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Use of APSIM to simulate water balances of dryland farming systems in south eastern Australia

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CSIRO Land and Water, Canberra
Technical Report 50/03, November 2003

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CSIRO Land and Water and APSRU

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ISSN 1446-6163

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Citation:

K. Verburg and W.J. Bond. 2003. Use of APSIM to simulate water balances of dryland farming systems in south eastern Australia. Technical Report 50/03, CSIRO Land and Water, Canberra, Australia.

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Summary

Changes to cropping systems and their management are needed to reverse the trend of rising water tables and associated salinisation in many parts of Australia. Field studies investigating the various options available to farmers are necessarily limited by the number of sites it is possible to instrument and the range of weather conditions experienced during the measurement period. Simulation analysis can extrapolate the experimental findings in time and space and explore the effects of management changes in more detail. The Agricultural Production Systems Simulator (APSIM) is particularly suited for this type of analysis, but concerns have been expressed about its ability to simulate deep drainage under dryland cropping correctly. A detailed evaluation of the performance of the APSIM model for water balance predictions of dryland agriculture in south eastern Australia was therefore carried out as part of GRDC funded project CSO197. The APSIM model was found to reproduce closely the water balance measurements from four phase farming data sets in the south eastern Australian cereal belt. The observed sensitivity of the water balance to management changes and to conditions during the summer fallow was reproduced well by the model. While there are a few issues that require further investigation and development, this suggests that APSIM is a valid tool for evaluating the impact of changes to cropping systems and agronomic practices on the water balance of dryland regions. Its application is demonstrated with three examples. Pitfalls associated with comparing the drainage predictions of long-term simulation analyses with comparatively short-term measurements from specific field sites are also discussed.

1 Introduction

It has been recognized that changes to cropping systems and their management are needed to reverse the trend of rising water tables and associated salinisation in Australia (Williams and Gascoigne, 2003). A number of field studies have investigated options available to farmers. These studies are, however, limited by the number of sites able to be investigated and influenced by site histories and the range of weather conditions experienced during the measurement period. Simulation analysis offers two advantages over field experiments: sensitivity to management can be evaluated in isolation from other effects, and results are not restricted to the weather conditions during the few years of a field experiment. The latter is particularly important when rainfall is highly variable from year to year, as it is in many parts of Australia. The Agricultural Production Systems Simulator (APSIM; McCown et al. 1996, Keating et al. 2003) is particularly suited to scenario analysis because of its dynamic representation of both crop growth and soil processes, and its capability to simulate conditional management rules. APSIM has been used in a number of simulation analyses that assessed the water balances of various dryland farming systems (e.g. Dunin et al. 1999, Keating et al. 2001, 2002). Some readers of these studies have deemed the predicted long-term average drainage values to be too large and questioned the ability of APSIM to predict deep drainage accurately. There was a need, therefore, for detailed evaluation of the capability of APSIM to simulate the water balance dynamics in these systems. Model testing and simulation analysis were added as an extension to the GRDC funded project CSO197 "Benefits and penalties to cereal crops grown after lucerne". In addition Land and Water Australia provided funding for an extension to project CDS20 to obtain data on soil drying during the second and third years of the lucerne phase and to test the model's ability to capture this drying process. Key findings of the model evaluation, as well as three long-term simulation analyses are presented here.

2 Data sets

Four data sets, which included sufficiently detailed and frequent measurements to capture the soil water dynamics, were used to evaluate the model. They were collected at Rutherglen VIC, Temora NSW, and in two paddocks at Charles Sturt University (CSU), Wagga Wagga NSW. These data sets involved both annual crops (e.g. wheat, canola, triticale, lupin) and lucerne, and had between 4 and 9 years of data, including monthly neutron moisture meter (NMM) measurements, crop biomass and yield measurements, and some soil nitrogen measurements. One of the paddocks at CSU had two replicate weighing lysimeters allowing direct assessment of evapotranspiration (*Et*) and drainage. Brief descriptions of the data sets are provided in Table 1.

Table 1: Data sets used in the evaluation of the performance of the APSIM model for water balance predictions of dryland agriculture in south eastern Australia.

