final report

Project code: B.DSS.0008

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Date published: February 2015

ISBN: 9781740362979

PUBLISHED BY
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Locked Bag 991
NORTH SYDNEY NSW 2059

Improved modelling of livestock production from lucerne

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

Abstract

In this project, the capacity of the GRAZPLAN pasture growth model to predict lucerne growth and development was improved by analysis of a range of information from the scientific literature. The descriptions of key processes (the developmental cycle, and in particular differences in winter activity; stomatal closure in warm, wet conditions; rooting front development; and nutritive value) were updated. The revised lucerne model was tested against 7 experimental data sets from across Australia that were chosen for their data quality. The testing revealed a number of limitations of the new lucerne model, but overall it is a considerable improvement over the previous version and it will be released for wider use in both research and decision support.

Executive summary

A number of models exist to predict lucerne (*Medicago sativa* L.) dry matter production however most of these models do not adequately represent the ecophysiology of the species well enough to predict its growth and quality across the range of environments in which it is grown in Australia. In this project, the capacity of the GRAZPLAN pasture growth model to predict lucerne growth and development was improved by re-estimating values for key parameters from information in the scientific literature. GRAZPLAN was also assessed for its capacity to reflect differences in the growth and physiology of lucerne genotypes with different winter activity (often referred to as 'dormancy' types).

Modifications were made to GRAZPLAN to improve its capacity to reflect changes in phenology due to environmental triggers such as short photoperiods, declining low temperatures, defoliation and water stress. Changes were also made to parameters influencing vapour pressure which improved the representation of transpiration and therefore biomass accumulation. Other developments improved the representation of root development and partitioning of canopy structure, notably the proportion of leaf and stem.

Data from replicated field experiments across Australia were identified for the purpose of model validation. These datasets were examined and prioritised on the basis of spatial coverage, availability of weather and soils information, whether they compared different cultivars and the length of experimental time and the detail with which stands were measured. In all, datasets from 6 sites with 19 site x cultivar combinations and 21 site-years were used in the evaluation. These data were broadly representative of the range of climate zones, soil types and farming systems in which lucerne is used throughout Australia. Validation of predicted lucerne growth rates was comprehensive due to the plentiful data, however validation of other parts of the model was restricted as information relating to plant roots, soil water, plant morphology and phenology were limited. In particular, data on the nutritional quality of the harvested plant material was limited to a single site-year.

Despite a number of limitations, the improved version of the model and parameter sets is a considerable improvement over the previous parameter set for lucerne and it will be released for wider use in both research and decision support. This study has highlighted the predictive power, versatility and robust nature of GRAZPLAN to predict the growth, development and nutritional quality of perennial species such as lucerne.

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1. Background

Lucerne-based pastures occupy about 3.2M ha in Australia (Robertson 2006). The proportion of land under lucerne is increasing (Donald *et al.* 2012); (Robertson 2006) considered that an increase in the area devoted to lucerne to 7.5M ha would be realistic in the medium term. With the development of new germplasm, it is being grown in cooler, wetter regions (Pembleton *et al.* 2010) and those with more acidic soils (Humphries and Hughes 2006; Humphries 2012). Lucerne is easily the most widespread perennial forage legume in Australia; as such it provides both inputs of biologically fixed nitrogen to the soil and also a pattern of growth that can exploit episodic summer rainfall. Forage evaluation studies in medium- and high-rainfall environments have confirmed the production and persistence advantages of lucerne over other dicotyledonous forages (Dear *et al.* 2008; Reed *et al.* 2008). Its capacity to de-water the soil profile (e.g. Dolling 2001) also makes it an important tool in combating secondary soil salinity and waterlogging.

If lucerne is to be more widely adopted, it will be important that landholders maximise its benefits to their livestock enterprises (usually as a part of a diverse feedbase), as well as optimizing the benefits and minimizing the costs of lucerne phases to subsequent crops. Because of the inherent variability of summer feed production by lucerne and the business risks this entails, modelling analyses (both as case studies and through decision support delivered by advisors) will be useful in informing decision-making about how much lucerne to grow and how best to optimise livestock production.

The ability to accurately predict responses in the growth and nutritional quality of lucerne to environmental variations is of primary importance in modelling production from grazing systems (Brown *et al.* 2012). The responses to environmental conditions of perennial forages such as lucerne are, however, more challenging to predict than for annuals due to the activity of the perennial organs (Teixeira *et al.* 2007b). In particular this involves the need to reflect the allocation and consumption of biomass in the perennial reserve organs in response to the wide range of environmental conditions (photoperiod and temperature) experienced by plants throughout the year. In most of the grazing regions of Australia, many of the factors that trigger the plant to transition into a period of reduced growth are usually interlinked: for example, photoperiod declines together with temperature and increasing temperatures are associated with increasing moisture deficit stress. Therefore a mechanistic understanding using a biophysical approach is of value.

As with many forages, the morphology and nutritive value of lucerne – and hence livestock production from it – varies throughout the year in response to environmental factors, plant maturity, defoliation regime and seasonal conditions (Christian 1977). Plant ontogeny and nutritional quality are tightly linked in lucerne, so that the ability to predict phenology is a key requirement for accurately predicting the quality of lucerne forage. Interactions between plants and grazing animals result in increased complexity and uncertainty (Snow *et al.* 2014), such as interactions between grazing intensity and phenology (Ru and Fortune 2000; Teixeira *et al.* 2007a; Teixeira *et al.* 2008).

Despite the fact that a considerable body of research worldwide has contributed much to the collective knowledge of the ecophysiology of lucerne – the ability to accurately model lucerne plant physiology across the full spectrum of environments, genotypes and cultivars remains elusive. A number of models of lucerne growth exist, such as CropSyst (Stöckle *et al.* 2003), APSIM (Robertson *et al.* 2002) and ALSIM (Fick 1984). These biophysical models of plant-soil-climate dynamics represent carbon assimilation, partitioning and utilization (Fick and Onstad 1988; Robertson *et al.* 2002) in order to simulate growth, development and N accumulation in response to temperature, photoperiod, soil water and N supply.

The above models were developed primarily for lucerne stands under cutting management. Most lucerne pastures in Australia are grazed by livestock rather than managed by cutting and as such there are a number of key differences in plant physiological responses in the two systems. The GRAZPLAN model of pasture growth (Moore *et al.* 1997), on the other hand, is primarily designed for grazing situations. It explicitly considers the nutritive quality of the forage and its interactions due to grazing, and has been used to study lucerne in farming systems in a range of different applications in Australia (Lilley *et al.* 2008; Ghahramani and Moore 2013; Moore 2014) and overseas (Cohen *et al.* 2003). The GRAZPLAN model can be used in conjunction with the APSIM crop growth models to examine mixed farming systems (e.g. Moore 2014). However the genotypic parameter set that describes lucerne in the GRAZPLAN model does not adequately capture the differences between genotypes, in particular differences in winter growth activity; and the model for lucerne has had little formal testing in Mediterranean and summer-dominant rainfall environments.

2. Project objectives

1. Review and revise the description of lucerne (i.e. the lucerne “parameter set”) in the GRAZPLAN pasture growth model to improve its predictions of growth rate and nutritive value,
2. Validate the predictions of the new parameter set against at least 4 experimental data sets from different areas within Australia, and
3. Release the new parameter set for use in the GrassGro decision support tool and the APSIM farming systems model.

3. Winter activity in lucerne

A period often referred to as ‘winter dormancy’ is a distinctive characteristic of the annual growth cycle of lucerne. The term ‘dormancy’ relates to a collection of processes that enable the plant to survive during the onset of stressful times of the year and that manifest as a slowing of shoot growth. For lucerne, however, the term *reduced winter activity* of the above ground biomass is a more appropriate description, as during this period the plant continues active photosynthesis but transitions from partitioning assimilates and activity to below-ground rather than above-ground structures.

Lucerne genotypes can be rated for their winter growth activity according to the extent of shoot elongation in winter. Plants are cut at the end of autumn and their productivity, canopy height and leaf:stem ratio 4 weeks later are used to assign a winter growth activity rating (WAR). Genotypes are rated from 1 (very inactive growth in winter) to 11 (highly winter active) but for the purposes of GRAZPLAN have been classed into four groups (Table 1).

Table 1. Winter activity classes for lucerne (Loo et al 2006)

Class	WAR ratings	Description
Winter inactive (WI)	1-3	Little autumn-winter growth.
Semi-winter active (SWA)	4-5	Low winter production. Have broad, low crowns. Used as a companion with annual legumes or grasses in long-term pastures.
Winter active (WA)	6-7	Growth slows during the winter months, but does not cease. Low crown. Suitable for long-term permanent pasture with long stand life.
Highly winter active (HWA)	8-11	Have high seedling vigour and first year production. Very productive but generally have poor persistence; require careful grazing and cutting to maximise persistence. Persistent under rotational grazing, but crown is commonly narrow and more exposed to grazing. Well suited to short rotations of 2 - 4 years.

The exact nature of the physiological differences between lucerne genotypes with differing WAR is not well understood. For example Wang *et al.* (2009) found for a range of genotypes with different WAR that there were differences in photosynthesis or photorespiration. Other authors have found that more winter-active cultivars do not initiate the dormancy process as early as winter-dormant cultivars (Bula and et al. 1956; Shih *et al.* 1967; Paquin and Pelletier 1980). Brown *et al.* (2005) suggested that the rate of leaf emergence also showed cultivar dependency, possibly in relation to assimilate supply from the perennial organs. However this is not clear from literature and the actual effects might be complicated by a genotype by environment interaction.

There are obstacles to accurately simulate the growth and development of lucerne that occur largely as a result of dormancy and the ecophysiology of the lucerne plant (*i.e.* physiological responses to its environment) (Brown *et al.* 2005; Teixeira *et al.* 2009). A number of areas remain elusive for modelling such as accurately predicting the phenology, particularly in the autumn, and its acquisition and use of below-ground reserves; capturing differences between lucerne cultivars with different levels of winter activity; and predicting changes through the year in the nutritive value of lucerne. A number of attempts have been made to express dormancy in lucerne models (Fick 1984; Kanneganti *et al.* 1998; Moot *et al.* 2001; Chen *et al.* 2008; Teixeira *et al.* 2009; Pembleton *et al.* 2011). Although these approaches have been effective in replicating biomass dynamics for a given dataset they are not physiologically robust and therefore it is difficult to confidently transfer the parameter sets across diverse combinations of climate and different farming systems in other locations.

4. Improving the parameter sets for lucerne in the GRAZPLAN model

The research reported in this section was a desktop study: the available literature on a range of aspects of lucerne physiology was reviewed and parameters describing the responses of multiple winter dormancy types of lucerne were derived from the information obtained. In some cases it proved necessary to calibrate model parameters against the validation datasets that are described later in the report.

The cycle of flowering under cutting and grazing

Many of the equations describing the phenology in the GRAZPLAN model rely on accumulation of thermal time. The base temperature for thermal time accumulation (K_{V3}) has been set to a value of 1°C following Moot *et al.* (2001) and Brown *et al.* (2005).

Water deficit has been shown to delay the start of flowering in lucerne (Halim et al. 1989, Peterson et al. 1992). Under soil water deficit, lucerne has distinctively shorter stems due to reduced elongation (Brown and Tanner 1983, Carter and Sheaffer 1983). Water stress increases leaf:stem dry matter ratio with smaller leaves (Whitfield et al. 1986, Halim et al. 1989).

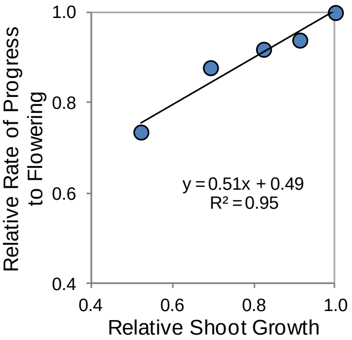

Figure 1. Relationship between the reduction in lucerne shoot growth rate due to water deficit and relative rate of development toward flowering. Values are derived from data in Halim et al. (1989) and Hattendorf et al. (1988).

Based on our review of the literature, the developmental cycle of lucerne at times when reduced winter activity is not in effect has been modelled as follows:

- At germination, or immediately following a period of reduced winter activity, a lucerne stand will grow vegetatively until a thermal time of 350°C.d has been accumulated.
- Once floral buds are initiated, the rate of development towards a fully opened flower is regulated by temperature. Flowering commences (i.e. 50% of stems have at least one flower) after a further accumulation of thermal time of 600°C.d; this value was estimated mainly from flowering date data in Zahid (2009). During this interval, the allocation of assimilate shifts away from roots and leaves toward stem production.
- An extended period of dry conditions (i.e. the growth-limiting factor for soil moisture remains below 0.25 for 15 consecutive days) will cause senescence of the stand, at which point vegetative growth re-commences.
- Defoliation during reproductive growth now alters the stage of phenological development (Table 2). For example, once flowering has begun, a defoliation that removes 25% of stand height returns the thermal time accumulation (relative to the start of reproductive growth) to half its pre-defoliation value, and removal of half or more of stand height takes the stand back to the commencement of reproductive growth.
- Water stress is modelled as slowing development toward flowering in regrowth stands of lucerne. Data from a water deficit experiment reported by Halim et al. (1989) and Hattendorf et al. (1988) was used to estimate that if water stress were to reduce growth rate to zero, phenological development in plants undergoing reproductive development would be slowed to half its unstressed rate (Figure 1).
- In the (unlikely) continual absence of defoliation, drought or conditions sufficient to induce reduced winter activity, the lucerne stand will continue to flower indefinitely.

