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An evaluation of selected perennial ryegrass growth models for development and integration into a pasture management decision support system

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SUMMARY

Four perennial ryegrass growth models were evaluated for their suitability to form the basis of a herbage growth model (HGM) for a decision support system (DSS). The successful candidate had to be suitable for further development to meet the specification of the DSS and following redevelopment it would then be integrated into a pasture management decision support system for dairy production. The models selected for evaluation were the Irish produced Brereton model (Brereton *et al*. 1996), the LINGRA model (Schapendonk *et al*. 1998), produced in the Netherlands, and a version of the English Johnson & Thornley (1985) model, developed for field use at the Northern Ireland Plant Testing Station (Laidlaw & Gilliland 2000). The fourth model was a version of the LINGRA model, simplistically adapted by the authors to take account of reproductive growth ($\text{LINGRA}_{\text{Rep}}$). The performance of the models was tested using the mean squared prediction error (MSPE) against a total of 28 seasons' growth data, collected from two sites; i.e. at the former Grassland Research Institute at Hurley, England and the Northern Ireland Plant Testing Station at Crossnacreevy. The Brereton model, when validated against the Hurley dataset, had the lowest MSPE of the four models, but had the highest MSPE against Crossnacreevy data. The PTS model did not perform as well as expected considering its mechanistic basis. Equally, the performance of the LINGRA model was poor at both sites. However, the $\text{LINGRA}_{\text{Rep}}$ performed well, having the lowest MSPE at Crossnacreevy and second lowest at Hurley. The LINGRA model was selected for development as the final HGM given that it proved suitable for adaptation and by making even simple adaptations, as in $\text{LINGRA}_{\text{Rep}}$, its performance could be substantially improved. Therefore, it was considered that it possessed the greatest potential for further development.

INTRODUCTION

Matching herbage supply to herbage demand is the fundamental objective of grassland management for dairy farmers operating pasture-based systems. Grassland budgeting is not an excessively difficult exercise in itself, employing simple arithmetic techniques. But because effective budgets must be drawn up in advance of the grass being produced, the accuracy of budgeting is severely limited by the uncertainty of future herbage supply. This is as a consequence of grass growth rates being highly variable both in time, i.e. within and between seasons at one location, and in space, i.e. between locations at any one time. Grass growth is determined by the interaction of many environmental and management factors and as such, forecasting grass growth rates is particularly difficult. However, the main determining factors are known to be the prevailing climatic conditions, notably radiant energy and water availability, related to the meteorological measurements; air temperature, light and rainfall. In addition, in production grassland, the level of N fertilizer applied is important. Other factors being equal, available nitrogen is often the

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main limiting factor for herbage production (Whitehead 1995). In recent years grassland scientists and modellers have begun to develop mathematical models to predict grass growth rates, generally using meteorological inputs (Sheehy & Johnson 1988). A growing number of models, originating from the Southern Hemisphere (Moore *et al.* 1997; Woodward 2001) to Northern Europe (Gustavsson *et al.* 1994; Höglind *et al.* 2001), have recently been presented in the literature.

The application of a biological model into a decision support system (DSS) is a practice adopted to provide a management tool to help remove uncertainty from many farming scenarios, improving confidence in planning farm strategies and in making decisions. The EU-funded Grazemore project aims to produce a DSS for dairy farmers, specifically in Northwest Europe, but will be operational in any temperate region, and requires a model to predict grass growth. As a prerequisite to the development of the herbage growth model (HGM) component of the DSS, candidate models were screened to assess their potential for this purpose. One model would be selected to form the basis of the HGM and this model would subsequently undergo extensive redevelopment to meet the prescribed HGM specification and to improve its predictive accuracy if required. The present paper presents the screening and selection process for four candidate models, with selection based on their performance, readiness for adaptation and biological and mathematical merit.