Data set	Project	Investigators	Period	System	Experimental measurements used for model testing
CSU Paddock 14 35°04'S, 147°21'E	CPI5 CSO197 CDS20	Dunin, Smith, Bond	1993-2002	Crop rotation with lucerne phase	Frequent soil water (NMM, 2-4 week intervals), lysimeter *Et* and drainage at 1.8 m, TDR at selected locations, core soil water and soil mineral N twice monthly (1993), monthly (1995-1996), or three times/year (1997-2002), bromide tracer, soil solution nitrogen, crop phenology, biomass partitioning, LAI and N uptake (5-10 times/year)
CSU Paddock 12 35°04'S, 147°21'E	CSO197 CDS20	Smith, Dunin, Bond	1997-2002	Crop rotation followed by lucerne phase	Frequent soil water (NMM, 2-4 week intervals), core soil water and soil mineral N three times/year, bromide tracer, soil solution nitrogen, crop phenology, biomass partitioning, LAI and N uptake (4-6 times/year), lucerne biomass (4-5 times/year)
Rutherglen 36°06'S, 146°30'E	DAV21 9	Ridley, Hirth	1993-1999	Lucerne, sequentially replaced by crop rotation	Frequent soil water (NMM, 2-weekly during growing season, from 1995), lucerne biomass (approx. 4 times/year), crop biomass at anthesis and final yield (from 1995), crop N uptake in selected treatments and years, core soil mineral N in autumn
Temora (Fergusons Lane) 34°26'S, 147°40'E	CSP243	Peoples, McCallum	1996-2000	Lucerne, sequentially replaced by wheat-canola rotation	Monthly soil water (NMM) from 1998, crop biomass at anthesis, final crop biomass and yield, core soil mineral N at sowing (1998, 1999)

3 Model parameterisation

During the course of this project, three new versions of APSIM were released (1.6, 2.0, and 2.1). This included new Wheat, Lupin and Weed modules, all of which are still evolving, as are the Lucerne and Canola modules. Testing in the current project led to significant improvements in these modules, which were incorporated in each new APSIM release. Final simulations presented here were carried out using APSIM version 2.1 patch 2, except for beta release (patch 3) versions of the legume and wheat modules.

Parameterisation of the model for each data set was based on site specific measurements of variables like bulk density, organic carbon, C/N ratio and pH. Where possible soil hydraulic properties were also derived from independent measurements. However, some model inputs could only be estimated from the experimental data (e.g. lower limit at Rutherglen and Temora, rooting depth of various crops). This means that separation between data used for parameterisation and that used for model evaluation could not be strictly maintained, although selection of parameter values was done on a physical basis, not by calibration of the model to the data. Where independent estimates were not available for crop-specific parameters, values were used that were consistent both within and across the four data sets and based on sound argument.

One of the additional challenges in this project was to simulate these experiments without the resetting of any variables. Many evaluations of models (including APSIM) are limited to data from one or two years, or have soil water and nitrogen reset every year. This means that any carry-over effects are ignored. This project was one of the first to test carry-over effects within rotations consisting of different crops.

Standard values were chosen for the model constants in SoilN2 and Residue2 (Probert et al., 1998a), with the following exceptions. Like Asseng et al. (1998) and Snow et al. (1999b), we found it necessary to increase the magnitude of parameters controlling potential mineralisation. We chose to use the value of 0.00025 day^{-1} of Snow et al. (1999b) for the potential decomposition rate for the humus pool (*rdhum)* and increase the daily potential decomposition rate for the soil biomass pool (*rdbiom*) in proportion to 0.0135 day^{-1}. The reduced effect of dry soil water conditions on mineralisation and nitrification that were proposed by Asseng et al. (1998) were also adopted. The potential decomposition rate of wheat surface residue (*pot_decomp_rate*) was decreased to 0.02 day^{-1}, from the 0.1 day^{-1} proposed by Probert et al. (1998a) based on a study at Warra, Queensland. The value of 0.1 day^{-1} was used for canola, lucerne, lupin, and weed residues. The need for a smaller value for wheat residues was qualitatively confirmed by surface residue measurements made during the 1992-93 and 2001-02 fallows at CSU (paddock 14). Smaller values were also used by Asseng et al. (1998: 0.05 day^{-1} for wheat residues vs. 0.1 day^{-1} for lupin residues) and Snow et al. (1999b: 0.025 day^{-1} for Eucalypt litter). While there is support for changes in parameters governing potential mineralisation and potential residue decomposition, we feel that more detailed, controlled studies are needed to improve their parameterisation.