Table 2. Parameters controlling the effect of defoliation on phenology (all cultivars).

Parameter	Value	Unit	Meaning
K_{V22}	0.0	0-1	Upper margin of the "phenology-sensitive horizon" during vegetative growth, as a fraction of plant height
K_{V23}	1.0	0-1	Thermal time (as a fraction of K_{V6}) for the upper margin of the phenology-sensitive horizon to reach the top of sward
K_{V24}	0.5	0-1	Final lower boundary of the phenology-sensitive horizon
K_{V25}	0.0	0-1	Height of removal for reset of phenology (as fraction of the lower boundary of the phenology-sensitive horizon)

Model logic describing reduced shoot activity during winter

As noted above, while large genetic variation in winter activity is found in lucerne, its physiological basis remains essentially unknown (Castonguay *et al.* 2006). The start of the period of reduced winter activity in lucerne is signalled by the reducing photoperiod and declining temperatures that are experienced in autumn. Shortening photoperiod initiates the process but decreasing temperatures are required to advance it. It seems that temperatures lower than about 15°C and photoperiods of around 13 hours are required for the process. It is unclear as to whether these triggers vary according to WAR, but similar values have been concluded from experiments in different environments and with different genotypes (Major *et al.* 1991, Brown *et al.* 2005, Sim 2014). Winter-dormant genotypes partition greater amounts of reserves to the taproot and consequently have a greater reduction in shoot growth than winter-active genotypes (Hodgson 1964, Teuber and Brick 1988).

After a careful review of the available literature, we concluded that (i) the existing sub-model for the timing of periods of reduced winter activity was inadequate to represent the behaviour of lucerne, and (ii) differences in WAR were best described as differences in the *intensity* of reduced winter activity rather than differences in its *duration*.

In the version of the GRAZPLAN model that was available at the start of this project, a "winter-dormant" phenological stage (a period with reduced meristematic activity, i.e. partial dormancy, and vegetative patterns of assimilate allocation) could be triggered by a linear combination of temperature and photoperiod falling below a threshold value. However, the 3-parameter equation proved to be inadequate to represent the onset of reduced winter activity. The phenology sub-model has therefore been modified to use 5 new parameters (Table 3):

Table 3. Parameters controlling the start and end of reduced winter activity (all cultivars).

Parameter	Value	Unit	Meaning
K_{V26}	0.0	°C	Lagged mean temperature below which reduced winter activity always ensues
K_{V27}	13.0	°C	Lagged mean temperature above which reduced winter activity is not promoted
K_{V28}	8.0	hour	Day length below which reduced winter activity always ensues (Schonhorst *et al.* 1957)
K_{V29}	14.0	hour	Day length above which reduced winter activity is not promoted
K_{V30}	5	day	Lag period for computing mean temperatures

A lagged mean temperature is computed as:

$$T_{lag}(t) = T_{mean}/K_{V30} + T_{lag}(t\text{-}1) \times (1–1/K_{V30})$$

and the sward displays reduced winter activity whenever the following condition holds:

$$RAMP(\ T_{lag},\ K_{V26},\ K_{V27}\ ) + RAMP(\ DL,\ K_{V28},\ K_{V29}\ ) \geq 1$$

The same equation controls both the start and end of the period of reduced winter activity. When reduced winter activity is no longer enforced, the phenological cycle recommences at the start of vegetative growth. Note that this submodel treats reduced winter activity as an enforced rather than induced partial dormancy, i.e. it ends shortly after environmental conditions become suitable for growth. This assumption is supported by the experimental evidence (McKenzie et al 1988).

Because the parameters of this new equation are taken to be the same for all genotypes, the simulated duration of reduced winter activity in a given environment will also be the same. (It was not possible to test this assumption using the available experimental datasets, but the available evidence provides little support for the alternative; see the discussion above.)

Differences in WAR classes are instead assumed to be due to two physiological differences:

- More winter-active genotypes undergo a smaller reduction in meristematic function during the period of reduced winter activity (represented by K_{MR1}, the maximum relative growth rate of shoots during the “winter-dormant” phenological stage). This results in a lower root:shoot ratio during the winter, i.e. proportionately less investment of assimilate into the taproot.
- More winter-active genotypes remobilize root reserves more rapidly into aboveground tissue when conditions are suitable, such as after defoliation and at the commencement of reproductive growth.

The parameter values describing these WAR differences (**Table 4**) were arrived at by trial-and-error calibration to the spring and summer experimental data sets, especially those with frequent defoliation, that are described later in this report.

Table 4. Parameters controlling differences in winter activity classes.

Cultivar Class	K_{MR1} (g g^{-1} d^{-1})	K_{TL1} (g g^{-1} d^{-1})	K_{TL2} (g g^{-1} d^{-1})
Highly winter active	0.020	0.30	0.05
Winter active	0.010	0.30	0.04
Semi-winter active	0.005	0.40	0.03
Winter inactive	0.000	0.40	0.02

Parameter K_{MR1} is the maximum relative growth rate of shoots during the “winter-dormant” phenological stage; parameter K_{TL1} is the threshold value of growth-limiting factors above which translocation from below-ground reserves takes place; and parameter K_{TL2} is the proportion of effective root mass that can be re-mobilized above ground in a single day if both environmental conditions are suitable and the current root:shoot ratio is above a target level set by the phenological stage.

Alterations to parameters for growth-limiting factors

Testing of the model in environments with moist soil during summer (especially Tamworth and the irrigated lucerne at Cranbrook) revealed that the original parameterization under-estimated growth rates under conditions of high soil moisture and high vapour pressure deficit. Accordingly the biomass-transpiration coefficient for all lucerne genotypes was increased to 9.0, e.g. a maximum transpiration efficiency of 45 kg/ha.mm at a typical early-summer VPD of 2.0 kPa[1].

The model was found to fit the experimental data better if the parameter setting the temperature above which photosynthesis proceeds at its maximum rate was increased to 18°C. This response was only detectable because the model was tested across environments with a range of winter temperatures.

Allocation of growth between roots, leaves and stems

Khaiti and Lemaire (1992) found that the seasonal variations in potential shoot production of lucerne were not determined by changes in the radiation use efficiency for the production of total biomass, but by the annual pattern of assimilate partitioning between roots and shoots. The seasonality in shoot production which is characteristic of lucerne – and which partly determines its pattern of forage supply – is therefore largely driven by differences in assimilation partitioning throughout the year.
Teixeira *et al.* (2008) found that the fractional partitioning of dry matter to roots increased from near zero in winter and early spring (reproductive growth) to more than 0.45 in autumn (i.e. the period of reduced activity). The latter figure corresponds to a root:shoot ratio of approximately 0.8, so the parameters giving the “target” root:shoot ratio has been decreased to this value during vegetative growth and to a lower value (0.3) once flowering has commenced.

When modelling experimental data sets that included data on the proportion of leaf in cut herbage, it became apparent that the original lucerne parameter set was predicting leaf fractions that were too low. This problem with the parameter set was addressed in two ways:

- The parameters governing allocation to leaf as a proportion of shoot allocation during vegetative growth were a fixed value of 0.80 (the original values ranged between 0.25-0.70).
- The original parameter set assumed that leaf and stem were distributed in equal proportions through the height profile of the sward. As can be seen in Figure 2, the upper layers of the sward have a much higher proportion of leaf, so that samples of herbage obtained by cutting have a higher proportion of leaf than the pre-cutting sward as a whole. The parameter K_{MO1}, which describes the variation of leaf:shoot mass with height, was fitted by least-squares minimisation to the data of Woodward and Sheehy (1979), resulting in a value of -0.30 (this value implies that there is a height below which all herbage is composed of stem).

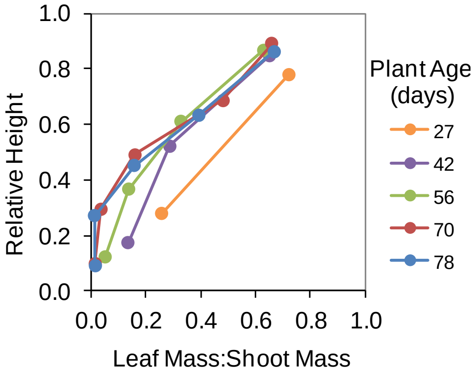

Figure 2. Leaf:shoot mass ratios in lucerne plants of different ages (Woodward and Sheehy 1979).

Leaf:stem ratio in lucerne is reduced by high temperature, as shown by Carter and Sheaffer (1983) who obtained greater leaf:stem dry matter weight ratios in cooler seasonal temperatures. This effect is captured in the GRAZPLAN model through the link between phenology and allocation: higher temperatures lead to a more rapid

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[1] Note that biomass-transpiration coefficients in different models are not directly comparable. For example, the APSIM-Plant model defines this parameter in terms of shoot rather than whole-plant NPP.

initiation of reproductive growth & of flowering, and the higher allocation to shoot during the reproductive phenological stage is allocated to stem production (see equation 36 of Moore *et al.* (1997).

Extension of the rooting front

When lucerne is grown in rotation with crops, a newly-sown lucerne stand grows its roots downward into the subsoil, so obtaining access to water not used by the preceding annual crops. The rate at which the rooting front develops (called the “extraction front velocity” or EFV) is therefore important in determining how long a lucerne stand takes to exploit this soil water resource.

The EFV of lucerne has been reported to vary from a minimum of 1.7 (Dolling *et al.* 2005a) to a maximum of 32 mm/d (Sim 2014); this last value is exceptional, however, and rates up to 17 mm/day have been more commonly observed (Jodari-Karimi *et al.* 1983; Meyers *et al.* 1996; Brown 2004; Dolling *et al.* 2005a).

In the GRAZPLAN model, the EFV is modelled as a function of soil bulk density, soil sand content, soil moisture content and thermal time. EFV increases with decreasing bulk density and with increasing sand content, both of which imply the existence of larger soil pores into which roots can penetrate.

Data presented by Dolling *et al.* (2005a) for 9 locations in Western Australia were used to estimate the parameters of the EFV sub-model, because only this data set included both a range of soil types and measurements of the soil attributes necessary to estimate EFV using the GRAZPLAN model equation. Rather than use the average EFVs over the whole soil profile presented by Dolling *et al.* (2005a), EFVs for the B horizons were estimated by linear regression of the data presented in their Figure 2. This was done to control the effects of soil moisture and temperature on EFV: the experimental conditions in the Dolling et al. experiment made it likely that there would always be soil moisture available at the base of the rooting front, and temperatures in the subsoils will not vary greatly from the long-term mean, allowing the measured EFVs in mm/d to be converted to the values in mm/°C.d that are predicted by the model equation.

The 4 parameters for the effect of bulk density and sand content on EFV (Table 5) were fitted to the measured EFVs by the method of least squares. Figure 3 compares the fitted and estimated EFVs, and Figure 4 shows the fitted relationship between EFV and bulk density for soils with a range of sand contents.
A complete listing of the new parameter set is given in Appendix 1.

Table 5. Fitted parameters controlling root extraction front velocity (all genotypes).

Parameter	Value	Unit	Meaning
K_{R2}	0.65	mm/°C.d	Maximum rate of root front extension
K_{R5}	1.95	Mg/m³	Threshold bulk density for reduced root extension in 100% sand
K_{R6}	-0.65	Mg/m³	Notional threshold bulk density for reduced root extension in 0% sand
K_{R7}	1.2	m³/Mg	Rate of decrease in root extension with increasing bulk density
K_{R8}	0.15	0-1	Minimum value of the bulk density effect on root extension

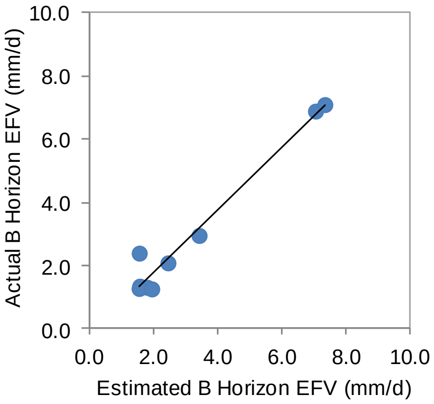


Figure 3. Observed vs fitted root extraction front velocities for B horizons in the data set of (Dolling *et al.* 2005a) The 1:1 line is shown.

