient transfers will rely on linking it with APSIM.

6.2.6. IFSM

IFSM considers the effects of the random transfers of nutrients by dividing the area of grazed paddocks into that affected by excreta and that unaffected (Rotz et al., 2013a). The area covered by excreta is determined by the amount of urine N excreted and thus varies with stocking rate. The area unaffected by excreta is simulated first to predict mineralization, nitrification, denitrification, volatilization, and leaching processes. The area under excreta is then simulated to predict the same processes under the higher level of soil N. The sum of emissions from the two areas predicts total losses from the pasture. Uniform distribution of P, K and S are assumed. All nutrient excretion when animals are not on pasture occurs in the housing facility. These manure nutrients are collected, sometimes stored, and then applied to crop and pasture land. Volatile losses such as ammonia are predicted from each manure source between excretion and soil incorporation. All remaining nutrients from collected manure are uniformly distributed on the land.

6.3. Possible solutions

While urine patches are clearly understood to be important in N cycling in grazed pastures, few simulation models consider the effect of the patchy urine deposition (Cichota and Snow, 2009) and this is primarily because the inclusion of the deposition process greatly increases the complexity of the simulation model. There is broad consensus (see literature above) that the random animal-mediated nutrient transfers are sufficiently important that they should be included in simulation models and there are a variety of solutions to this challenge. Some modellers have decided to ignore the effect — and if the primary aim is to model production rather than environmental effects, then that position may be quite justifiable (Snow et al., 2009). Some authors (McGechan and Topp, 2004; Romera et al., 2012; Li et al., 2012) have taken an approach to model the pasture and leaching at the scale of an isolated patch and then scale up to the paddock level post-simulation. These solutions require relatively little model development and are computationally-efficient, but they cannot capture the effects of feedbacks into the system caused by changes in N retention. Far more complex solutions such as Schwinning and Parsons (1996b) and Snow et al. (2009) can be informative but they do not lend themselves to practical application or routine usage within models at the paddock or farm level.

Routine implementation of urine patches into a simulation model will require a balance between realism and pragmatism as it is not practical to include the full complexity involved in the model. IFSM and AgMod have implemented different, but equally pragmatic, solutions as described above. The Hutchings et al. (2007) patching model implemented in FASSET (cloning the grass and soil models on-demand) presented technical challenges that limited the duration of the model run but showed considerable promise. A new solution based on Hutchings et al. (2007) is currently under development in APSIM (R. Cichota, AgResearch, personal communication) but will involve cloning only the soil C–N part of the simulation model to create a patch. This solution uses a justification based on Snow et al. (2009) that ignoring the patches will cause an acceptable error in pasture growth as a simplification and will use the information from Cichota et al. (2013b) to drive the reincorporation of patches into the bulk soil. The early results are promising but full testing is not yet complete.

One challenge with any scheme to simplify the representation of urine patches in simulation models is validation. There are few reliable whole-paddock leaching datasets and those that are in existence have large uncertainties. Those uncertainties will largely be irreducible unless a new measurement system that integrates over larger areas is developed and successfully tested (Lilburne et al., 2012). Under these circumstances sensitivity (or plausibility) testing (e.g. Holzworth et al., 2011) can play an important role, but this is only valid if careful attention has first been paid to validating the more detailed processes.

None of the models included in this review consider the effect of systematic animal-mediated transfers of nutrients; however, the model described by Topp and McGechan (2003) clearly showed that the impact of animals congregating near water sources and fence lines was important in Scottish dairy farms even at low stocking rates. We suggest that this is a challenge that could benefit from more attention as measurements in flat (White et al., 2001) and sloping (Betteridge et al., 2010) land have shown distinct and repeatable patterns of excreta deposition. As our quantitative understanding of the impacts of animal social behaviour improves, an approach similar to that in IFSM for random transfers, of reserving a category of land for this purpose, might be a pragmatic solution. More complex explicit solutions might be required in order to test these pragmatisms in the simpler solutions.

