4SPaM: a process-based and weather-driven population model for managing weeds in temperate pastures

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Summary The four Species Pasture Model (4SPaM) has been developed by the CRC for Weed Management Systems (CRCWMS) to analyse the ecological and economic impacts of management strategies against pasture weeds across temperate Australia. Weeds dominate pasture by outcompeting desirable species within the grazing environment. Existing pasture productivity models such as GrassGro™, are not designed to accurately simulate weed management scenarios. Between-species interactions are not simulated in sufficient detail to produce confident projections of plant community dynamics. The complex competitive interactions in multi-species pasture, when the aims are both to suppress the weeds and to augment the desirable pasture components, makes single optimal pasture management solutions unobtainable. Integrated weed management options, climate, soil fertility, and initial sward composition all interact in complex ways, which are hard to comprehend without the aid of a dynamic system model that simulates these factors. 4SPaM is a modular process-based ecological model that includes four main functional plant groups commonly found in temperate pastures (annual grass weed, perennial grass, annual broadleaf weed and annual legume), weather, soil fertility, herbicide applications, hay and silage-cutting, and sheep flock management. 4SPaM simulates the state of the pasture, sheep flock and gross-margins, and will be loose-coupled to a dynamic programming economic model to identify optimal management technologies and their benefits for each climatic location. The model is being tested using the outcomes of field trials, and when reliably calibrated will provide a vehicle aimed at expanding the applicability of IWM solutions Australia-wide.

Keywords DYMEX, temperate pastures, sheep-grazing systems.

INTRODUCTION

The economic productivity of pastures based on perennial grasses has been in a steady decline from at least the early 1970s (Vere 1998). This is principally due to the ingress of weed species (especially annual grass and broadleaf weeds), and the accompanying decline in desirable perennial grass species.

Various technologies have been developed to manage weeds in pastures (e.g., herbicides, grazing management, fertiliser and biological control), and management recommendations now exist for the major temperate pasture weeds. The performance of these technologies, however, is unsatisfactory when used alone. The sub-optimal condition of most paddocks within the temperate perennial pasture zone (Dellow *et al.* 2002), however, attests to the fact that many of the available technologies are not well coordinated and poorly adopted on-farm. To extract maximum return on investment and to avert problems such as herbicide resistance, these technologies need to be combined in a coherent strategy that both targets weed species and promotes perennial grasses under conditions of variable climate and within a whole-farm context.

One of the major barriers to the development and adoption of successful weed control strategies has been the lack of tools to predict the likely effects of a proposed set of management options on the pasture resource and the inability to assess the potential long-term economic benefits of adopting these technologies. It is relatively straightforward to compare the short-term performance of individual *techniques*. Comparing *strategies*, however, is much more difficult, given the almost limitless manner in which individual techniques can be combined into strategies, and the difficulty in predicting interactions between them. Similarly, the effects of climate variability at the seasonal and longer timescales limit the value of short-term comparisons. The cost of field-based research makes the exhaustive comparison of all but a limited number of strategies prohibitive, even in the short-term.

The identification of promising pasture management strategies can be greatly assisted by the use of an appropriate process-based pasture model. The benefits of such models are numerous:

- providing insights that would be impossible or difficult to produce otherwise;
- allowing the exploration of relationships in ways not otherwise available;
- identifying potential gains to research;
- allowing experimentation with a wider range of variables than otherwise feasible (Cacho *et al.* 1995).

To properly evaluate the benefits of adopting different strategies, it is necessary to employ an economic analysis framework, which can integrate the effects of climate variability and management decisions. It is only with proper economic evaluation that the best management strategy can be determined and the full value of industry-funded research can be realised. This type of analysis will identify promising strategies that can then be field-tested and used to demonstrate to landholders the potential benefits of basing management strategies on the pasture condition.

Temperate grazing systems models have been developed previously (Doyle *et al.* 1989, Cacho *et al.* 1995, Moore *et al.* 1997, Donnelly *et al.* 1997). These models have tended to focus attention upon the livestock production aspects, with relatively little or no attention being paid to the effects of management decisions upon the botanical composition of the pasture sward. More detailed competition and diet selection models such as those developed by Schwinning and Parsons (1996), Newman *et al.* (1995) and Parsons *et al.* (1994) have utilised a two-species (perennial grass-legume) pasture system, ignoring broadleaved weeds and annual grasses.