Simulations of the Rutherglen and Temora data sets used the SoilWat2 water balance module. Evaporation from the soil surface using this model is based on the concept of first and second stage evaporation (Probert et al. 1998a). Previous studies found it necessary to use different values of the evaporation parameters (*U* and *cona*) for winter (2 and 2) and summer (6 and 3.5) conditions (Verburg et al. 2003, N.I. Huth and S. Asseng, personal communications, 2000). We found that use of the smaller values in winter improved the simulations, so despite the lack of independent support, we have adopted them here. The different values for summer and winter suggest that the rate of second stage evaporation is not independent of evaporative demand and is an issue that is currently being looked into.

SoilWat2 uses the USDA curve number approach to calculate runoff caused by infiltration excess from daily rainfall data. The model automatically adjusts the runoff response curve it uses for antecedent moisture conditions, residue and crop cover. Model input is restricted to a bare soil curve number for average antecedent rainfall conditions, which we estimated from the soil surface conditions and the mean slope of the field site using the method of Littleboy (1997).

The simulations of the two data sets from CSU (Wagga Wagga) used the APSWIM water balance module as good estimates of soil hydraulic properties were available. The APSWIM module is derived from the Soil Water Infiltration and Movement model (SWIM, Verburg et al., 1996).

4 Simulations of data sets

4.1 CSU Paddock 14

Description of experimental data and model parameterisation

Periods and treatments simulated

Experimentation at this site started in 1989, with installation of two weighing lysimeters for measurement of evapotranspiration (*Et*) and drainage. One lysimeter was installed in the middle of the north section of Paddock 14 and the other in the south section. In the early years frequent measurements were only made during the growing seasons. A continuous record of daily measurements (subject to occasional interruptions) started in 1993, with field measurements of soil and crop status made as well. The lysimeters were managed to represent the conditions of the field as closely as possible (Dunin et al. 2001). Nevertheless, they had different residue management (90-95 % of crop residues removed for laboratory analysis at harvest in the lysimeters), slightly different soil properties (due to the lysimeter monoliths coming from a low-lying corner of the field, and experienced different trafficking and tillage operations), different weed dynamics, a different depth of rooting for lucerne (maximum 1.8 m in the lysimeters), and a different bottom boundary condition (seepage at the bottom of the lysimeters). In November 1996 the south lysimeter received 195 mm irrigation as part of a separate experiment whereas only 30 mm was applied to the north lysimeter. For model testing purposes the lysimeters and the field therefore needed to be simulated as separate treatments. In addition, because the crops in 1993 in the north and south sections of the paddock were treated differently (Smith et al. 2000), and because conditions in the two lysimeters were slightly different from time to time, four treatments were simulated: north and south lysimeters and north and south fields. Because there were fewer measurements in the field than the lysimeters, the lysimeter data are mainly used here for the model testing. Similar to Dunin et al. (2001), 20 periods were distinguished for analysis purposes (Table 2). Note, however, that the simulations were continuous, with no resetting of parameters unless otherwise noted for specific sensitivity tests.

Table 2: Periods used for analysis of simulation results of CSU Paddocks 12 and 14, along with rainfall records used.