The Northern Hemisphere models show particular strength in handling the effects of housing and manure handling. In colder climates where animals are maintained in a housing facility for at least a portion of the year, manure collection, storage and handling are important components of the production system. Gaseous emissions are an important component of these manure systems and much effort has been given to process level modelling of ammonia emissions from barns, manure storage and following field application (Rotz et al., 2013b). Not all housing and handling systems have been fully evaluated though, leaving opportunity for further model development and evaluation. For these systems, other emissions such as hydrogen sulphide and volatile organic compounds can be important. Although progress is being made toward process level simulation of these compounds (Rotz et al., 2013a), much is still unknown about the processes controlling their formation and emission. The lesser importance of housing systems in farm systems in Australia and New Zealand has resulted in the Southern Hemisphere models largely ignoring these managerially-mediated transfers. There is, however, current development work in APSIM (J. Vejlín, University of Aarhus, personal communication) to include descriptions of housing systems for pigs and a prototype dairy farm model that includes transfer to lanes and an effluent system is also under development (R. Vibart, AgResearch, personal communication).

7. Managing the whole farm

7.1. The challenge

Farm management is the process by which resources are manipulated over time by a manager trying, with incomplete information, to achieve multiple and possibly competing goals (Dillon, 1979). In common with other agricultural systems, managing grazed systems involves the input of resources into natural systems for the purpose of harvesting products for sale. The farmer makes decisions about the planning and implementation of technical operations with the intent of achieving objectives. From a systems perspective, an agricultural production system is composed of, at least, a biophysical system (land, crops, livestock, etc.), a decision system (the farm manager) and an operating system that implements the decisions using various resources (input,
labour, machinery, etc.). Farm management with grazing systems is the art of integrating animals and feed with land and other resources.

Grazing management strategies are designed to ensure a year-round balance of forage supply and demand, almost always attempting to reduce the effect of seasonal and year-to-year weather variability. Long-term success or failure of any grazing management strategy hinges upon the farmer's ability to control the frequency and severity of defoliation of plants over time and space in such a way as to meet desired goals under any weather conditions. This result in highly complex systems (Gray et al., 2003; Bergez et al., 2012; Cros et al., 2004; Martin et al., 2011b; Nuthall, 2012) that challenge both our understanding and the management component of simulation models — as recently reviewed by Martin et al. (2013).

7.2. Current approaches

7.2.1. APSIM

APSIM uses a rule-based management scheme. The management policy is decomposed into a set of simple actions; the kinds and timing of actions are controlled by rules that are expressed in a script. The first version of the manager language allowed simple if-then-else statements while the current version supplies users with the full syntactic power of languages such as Visual Basic or C#; see Moore et al. (2014) for examples. Rule scripts can be encapsulated into “templates” that have their own simple user interfaces. Users can, without needing to compile the model, set critical values or choose options from that interface but can also access and modify the underlying rules or create entirely new rules.

7.2.2. AgMod

AgMod uses rule-based management with user-definable critical values and options. For example, stock may move between paddocks based on factors such as pasture mass and leaf stage. Similarly, supplementary feeding sequences between pasture, forage, concentrate and mixed rations can be defined for different animal physiological states (such as lactating or pregnant), and throughout the year. The user can select from many supplied rule sets but cannot change the underlying rules or create new rules without access to the developer.

7.2.3. DIESE

In DIESE, the underlying ontology acts as a meta-model. Implementing a farm system amounts to particularising the ontology concepts as needed by the application domain and then instantiating the corresponding software classes to capture the specific aspects of the production system to be simulated. A discrete event simulation mechanism implements the step-by-step interpretation of the strategy and the progressive execution of the decisions. This in turn alters the biophysical state of the modelled farm that also responds to external factors, e.g. weather, influencing biophysical processes. The classical approach to representing decision making in simulation models is to express decision behaviour through a set of decision rules. The DIESE approach (Martin, Clouaire and Rellier, 2009) provides a very rich conceptual basis to describe decision making. It refers explicitly to management-relevant notions such activities, resources, plans and also the rules needed to adjust the plan when particular events occur. The implementation of a management strategy through DIESE requires the user to declare the application-specific management entities in an input file using a dedicated script-like language. The C++ classes that constitute the model are compiled at development time. At execution time only a parsing of the input file is needed. DIESE is well adapted for modelling of the farmer’s behaviour as a cognitive agent interacting with, and operating on, a biophysical system.