This paper briefly describes the 4SPaM model. Its performance will be presented elsewhere.

MODEL DESCRIPTION

The four species pasture model (4SPaM) was developed as a platform to explore the responses of four pasture species under various management regimes. It is a process-based population model developed using the DYMEX™ population modelling system (Maywald *et al.* 1999).

4SPaM includes lifecycles for four common species that represent the different functional plant forms typically found in temperate pastures in southern Australia (Table 1). While the species themselves are frequently found in pasture communities in the temperate zone of Australia, the intention was to produce a model that could characterise pasture dynamics at the level of the plant functional form. The model operates on a weekly timestep and includes selective grazing, soil moisture and individual plant growth submodels. The model is driven by easily obtainable weather data (daily or weekly values for minimum temperature, maximum temperature, total precipitation, and either class A pan evaporation or relative humidity at 0900 and 1500). Because of its modest data requirements, 4SPaM can be adapted for use at various locations throughout Australia by selecting appropriate weather data files and modifying a minimum number of site-specific parameters.

Lifecycles The DYMEX population modelling framework provides a useful *specific formalism* for modelling populations in the form of the familiar concepts of cohorts of lifestages within lifecycles. Lifestages are flexibly defined by the user in terms that are meaningful for the species and system being studied.

All model processes are updated at each timestep. Thus, life processes (e.g., mortality, growth, seed production, physiological development) are defined in terms of weekly difference equations. New cohorts are generated in any timestep in which there is a stage transfer (e.g., a new seedling cohort is created each week that seeds transfer to seedlings through germination). This framework provides a large degree of temporal precision in tracking the size distribution of plants; accounting for factors such as false seasonal breaks.

Plant growth rate The growth rate of plants is partly governed by a species-specific potential relative growth rate. The actual rate of growth attained by a plant each week is also a function of soil moisture, temperature, nutrient status, plant age/size, plant competition and grazing reductions.

Selective grazing Sheep do not tend to graze pasture species with equal intensity, based upon relative abundance measured in terms of either relative frequency or biomass. Instead, sheep graze plants in a highly selective manner that appears to be based upon factors such as relative digestibility, accessibility and palatability (Hamilton *et al.* 1973, Jamieson and Hodgson 1979). These factors were considered by a panel of

Table 1. Plant functional forms and representative species included in 4SPaM.

Functional form	Scientific name	Common name
Winter annual forb	*Echium plantagineum* L.	Paterson's curse
Winter annual grass	*Vulpia* spp. (mostly *V. bromoides* (L.) Gray and *V. myuros* (L.) C.C. Gmel.)	Vulpia, silver grass
Winter-growing perennial grass	*Phalaris aquatica* L.	Phalaris
Winter annual legume	*Trifolium subterraneum* L.	Subterranean clover

pasture experts and integrated into a set of curves relating the biomass of each plant species to their relative attractiveness to sheep (Figure 1). The lower x-intercept indicates the plant size below which sheep cannot physically access any biomass.

The selective grazing module allocates plant biomass to animal consumption in an iterative, numerical manner within each timestep. All plant cohorts are ranked according to their calculated Selective Grazing Index (SGI, Figure 1). Sheep remove biomass from the most attractive cohort(s) in a series of grazing *nibbles* (iterations within a timestep). The size of the nibbles equals the weekly sheep biomass demand divided by the user-selectable number of iterations (default 8). When two or more highest-ranked cohorts have a similar SGI value, they are consumed in direct proportion to their total biomass. The total amount that can be consumed from each plant in a cohort is limited to that amount above the lower biomass value at which their SGI value falls to zero. If a plant cohort is unable to satisfy all of its allocation to grazing during a nibble, then the deficit is allocated to the next highest ranked cohort(s) until either the nibble is satisfied or all cohorts have been reduced to an SGI value of zero. After each nibble, the SGI value of each grazed cohort is recalculated based upon its reduced biomass. The cohorts are then re-ranked prior to the next nibble. If there is sufficient biomass available, the grazing continues until the nibbles have been completed. A tally is kept of the total amount grazed each week and the metabolisable energy value of the consumed biomass. If there is insufficient biomass available, the program exits the SGI module prior to completing all of the nibbles. The difference between the amount of energy sheep require to maintain body condition and the amount extracted from the grazed material is used to trigger a supplementary feeding event. This event calculates the amount of economic cost associated with a feed deficit or supplementary feeding event.