Period	Season	Paddock 14 (N and S)	Paddock 12	Start	Finish	Rainfall† (field) (mm)	Rainfall‡ (lysimeters) (mm)
1	OS 1992-93	Wheat stubble		15-Dec-92	06-May-93	152	152
2	GS 1993	Wheat +/- N		07-May-93	08-Dec-93	469	427
3	OS 1993-94	Wheat stubble		09-Dec-93	17-May-94	287	265
4	GS 1994	Lucerne		18-May-94	13-Dec-94	220	175
5	OS 1994-95	Lucerne/fallow		14-Dec-94	11-Apr-95	183	159
6	GS 1995	Re-sown lucerne		12-Apr-95	26-Oct-95	470	430
7	OS 1995-96	Cont. lucerne		27-Oct-95	18-Apr-96	356	324
8	GS 1996	Cont. lucerne		19-Apr-96	02-Dec-96	400	361
9	OS 1996-97	Cont. lucerne	Fallow	03-Dec-96	22-Apr-97	164	154
10	GS 1997	Cont. lucerne	Canola	23-Apr-97	10-Nov-97	235	236
11	OS 1997-98	Lucerne/fallow	Canola stubble	11-Nov-97	07-Apr-98	62	59
12	GS 1998	Canola	Triticale	08-Apr-98	04-Nov-98	401	337
13	OS 1998-99	Canola stubble	Triticale stubble	05-Nov-98	19-May-99	345	302
14	GS 1999	Triticale	Lucerne	20-May-99	08-Dec-99	388	362
15	OS 1999-00	Triticale stubble	Cont. lucerne	09-Dec-99	12-Apr-00	202	191
16	GS 2000	Lupins	Cont. lucerne	13-Apr-00	11-Dec-00	477	450
17	OS 2000-01	Lupin stubble	Cont. lucerne	12-Dec-00	10-Apr-01	146	132
18	GS 2001	Wheat	Cont. lucerne	11-Apr-01	04-Dec-01	285	268
19	OS 2001-02	Wheat stubble	Lucerne removal	05-Dec-01	09-May-02	216	211
20	GS 2002	Triticale	Winter wheat	10-May-02	18-Oct-03*	144	156

GS = growing season, OS = off-season, summer fallow

* Crops aborted and harvested early for silage

† Rainfall measured by field rain gage (after February 1997) or from the nearby Bureau of Meteorology station 73127

‡ Rainfall measured directly by the lysimeters

Parameterisation and inputs

The soil at the site is a Eutrophic Red Kandosol (Isbell, 1996). Parameterisation of the model was based on site specific measurements of bulk density, organic carbon, and pH. Estimates of soil hydraulic properties for

the APSWIM water balance module were based on an internal drainage experiment for in-situ water retention and hydraulic conductivity relationships, laboratory measurements of water retention and near-saturation on soil cores, and an assessment of the lower limit in deep soil cores. They are summarised in Appendix A. The maximum effective rooting depth of annual crops was set at 1.3 m, based on neutron moisture meter observations in the field. The maximum rooting depth for lucerne was set at 1.8 m (lysimeters) and 6.0 m (field).

From February 1997, rainfall for the field simulations came from an on-site meteorological station. Prior to this, and for periods when the on-site station failed, data were obtained from the nearby (< 1 km) Australian Bureau of Meteorology station 73127 run by the NSW Department of Agriculture Research Station. Rainfall for the lysimeter simulations was obtained from the continuous lysimeter output when possible. Continuous lysimeter output was not available when the lysimeters' balance mechanisms were driven offscale by large rainfall events, or when the chart recorders failed. During those times, rainfall data was obtained from the on-site meteorological station or, if that was unavailable, from station 73127. It can be seen from Table 2 that there were often large differences between the lysimeter rainfall record and that from nearby rain gages. The reasons for these differences are not completely understood, but observations during recent years suggest that they are a combination of natural rainfall variability during scattered showers, systematic differences when storms arrive from certain directions, and small losses by the lysimeters when they fail to detect rainfall under certain conditions. While the on-site meteorological station measured solar radiation and maximum and minimum temperature since February 1997 (with a few interruptions), it was decided to use instead the continuous record from SILO Patched Point Dataset (Jeffrey et al., 2001) for station 73127 for the whole simulation period.

Initial conditions

The simulations were initialised on 15 December 1992 immediately after the harvest of the 1992 wheat crop. No direct estimates of initial soil water content or storage were available (the lysimeters only measure storage changes not the absolute storage). The initial soil water content profile was assumed to be at drained upper limit (DUL) at and below the bottom of the root zone (> 1.0 m), because 1992 was quite a wet year and the north lysimeter drained in September 1992. Water contents from 0 to 1 m were based on soil core values taken from the paddock on 3 March 1993, the first available data from the site. There was 86 mm of rainfall between 15 December 1992 and 3 March 1993, the two largest daily values being 20.5 mm and 12 mm. On the basis of observations of similar events in recent years, it was assumed that this rainfall did not penetrate very deeply and would have been quickly lost by evaporation. As it had not rained for 9 days before 3 March 1993, whereas it did rain 6.5 mm on 14 December 1992 (but not for 6 days before that), the water contents in the top 0.2 m of the soil were increased to reflect that.