7.2.4. FASSET

FASSET requires annual management plans for all fields (e.g. crop sown, amount and timing of N fertiliser and manure) and multi-year feeding plans for individual groups of classes of livestock. The feeding plan includes the diet to be supplied during one or more periods of the year. For grazed feed, the model allocates fields closest to the milking parlour to lactating cows. The type and amount of supplementary feed to be fed is dependent on herbage mass available for grazing. The grassland is managed by first calculating the expected annual demand for conserved roughage and then determining the proportion of the grassland area to be used for the production of conserved roughage, based on expected annual roughage production per unit area. The remaining area is allocated to grazing, with the amount of supplementary feed varied as indicated in the livestock feeding plans, to compensate for weather-driven variations in herbage mass available.

7.2.5. GRAZPLAN

The AusFarm implementation of these models uses rule-based management with the full functionality of a C++ script. Scripts can be highly detailed (for examples see Moore et al., 2014) and do not have a user interface. Users can modify or create new scripts without needing to compile the model. The GrassGro decision support tool (Moore et al., 1997; Herrmann and Zurcher, 2011) provides a graphical user interface to a constrained, but still flexible, set of management options for stocking rates, replacement policies, the reproductive cycle and grazing management in a range of sheep and cattle enterprises.

7.2.6. IFSM

IFSM is constructed to simulate representative dairy or beef farms and has considerable flexibility to range across systems varying from those that are primarily housed to primarily grazed. Farm management is largely rule-based but IFSM is one of the few simulation models to include a linear program component. In this case, the linear program is used to find the least-cost balanced ration using weightings that result in a preference to making the best use of home-grown feeds and preferring pasture over silage. The objective of the ration calculation is to meet as much of the forage requirement through grazing as possible but limited by the availability of that forage as determined by the growth part of the model.

7.3. Possible solutions

Moore et al. (2014) review the state of the art of representing the manager in simulation models. They divide solutions into rule- and planning-based managers. Rule-based managers represent decisions based on the current state of the farm system (e.g. if soil water storage is less than a critical value then irrigate now) and most of the managers in agricultural simulation models fall into this category. Rule-based managers can be set up to mimic standard rules-of-thumb in many situations but, as pointed out by Moore et al. (2014), they can lead to very unrealistic discontinuities in management action. Nevertheless, they are well accepted and, in principle, are easy to understand.

We note, however, that rule sets can quickly become quite deeply nested and therefore rather complicated. We speculate that in these cases there might be a role for Bayesian Network (BN) models. There are few examples that we know of where BNs have been nested in dynamic models, see Bashari et al. (2008) and Nicholson and Flores (2011). These authors did not specifically use...
the BN to mimic a decision process, but one can imagine several refined but relatively complex decisions (e.g. irrigation management under water constraints, deciding when to dry-off cows in the autumn) where BNs can be reasonably developed using expert opinion and then applied as a decision rule within a simulation model.

Rule sets can be implemented by the developer with the user having access to the controlling parameters through a relatively simple interface. AgMod has some examples of highly detailed management rules thatfits this description. The AusFarm implementation of GRAZPLAN has taken a different approach with the rules implemented in a script for which the user interface is the script itself. The former system is highly attractive for new users but becomes limiting when experienced users wish to implement something not considered by the developer. The latter system can be utterly daunting for new users but is very efficient for experienced users. APSIM has implemented a mixed approach where the user has access to the script, and can create entirely new scripts, but there is also a simple user interface and in the first instance a user may primarily choose from lists or options. This dual approach means that the existing scripts can become templates for new scripts and provides flexibility for both new and experienced users.