MATERIALS AND METHODS

Specification and selection process

The criterion by which the models were judged was mainly based on their potential for adaptation to meet the specification required of the HGM. Precision using real growth and meteorological data from two contrasting grass-growing regions within the UK was tested to determine potential performance of the models. However, exceptional performance at this stage was not critical given that the models would be further developed. The prescribed specification for the HGM included: prediction of growth rates of perennial ryegrass (*Lolium perenne* L.); estimate of herbage quality parameters in the form of organic matter digestibility (OMD) and crude protein (CP) content of the herbage, prediction of white clover production and prediction of effects of a range of N fertilizer levels combined with the ability to function within the whole of the Northwest European latitude range.

The sites for the validation tests were the former Grassland Research Institute at Hurley, in Southern England, and the Plant Testing Station of Northern Ireland.

Overview of candidate models

A good basis for the selection of the candidate models was given by the comparison made by Brereton & O'Riordan (2001) who also highlight the differences in the three basic models evaluated in the present study. However, they did not test any adaptations to the basic models, use contrasting locations or complete statistical analysis as conducted here. In the present study, four models were evaluated in total and represented different genres of growth model. The model of Brereton *et al.* (1996) represented an empirical model, and is based on the efficiency with which solar energy is converted into dry matter, but influenced by environment and management. The LINGRA model (Schapendonk *et al.* 1998), a mainly mechanistic model developed in the Netherlands, is derived from a general crop growth model but with coefficients specific to grass. The third model, the PTS Herbage Growth Model, is based on the highly complex mechanistic model of Johnson & Thornley (1983, 1985), characterized by its ability to predict the proportion of leaves in different age classes, but incorporating empirical relationships for application to field conditions (Laidlaw & Gilliland 2000). In addition to the three base models being evaluated, a version of the LINGRA model was adapted by the authors to take account of the seasonal physiological effects of reproductive growth and this model was also evaluated ($\text{LINGRA}_{\text{Rep}}$). The original LINGRA model does not account for reproductive growth, while each of the other models do, so a version which considers reproductive growth would be necessary to avoid discrimination against the LINGRA model.

Models

All of the models use quantifiable meteorological measurements as their main driving variables. The required inputs are in the form of daily mean air temperature, daily photosynthetically active radiation (PAR) (derived from measured irradiance levels) and daily rainfall. In their original formats transcribed in this study, only the Brereton model is capable of predicting in response to variable rates of applied N fertilizer, and in this case, the rate of fertilizer N is an additional input variable.

Brereton model

This model was developed at the Teagasc Research Centre at Johnston Castle in Wexford, Ireland. It is driven mainly by empirical relationships, relating growth of the crop as a whole to temperature and light (Brereton *et al.* 1996). It is static in that it does not describe growth over time by daily iterations of growth rates, but rather estimates yield at the end of a stipulated time period, given the environmental conditions during the period. It was originally created as a basis for evaluating the farm-scale behaviour of grassland systems and the dynamics of grazing management as affected by weather conditions from year to year on farms in Ireland. The model does not, and was not intended to, describe the nature of grass growth, as it is not process-based. Herbage growth is calculated purely on a crop-scale without organ or even plant-level components such as leaf area index or tiller number being estimated.

Herbage mass production for a regrowth period is calculated from the mean radiation received at the crop surface during the regrowth period, with the efficiency of the conversion of light to plant energy dependent on the mean temperature during this period. Herbage yield is initially calculated with parameters selected to represent a reproductive crop after 28 days' regrowth, with growth unrestricted by N supply, other soil nutrients and water deficit. This potential growth is subsequently adjusted accordingly for ontogeny, nitrogen input, soil water and duration of regrowth period.

