Development, Testing And Implementation Of A Generic Pasture Growth Model (CLASS PGM)

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EXTENDED ABSTRACT

This paper describes the development and testing of a generic pasture growth model CLASS PGM (Vaze et al., 2004b) which can be used to simulate growth of composite pasture types of multiple species that may be summer or winter active, perennial or annual. The model includes carbon assimilation through photosynthesis and respiration followed by tissue growth, turnover and senescence. Environmental conditions as well as soil water, nutrient and salinity status influences pasture growth and tissue dynamics.

The model allows the user to simulate a range of grazing management strategies. Concepts and theoretical basis of the pasture growth model is based upon the detailed technical report on pasture and crop growth modules (Johnson, 2003). The model is supported by the Richards' equation - based hydrology tool, Unsaturated Moisture Movement Model U3M-1D (Vaze et al., 2004a).

Testing of CLASS PGM has been done at two levels. The first level includes testing of the growth component wherein hydrological variations (eg. soil moisture, rainfall and evaporative demand etc.) are switched off and known climate and hydrological input were used to check growth computations from PGM against results from Johnson (2003) and manual calculations from the algorithms. A second level of checking was done against the water balance computations from HYDRUS-2D (Šimunek et al., 1999). The pasture growth component was switched off and results from the water balance component on soil moisture and plant transpiration across the soil profile were checked against results from the HYDRUS-2D model.

This paper presents the results from model validated using five years of soil moisture, pasture herbage mass and grazing data for a grazing experiment at Wagga Wagga, New South Wales (Johnston *et al*. 2005). When compared with herbage mass and soil moisture data from the experiment, CLASS PGM was found to adequately portray the patterns and amplitudes of pasture growth, and soil water recorded in the experiment.

CLASS PGM is part of the CLASS modelling framework which consists of a suite of tools required for physically based distributed eco-hydrological modelling. The Department of Infrastructure, Planning and Natural Resources (DIPNR) and the Cooperative Research Centre for Catchment Hydrology (CRCCH) have developed the CLASS framework. The CLASS model, its components and their algorithms are described in a detailed technical report (Tuteja et al., 2004). The tools from the CLASS framework can be used to investigate the effects of landuse and climate variability on both paddock scale as well as the catchment scale.

CLASS PGM is supported by a windows based user friendly graphical users interface (GUI). CLASS Pasture Growth Model can be downloaded free from the Cooperative Research Centre for Catchment Hydrology (CRCCH) Toolkit website (http://www.toolkit.net.au/class).

1. INTRODUCTION

In collaboration with the Cooperative Research Centre for Catchment Hydrology, models are being developed by the Department of Infrastructure, Planning and Natural Resources for analysing and assessing the impact of combinations of land uses (e.g. forestry, grazing, cropping) on small to medium sized catchments (2000-5000 km^2) in the medium to high (400 to > 1000 mm) rainfall zone of south-eastern Australia.

At the core of these models are modules that simulate photosynthesis and respiration, and tissue growth, turnover and senescence of crops, pastures and trees. Soil hydraulic properties derived from pedo-transfer functions, or measured data for particular locations are used to simulate soil water fluxes through the system. When fully implemented, the models will be linked through a GIS interface to provide a pixel-scale mosaic of land use impacts whose whole-catchments outcomes are evaluated.

The CLASS suite of tools will be used to guide investment decisions for Catchment Management Authorities, evaluating outcomes against investments, as well by other clients such as local Government, inter-agency Commissions such as the Murray-Darling Ministerial Council, and for specific purposes such as environmental reporting.