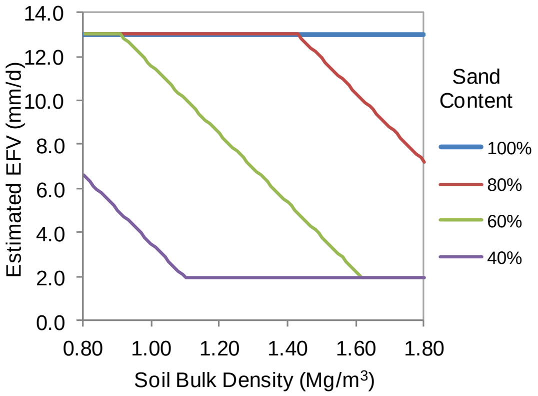


Figure 4. Fitted response of root extraction front velocity to bulk density and sand content in the layer containing the current rooting depth, on a (summer) day where 20°C.d of thermal time accrues.

Changes to the dynamics of herbage quality

In initial simulations of the Cootamundra dataset (Hayes et al. 2010), the modelled digestibility was too low and the modelled crude protein content was too low. The parameters describing the initial digestibility of both leaf and stem were increased to 85%, the minimum digestibility of green leaf during non-reproductive growth was increased to 75% and the rate constant describing the relative decline in digestibility of green stem was reduced to 0.002 (°C.d)$^{-1}$. The minimum N concentration of green stem was decreased to 30 g/kg when DMD=85%, 18 g/kg when DMD=65% and 10 g/kg when DMD=45%.

5. Experimental data sets for validation

Because the GRAZPLAN models are applied across a wide range of environments, the first criterion for selection of the available databases for model validation was to obtain experimental datasets that gave reasonable coverage of this environmental diversity within Australia. Experiments covering longer spans of time are also preferable because they allow the model to be tested against a greater range of temperature and moisture conditions.

A range of datasets were sourced and a final set of 7 experiments was

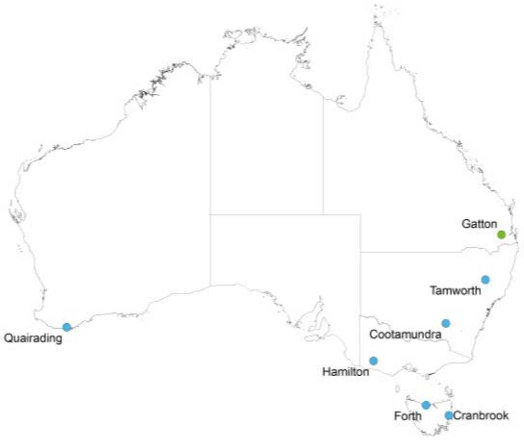


Figure 5. Locations of the experimental data sets that were used for testing the lucerne parameter set for the GRAZPLAN pasture model. Gatton (shown in green) was used in long-term simulations to examine patterns of growth predicted by the parameter set.

chosen based on the availability of adequate site characterisation in terms of soil properties and local meteorological conditions during the experiment, the length of record, whether shoot biomass accumulation was recorded at for least 10 intervals, the inclusion of a number of cultivars (differing in their WAR) in the experiment, and the availability of data other than shoot production (*e.g.* chemical composition of the shoot material, leaf:shoot proportion, root data, soil water dynamics *etc.*). The locations of the selected experimental data sets are shown in Figure 5 and the experiments are summarised in Table 6; further details of the datasets are given in Appendix 2.

Table 5. Details of experimental datasets used in the evaluation of the new GRAZPLAN parameters for lucerne. (Climate summaries are for 1950-2013.)

Location	Latitude	Average Temperature (°C)	Average Rainfall (mm)	Soil	Cultivar Classes Represented				Key references
					WI	SWA	WA	HWA	
Forth	41°20'S	12.1	975	Red Ferrosol	X	X	X	X	Pembleton et al. 2010
Cranbrook	42°01'S	12.9	632	Red Ferrosol	X	X	X	X	Pembleton et al. 2010
Tamworth (Boschma)	31°15'S	16.7	678	Brown Chromosol	X			X	Li et al. 2010
Tamworth (Lodge)				Brown Chromosol	X	X	X	X	Lodge 1985
Hamilton	37°84'S	13.1	681	Brown Chromosol		X	X	X	Li et al. 2010
Cootamundra	34°40'S	15.1	660	Yellow Dermosol			X		Hayes et al. 2010
Quairading	32°02'S	17.6	366	Gravelly pale deep sand			X		Dolling *et al.* 2005b Latta and Lyons 2006

Simulation of the experimental data sets: methods

Simulations of each experiment were constructed using the GRAZPLAN pasture and livestock models (Moore et al. 1997, Freer et al. 1997) linked to the APSIM soil water and soil nutrient cycling models (Holzworth et al 2014) by using the AusFarm software (version 1.4.8). Weather data (precipitation, maximum and minimum air temperature, vapour pressure deficit, solar radiation) were obtained from local weather stations where possible; otherwise a Patched Point dataset for the closest climate station was extracted from the SILO data base (Jeffrey et al. 2001).

Soil physical and chemical attributes were taken from on-site measurements where available; otherwise soil attributes were acquired for the most suitable detailed information in databases such as APSoil (Dalgliesh et al. 2009) based on advice from local experts. Local soil data for the Tamworth experiments in particular was limited, which introduces uncertainty into model predictions from the outset.

Details of management practices such as sowing, fertiliser use, grazing, cutting and weed control were extracted from publications relating to each experiment (Table 5) and reproduced using the management-rule system that is available in AusFarm (Moore et al. 2014). Where descriptions of management activities were incomplete, they were inferred based on the authors' and local experts' knowledge of the same or similar systems. Information on cutting heights and the durations and stocking densities in periods of grazing was frequently not reported.

The initial conditions of the soils at the time of sowing of the lucerne were not recorded in any of the experiments used for validation. In order to reduce this potentially large source of uncertainty in soil moisture, carbon and nitrogen pools, we ran each simulation for a period prior to the commencement of each experiment. In a number of cases the pre-experimental management of the sites was not clearly reported; pre-experimental conditions for these experiments were modelled based on the advice of local experts; typically a fallow period was simulated prior to sowing of the lucerne.

In order to realistically represent the experiments, simulations consisted of mixed swards rather than monocultures, even though the botanical composition – or content other than lucerne – was only recorded for a minority of sampling dates. In most cases this meant the inclusion of a winter grass, forb (such as a broadleaf weed) and sometimes (if reported) an annual legume and summer grass.

Where not available from records or local experts, the maximum rooting depth of each species was set based on soil physical properties (*e.g.* bulk density). All species except lucerne were sown in the simulations prior to the start of the fallow period.

The experiments were defoliated in various ways, following the management reported in the papers describing them. Some trials were grazed, some were cut, others were grazed and then the residual biomass cut to a set height. Cutting events were modelled using the corresponding event in the GRAZPLAN model, with a best-available estimate of the cutting height used. Mown biomass was either removed from the plot or retained, as reported for each experiment. Grazing was often reported as ‘crash grazing’, i.e. sheep grazed the experimental plots at a high stocking density until herbage mass was reduced to a low level. In these experiments, the length of each modelled post-harvest grazing period depended on the availability of forage. In other cases the number of sheep was adjusted according to the pre-grazing biomass so that animals were on the plots for a set period of time.

In some of the experiments, the height to which biomass samples were cut was not the same as the height to which plots were subsequently mown. The actual sampling height was taken into account when recording biomass values for comparison with measured data, including the differentials in leaf proportion in the sampled biomass and the un-sampled residual.

6. Validation of the parameter sets against experimental data

In this section, model predictions for a selected winter activity class are compared against the corresponding data from each of the 7 experiments. A winter-active or highly winter-active genotype has been selected in each case as these genotypes are generally the best adapted to Australian conditions.

For each data set and sampling interval, the pasture growth rate from the end of cutting or grazing to the next herbage sampling date has been calculated; this is the “actual” pasture growth rate (PGR). The corresponding modelled PGR has been calculated in the same way and compared to the actual PGR for each time interval. Modelled time courses of biomass are shown for biomass “above cutting height”, i.e. above the height at which biomass samples were cut; this was not generally the same as the height at which the entire plots were mown.

Tasmania – Forth and Cranbrook

Model predictions for irrigated lucerne stands at two locations in Tasmania are shown in Figures 6 (Forth) and 7 (Cranbrook). The model captures the seasonal patterns of pasture growth quite well over the 6 site-years at these two locations, with root mean square deviations (RMSD) for PGR of 27 kg/ha/d at Forth and 44 kg/ha/d at Cranbrook. At both locations, the regression of actual PGR compared to modelled

PGR is not significantly different from the 1:1 line. Overall, the model underestimates total pasture growth at Forth by about 15%, in particular for seedling stages and also in spring and early summer. At Cranbrook the model estimates total growth by 12% and there is no consistent relationship between the residuals and the time of year.

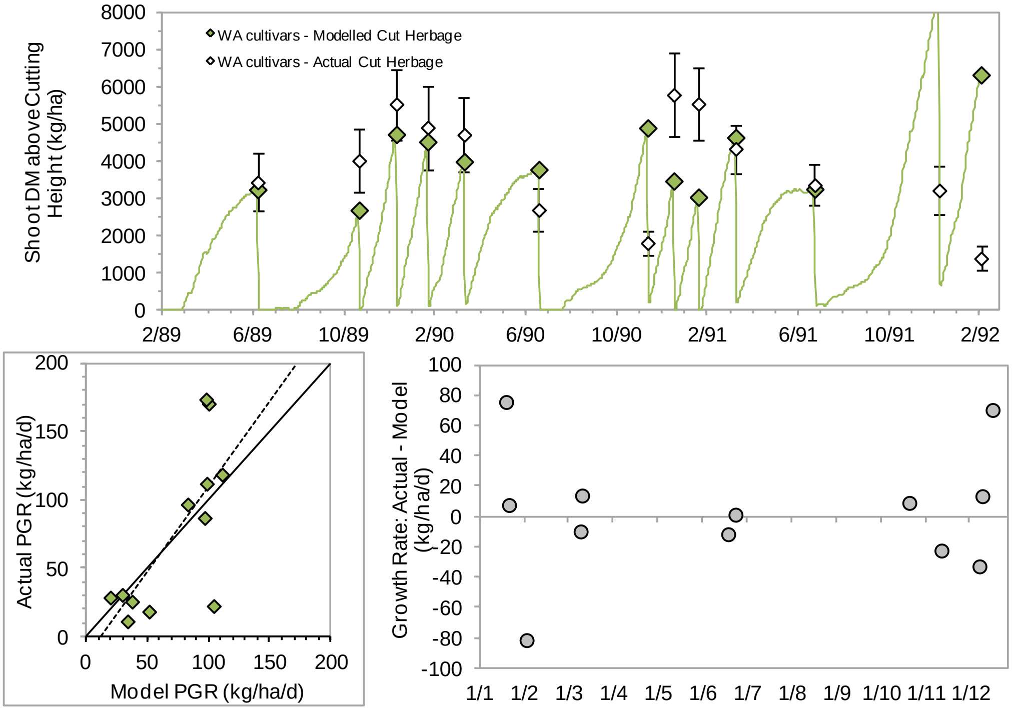


Figure 6. Actual and predicted (modelled) harvested dry matter for winter-active lucerne growing at Forth, Tasmania. The upper pane shows the amounts of sampled biomass at each cutting date (error bars show the standard deviation about the mean); the lower-left pane compares modelled and actual pasture growth rates (PGR); and the lower-right pane shows the residuals of the growth rates as a function of the day of year on which samples were cut. In the actual-vs-model chart, a 1:1 relationship is shown as a solid line and the regression of actual on modelled PGR is shown as a dotted line.