LINGRA model

The second model, LINGRA (Schapendonk *et al.* 1998), is a mechanistic, dynamic, deterministic model developed at the DLO Institute for Agrobiology and Soil Fertility, Wageningen, in the Netherlands. This model was primarily designed for herbage yield forecasting in perennial ryegrass swards but also used for quantification of land-use evaluation and has been used to study the effects of climate change on grass growth (Rodriguez *et al.* 1999). It progressed from a growth model originally developed for potatoes (Spitters & Schapendonk 1990) referred to as LINTUL (Light INTerception and UtiLisation simulator) and adapted for use with perennial ryegrass (LINtul-GRAss). Latterly it has been re-parameterized for use with Timothy (*Phleum pratense*) (Höglind *et al.* 2001). LINGRA was included in the Crop Growth Monitoring Scheme (Bouman *et al.* 1996) and used by the Joint Research Centre of the EC for crop yield forecasting in the EU (Vossen & Rijks 1995).

In contrast to Brereton's model, LINGRA is dynamic and calculates daily rates of change of most of its variables, including growth rate. The daily iteration of rates of growth produces the eventual herbage yield after a designated regrowth period. LINGRA is described as a source/sink model whereby the temperature-dependent sink demands and radiation-dependent source supply of the crop are calculated and actual daily growth rate is determined as the minimum of either the source or the sink. The source and the sink can be termed as semi-independent because although they are independently calculated, each interacts with the other through a feedback mechanism. Excesses of source carbon go to carbohydrate storage, which becomes available for remobilization if photosynthetic supply is lower than the demand of the sink. Photosynthetic supply is determined from the basic light utilization model for crop growth described by Monteith (1977) and hence source-limited growth is characterized by photosynthetic light-use efficiency of the canopy and remobilization of stored assimilate in the stubble. Sink strength is determined as the temperature-driven leaf area increase, calculated from tiller number and leaf formation and elongation rates. Rate of change of tiller population density is also calculated, driven mainly by environmental conditions and carbon reserves in the plant. Although leaf area is calculated, the leaf component is determined at the crop level and it is not compartmentalized into lamina and sheath fractions. However, the water availability component of the model was substituted from that in the original model (Schapendonk *et al.* 1998) to a water availability sub-model using the Aslyng scale (Aslyng 1965) and potential evapotranspiration calculated from Brereton *et al.* (1996), adopting the Priestley & Taylor (1972) formula.

LINGRA$_{Rep}$ model

The LINGRA$_{\mathrm{Rep}}$ model was similar in every way to the original LINGRA model other than minor adjustments to account for seasonal physiological variation induced by reproductive growth. A simple adjustment of sink strength was made to account for stem and flower production in spring/summer (Leafe *et al.* 1974; Parsons & Robson 1982). Normal vegetative sink strength was increased by an adjustment factor, increasing up to a peak of a factor of 2·5 times and peaking at a prescribed heading date, with a 28 day activity period operating both before and after the occurrence of this peak, reproductive sink strength. Heading data were taken to be 10 May for the early heading Hurley site, and 25 May for the intermediate heading varieties, used at the Crossnacreevy site. In addition, two co-efficients, specific leaf area (SLA) and leaf width (which are both constant in the original LINGRA model) were adjusted so as to vary sigmoidally as the season progressed, from maximum values in spring to minimum values in autumn.

PTS model

This model was developed at the Plant Testing Station of Northern Ireland as a means of providing grass growth rates under local conditions to farmers and advisors to aid with pasture management. It is a version of the mechanistic Johnson & Thornley (1983, 1985) model and modified for practical field applications, mainly using empirically derived relationships (Laidlaw & Gilliland 2000).

The mechanistic base of the model describes, for given meteorological conditions, photosynthesis of the canopy (influenced by the leaf area index (LAI), leaf arrangement and potential photosynthesis of single leaves), growth (a function of the amount of structural and storage carbon with the principal sink being leaf laminae and sheaths). Also, LAI, determined by leaf appearance rate (a function of temperature and available assimilate) and the passage of leaves through four age classes leading to senescence.

The empirical relationships take account of the effect on regrowth of reproductive development, decapitation of flowering stems, build up of vegetative tillers post-flowering and the effect of drought stress on photosynthetic rate and potential growth rate. Some of the coefficients, e.g. estimates of the proportion of decapitated tillers and seasonal changes in potential photosynthesis of single leaves, have been derived from experiments carried out at the Plant Testing Station. Inputs required are daily solar radiation, maximum and minimum air temperature, rainfall and daylength. It had previously been validated locally against mean weekly grass growth rates from multisite trials (Laidlaw, unpublished).