As no measurements of initial nitrate were available, the initial profile (15 December 1992) was based on measurements made on 3 March 1993 (from 0.2 m depth) and 25 November 1993 (0 to 0.2 m depth). The latter represented the surface soil nitrogen status close to harvest in a season of similar wetness as the 1992 growing season (field June – November rainfall 430 mm in 1992 and 440 mm in 1993). It was assumed that the rainfall events between December and March were not large enough to cause significant leaching or denitrification.

Differences between the two lysimeters – the importance of weed growth

Separate operations records were compiled for the field and the two lysimeters because management was sometimes different (e.g. sowing, spraying and fertilising dates for the lysimeters were often a few days different from those for the field). In addition, the amounts of weed growth and/or residue cover were often different between field and lysimeters and between the lysimeters themselves (e.g. Fig. 1). These differences were found to have a marked impact on measured *Et*. In all but two summer fallow seasons there was a difference in *Et* between the north and south lysimeters, ranging from 11 to 54 mm. Differences were also observed during growing seasons, despite attempts to manage the two lysimeters to be the same. During the three cropping seasons from 1999 to 2001 there were differences in *Et* measured by the two lysimeters of between 18 and 35 mm. The lucerne phase in Paddock 14 (1994 to 1997) was probably the most difficult period in this respect, with lucerne suffering from weed infestations, waterlogging, and two replantings of lucerne being necessary. This caused significant differences between the *Et* measured by the two lysimeters (Fig. 2).

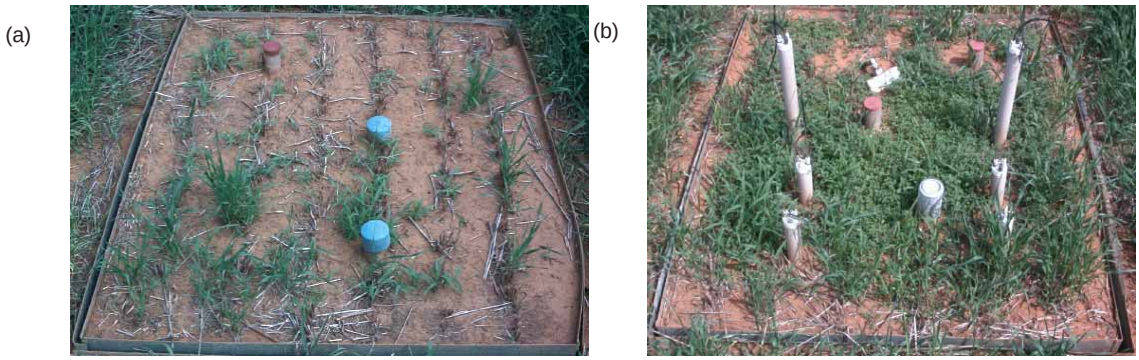

Figure 1: Weed cover on (a) north and (b) south lysimeters in March 2001 (2001-02 summer fallow period).