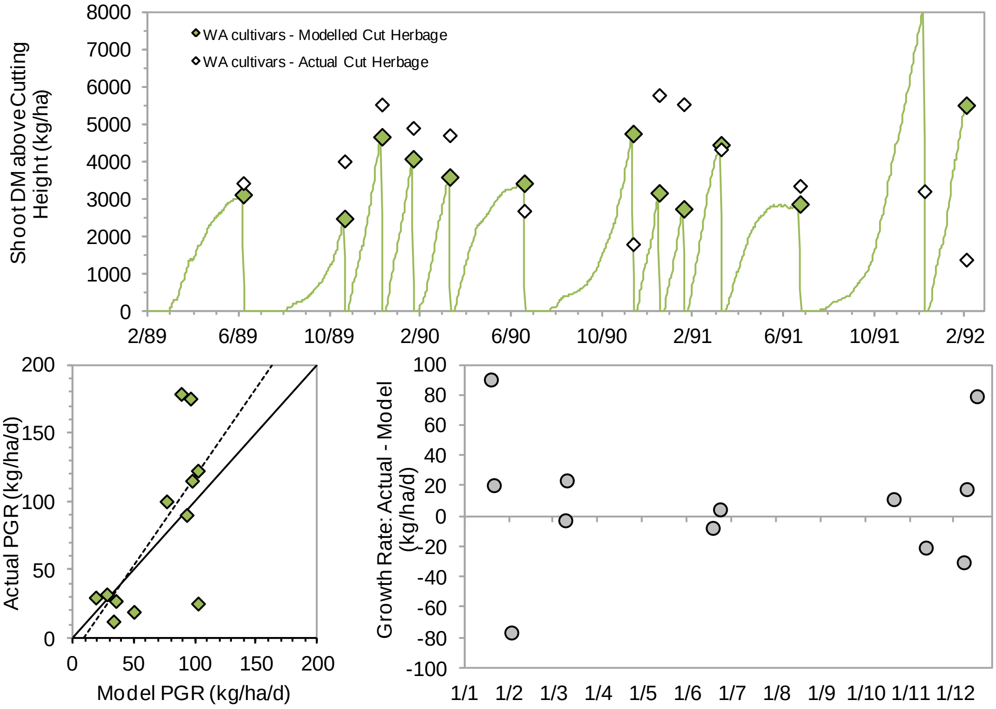


Figure 7. Actual and predicted (modelled) harvested dry matter for winter-active lucerne growing at Cranbrook, Tasmania (error bars show the standard deviation about the mean). Results are presented in the same fashion as in Figure 6.

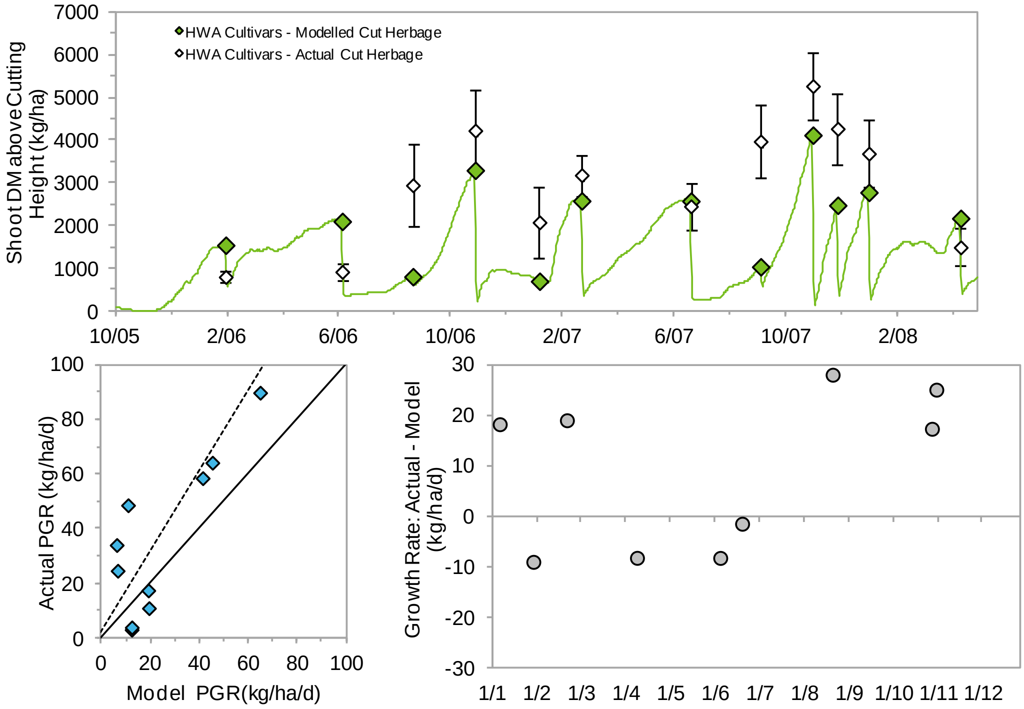


Figure 8. Actual and predicted (modelled) harvested dry matter for highly winter-active lucerne growing at Hamilton, Victoria (error bars show the standard deviation about the mean). Results are presented in the same fashion as in Figure 6.

Victoria – Hamilton (Nie)

As can be seen in Figure 8, a high correlation (87%) between actual and modelled PGR values in the Hamilton dataset is offset by the model under-predicting total herbage production by the highly winter-active genotypes. The overall result is a still-acceptable RMSD of 28 kg/ha/d (or about 50% of the mean PGR over all cutting dates); however the under-prediction of lucerne growth means that the regression of actual PGR on modelled PGR is statistically distinguishable from the 1:1 line. In this experiment the winter-active genotypes yielded less than both the highly winter-active and semi-winter-active types, and so the model represents the performance of the winter-active genotypes rather better, with negligible bias in the overall prediction of growth.

The model successfully captures the high spring growth rates in the Hamilton data set (in contrast to the Tasmanian locations, where growth rates were highest in summer). The GRAZPLAN model's predictions for the Hamilton dataset do not show systematic errors at particular times of year.

Southern NSW – Cootamundra

For the Cootamundra experiment there was only moderate (although statistically significant) agreement between actual and modelled PGR values, with a RMSD of 19 kg/ha/d. There was no distinguishable pattern in the model deviations due to seasonality; instead the model tended to under-predict PGR in the later part of the experiment (Figure 9).

Soil water contents were measured during the Cootamundra experiment. For the topsoil there was initially a large difference between modelled and actual soil water content when the lucerne was in juvenile stages (Figure 10). However this effect

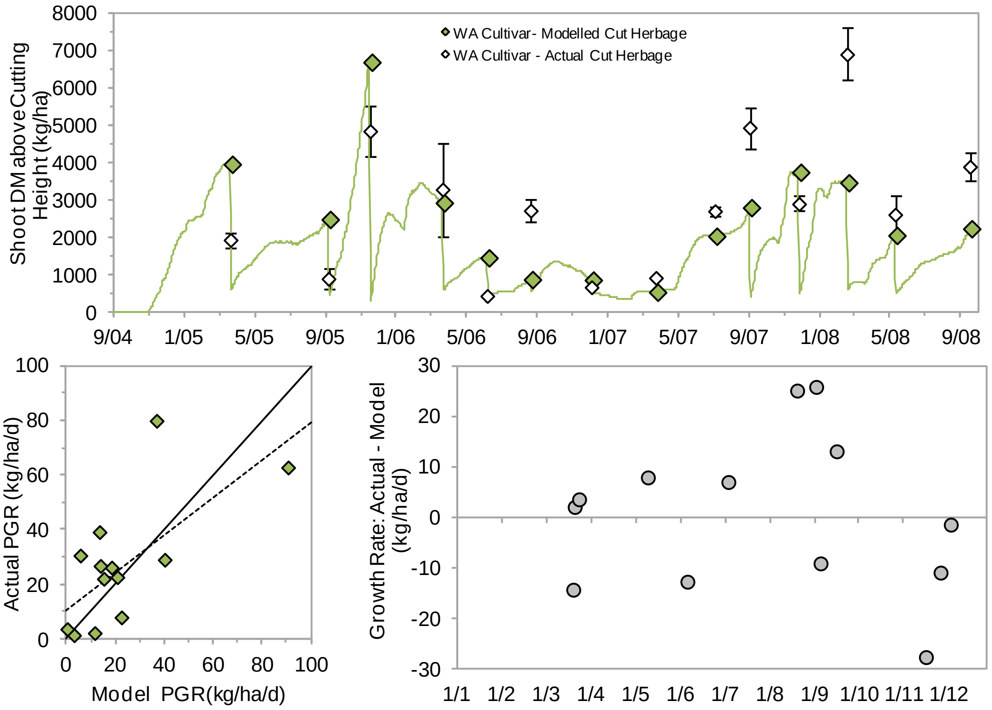


Figure 9. Actual and predicted (modelled) harvested dry matter for winter-active lucerne growing at Cootamundra, New South Wales (error bars show the standard deviation about the mean). Results are presented in the same fashion as in Figure 6.

lessened towards the start of 2006 with stand maturity and for the remainder of the period there was close agreement in the soil moisture of the surface layers.

For the subsoil there was initially close agreement between actual and modelled data, with the middle of the experimental period quite close (Figure 10). However in the third year of the experiment, the modelled and actual subsoil water contents diverged as the modelled sward continued to extract water. (Note, however, that Figure 9 shows that the modelled stand was under greater water stress during this period than the actual stand must have been.)

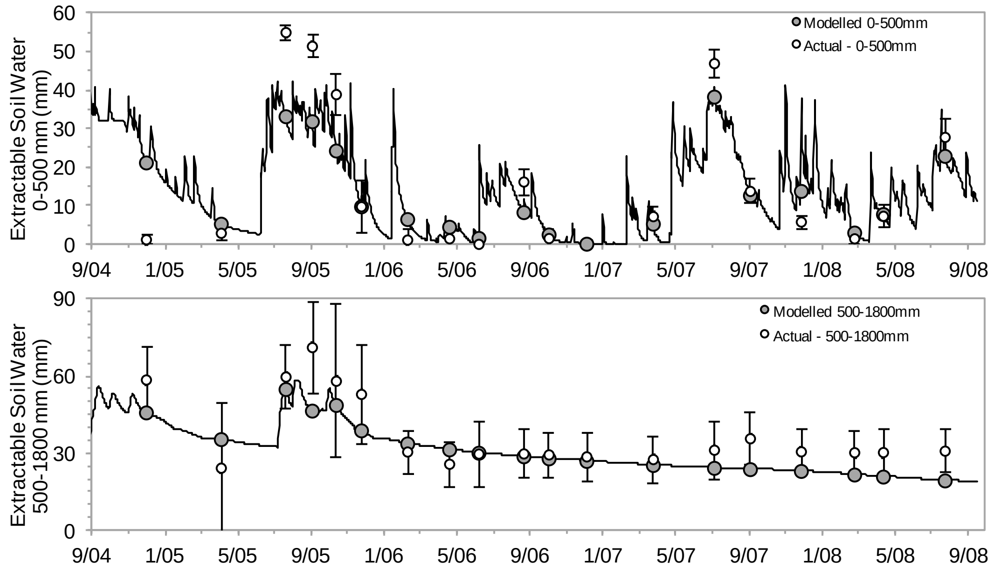


Figure 10. Actual and modelled soil water content (mm) from 0-500mm depth (top) and 500-1800mm depth (bottom) under winter-active lucerne grown under cutting management at Cootamundra, New South Wales (error bars show the standard deviation about the mean).

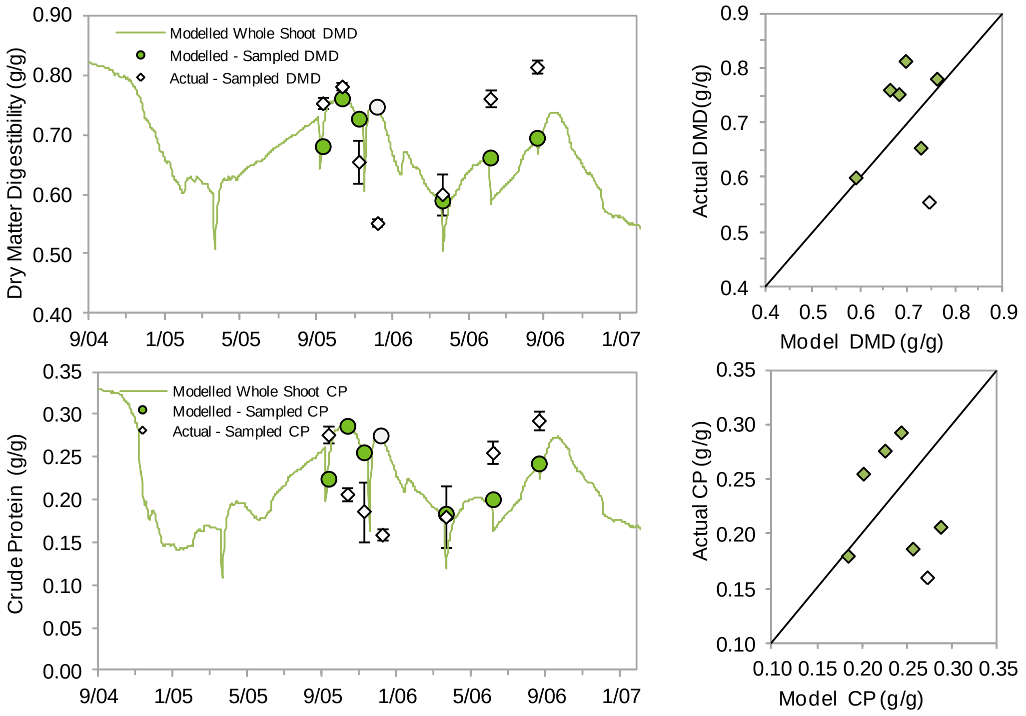


Figure 11. Actual and modelled digestibility (DMD, g/g) and crude protein content (CP, g/g) of biomass sampled from winter-active lucerne grown under cutting management at Cootamundra, New South Wales.