Validation

Due to the specific input requirements of the models, suitable herbage growth and meteorological data sets readily available at the time of testing were restricted to data over 17 years (1966–1983) from the former Grassland Research Institute site at Hurley in Berkshire, England (Hurley data) and over 11 years (1990–2001) from the Plant Testing Station of Northern Ireland, Crossnacreevy (Crossnacreevy data). Data from 1979 at Hurley and 1993 at Crossnacreevy were excluded due to incomplete meteorological datasets. At Hurley, plots were cut on week 14 of each year and were subsequently cut every 4 weeks thereafter, until early November. At Crossnacreevy, yields were recorded from plots in Recommended List trials for perennial ryegrass and managed as described by Weddell *et al.* (1997). From 1990 to 1994, mean growth rate of all cultivars in the test programme (i.e. early, intermediate and late heading varieties) were included, whereas from 1995, only intermediate heading cultivars were considered. Mean dates for the eight or nine cuts taken annually at Crossnacreevy were: 13 April, 2 May, 23 May, 13 June, 5 July, 4 August, 5 September, 4 October and 31 October. Mean regrowth period was 22·3 (S.D. 8·8) days. For both datasets, growth rates for cuts eight and nine were taken as a mean, as a ninth cut was not taken in all years.

For the Hurley site, solar radiation was converted from sunshine hours to PAR in MJ/m^2/day since irradiance was not directly measured, using the equation of McEntee (1980), incorporating latitude and day length. At these latitudes, measurements of PAR by both methods show a good correlation (Barrett, unpublished). Mean meteorological data from the two sites, recorded from March to October, for the years during which herbage growth was measured are presented in Table 1. Daily air temperature, meaned over 16 years, at Hurley was almost 1 °C higher than mean air temperature meaned over the 11 years during which herbage growth was measured at Crossnacreevy. Equally, photosynthetically active radiation (PAR) was 21% higher and rainfall 21% (187 mm) lower at the Hurley site compared to the Crossnacreevy site.

Table 1. *Mean temperature, PAR and total rainfall recorded between March and October inclusive for all years tested, and the maximum and minimum values of each over the range of years tested at the Hurley and Crossnacreevy sites*

	Mean daily temperature (°C)	Mean daily PAR (MJ/m/day)	Total rainfall (mm)
Hurley			
Max	13·1	7·5	581·3
Min	11·2	6·1	305·3
Mean	12·1	6·7	451·5
Crossnacreevy			
Max	11·8	6·2	741·5
Min	10·5	5·2	516·4
Mean	11·2	5·6	638·7

Statistical analysis

The actual (A) and predicted (P) growth rates were compared using the mean-square prediction error (MSPE) (Rook *et al.* 1990), defined as

$$\begin{aligned}\mathrm{MSPE} &= \frac{1}{n} \times \sum (A-P)^2 \\ &= (A_m - P_m)^2 + S_P{}^2(1-b)^2 + S_A{}^2(1-R^2) \quad (1)\end{aligned}$$

where n equals the number of A and P pairs compared i.e. total harvests over all years (Hurley, $n=136$; Crossnacreevy, $n=88$). MSPE can also be expressed as the sum of three components (Eqn 1) (Theil 1966; Bibby & Toutenburg 1977), namely, the mean bias $(A_m - P_m)^2$, the line bias (deviation of the slope of the regression line of P regressed upon A) $(S_P^2(1-b)^2)$ and the random variation about the line $(S_A^2(1-R^2))$. Each is expressed here as a proportion of the total MSPE. A_m and P_m are the means of A and P, respectively, S_A and S_P are the variances of A and P, respectively, b is the slope of the line of P regressed upon A, while R^2 is the correlation coefficient of

Table 2. *Comparison of precision of the four growth models with actual data from the Hurley site*