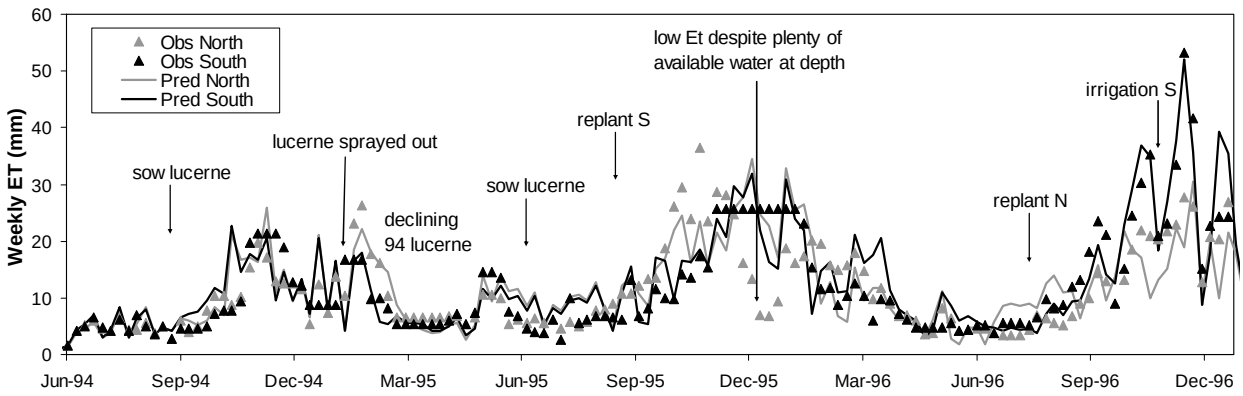

Figure 2: Observed and predicted weekly *Et* during 1994-1996 (lucerne phase), highlighting differences between lysimeters.

Different weed growth during the summer fallow was also found to impact quite strongly on drainage collected from the lysimeters, as shown in Fig. 3. Although the north lysimeter received supplemental nitrogen fertiliser in early August 1993, cumulative *Et* from the two lysimeters differed by less than 6.5 mm until early October (Fig. 3a). Most drainage had already occurred by late September (Fig. 3b), with significant differences between the two lysimeters in both amount and timing. In the 1995 growing season the maximum difference between cumulative *Et* from the two lysimeters up to early October was 15 mm (6 June, Fig. 3c). Nevertheless, there was a big difference in timing and amount of drainage (Fig. 3d), with the south lysimeter, which had the largest *Et*, having the earlier and larger drainage. In both cases, these differences in drainage must have been a consequence of the two lysimeters having different soil water storage at the start of the growing season, as a result of different uptake and evaporation patterns during previous seasons.

An analysis of changes in storage in both lysimeters between 15 December 1992 and when they first drained in 1993 suggests that both lysimeters would have had a similar water content profile on 15 December 1992. The south lysimeter had increased its storage by 68 mm when drainage was first collected (27 July 1993), while the north lysimeter had added 74 mm when it first drained (10 August 1993). The major drainage event for both lysimeters was collected on 21 September 1993, on which date the south lysimeter had accumulated 74 mm storage since 15 December 1992, while the north lysimeter had accumulated 79 mm. The similarity of these amounts of storage prior to drainage suggests that, in the absence of other information, it is reasonable to assume that the lysimeters had the same storage on 15 December 1992, within 5 mm. This in turn implies that the different drainage patterns observed during July – September 1993 were a consequence of different evapotranspiration, likely to have been caused by different weed growth, during the 1992-93 summer fallow.

Analysis of the lysimeter data during 1994-1995 shows that *Et* for the two lysimeters was only 13 mm different for the period between sowing of lucerne in August 1994 and the attempt to remove lucerne in January 1995. Between January and April (just prior to the autumn break), however, the north lysimeter had

33 mm more *Et* than the south. The different amounts of *Et* after 12 January 1995 were most likely a consequence of more effective removal of lucerne on the south lysimeter, which is supported by the recorded observation that less biomass was removed from that lysimeter in June 1995 at re-sowing of the lucerne.

Differences such as those described above between the *Et* and drainage measured on the two lysimeters illustrate their different response to management procedures, and demonstrate the necessity for different input files for their operations records. These differences also illustrate the natural variation that is possible in both *Et* and drainage as a result of differences in residue cover, weed growth, and crop performance. This will be discussed in more detail later.