Figures 11 and 12 show the predictions by the GRAZPLAN model of dry matter digestibility and crude protein content of the lucerne forage in the Cootamundra experiment during 9 months in 2005-06. Because the forage quality samples were made in between the herbage mass sampling dates, including at times where the leaf:stem ratio of the stand would have been changing rapidly (e.g. the points shown in light grey in Figure 11, where the sampling date was shortly after the herbage was cut), the RMSDs of prediction are quite high (0.08 for digestibility and 0.06 for crude protein). The modified parameter set nonetheless provides a greatly improved prediction of forage quality than did the parameter set that was current at the beginning of the project, which significantly underestimated DMD in particular; the new parameters capture about 30% of the variation in DMD across sampling dates. As can be seen in Figure 12, the co-variation between herbage digestibility and crude protein content at the sampling dates is quite well captured by the model.

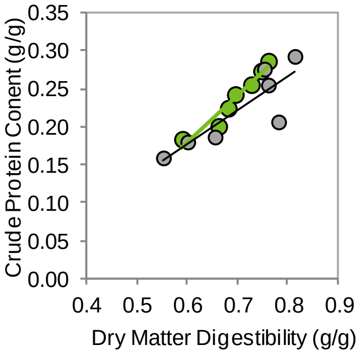


Figure 12. Actual and modelled relationships between digestibility and crude protein in sampled herbage for winter-active lucerne grown under cutting management at Cootamundra, New South Wales.

Northern NSW – Tamworth

Lucerne growth rates in two Tamworth experiments were not as well predicted as at the southern Australian locations. Growth rates in the Boschma experiment were modelled with a RMSD of 17 kg/ha but this was a much greater proportion of the average growth rate than for the southern locations. The relationship between predicted and actual growth rates in this experiment did not depart significantly from the 1:1 line overall, but autumn growth rates were over-predicted (Figure 13 and Figure 17). As with some of the other experiments, the early development of the lucerne stand was not well predicted.

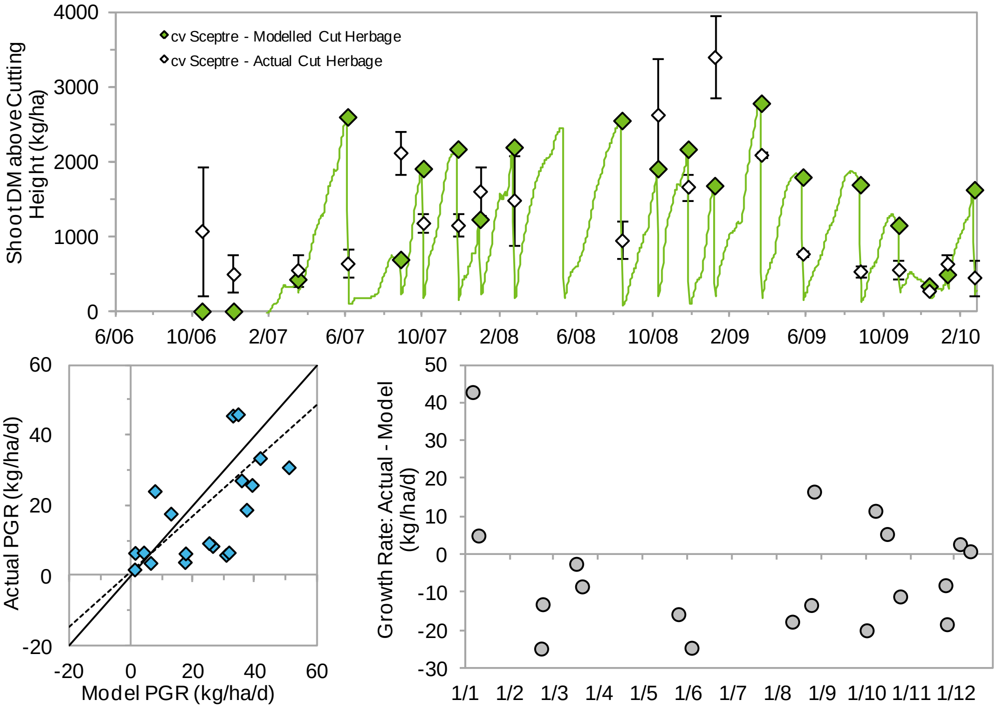


Figure 13. Actual and predicted (modelled) harvested dry matter for highly winter-active lucerne growing at Tamworth, New South Wales from June 2006 to February 2010 (Boschma experiment). Results are presented in the same fashion as in Figure 6.

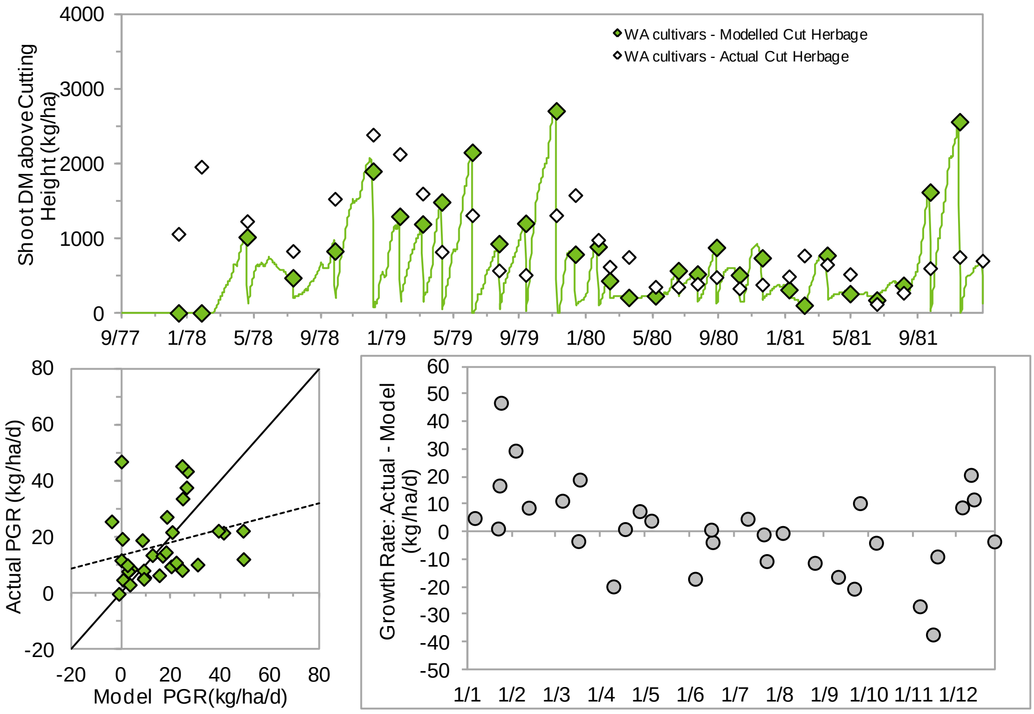


Figure 14. Actual and predicted (modelled) harvested dry matter for winter-active lucerne growing at Tamworth, New South Wales from September 1997 to December 1981 (Lodge experiment). Results are presented in the same fashion as in Figure 6.

While the GRAZPLAN model succeeded in representing the period of low lucerne growth and the subsequent recovery in the Lodge experiment, the quantitative performance of the model in this experiment was the poorest of the 7 data sets. Once again the early production of the lucerne was under-predicted, and in this data set the model under-predicted summer growth rates (Figure 14 and Figure 17). The Lodge experiment was the oldest of the data sets – employing a range of cultivars that are now outdated – and was also the dataset for which the information about the management of the stand was least well described.

Western Australia – Quairading

The changes in lucerne growth rate over time were quiet well predicted in the Quarading data set, with the slow establishment of the stand and the failure of growth at the end of the experiment both being predicted by the model (Figure 15). The correlation between actual and predicted growth rates was quite high (58%) and the relationship between actual and modelled growth rates was close to the 1:1 line. There was no apparent relationship between the time of year and the residuals in the model's predictions (Figure 15).

Soil water contents were measured through the Quairading experiment. The modelled extraction of soil water from the surface 800mm was too high early in the experiment (as at Cootamundra), but the pattern of extraction of water from the subsoil was quite well predicted (Figure 16).

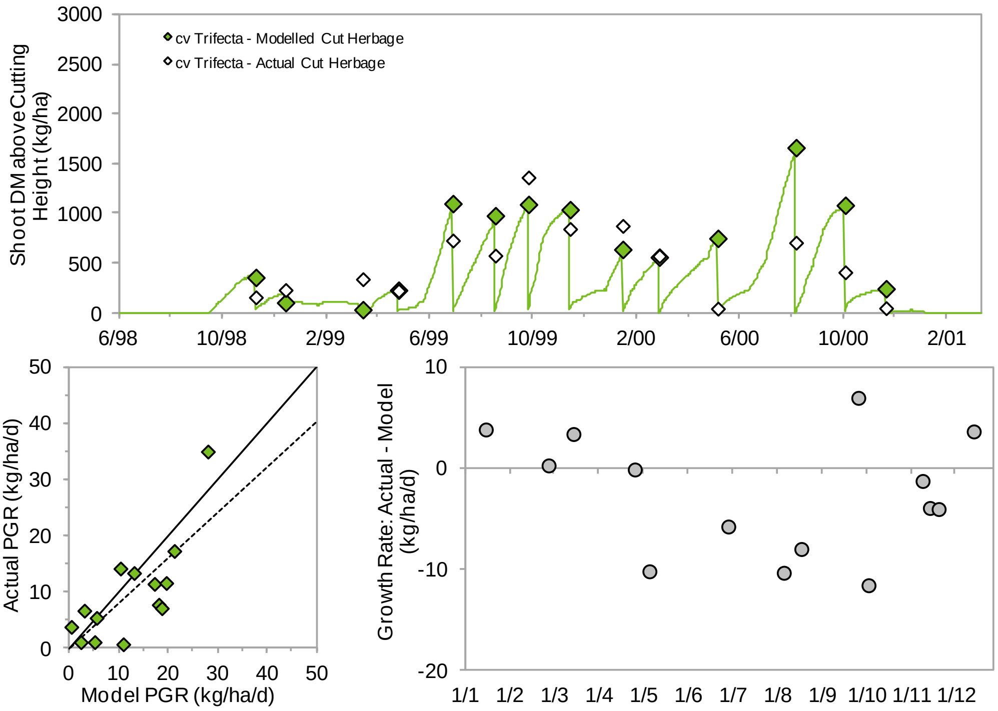


Figure 15. Actual and predicted (modelled) harvested dry matter for winter-active lucerne growing at Quairading, Western Australia. Results are presented in the same fashion as in Figure 6.