	Growth rates						Proportion of MSPE		
Model	Actual	Predicted	Bias	R^2	MSPE	MPE	Bias	Line	Random
Brereton	34·5	41·0	5·5	0·67	355·3	0·55	0·119	0·088	0·793
LINGRA	34·5	54·1	19·4	0·27	1194·4	1·00	0·321	0·152	0·527
PTS	34·5	46·0	11·5	0·34	737·7	0·79	0·178	0·050	0·772
$\text{LINGRA}_{\text{Rep}}$	34·5	40·2	5·7	0·48	589·5	0·70	0·055	0·184	0·761

the line. The mean prediction error (MPE) is also calculated and is determined from the MSPE (Eqn 2) (Yan & Agnew 2000).

$$\text{MPE} = \frac{\text{MSPE}^{\frac{1}{2}}}{A_m} \qquad (2)$$

RESULTS

Model performance

Although suitable growth and weather data were limited, the difference in conditions between the two sites was evident. It was initially intended that the two datasets chosen would provide sufficient climatic variation to undertake relatively extensive evaluation of the models. For example, it was clear that the Hurley site suffered moisture stress for substantial periods in most of the years. This would have partly accounted for the difference in average annual growth rates between the two centres (34·5 *v.* 56·7 kg DM/ha/day). However, the differences in varieties of perennial ryegrass between the two sites would also have contributed to the difference, given the advances made by breeders in the last three decades of the 20th century, with yield improvements reported to be in the region of 0·5% per annum (Camlin 1997).

Hurley

Over the 17 years and eight regrowth observations per season, mean growth rate at Hurley was 34·5 kg DM/ha/day (Table 2). All of the models returned higher mean growth rates than the observed mean, with the predictions from the $\text{LINGRA}_{\text{Rep}}$ model being the closest at 40·2 kg DM/ha/day, producing a bias of 5·7 kg DM/ha/day. The largest bias was returned by the original LINGRA model, of 19·4 kg DM/ha/day. The Brereton model had the highest regression coefficient ($R^2=0·67$), compared with $R^2=0·27$, for the lowest, from the LINGRA model. The PTS and $\text{LINGRA}_{\text{Rep}}$ models were intermediate, with $R^2=$ 0·34 and 0·48, respectively. The MSPE and, hence, MPE, were lowest for the Brereton model indicating the best precision of all the models at this site, while $\text{LINGRA}_{\text{Rep}}$ delivered the second most precise predictions. The least accurate predictions for the Hurley data set came from the LINGRA model, indicated by the highest MSPE and MPE values of all the models, accompanied by a high bias and R^2 value.

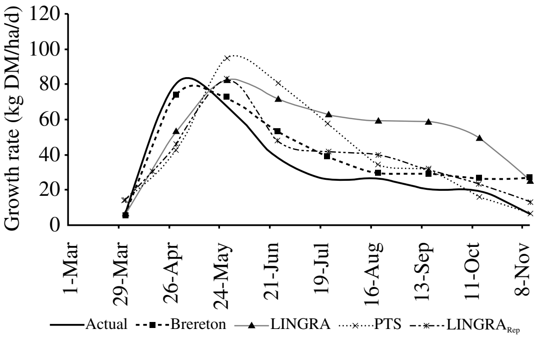

Fig. 1. Mean seasonal actual growth rates (kg DM/ha/day) at Hurley and predicted growth rates of the four models evaluated.