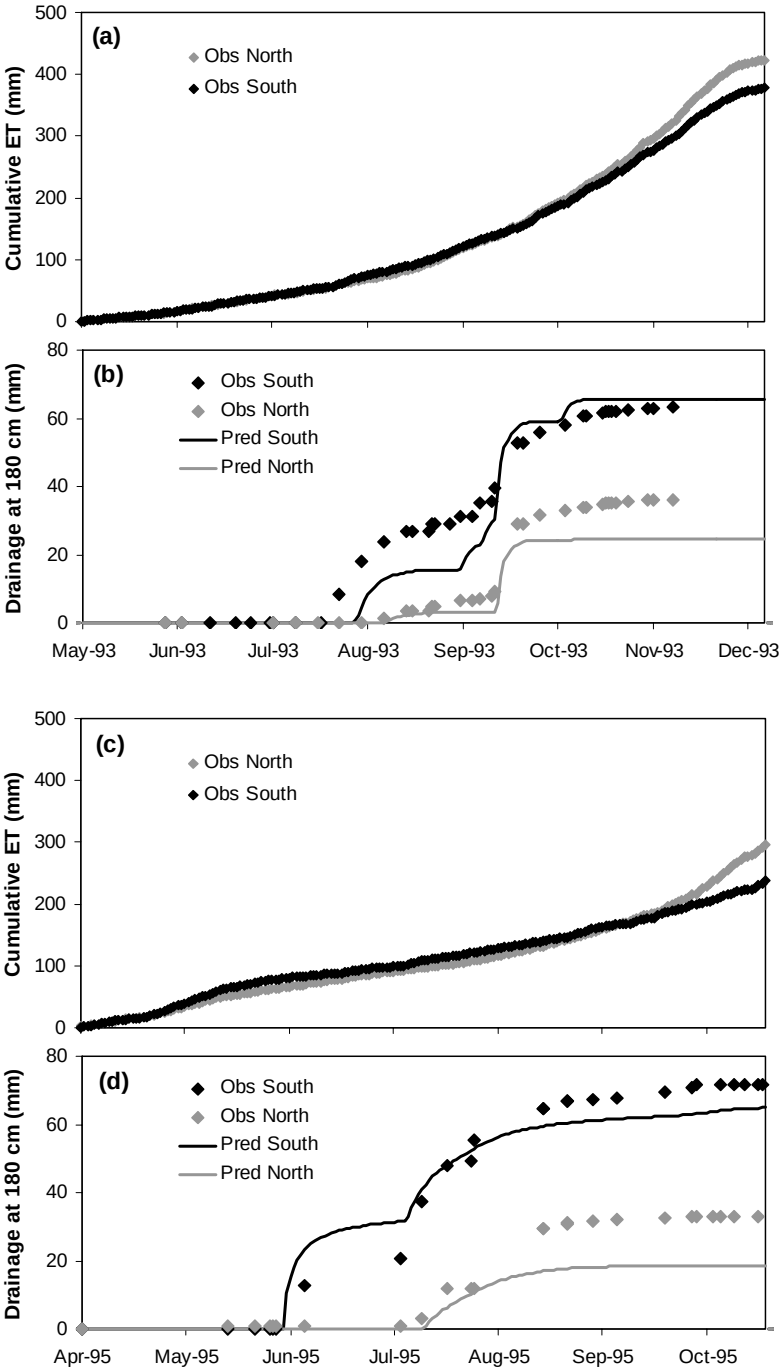

Figure 3: Observed cumulative *Et* during (a) 1993 and (c) 1995 growing seasons; (b), (d) Observed and predicted drainage from lysimeters.

Model evaluation

Simulation of fallow periods – bare soil, weeds, and residue effects

Detailed observations during the 2001-02 summer fallow, allowed the best test of the model's ability to simulate entry and redistribution of rainfall, transpiration by weeds, evaporation from the soil surface and the effects on evaporation of residue cover. Weeds were included in the model using a weed germination scheme adopted from Fischer et al. (1990), with weeds germinating on the first rain event after harvest that exceeded a total of 25 mm (Dec – Feb) or 20 mm (Mar – Apr) over two consecutive days. For 2001-02 two rainfall events sufficient for germination occurred: 69 mm on 4-5 Feb and 56 mm on15-16 Feb. Weed density and composition, a mixture of deep-rooted wheat plants and shallow-rooted grassy and broadleaf C3 annual weeds, were based on observations of weed growth made during that period.

As shown in Fig. 4, *Et* was quite well simulated from harvest (4 Dec 2001) when the soil was bare, through the weed germination in February, up to and following the sowing of triticale in June 2002. Predicted soil water changes following the first large rainfall event (4-5 Feb), when the soil was bare, compared very favourably with TDR measurements (Fig. 5).

The different *Et* between the two lysimeters in response to different weed growth was captured reasonably well by the model. These results show that when appropriate information is given to the model, it can simulate *Et* quite accurately. The brief overprediction of *Et* in mid-April was most likely due to imperfect description of senescence in the weed module, which is still under development and this is an area for further improvement. The slight overprediction in March on the north lysimeter could be due to not taking into account spatial distribution of the weeds (Fig. 1a), which may have affected competition between them.