The amount of energy derived by the sheep from the consumed biomass depends upon the mix of plant species consumed and the phenophase of those plants. A table of monthly average values of metabolisable energy density (Mj g^{-1}) for each plant species is used to calculate the amount of energy consumed by the flock, based upon their consumption patterns. The minimum amount of metabolisable energy needed by the average sheep in the flock per week in order to maintain condition (live weight) is read from a table. The threshold minimum amount of energy was subtracted from the amount derived from the pasture biomass to determine whether the average sheep in the flock lost, maintained, or gained in condition (live weight). If weight loss was beyond a chosen threshold, then a supplementary feeding event is triggered. The amount of feed supplied equals the amount of the energy deficit. The costs of providing feed are summed throughout each simulation.

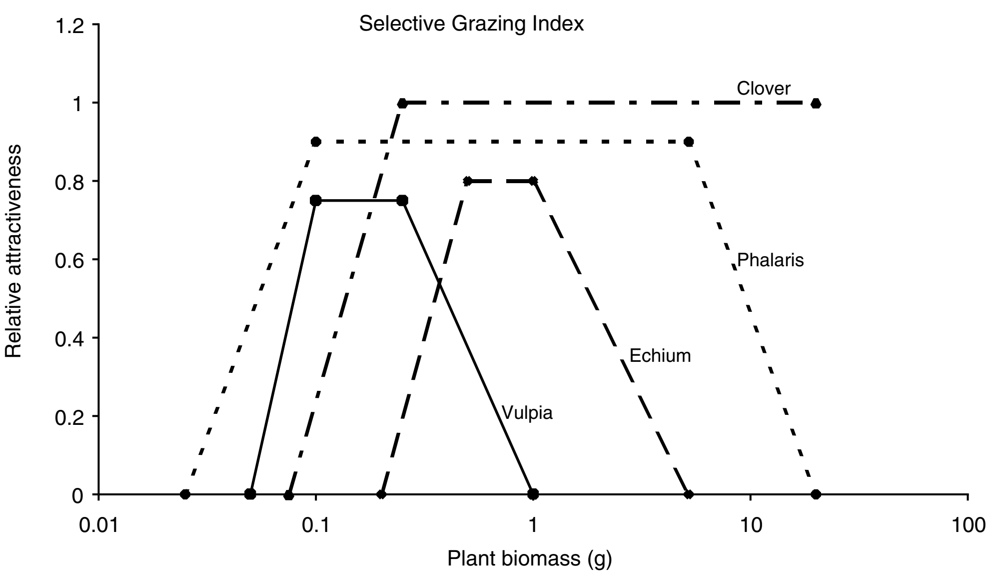

Figure 1. Selective Grazing Indices representing the relative attractiveness of plants to sheep as a function of species and biomass. These functions were derived from a workshop of pasture researchers and agronomists.

Competition and self-thinning In 4SPaM, plant competition reduces growth rate in an asymmetric manner; larger plants are affected less than smaller plants. Competitive effects commence as the sum total of the ecological fields of plants in the sward approaches the area of the paddock (the carrying capacity). At total values above the carrying capacity, small plants are progressively removed from the simulation until the total ecological field values equal the carrying capacity. With this approach, mixed-species populations effectively increase in biomass density up the -3/2 self-thinning line as a function of their net growth rate after any grazing (Westoby 1984).

Weed management techniques 4SPaM includes the ability to simulate variations in sheep stocking regime, applications of herbicides and fertiliser, and biological control. These functions have been calibrated using sets of field observations.

DISCUSSION

In model verification runs, the gross behaviour of 4SPaM compared well with the outputs from the CRC for Weed Management System's IWM project (Huwer *et al.* 2002). Whilst this comparison gives some measure of confidence in the model, the measurements taken in the IWM project were not suitable to enable a detailed validation of 4SPaM.

4SPaM provides the first model to explore the long-term degradation and restoration processes of pasture species composition in response to management decisions and climate variability. When linked to a dynamic programming economic model it will be able to demonstrate the trade-offs between short- and long-term profitability in pasture management, identify promising successful weed control strategies and provide a potent tool to enhance adoption of these strategies.

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