Figure 1 shows the pattern of overall growth rates for the four models against the actual observed growth rate at Hurley. Actual growth was severely depressed in late summer due to drought in the light Hurley soils. This growth depression was generally reflected by the output of the models, with the exception of LINGRA, which maintained an excessively high growth rate throughout much of the season. The relatively high proportion of the MSPE being in the bias component displays this point. However, this was not the case with the $\text{LINGRA}_{\text{Rep}}$ model, and output was considerably better. The PTS model tended to predict well late in the season, but generally over-predicted in the early and mid-summer periods. Output from the Brereton model was particularly close to actual growth over the whole growing season at Hurley. Notably, this model was effective in predicting the timing of the early spring/summer peak growth rate, while the other models tended to predict this 2–3 weeks later than when it was observed to occur. Therefore, overall, at the Hurley site the Brereton model performed best, followed by the $\text{LINGRA}_{\text{Rep}}$ model, with the PTS

Table 3. *Comparison of precision of the four models with actual data from the Crossnacreevy site*

	Growth rates						Proportion of MSPE		
Model	Actual	Predicted	Bias	R^2	MSPE	MPE	Bias	Line	Random
Brereton	56·7	55·6	−1·1	0·20	975·7	0·55	0·001	0·265	0·733
LINGRA	56·7	66·0	9·3	0·54	578·2	0·42	0·147	0·142	0·710
PTS	56·7	57·2	0·5	0·62	352·3	0·33	0·001	0·038	0·962
$\text{LINGRA}_{\text{Rep}}$	56·7	59·0	1·3	0·65	333·8	0·32	0·016	0·055	0·930

and original LINGRA models showing relatively poor levels of performance.

Crossnacreevy

At the Crossnacreevy site (Table 3), mean growth rate over all the observed regrowth periods was 56·7 kg DM/ha/day, and substantially greater than the mean growth rate at Hurley. In this case prediction bias was, in general, lower than that found at Hurley. The Brereton model produced a negative bias, indicating an overall under-prediction by the model. However, three of the four models returned a bias of <2 kg DM/ha/day, with only the LINGRA model being the exception, over-predicting by 9·3 kg DM/ha/day. Regression of the predicted upon actual showed that the $\text{LINGRA}_{\text{Rep}}$ model had the best fit, indicated by the highest regression co-efficient, $R^2 = 0{\cdot}65$. Likewise, good precision was found in the $\text{LINGRA}_{\text{Rep}}$ model by having the lowest MSPE and MPE values of all the models. Again, the main proportion of the MSPE was contributed by the random component, within the range of 0·71 (LINGRA) to 0·96 (PTS) indicating that little bias or line variation was found for any of the models. However, the line variation for the Brereton was relatively high at 0·27, indicating a general inadequacy in the model, with the slope of the regression of actual on predicted values to be less than unity. This is shown in Fig. 2, resulting in an overall under-prediction of the actual.

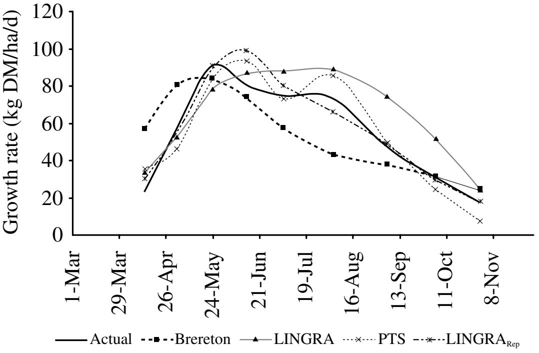

Fig. 2. Mean seasonal actual growth rates (kg DM/ha/day) at Crossnacreevy and predicted growth rates of the four models evaluated.

DISCUSSION

Model comparisons

From statistical analysis of predictions for both sites, the Brereton model performed well with the Hurley dataset, particularly considering its simple, empirical nature. However, its performance using Crossnacreevy growth data was the poorest of all the models, with a low R^2 value and high MSPE and MPE values, characterized in Fig. 2 by the poor fit of the seasonal profile. It was considered that if this model was selected as the basis for development of the Grazemore HGM, other difficulties would arise for two main reasons. Firstly, empirical models tend not to perform well on conditions other than those in which they have been parameterized. Given the latitudinal, and therefore, climatic range in which the HGM is intended to operate it was envisaged that the Brereton model, not being process based, would tend to return more imprecise predictions the further away from its original conditions it is operated. Its initial performance did not warrant further investigation in this respect. Secondly, sub-models would have to be added to predict leaf content, OMD or CP content, and the model is concerned only with conversion of solar energy to dry matter herbage yield. The addition of sub-models would be difficult to link to its empirical mechanism. However, it does take account of applied N fertilizer and has been used relatively successfully to predict growth of the grass component in a grass-white clover model (Kilpatrick & Laidlaw 1988) and, while operating well on Hurley data, will not be used for the basis of the HGM.