2. MODEL CONCEPTS

Pasture growth and utilization results from a complex set of interactions between pasture plants, the environment, soil conditions, and grazing animals, and there is a range of possible approaches to modelling these processes. The level of complexity chosen in this model attempts to strike a balance between realism and tractability. The aim is to remain biophysically realistic while keeping the description of each individual process relatively simple. It is possible to use a growth curve approach, whereby a single expression is used to describe the daily net pasture production. However, it is difficult to expand this to allow for the important process of litter production and turnover, which can play a vital role in the water and nutrient dynamics in pastures. Conversely, very detailed models of photosynthesis, plant morphological development, and so on, can be used, although these models can be unwieldy to work with.

The approach here aims to include the key processes of pasture growth and utilisation, as well as the interaction between the pasture and the environment. It is structured in such a way as to allow future developments to incorporate the influence of soil organic matter and nutrient dynamics.

The pasture growth module is based on the physiological approach developed by Ian Johnson, Tony Parsons and John Thornley in various publications of pasture growth and grazing dynamics. The principal references are Johnson and Thornley (1983); Johnson and Parsons (1985); Parsons *et al.* (1988).

The following key points apply:

- The model is constructed for generic pasture species so that particular species are defined through the basic model parameters.
- The model includes carbon assimilation through photosynthesis and respiration followed by tissue growth, turnover and senescence.
- Pasture growth and tissue dynamics are influenced by the environmental conditions (light and temperature) as well as the soil water, nutrient and salinity status.
- Multiple species are considered, which may be perennial, annual, legume, C3, C4.
- For annual species, vegetative (emergence to anthesis) and reproductive (anthesis to maturity) growth phases are included.
- A simple treatment of animal intake is presented to simulate the effects of grazing. However, animal growth and physiology are not included.

The pasture growth computations are coupled with Richards' equation based water balance modelling using U3M-1D. U3M-1D can be used for partitioning water balance in the unsaturated zone. Non-reactive solute balance across the soil profile can also be performed using advective transport. U3M-1D is similar to the concepts used in HYDRUS-2D (Šimunek et al., 1999).

In U3M-1D, a soil water excess is calculated when the available soil moisture in a soil layer/material is greater than the saturated soil moisture content. The excess is estimated as the difference between the available and saturated soil moisture contents and it may be interpreted as available for vertical preferential flow, or lateral drainage depending on known soil characteristics.

Where the user has sufficient data, the model provides the option of entering specific soil hydraulic parameters (SHP) using three commonly used alternative hydraulic models - van Genuchten (1980), Vogel and Cislerova (1988) or Brooks and Corey (1966). If specific data is not available then the user can select a "soil type" from the internal soils catalogue and adopt the preset parameters (Carsel and Parrish, 1988; van Genuchten *et al*., 1991). Based on the chosen soil hydraulic model, the program will use the appropriate equations to generate the soil hydraulic properties for the parameters entered by the user.

Main features of CLASS PGM include:

- Capability to simulate growth of composite pasture types of multiple pasture species that may be summer or winter active, perennial or annual.
- Seamless integration with the Richards' equation based hydrology, an established and proven technology for accurate water balance simulations.
- Provides the ability to simulate interactions between pasture growth and water balance using robust plant physiology and unsaturated zone hydrology concepts.
- The model uses adaptable sub-daily simulation time steps by sensing transient nature of the atmospheric conditions and attempts to overcome the divergence problems usually associated with solution of the Richards' equation.

3. MODEL IMPLEMENTATION AND DATA USED

For model developers, providing confidence that the simulated system adequately portrays interactions in the 'real' world, as measured in experiments is a major challenge. There are several issues. Firstly, it is unusual in experiments conducted independently of model development for all parameters that the model requires, to be measured. The second issue is that experimental measurements are subject to various sources of variation or error, such as sampling error, spatial variability due to location etc. as well as possibly transcription errors. These errors flow through to the various data that may be used as comparator variables. In contrast to measured data, identical runs of a deterministic model will always provide the same results, thus estimates provided by models are error-free.