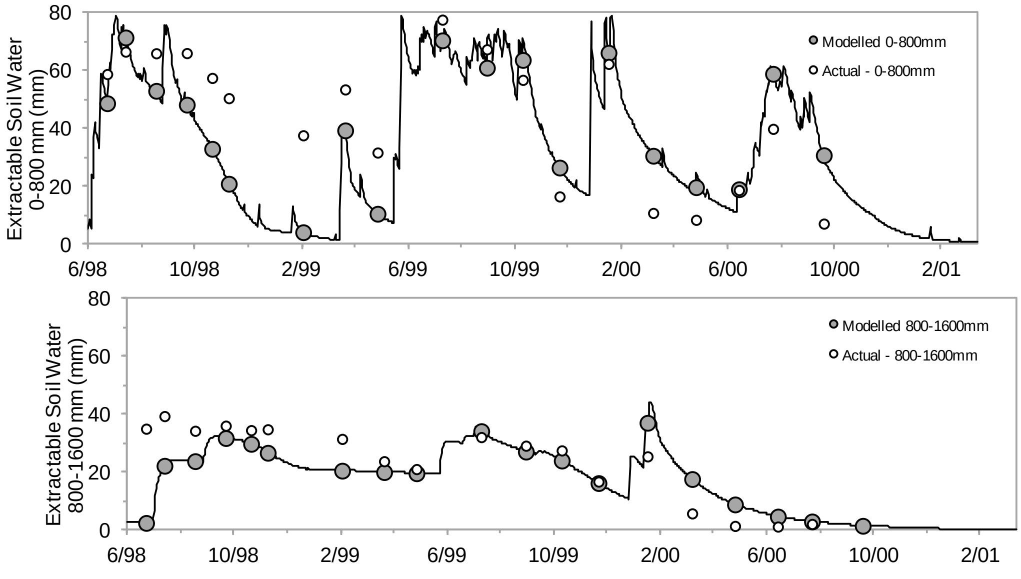
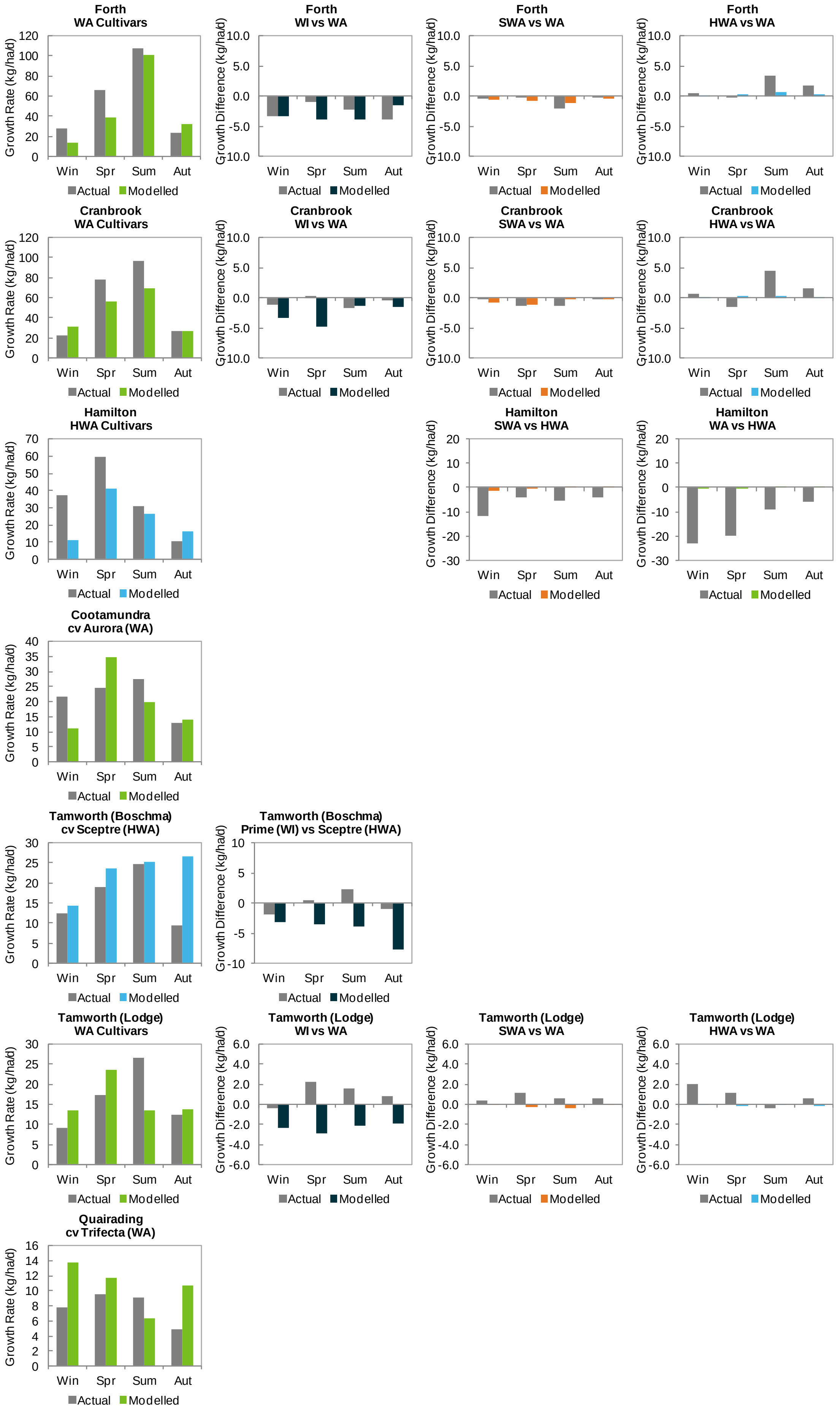


Figure 16. Actual and modelled soil water content (mm) over the 0-800mm and 800-1600mm depths under winter-active lucerne grown under cutting management at Quairading, Western Australia.

Figure 17 (overleaf). Actual and modelled seasonal pasture growth rates of reference genotypes in each of 7 experimental data sets, and (where available) the differences in actual and modelled seasonal average PGR between other winter activity types and the reference genotype.


Forth
WA Cultivars
Growth Rate (kg/ha/d)
120
100
80
60
40
20
0
Win
Spr
Sum
Aut
Actual
Modelled
Forth
WI vs WA
Growth Difference (kg/ha/d)
10.0
5.0
0.0
-5.0
-10.0
Forth
SWA vs WA
Forth
HWA vs WA
Cranbrook
WA Cultivars
Cranbrook
WI vs WA
Cranbrook
SWA vs WA
Cranbrook
HWA vs WA
Hamilton
HWA Cultivars
70
60
50
40
30
20
10
0
Hamilton
SWA vs HWA
20
10
0
-10
-20
-30
Hamilton
WA vs HWA
Cootamundra
cv Aurora (WA)
40
35
30
25
20
15
10
5
0
Tamworth (Boschma)
cv Sceptre (HWA)
30
25
20
15
10
5
0
Tamworth (Boschma)
Prime (WI) vs Sceptre (HWA)
10
5
0
-5
-10
Tamworth (Lodge)
WA Cultivars
Tamworth (Lodge)
WI vs WA
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
Tamworth (Lodge)
SWA vs WA
Tamworth (Lodge)
HWA vs WA
Quairading
cv Trifecta (WA)
16
14
12
10
8
6
4
2
0

Seasonal growth patterns and differences between winter activity types

Figure 17 summarises the overall patterns of lucerne growth in the 7 experiments and also the modelled patterns of growth rate over the same periods of time and calculated in the same way (i.e. allocating growth in each cutting interval by assuming that the rate of growth over each cutting interval was constant). While the model over- and under-predicts growth rates in each season, the only consistent bias in these average growth rates is a tendency for the model to over-predict autumn growth rates; in the other seasons, the model over-predicts for some experiments and under-predicts for others. Figure 18 shows that when summarised across seasons and experiments, the new parameter set captures most of the variation in the *patterns* of lucerne growth rate. The model explains 82% of the variation across seasons and experiments, with a RMSD of only 11 kg/ha/d.

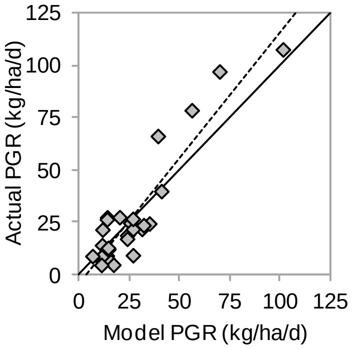


Figure 18. Actual vs predicted average seasonal growth rates in each of the 7 experiments.

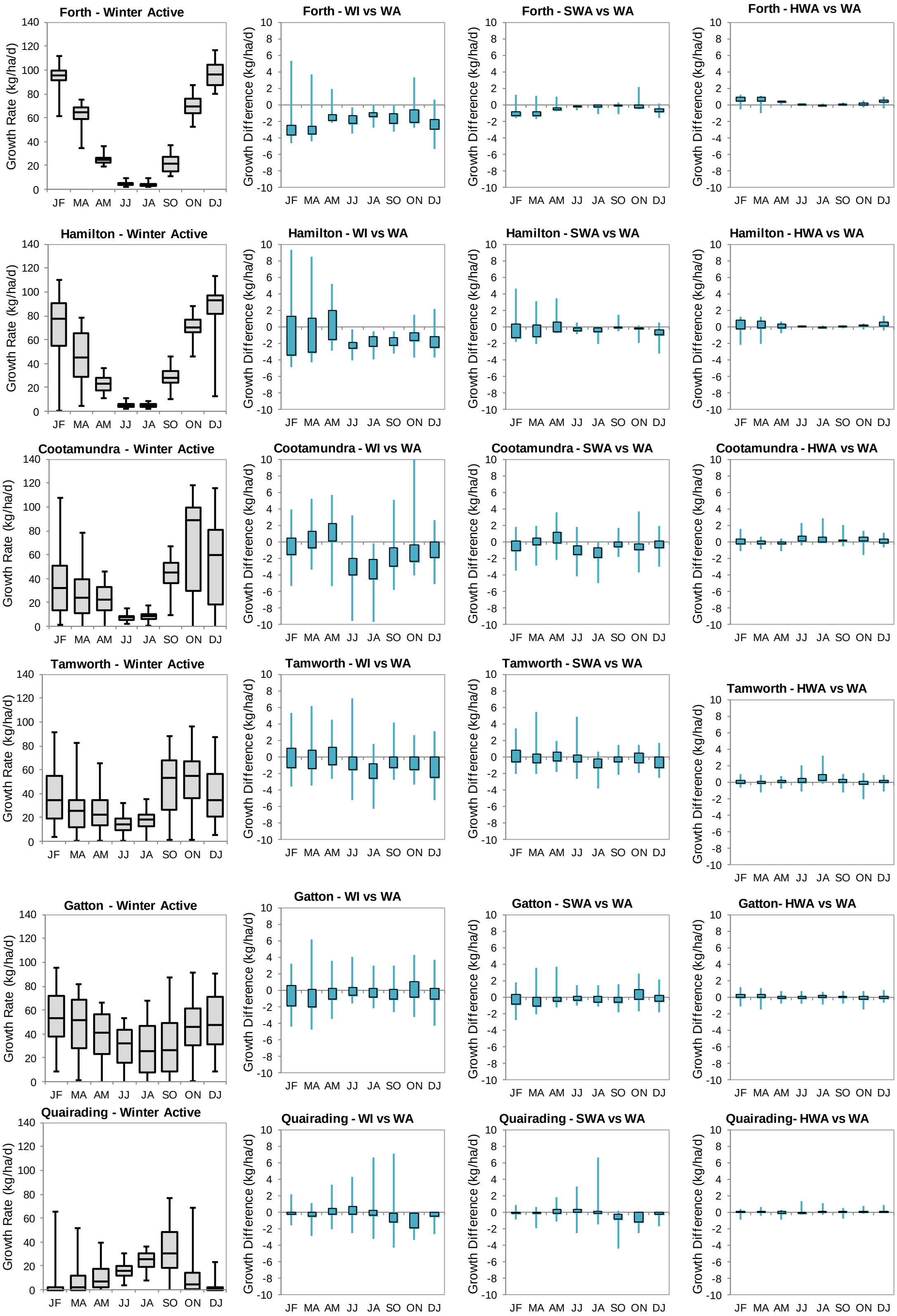
Figure 17 also compares the modelled and actual differences in PGR between the reference winter activity type and other types in each experiment. The capacity of the new parameter set to predict differences between winter activity was relatively modest. Overall, the new parameters were quite successful at describing the differences between the cultivars in the Tasmanian experiments, but predicted an advantage for winter-active genotypes at Tamworth that was not reflected in the experimental results.

At Hamilton, the lower overall production of semi-winter active genotypes relative to highly winter active genotypes was correctly predicted (although underestimated) but the large measured difference between winter active and highly winter active genotypes was not captured by the model. Given the non-linear response between winter activity rating and total production in this experiment, it appears that some other factor not accounted for in the model – perhaps disease – may have influenced the production of the winter-active cultivar (SARDI 7).

7. Long-term behaviour of modelled lucerne stands

The new lucerne parameter set was used to simulate long-term patterns of growth rate in permanent, dryland lucerne monocultures managed by cutting. Eight cutting dates at regular intervals of 45 days were used, with the first cut on 1 September so that the winter cutting interval was slightly longer than the other seven. Simulations were run from 1 January 1970 and average growth rates for cutting intervals that ended in the 40 years 1972-2011 were summarised.

Figure 19 (overleaf). Modelled pasture growth rates of 4 winter activity types of lucerne in 7 contrasting environments across Australia. The left-hand charts show box plots of modelled PGR for winter-active lucerne growing on a Red Chromosol at each location over the 40 years 1972-2011. The time intervals are the periods between herbage cuts at regular intervals of 45 days starting on 11 September. The remaining columns show box plots of the difference between PGR of 3 other winter activity types of lucerne and the winter-active type, when modelled using the same weather, soils and management. Note that the results are for lucerne grown for a continuous period of 40 years, not for successive phases of lucerne in pasture-crop rotation.