The other models, however, fulfilled the criteria of being wholly or partially mechanistic. They are, therefore, more robust at different geographical locations and more versatile for the addition of sub-model components. This was displayed by the adjustments made by the authors to the LINGRA model resulting in a major improvement in its performance.

The PTS model, although mechanistic, did not perform as well as expected given its complexity. At the Crossnacreevy site, its performance was similar to that of the best performing model. Yet, at the Hurley site its performance was poor, with low R^2 values and high MSPE and MPE values. As compared to the PTS model, LINGRA, although similarly mechanistic, is not excessively complex. It does not consider processes at the biochemical level or have highly lengthy procedures, as in the PTS model. The degree of complexity of the LINGRA model was considered ideal for further development and eventual integration into a decision support application as compared to the more complex type. The latter is more appropriate in knowledge synthesis and process understanding applications (Elston 1991), as in the Johnson & Thornley (1983) based PTS model.

Although performance of the original LINGRA model was the poorest of all the models tested here, the $\text{LINGRA}_{\text{Rep}}$ model's ability to predict herbage growth over contrasting environments was considerably more accurate. Therefore, given the improvements that could be made with limited development and that a 12-month phase was envisaged for the total redevelopment of the selected model, the LINGRA model was chosen as the base model for the European HGM. It was considered that substantial improvements could be made to the LINGRA model during the redevelopment phase, making its output satisfactory for decision support.

Development of the HGM from LINGRA

It was recognized that the LINGRA model also had considerable biological and mathematical merit. One such advantage of LINGRA is that its structure is based on tiller growth and development. However, critically, it lends itself well to adaptation, as was amply displayed by the comparison of LINGRA and $\text{LINGRA}_{\text{Rep}}$. The inclusion of a sub-model for reproductive growth was an obvious starting point for these adaptations where improvement could be made quickly. In its original form, LINGRA did not take account of reproductive growth. The shape of the growth curve produced by the LINGRA model was notable for a lack of a spring/summer peak and an over-prediction of growth later in the season. Maximum annual growth was often predicted in mid-summer rather than spring/summer as LINGRA is unable to differentiate between vegetative and reproductive phases of growth. Reproductive growth characteristically results in a high rate of production, due to the rapid development of stem and subsequently flowers and seed heads (Leafe *et al.* 1974). Stem and flower material has a higher density than leaf material and a high proportion of the sward is composed of reproductive material during this time (Wilman *et al.* 1976; Parsons & Robson 1982).

Though robustly constructed, LINGRA's systematic structure lends itself to further adaptations, possessing numerous contact points for the addition of other sub-models. This was recognized to be a critical factor given the additions that were to be worked into the model during the redevelopment phase to follow. The addition of sub-models to estimate herbage quality, white clover production and the response to N fertilizer was an important consideration for the model, given that these components are essential to any grazing management decision support system. Development of these sub-models, along with amendments of other poorly performing components of the model would be given priority during the redevelopment phase scheduled for the successful candidate model before being employed in a decision support system. Based on the good performance of the adapted LINGRA model, overall, LINGRA was considered to represent a well constructed, robust, but malleable model that could be improved with the addition of further sub-models as needed in the future. Therefore, it was considered to be a good starting point from which to base the development of a new HGM for decision support.

CONCLUSIONS

Although performance was not consistently good from any of the models screened, performance from the LINGRA model was substantially improved by adding a simple mechanism to take account of reproductive growth. The model was of robust mechanistic structure and its potential was good for adaptation and for improving performance. Both were key to the eventual success of the model as a herbage growth model and for its integration into the EU Grazemore DSS management tool for use on European dairy farms.

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