A third issue concerns the basis of being satisfied that the model acceptably emulates the system. Because of the nature of modelled and experimental data, it is not possible to be categorical about 'lack of fit'. Difficulties may lie with conceptualisation of the system, or the implementation of the model, or it may be due to unexplained variation (or biological complexity) within the data. Thus comparisons are necessarily subjective.

3.1. Data

Data for a *Phalaris aquatica* L. (phalaris) pasture grazed in rotational sequence by Merino wether sheep, was compared with simulated data derived using CLASS PGM. The dataset was from a larger experiment described in detail in Johnston *et al*. (2005), which was conducted near Wagga Wagga, New South Wales, Australia (35°08′ S Latitude, 147°19E Longitude; elevation 222 m; median annual rainfall 560 mm). Meteorological data were available 300 m from the site.

The pasture and sheep data were for one replicate *P. aquatica* paddock (0.165 ha), which was sown in September 1992 and oversown with annual species (*Lolium rigidum* Gaudin. (annual ryegrass) and *Trifolium subterraneum* L. (subterranean clover) in May 1993. From 1993 onwards, it also contained a range of common annual C_3 and C_4 weeds. The pasture was grazed for 2 weeks and rested for 4 weeks, at a base stocking rate of 10 sheep/ha from September 1993 to September 1998.

From time to time, additional sheep grazed the pasture depending on herbage mass (HM) at the commencement of the grazing period (usually if HM > 1500 kg DM/ha). During droughts, when herbage mass was low (<500 kg DM/ka), grazing was suspended to protect the wellbeing of the pastures and the sheep.

The mottled Brown Chromosol soil at the site consisted of a sandy loam topsoil (0 – 0.17 m); grading to a sandy clay loam (0.17 – 0.35 m); overlying a clay loam subsoil (0.35 – >1.25 m) (Johnston and Cornish 2005).

Soil moisture status (kPa) was monitored in the *P. aquatica* paddock on a daily basis using gypsum blocks. As detailed in Johnston and Cornish (2005), these data were converted to volumetric water content [θ (v/v)] using regression relationships, based on retention curves and soil bulk density data.

Soil textural classes and moisture retention curve data for each of the soil horizons were used in the analysis of soil hydraulic properties using RETC. Saturated hydraulic conductivity (k_{sat}) was measured for each horizon using well permeameters. Soil hydraulic properties are given in Table 1.

Table 1. Soil hydraulic properties

Soil horizon and depth (cm)	θ_r (v/v)	θ_s (v/v)	α (1/cm)	n	k_{sat} (cm/d)
A_1 (0-20)	0.1	0.4	0.075	1.2998	80
A_2 (20-40)	0.0885	0.4252	0.04	1.2762	20
B_{21} (40-70)	0.1356	0.4399	0.00347	1.3756	5
B_{22} (>70)	0.1911	0.4592	0.008	1.5465	2

3.2. Model Implementation

CLASS PGM was implemented using soil hydraulic properties given in Table 1, together with default plant growth parameters (Johnson 2003). A total of about 28 parameters (depending on species) described the growth of: a C_3 perennial grass (*P. aquatica*), C_3 annual grass (*L. rigidum* and other species), C_3 annual legume (*T. subterraneum*) and C_4 annual species, which were mainly grasses. The following scenarios were tested:

The control scenario. Grazing of wether sheep at a stocking rate of 10 sheep/ha, between herbage mass limits of 1300 kg DM/ha (sheep onto the pasture), and 500 kg/ha (sheep removed from the pasture). Species included in the control scenario were C_3 perennial (phalaris), C_3 and C_4 annuals and C_3 annual legume.

Exploratory scenarios. After the model was calibrated against experimental data, additional scenarios explored the impact of different groups of species. Scenarios were: C_3 and C_4 annual species only (i.e. no C_3 perennial); C_3 perennial and C_3 annuals only (i.e. no C_4 annuals) and C_4 perennials in place of C_3 perennials, with C_3 and C_4 annuals, and C_3 legumes.