A minority of simulation models use planning-based systems where the manager makes decisions based on an assessment of the likely future state of the farm system. Moore et al. (2014) observe that planning-based systems probably offer greater benefits to pastoral systems than to cropping systems because of the need to manage the future states of these slow-response systems. A plan-based system, such as SEDIVER (Martin et al., 2011a,b), helps to coordinate management activities coherently along the three dimensions of time, space and resources. In such a system, the plan is built by the modeller but is modified by the system as necessary. Plan-based systems support whole-farm anticipatory management approaches, but need a flexible specification in order to cope with a range of possible situations. We also note the development of more flexible and graphical solutions for describing the management of arable farms (Rodriguez et al., 2011) and suggest that such solutions might be sufficiently adaptable to represent at least parts of the management of pastoral farms. We note that rule-based and planning-based approaches to representing management are complementary, rather than exclusive, alternatives.

Linear programming (LP) or other optimisers such as genetic algorithms (e.g. Matthews et al., 2000) are other mechanisms by which a planner might be embedded in a simulation model. Berntsen et al. (2003) employed an LP in FASSET to select land use options but the LP has been excluded from recent versions because the software issues associated with the link between the LP (written using GAMS) and the biophysical model (written in C++) were too great. These challenges were software-specific and we note the IFSM includes an LP for feed rations and, in a very different domain of application, Hulsemann et al. (1996) uses an LP for longer range planning within a dynamic simulation model. There have been a few examples of general planners within simulation models (e.g. Snow and Lovatt, 2008; Snow et al., 2006). These systems are difficult to implement and difficult to explain (in contrast to LP planners or rule-based systems) but might have a role to play in exploring human learning from slow-response systems with error-prone measurement or observations of current states.

8. Future prospects and concluding statements

About six years ago Bryant and Snow (2008) reviewed a range of pastoral farm system models – most of which are also included in this current review. Some of the points that were suggested as meriting more attention in that 2008 review included: the representation of farm management; heterogeneity in the soil-plant system; the effect of pests and diseases on pasture production and animal performance; representations of voluntary feed intake and rumen process models; the effects of specific genes and gene by environment interactions on animal and plant performance; and the implementation of robust and flexible software design processes. Although those particular points were by no means exhaustive, or necessarily shared beyond the original authors, here it would be useful to reflect on progress made since that review was published.

In our opinion, there have been significant advances in the representation of farm management since 2008. Indeed DIESE is based on the representation of such processes in a plan-based framework and the flexibility of the scripting system as described by Moore et al. (2014) adds considerably to our capacity to implement farm management systems. However there is considerably more scope for development in the more traditional rule-based representation of the manager, perhaps in tandem with planning-based approaches as described in Section 7.3.

Since the 2008 review, there have been advances in the range of methods for simulation models to consider the random transfer of nutrients by animals. The advances include better understanding of when such transfers might reasonably be ignored (Snow et al., 2009; Bell et al., 2011) or simplified (Cichota et al., 2013b). There have also been a diversity of approaches developed for including random transfer – such as that in AgMod and that currently being implemented in APSIM. However, to our knowledge, there has been little or no attention paid to capturing the effects of the systematic transfers of nutrients, despite that the impacts of this are well-known.

The models reviewed here have modelled animal intake and implied rumen processes at a very simple or relatively simple level of complexity. Other models have implemented much more complex descriptions of voluntary intake and of rumen processes – see Gregorini et al. (2013b) for a review. In our opinion, it is important to have such complex models available for specific questions (e.g. the impacts of particular pasture characteristics on animal performance, to understand and improve the prediction of methane production) but they are generally too complex for routine use in farm system models. If software systems and intellectual property considerations allow, then the best approach is to have the potential to link a more complex model developed elsewhere into a simulation with greater strengths in other processes rather than generally increasing the overall complexity of all models.