Forth - Winter Active
Forth - WI vs WA
Forth - SWA vs WA
Forth - HWA vs WA
Hamilton - Winter Active
Hamilton - WI vs WA
Hamilton - SWA vs WA
Hamilton - HWA vs WA
Cootamundra - Winter Active
Cootamundra - WI vs WA
Cootamundra - SWA vs WA
Cootamundra - HWA vs WA
Tamworth - Winter Active
Tamworth - WI vs WA
Tamworth - SWA vs WA
Tamworth - HWA vs WA
Gatton - Winter Active
Gatton - WI vs WA
Gatton - SWA vs WA
Gatton- HWA vs WA
Quairading - Winter Active
Quairading - WI vs WA
Quairading - SWA vs WA
Quairading- HWA vs WA
Growth Rate (kg/ha/d)
0
20
40
60
80
100
120
140
Growth Difference (kg/ha/d)
-10
-8
-6
-4
-2
0
2
4
6
8
10
JF
MA
AM
JJ
JA
SO
ON
DJ

Long-term average pasture growth in these “plausibility” simulations is high (Table 7), reflecting the lax defoliation regime, lack of weed competition and the ready supply of N to the lucerne through biological fixation. At Hamilton, for example, intensively managed perennial grass pastures have an average productivity of about 13 t DM/ha/year (Cayley et al. 1998). The modelled median lucerne growth rates follow a similar seasonal pattern to the corresponding experimental datasets at Forth, Cootamundra and Tamworth. At Hamilton, however, the long-term simulation has a higher summer than spring growth rate, and at Quairading a permanent lucerne stand (which will “mine” any stored soil water after 3-4 years) is predicted to grow very little over summer, unlike the lucerne ley pastures in the Quairading experiment.

The main feature of the growth rate patterns presented in Figure 19, however, is the high variability in lucerne growth rates between years (except at Forth, even under dryland conditions).

Table 7. Long-term average (1972-2011) pasture growth by modelled lucerne stands at 6 locations and its variability

Location	Average Annual PGR (t/ha)	Standard Deviation of Annual PGR (t/ha)
Forth	17.0	1.2
Hamilton	15.0	3.1
Cootamundra	12.1	4.6
Tamworth	11.8	3.9
Gatton	14.7	5.6
Quairading	5.2	2.1

8. Discussion

The methods used in this project mean that the test of the new GRAZPLAN model parameters is particularly rigorous by the standards of grassland model validation studies. First, we have tested the model across a wide range of environments. Second, we have made a considerable effort to base the soil descriptions and weather data on locally-measured values. Fourth, by using the management logic available in the AusFarm software, we have mimicked the actual experimental management as closely as possible, taking the individual features of each experiment into account.

We have also increased the rigour of our validations by assessing the GRAZPLAN model’s performance from its predictions of growth rate, rather than from predictions of harvested biomass. In grazing experiments, biomass measurements are auto-correlated, and so it is easier to predict them to a given level of accuracy than it is for growth rates. In cutting trials such as those used here, the harvested biomass is the product of the average growth rate (which must be predicted by a model) and the interval between cuts (which is known in advance of the model run); if there is variation in the cutting intervals, therefore, the correlations between predicted and actual growth rate are expected to be lower than those between predicted and actual yield.

Predictions of lucerne growth rate over short intervals

Mean prediction errors of PGR in our validation simulations (MPE, i.e. the RMSD of PGR as a proportion of the mean PGR) ranged from 0.33 at Forth to 0.81 and 0.96 in the two Tamworth experiments (Bosch and Lodge respectively); the average MPE across sites was 0.65.

To place this result into context, it is useful to compare it to other studies. The only pasture model validation study we are aware of that addressed a comparable number of sites and which also predicted PGR rather than biomass was a study by Barrett et al. (2005). They used the GrazeGro model (which should not be confused with the GrassGro decision support tool) to simulate perennial ryegrass pastures in cutting trials at 5 European locations; they included 9 site-years (compared with 21 site-years in our analysis). Barrett et al. (2005) obtained mean prediction errors ranging from 0.20 to 0.76, with an overall MPE of 0.45.

While Barrett et al. (2005) were able to predict ryegrass growth with MPEs considerably lower that obtained in our lucerne modelling, they were working in much more productive environments; the mean measured PGR in their study was 50 kg/ha/d, compared with 32 kg/ha/d in our 7 data sets. Because relative *measurement* errors increase as yields decrease, MPE of any model can be expected to be higher in less-productive environments. Average PGR for the four southern Australian lucerne experiments was 46 kg/ha/d and the MPE over these experiments was 0.52, which is comparable to the value obtained by Barrett et al. (2005). It should be noted that the GrazeGro study used data sets with only established grasslands, unlike the present experiments.

In their validation of APSIM-Lucerne, Robertson et al. (2002) used a single experiment at Lawes, Queensland over 2 years. The MPE for pasture growth rate in that simulation was 0.48 (from analysis of their Figure 7); because the Lawes experiment was irrigated and growth rates were high, this result is best compared with the MPE of 0.33 obtained here for Forth.

In a number of the validation simulations, the early growth of the lucerne stand was not well simulated. One reason for this is that the GRAZPLAN model represents sowing according to the mass of seed sown, and assumes 100% viability. This assumption is likely to be faulty for lucerne. In the Quairading experiment, for example, 5 kg/ha of seed was sown; at a mean seed weight of 1.7 mg, this corresponds to nearly 300 seeds/m^2 sown but only 38 plants/m^2 established. It may be necessary to specify sowing events in terms of the numbers of plants establishing, as in the APSIM crop growth models (including APSIM-Lucerne).

Predictions of lucerne growth rate patterns across sites and seasons

When the effects of the environmental conditions in particular years are averaged out and the time frame of comparisons is extended from single cutting intervals to entire seasons (i.e. 3 months), Figures 17 and 18 show that the performance of the GRAZPLAN model with the new lucerne parameter set is encouraging. Nonetheless, there are some features of our results where the model could do better. The general over-prediction of growth rates in autumn is presumably due to the intensity of water limitation not being accurately modelled overall.

There is a tendency for the model to under-predict total lucerne production in maritime environments (Forth, Hamilton) and to over-predict it in continental environments (Tamworth, Quairading). This appears to be related to the term in the growth rate equation that limits growth due to stomatal closure under high vapour pressure deficits. For consistency with APSIM crop growth models, VPD in the GRAZPLAN model is calculated from air temperature by assuming that dew point temperature equals the minimum temperature. This assumption does not hold in all environments and it may be that a more accurate approach to estimating VPDs would allow this error in the model to be corrected.

Modelling the nutritive value of lucerne

As reported earlier in the project, we reviewed a large number of experimental datasets before settling on the set of 7 experiments used here to validate the model. High-quality data on the nutritive value of lucerne were scarce, and in the end we were only able to calibrate the lucerne parameter set against 1 site-year of DMD and crude protein measurements. The new parameter set now produces much more realistic leaf:stem ratios (typically about 1:1 at flowering, where the original parameter set produced ratios nearer to 1:1.5) and its long-run average predictions of DMD and crude protein have significantly improved. Difficulties with matching the sampled herbage to modelled quantities, and the highly dynamic nature of nutritive value changes during lucerne regrowth, mean that the predictive skill of the model against the single available data set was only modest.

Differences between winter activity types in lucerne

We were surprised to discover that, despite numerous chamber and glasshouse studies, the physiological basis of winter-activity differences in lucerne remains essentially unknown (Castonguay *et al.* 2006). The assumptions we have embedded in the new parameterisation of the phenology of lucerne, and in the responses of shoot growth and relocation to the period of reduced winter activity represent a hypothesis about this physiological basis that could profitably be explicitly tested.

Our attempt to represent the differences between the winter-activity types was only partially successful. Our current model correctly predicts that winter-active genotypes will have higher production in southern Australia, but the apparent advantage of winter-inactive types in the Tamworth experiments was not reproduced. Examination of the winter-active vs winter-inactive genotype comparison in Figure 19, however, suggests that the model *is* predicting a south-north gradient in the differential between cultivars, but a gradient of smaller magnitude than the experimental datasets suggest. We therefore conclude that the new set of parameters for different winter activity types of lucerne is an improvement over the previous parameter set, but that further work on this aspect of the lucerne model will be needed.

The persistence of lucerne in a range of Australian environments has long been recognised as a problem (e.g. Li *et al.* 2010). Because the GRAZPLAN model is biomass- rather than population-based, it is likely to be over-predicting persistence; this is another topic that would benefit from further attention.

9. Conclusions

If lucerne is to be more widely adopted, it will be important that landholders maximise the benefits of lucerne (usually as a part of a diverse feedbase) to their livestock enterprises, as well as optimizing the benefits and minimizing the costs of lucerne phases to subsequent crops. This study has quantified the strengths and limitations of the re-parameterized GRAZPLAN model for lucerne; the new parameter set is a clear improvement over the previous version and should be released for wider use.

The GRAZPLAN pasture growth model has been configured to model lucerne, both in grazing and in mixed farming systems but there are a number of areas where the performance of the model is known to be in need of improvement. Further testing against data sets that contain information about the nutritive value of harvested herbage would be particularly useful.

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Appendix 1. Parameters for lucerne in the GRAZPLAN pasture model

Cultivar-specific parameters are denoted by “cvv”; these values are given in the body of the report.

Parameter	Value	Units	Meaning
grass	FALSE		TRUE for grasses
legume	TRUE		TRUE for legumes
annual	FALSE		TRUE for annuals, FALSE for perennials
isc4	FALSE		TRUE if the species has the C_4 photosynthetic pathway
longday	FALSE		TRUE if long days required to induce reproductive growth
K_{V1j}		/d	Vernalisation rate at 0ºC
K_{V2j}		/ºC	Effect of temperature on vernalisation rate
K_{V3j}	1.0	ºC	Base temperature for degree-day computations
K_{V4j}		hr	Day length for commencement of reproductive growth
K_{V5j}	350	ºd	Degree-day sum for commencement of reproductive growth
K_{V6j}	600	ºd	Degree-day sum for commencement of flowering
K_{V7j}		d	Maximum length of flowering period
K_{V8j}		d	Effect of soil moisture stress on flowering duration
K_{V9j}		ºd	Degree-day sum beyond which the reproductive phenostage can end
K_{V10j}	0.25	0-1	Value of the soil moisture growth-limiting factor that defines "drought" for the senescence calculations
K_{V11j}		ºC	Temperature threshold for the end of summer dormancy
K_{V12j}		0-1	Soil moisture threshold for the end of summer dormancy
K_{V13j}		d	Initial duration of cool, moist conditions to break summer dormancy
K_{V14j}		d	Time required for summer dormancy requirement to reduce to zero
K_{V15j}	0.5	0-1	Reduction in the rate of development due to water stress in pre-flowering, reproductive plants
K_{V19j}		0-1	Decrease in the moisture threshold for summer dormancy after KV14j days
K_{V20j}	15.0	d	Length of the drought period required to induce senescence (i.e. end reproductive growth) when DD(j)= KV9j
K_{V21j}		ºd	Value of DD(j) at which senescence occurs in the absence of drought
K_{V22j}	0.0	0-1	Upper margin of phenology-sensitive horizon during vegetative growth
K_{V23j}	1.0	0-1	Thermal time (as fraction of K(V,6)) for upper margin of phenology-sensitive horizon to reach top of sward
K_{V24j}	0.5	0-1	Final lower boundary of phenology-sensitive horizon
K_{V25j}	0.0	0-1	Height of removal for reset of phenology (as fraction of lower boundary of phenology-sensitive horizon)
K_{V26j}	0.0	°C	Lagged mean temperature below which reduced winter activity always ensues
K_{V27j}	13.0	°C	Lagged mean temperature above which reduced winter activity is not promoted
K_{V28j}	8.0	hour	Day length below which reduced winter activity always ensues (Schonhorst *et al.* 1957)
K_{V29j}	14.0	hour	Day length above which reduced winter activity is not promoted
K_{V30j}	5	day	Lag period for computing mean temperatures
K_{I1j}	0.0260	m^2/g	Reference specific leaf area (ratio of leaf area index to leaf weight)
K_{I2j}	0.0040	m^2/g	Reference specific stem area
K_{I3j}	13.5	MJ/m^2/d	Curvature factor for effect of light on specific area
K_{I4j}	15	ºC	Temperature threshold for maximal specific area
K_{I5j}	0.6	0-1	Relative specific area at 0ºC
K_{I6j}	0.12	-	Relative decrease in specific leaf area at twice reference [CO2]
K_{I7j}	0.50	0-1	Apparent light extinction coefficient under ungrazed conditions
K_{I8j}	0.60	0-1	Apparent extinction coefficient under heavily grazed conditions
K_{I9j}	0.80	0-1	Apparent extinction coefficient of standing dead