For the control scenario, data for the experimental period were compared. For other scenarios, data were summarised for the 10 year period from 1993 to 2002.

4. RESULTS AND DISCUSSION

4.1. Comparison with experimental data.

The fit achieved between predicted total herbage mass and measured data for the *P. aquatica* pasture is shown in Figure 1. Linear regression of these data resulted in the following relationship:

Experimental HM = 1.04(predicted HM) + 253.3

($R^2 = 0.58$).

The experiment was not grazed until 16 September 1993, thus the experimental pasture contained a large amount of accumulated herbage prior to this time. Towards the end of the experiment the *P. aquatica* pasture was grazed at lower stocking rates than the modelled scenario, which resulted in experimental HM levels being higher than as predicted by the model.

The modeled scenario duplicated the seasonal pattern of HM accumulation, and the production amplitudes achieved in the experiment satisfactorily.

Soil water data for the period of the experiment are compared with data predicted by CLASS in Figure 2 for 60 cm and 120 cm depths.

While the soil on which the experiment was conducted was found to have low subsoil saturated hydraulic conductivity (Table 1), during extended dry periods it was observed to contain cracks and macropores that extended to considerable depths (>1.5 m).

Significant rainfalls (>25 mm/day) in summer and autumn were observed by Johnston and Cornish (2005) to penetrate deeply into the soil and result in rapid increases in soil water content at 120 cm depth. They attributed this to preferential flow through the matrix of macropores and vertical cracks. Preferential flow was not in evidence in winter and spring, presumably the soil had wet up and expanded, and plant roots had extended into the macropores limiting downward water movement to rates limited by the soil's saturated and unsaturated hydraulic conductivity.

Preferential flow was not accommodated by CLASS PGM. Thus relative to the modeled data, in summer and autumn, CLASSPGM tended to underestimate total soil water, while during winter and spring measured and predicted data were closely aligned (Fig. 2).

Monthly deep drainage and excess water estimated by CLASS PGM over 10 years (which included the experimental period) for the experimental scenario are given in Tables 2 and 3 respectively.

For the 10 year period, drainage below 2 m ranged from 0.27 to 2.83 mm/year, and totalled 9.37 mm or 0.16% of the rainfall of 5760 mm. Excess water, which was available for either lateral or preferential flow, ranged from 0.0 to 173.0 mm/year, and totalled 11.7% of the rainfall. Rates of deep drainage were greatest in summer and autumn; highest volumes of excess water were generated in wet years in winter and spring (Table 2 and 3).

In autumn, a high proportion of excess water may have moved preferentially downward, however it is a common observation in the district that during late winter, low-lying landscape elements become partially saturated by the movement of water from upslope.

4.2. Scenario Testing

For all scenarios, deep drainage and water excesses were the smallest components of the water balance (in total less than 15% of the average rainfall). This was mainly because the winter months are characterised by low potential evaporation, high rainfall frequency and small rainfalls/day, and summer months, by high potential evaporation, low rainfall frequency and high rainfall/day. Soil water accumulates in winter, while in summer, lengthy rainless periods cause it to be used or directly evaporated.

Results of the scenario tests (Table 4) show that absolute differences between scenarios were small. However, relative to the control, differences of 10% and 30% in excess water and deep drainage were predicted for a pasture that was either leniently grazed, or if it contained C_4 rather than C3 perennial grasses.

Although Johnston and Cornish (2005) found differences in the abilities of species (C_3 and C_4 perennials) to create and maintain soil water deficits in autumn and at other times of the year, the modeling scenarios suggest that in gross terms, it is unlikely that pastures or the way they are managed would impact greatly on the water balance.

Several issues impacted on the modelled scenarios. These included that the model was not able to emulate the same time-based grazing as was the case in the experiment. A second issue was that the extent to which the pastures could dry the soil (wilting point) was a soil parameter in CLASS PGM. However, in the experiment this varied between species and may have impacted on their water use. Thirdly, accounting for preferential flow is not possible with a 1-D matric-flow modeling framework, but in the experiment, it was concluded that preferential flow could be a potentially important pathway for deep drainage.