Advances in software design and processes have allowed greater flexibility of model development and usage in the last several years and there has been a trend for greater usage of general frameworks (Martin-Clouaire and Rellier, 2009; Moore et al., 2007). There has also been a trend for greater openness of model source code and decentralised development (e.g. Holzworth et al., 2014) and greater clarity regarding the strengths and weaknesses of models resulting from more model inter-comparison projects such as AgMIP (Rosenzweig et al., 2013). In our opinion, these processes are moving in a direction favourable to more robust and efficient model development and usage.

None of the models here have explicitly considered the effects of pests (including weeds, but see Whish et al., 2014) and diseases (including internal parasites) on pastures or animals. A literature search did not reveal significant developments elsewhere, despite there being a number of well-developed models of gastrointestinal parasites (e.g. Learmount et al., 2006; Leathwick, 2012). The impacts of pests is seen as a critical climate change issue (Morton, 2007; Thornton et al., 2009; Lieffering et al., 2012) and we suggest that this remains a topic requiring attention in the near future.
Bryant and Snow (2008) also suggested that gene-environment interactions should receive more attention. There have been significant developments in this space using cropping models (Hammer et al., 2006; Chenu et al., 2011; Tardieu and Hammer, 2012) but relatively little, that we know of, within pastoral systems despite some work on evaluating breeding targets or desirable traits in plants (Donnelly et al., 1994; Snow and White, 2013) and animals (Moore and Ghahramani, 2014). Forage breeding programmes have not made the same degree of progress as seen in other plant breeding programmes (Lee et al., 2012). We see a strong role for pastoral simulation modelling in designing pasture plant breeding systems and to assist in setting plant breeding objectives, particularly those needed to meet the twin aims of production and environmental goals (Clark et al., 2007; Chapman et al., 2003; Snow and White, 2013).

Not considered by Bryant and Snow (2008) were the impacts of extreme events on the pastoral system. More recent work in the arena of climate change impacts and adaptation has shown that extreme climate events are important for soil processes (Newton et al., 2010; Reichstein et al., 2013), plants (Reyer et al., 2013; Sánchez et al., 2014) and animals (Thornton et al., 2009) but are poorly described and predicted (Cullen et al., 2012; Leffering et al., 2012). In a climate-challenged future, incorporating the likely impacts of drought, heat waves, fire and flooding on plants and animals will be important and the results of the more recent work cited above can provide a basis for improving existing models.

Given the diversity of pastoral farming systems and a wide range of modelling purposes there is a considerable need for flexibility of modelling approach. Recent software developments in open and flexible modelling platforms such as RECORD (Bergez et al., 2013), OMS (David et al., 2013) and OpenMI (Knapen et al., 2013) can assist with reusability of models and model components. Indeed, two of the models reviewed, APSIM and DIESE, are themselves open model platforms. Modern software design can assist with reusability and connections between model components (Holzworth et al., 2010) and so allow the model developer to concentrate on the farm system and scientific challenges to modelling grazed systems. Robust and flexible process-based simulation models of pastoral and integrated systems are needed to investigate the adaptation of production systems to increase productivity (Bell et al., 2008; Chapman et al., 2008b; Rodriguez and Sadasr, 2011; White et al., 2010), decrease environmental effects (Vogeler et al., 2013a), assist understanding of climate change issues (Del Prado et al., 2010) and to meet the demand of farmers for a better quality of life (Hostiou and Dedieu, 2012; Martin et al., 2013). Here we have reviewed six simulation models against the key challenges for modelling the additional complexity that pastoral systems face compared to arable systems. We have placed particular emphasis on the range of possible solutions with the point of view that diversity will give flexibility of future usage. We find that in most cases there is a diversity of solutions incorporated into the models reviewed and that there is the potential to capture additional diversity, if needed, from other models provided the software and legal constraints are not too onerous. In addition, we note an apparent lack of development in the modelling of the effects of extreme events, 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.

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