Parameter	Value	Units	Meaning
K_{I10j}	1.00	0-1	Apparent extinction coefficient of litter
K_{WU1j}	0.35	0-1	Available soil water threshold for growth limitation
K_{WU2j}	1.0	0-1	Proportion of any transpiration deficit that can be recovered from moist layers
K_{WU5j}	150	s/m	Reference leaf stomatal resistance at 350 ppm CO$_2$
K_{WU6j}	0.5	-	Relative change in leaf stomatal resistance at 700 ppm CO$_2$
K_{RU1j}	2.35	g/MJ	Radiation use efficiency (gross assimilation) under reference conditions
K_{RU2j}	99.9	MJ/m^2/hr	Effect of radiation intensity on radiation use efficiency
K_{RU3j}	0.6	0-1	Relative photosynthetic efficiency of stems
K_{RU4j}	16.0	ppm	CO2 compensation point at 0ºC
K_{RU5j}	35.0	Ppm	CO2 compensation point at 20ºC
K_{RU6j}	55.0	ºC	Maximum temperature for CO2 compensation function
K_{BT1j}	15.0	kPa g kg-1	Biomass-transpiration coefficient
K_{T1j}	6.0	ºC	Temperature for 5% of maximum gross assimilation rate
K_{T2j}	18.0	ºC	Temperature for 95% of maximum gross assimilation rate
K_{W1j}	0.70	0-1	Transpiration ratio below which assimilation rate decreases
K_{WL1j}	0.85	0-1	WFPS threshold for waterlogging
K_{WL2j}	23.0	-	Curvature of growth limitation by waterlogging
K_{MR1j}	**cvv**	/d	Maximum relative growth rate of shoots during dormancy
K_{U1j}	**cvv**	-	Threshold growth-limiting factor for translocation from belowground reserves
K_{U2j}	**cvv**	/d	Relative rate of translocation from belowground reserves
K_{U3j}		0-1	Maximum proportion of stem (or shoot) mass at flowering to be relocated to seed
K_{U4j}		ºd	Degree-days required for completion of relocation from stem to seed
K_{RE1j}	0.3	g/g/d	Maintenance respiration rate at 10ºC (g DM/g N/d)
K_{RE2j}	1.8	-	Q10 factor for maintenance respiration
K_{RE3j}	0.20	0-1	Reduction in maintenance respiration in summer- or winter-dormant plants
K_{RE4j}	0.25	g/g	Growth respiration rate
K_{A1j}	0.80	-	Target root:shoot ratio during vegetative growth
K_{A2j}	0.30	-	Target root:shoot ratio during reproductive growth
K_{A3j}		-	Maximum allocation to reproductive structures
K_{A4j}	0.90	0-1	Maximum value of the ratio (leaf allocation):(shoot allocation)
K_{A5j}	0.40	0-1	Minimum value of the ratio (leaf allocation):(shoot allocation)
K_{MO1j}	-0.3	-	Parameter governing height distribution of leaves
K_{R1j}	3000	mm	Maximum rooting depth under optimal soil conditions
K_{R2j}	0.65	mm/ºd	Maximum rate of root front extension
K_{R3j}	0.0	ºC	Base temperature for root front extension
K_{R4j}	0.25	0-1	ASW below which root extension is reduced
K_{R5j}	1.95	Mg/m^3	Threshold bulk density for reduced root extension in 100% sand
K_{R6j}	-0.65	Mg/m^3	Threshold bulk density for reduced root extension in 0% sand
K_{R7j}	1.20	m^3/Mg	Rate of decrease in root extension with increasing bulk density
K_{R8j}	0.15	0-1	Minimum value of the bulk density effect on root extension
K_{R9j}	85	m/g	Specific root length
K_{R10j}	0.00022	m	Average radius of effective roots
K_{D1j}	800	ºd	Thermal age at which death of shoots commences
K_{D2j}	0.005	/ºd	Background death rate of old shoots in seedlings & established plants
K_{D3j}	0.003	/ºd	Additional death rate of all shoots in senescing plants
K_{D4j}	-4.0	ºC	Temperature for 5% mortality at the first frost (formerly K_{D2j})
K_{D5j}	-11.0	ºC	Temperature for 95% mortality at the first frost (formerly K_{D3j})
K_{D6j}	1.0	ºC	Frost-hardening factor (formerly K_{D4j})
K_{D7j}		0-1	Value of the seedling stress index at which seedling mortality commences (formerly K_{Z1j})
K_{D8j}		0-1	Value of the seedling stress index for 100% seedling mortality (formerly K_{Z2j})
K_{D9j}		/d	Lag coefficient for computation of the seedling stress index
K_{DR1j}		/d	Specific root "aging" rate at 10ºC
K_{DR2j}	0.0025	/d	Specific root loss rate at 10ºC
K_{DR3j}		g/g	Recovery rate of mass from dying roots
K_{DR4j}	1.5	-	Q10 for root aging and loss
$K_{F1,leaf,j}$	0.003	/d	Fall of standing dead: reference rate for leaf

Parameter	Value	Units	Meaning
$K_{F1,stem,j}$	0.001	/d	Fall of standing dead: reference rate for stem
K_{F2j}	40	-	Fall of standing dead: maximum relative effect of precipitation
K_{F3j}	10	/mm	Fall of standing dead: curvature of precipitation effect
K_{F4j}	30	/kg animal/d	Fall of standing dead: trampling effect
$K_{BR1j,leaf}$	0.10	/d	Background specific rate of breakdown of leaf litter
$K_{BR1j,stem}$	0.02	/d	Background specific rate of breakdown of stem litter
K_{BR2j}	10	-	Litter breakdown: trampling effect
K_{BR3j}	0.02	/d	Specific rate of incorporation under dry soil conditions
K_{BR4j}	0.05	/d	Specific rate of incorporation under wet soil conditions
$K_{Q1,leaf,j}$	0.85	g/g	Average digestibility of newly-produced leaf
$K_{Q2,leaf,j}$	0.75	g/g	Minimum digestibility of green leaf during vegetative growth
$K_{Q3,leaf,j}$	0.70	g/g	Minimum digestibility of green leaf during reproductive growth
K_{Q4j}	300	ºd	Thermal time during which green leaf maintains its digestibility
$K_{Q5,leaf,j}$	0.006	/ºd	Rate parameter for decline of DMD of green leaf
$K_{Q1,stem,j}$	0.85	g/g	Average digestibility of newly-produced stem
$K_{Q2,stem,j}$	0.70	g/g	Minimum digestibility of green stem during vegetative growth
$K_{Q3,stem,j}$	0.45	g/g	Minimum digestibility of green stem during reproductive growth
$K_{Q5,stem,j}$	0.002	/ºd	Rate parameter for decline of DMD of green stem
K_{Q6j}	4.0	ºC	Base temperature for maturation & senescence of green tissue
K_{Y1j}	0.024	/d	Reference rate of microbial decomposition of digestible DM
K_{Y2j}	4.7	-	Factor for temperature response of decomposition
K_{Y3j}	32	ºC	Factor for temperature response of decomposition
K_{Y4j}	0.05	-	Minimum value of the moisture factor for standing dead
K_{Y5j}	7	g/g	Maximum moisture content of standing dead
K_{Y6j}	-0.2	-	ASW for 5% of maximum decomposition
K_{Y7j}	0.85	-	ASW for 95% of maximum decomposition
K_{Y8j}	0.125	0-1	Relative rate of decomposition of indigestible DM
$K_{NU1N,leaf,j}$	0.060	g/g	Maximum content of N in green leaf at maximum DMD
$K_{NU2N,leaf,j}$	0.030	g/g	Minimum content of N in green leaf at maximum DMD
$K_{NU3N,leaf,j}$	0.026	g/g	Minimum content of N in green leaf at midpoint DMD
$K_{NU4N,leaf,j}$	0.022	g/g	Minimum content of N in green leaf at minimum DMD
$K_{NU5,leaf,j}$	0.1	-	Relative decrease in leaf N content (per unit leaf area) at twice reference [CO2]
$K_{NU1N,leaf,j}$	0.040	g/g	Maximum content of N in green stem at maximum DMD
$K_{NU2N,leaf,j}$	0.030	g/g	Minimum content of N in green stem at maximum DMD
$K_{NU3N,leaf,j}$	0.022	g/g	Minimum content of N in green stem at midpoint DMD
$K_{NU4N,leaf,j}$	0.015	g/g	Minimum content of N in green stem at minimum DMD
$K_{NU5,leaf,j}$	0.0	-	Relative decrease in stem N content (per unit mass) at twice reference [CO2]
$K_{NU1N,root,j}$	0.015	g/g	Maximum content of N in live root
$K_{NU2N,root,j}$	0.015	g/g	Minimum content of N in live root
$K_{NU5,root,j}$	0.0	-	Relative decrease in root N content (per unit mass) at twice reference [CO2]
K_{FX1j}	0.20	0-1	N-fixation: relative depth of nodulation
K_{FX2j}	0.15	0-1	N-fixation: nodulation at depth:nodulation at surface
K_{FX3j}	0.85	0-1	N-fixation: ASW for maximum fixation rate
K_{FX4j}	30	mg/l	N-fixation: solution NO3 conc. for maximum fixation rate
K_{FX5j}	90	mg/l	N-fixation: solution NO3 conc. for suppression of fixation
$K_{UE1,NO3,j}$	1.0	-	Uptake effectiveness parameter for nitrate
$K_{UE1,NH4,j}$	1.0	-	Uptake effectiveness parameter for ammonium
K_{RL1Nj}	0.33	/d	Relocation rate parameter for element *e* (*e*=N, P, S)
K_{AA1j}	1.2	mol/kg	Ash alkalinity of newly-grown leaves
K_{AA2j}	1.2	mol/kg	Ash alkalinity of newly-grown stems
K_{AA3j}	0.6	mol/kg	Ash alkalinity of newly-grown roots
K_{AA4j}	1.2	mol/kg	Ash alkalinity of newly-grown seeds
K_{AA5j}	4.5	-	pH below which no cation uptake takes place
K_{AA6j}	5.0	-	pH above which maximal cation uptake takes place
K_{HRj}	1.6	-	"Height ratio": also governs the size of the ungrazeable portion of the pasture
K_{SFj}	0.0	-	Parameter controlling the relationship between DMD and relative quality

Appendix 2. Descriptions of experimental data sets

Tasmania – Forth & Cranbrook

This experiment compared commercially available cultivars and experimental breeding lines at Forth and Cranbook, Tasmania (Pembleton *et al.* 2010b). Cultivars spanned winter activity ratings from 3 to 9. Data for a 34-month period include shoot biomass (16 dates) and persistence (3 dates). Soil and weather information are less well characterized than the preceding 3 experiments, but this experiment complements the comparison of winter activity types in the Boschma experiment.

Hamilton

This study comes from the Hamilton (Western Victoria) site of the same national experiment as the Boschma dataset (Li *et al.* 2010). Data selected from the database for cultivars from the Sceptre (winter activity rating 9), SARDI 5 (5), SARDI 7 (7) and SARDI 10 (10). Suitable soil data are available from Dr Malcom McCaskill (DEPI) and high quality weather data were collected on-site. Data available for validation from a 26 month period (from 2006-2008) that includes shoot dry matter (12 dates); seedling density (1 date); flowering percentage (1 date); greenness (2 dates); basal (2 dates); and plant frequency (2 dates). It has been ranked lower than the Boschma and Pembleton data sets because of its shorter duration.

Cootamundra

This experiment, conducted at Cootamundra (Southern NSW), was designed to assess a range of perennial pasture species for their productivity, water use and persistence (Hayes *et al.* 2010a; Hayes *et al.* 2010b). One lucerne cultivar (Aurora, with a winter activity rating of 6, i.e. semi-dormant) was assessed. Data available from the 42 months of measurement include dry matter cuts (14 dates), quality (7 dates), soil water (14 dates and 8 depths) and botanical composition (9 dates). In addition to being located in the Riverina region where lucerne is a particularly important forage species, this study allows us to examine the water use and root front development of lucerne over an extended period that included a severe drought.

Tamworth (Boschma)

This study at Tamworth (Northern NSW) was part of a larger national experiment designed to assess an array of *Medicago* spp. for their productivity and persistence under grazing (Li *et al.* 2010). The dataset contains a large range of germplasm but those chosen for validation are Sceptre (winter activity rating 9), Prime (4), PA21 (unrated but maybe 5) and Zanjani (unrated but maybe 7) as they enabled a good comparison of different winter activity groups in addition to Sceptre, which can be used as a reference cultivar across the experiments. Over the period of the study that biomass measurements were made (40 months from 2006-2010) 21 dates with dry matter are available for each of the 4 treatment replicates. Suitable GRAZPLAN-ready soil data are available as are local climate data of sufficient quality. This experiment allows us to directly compare lucerne cultivars of differing winter activity.

Tamworth (Lodge)

This experiment was conducted at Tamworth (Northern NSW; Lodge (1985). It examined the effects of dryland grazing by sheep and of haycutting over a 4-year period (1978-1981) on the dry matter production and persistence of 24 lucerne cultivars. Dry matter production data are available for 31 dates over 48 months but the cultivars unknown and there are no replicate data. Adequate soils and weather information have been collected on-site.

Quairading

This experiment, conducted at Quairading (Southern WA), was used in various published studies (Dolling *et al.* 2005; Latta and Lyons 2006; Dolling *et al.* 2007). Data are for one cultivar, (Trifecta, winter activity rating of 7). Data are available for a 24 month period (1998-2000), shoot biomass 14 dates, soil water (22 dates). Soil data is GRAZPLAN-ready and APSIM simulations are already established and published. This study was given a high priority because it extends our work to Western Australian environments and because it includes soil water measurements.