5. CONCLUSIONS

When compared with herbage mass and soil moisture data from a grazing experiment conducted at Wagga Wagga NSW Australia, CLASS PGM was found to adequately portray the patterns and amplitudes of pasture growth, and soil water recorded in the experiment.

Soil water excesses and the drainage of water below the root zone (2 m) were determined largely by the low hydraulic conductivity of the subsoil, and seemed not to be influenced greatly by the species in the pasture, or grazing intensity. The potential for deep drainage was low. The highest proportion of water in excess of the soils water holding capacity appeared in the water balance potentially as lateral flow. Soil factors could modify whether this water moved down-slope, or vertically as preferential flow. Further analysis of the experimental data is warranted.

6. REFERENCES

Brooks, R.H. and Corey A.T. (1966). Properties of porous media affecting fluid flow, Journal of the Irrigation & Drainage Division 2 (June), American Society of Civil Engineers, pp 61-88.

Carsel, R.F., and Parrish, R.S. (1988). Developing joint probability distributions of soil water retention characteristics, Water Resources Research, 24: pp 755-769.

Johnson, I. R. and Parsons, A. J. (1985). A theoretical analysis of grass growth under grazing. Journal of Theoretical Biology, 112, pp 345 – 367.

Johnson, I. R. and Thornley, J. H. M. (1983). Vegetative crop growth model incorporating leaf area expansion and senescence, and applied to grass. Plant, Cell and Environment, 6, pp 721-729.

Johnson, I.R. (2003). A mathematical approach to modelling pastures and crops for Australian conditions, A consultancy report prepared for the NSW Dept of Infrastructure Planning and Natural Resources.

Johnston, W. H. and Cornish, P. S. (2005). *Eragrostis curvula* (Schrad.) Nees. Complex pastures in southern New South Wales, Australia: impact of *E. curvula*, *Medicago sativa* L. and *Phalaris aquatica* L. pastures on soil water. *Australian Journal of Experimental Agriculture* (in press).

Johnston, W. H., Cornish, P. S. and Shoemark V.F. (2005). *Eragrostis curvula* (Schrad.) Nees. complex pastures in southern New South Wales, Australia: a comparison with *Medicago sativa* L. and *Phalaris aquatica* L. pastures under rotational grazing. *Australian Journal of Experimental Agriculture* 45, pp 401-420.

Parsons, A. J., Johnson, I. R. and Harvey. A. (1988). The use of a model to optimise the interaction between the frequency and severity of intermittent defoliation and to provide a fundamental comparison of the continuous and intermittent defoliation of grass. Grass and Forage Science, 43, 49-59.

Šimunek, J., Sejna, M., and van Genuchten, M.Th. (1999). HYDRUS-2D/MESHGEN-2D, Simulating Water Flow and Solute Transport in Two-Dimensional Variably Saturated Media, IGWMC – TPS 53c, Colorado School of Mines, USA.

Tuteja, N. K., Vaze, J., Murphy, B. and Beale, G. T. B. (2004). CLASS – Catchment scale multiple-landuse atmosphere soil water and solute transport model, Department of Infrastructure, Planning and Natural Resources and Cooperative Research Centre for Catchment Hydrology, Technical Report 04/12, Australia, ISBN 1 920813 17 9.

van Genuchten, M. Th. (1980). A Closed Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils, Soil Sc. Soc. Am. J., 48, 703-708.

van Genuchten, M.Th., Leij, F.J., and Yates, S.R. (1991). The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils, U.S. Salinity Lab., U.S. Dept. of Agriculture, Agricultural Research Service, Riverside, California, EPA/600/2-91/065.

Vaze, J., Teng, J., and Tuteja, N.K. (2004b). CLASS Pasture Growth Model PGM. User's Manual. NSW Department of Infrastructure, Planning and Natural Resources, Australia and Cooperative Research Centre for Catchment Hydrology, Australia, ISBN 0 7347 5514 7.

Vaze, J., Tuteja, N.K. and Teng, J. (2004a). CLASS Unsaturated Moisture Movement Model U3M-1D. User's Manual. NSW Department of Infrastructure, Planning and Natural Resources, Australia and Cooperative Research Centre for Catchment Hydrology, Australia, ISBN 0 7347 5513 9.

Vogel, T., and Cislerová, M. (1988). On the Reliability of Unsaturated Hydraulic Conductivity Calculated from the Moisture Retention Curve, Transport in Porous Media, 3, 1-15.

Table 2. Deep drainage estimates for the 10 year period from 1993 (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year total
1993	0.24	0.22	0.25	0.25	0.26	0.25	0.25	0.24	0.22	0.22	0.21	0.22	2.83
1994	0.22	0.20	0.22	0.21	0.21	0.19	0.19	0.18	0.17	0.17	0.15	0.15	2.26
1995	0.14	0.12	0.13	0.12	0.12	0.11	0.11	0.10	0.10	0.09	0.09	0.09	1.31
1996	0.09	0.08	0.08	0.08	0.08	0.07	0.08	0.07	0.07	0.07	0.06	0.06	0.89
1997	0.06	0.05	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.60
1998	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.41
1999	0.03	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.29
2000	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.24
2001	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.27
2002	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.27
Month total	0.89	0.79	0.87	0.83	0.84	0.80	0.80	0.77	0.72	0.71	0.67	0.68	9.37

Table 3. Excess soil water for the 10 year period from 1993 (mm)

	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year total
1993	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	105.7	36.9	0.0	0.0	142.7
1994	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1995	0.0	0.0	0.0	0.0	36.6	51.6	77.7	7.1	0.0	0.0	0.0	0.0	173.0
1996	0.0	0.0	0.0	0.0	0.0	0.0	55.8	42.6	0.0	0.0	0.0	0.0	98.4
1997	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1998	0.0	0.0	0.0	0.0	0.0	0.0	0.0	53.1	0.0	0.0	0.0	0.0	53.1
1999	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	40.0	54.4	0.0	0.0	95.3
2000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	82.2	29.1	0.0	0.0	0.0	111.3
2001	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2002	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Month total	0.0	0.0	0.0	0.9	36.6	51.6	133.5	185.1	174.8	91.3	0.0	0.0	673.7

Table 4. Results of scenario testing

	C3 perennial + C3 and C4 annuals			No C3 perennial		No C4 annual		C4 in place of C3 perennial	
	Control	Scenario2	Scenario3	Scenario4	Scenario5	Scenario6	Scenario7	Scenario8	Scenario9
FOO_in (kg/ha)	1300	1300	1300	1300	1300	1300	1300	1300	1300
FOO_out (kg/ha)	500	600	500	500	300	500	500	500	500
Grazing rate (sheep/ha)	10	10	15	15	15	10	15	10	15
Excess water (mm/yr)	67.4	67.6	65.0	68.7	68.8	65.4	64.8	65.8	60.7
Relative to control (%)	100.0	100.3	96.4	101.9	102.1	97.0	96.1	97.6	90.1
Deep drainage (mm/yr)	1.0	0.7	0.9	1.8	1.9	0.8	0.8	0.7	0.7
Relative to control (%)	100.0	70.0	90.0	180.0	190.0	80.0	80.0	70.0	70.0
Average SR (Sheep/ha)	4.1	4.0	3.2	11.8	2.4	3.7	3.5	3.7	4.1

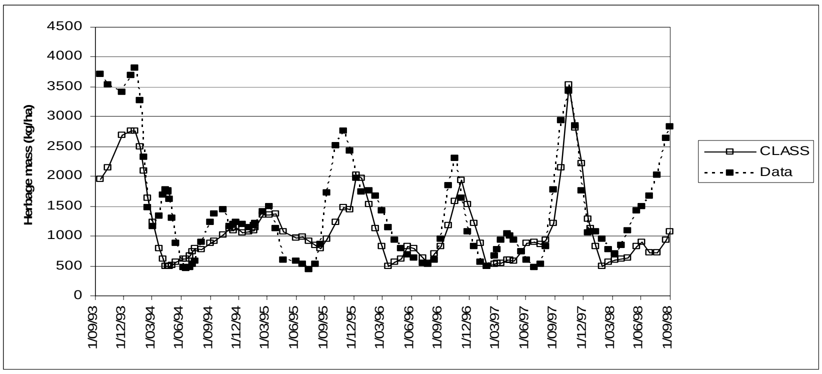

Figure 1. Comparison of predicted (solid line, open squares) total herbage mass and experimental observed data (dashed line; solid squares) for the period of the experiment.

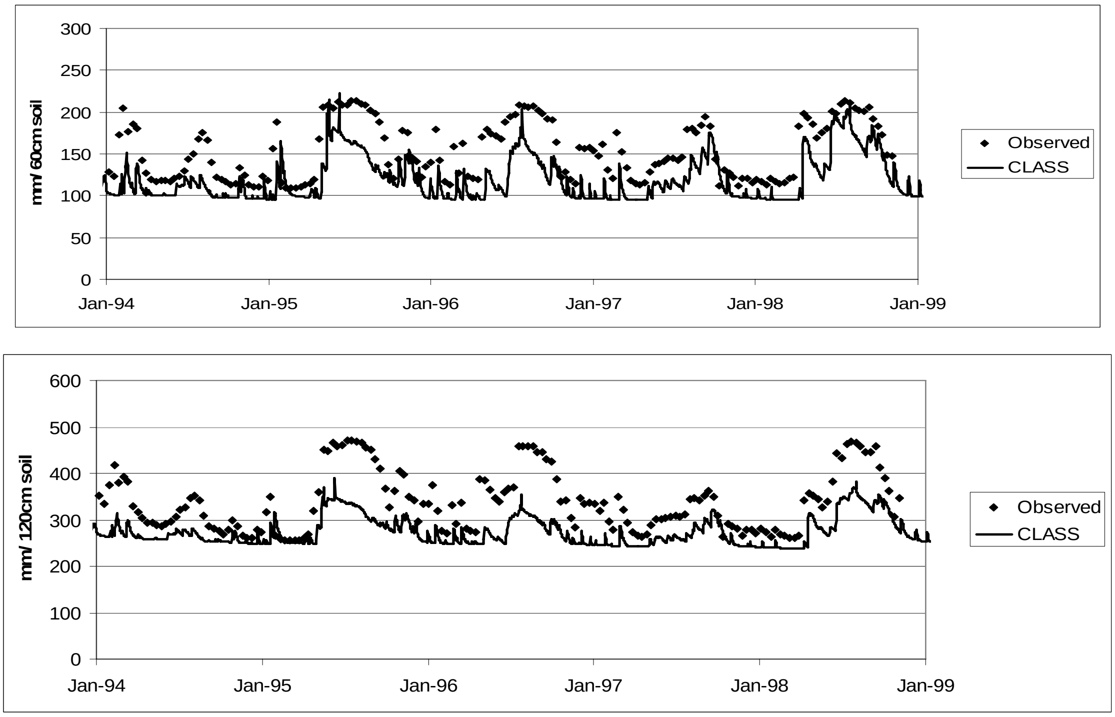

Figure 2. Total soil water (mm) to depths of 60 cm (top figure) and 120 cm (bottom figure) estimated from gypsum block data (♦) and predicted by CLASS_PGM (solid line)