Prior to sowing triticale in June 2002, residues were removed from the surface of the lysimeters. This caused a large increase in observed *Et*. The model correctly captured this effect of residue removal, as shown by both the good agreement between measured and predicted *Et* in June and July, reinforced by the poor prediction if it was assumed that residues were not removed (Fig. 4).

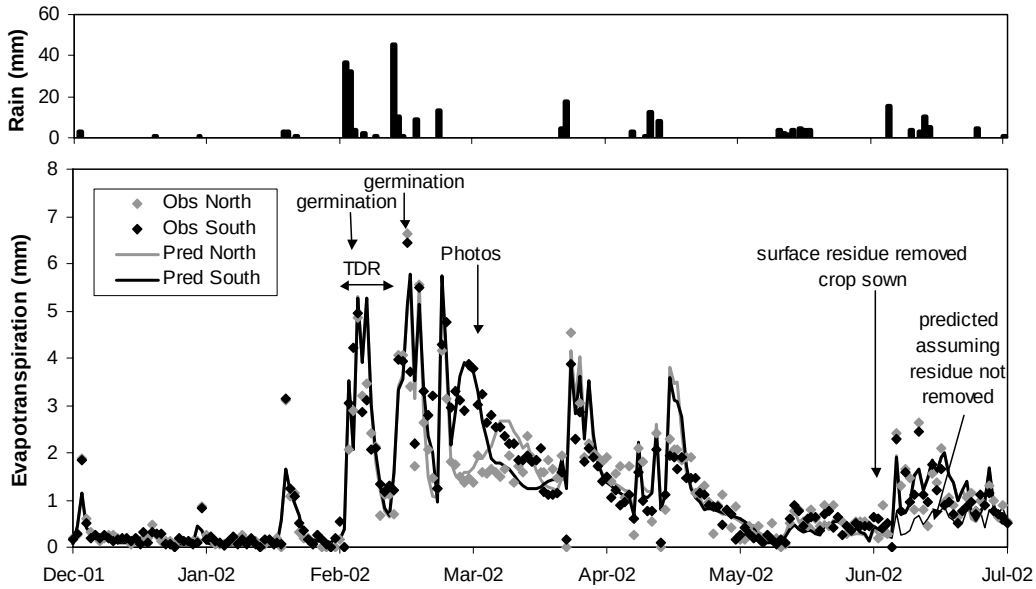

Figure 4: Observed (symbols) and predicted daily *Et* during the 2001-02 summer fallow. Additional prediction of south lysimeter assuming surface residue not removed at sowing of crop in June 2002.

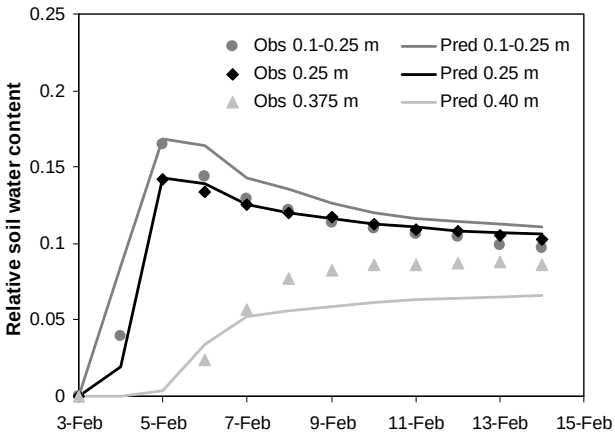

Figure 5: Observed (symbols) and predicted soil water after a rainfall event on bare fallow soil during the 2001-2002 summer fallow (south lysimeter).

Inclusion of weed growth during the summer fallows in the continuous 1993 to 2002 simulation improved the predictions of *Et*. Observations of weed growth were not recorded prior to 1999. On the basis of the 1999 to 2002 observations, however, it was assumed that more vigorous summer weed growth occurred on the lysimeter with larger *Et* in the fallow period, usually the north lysimeter. Nominal weed densities of deep and shallow rooted weeds, also based on the 1999 to 2002 observations, were used. The weed germination scheme of Fischer et al. (1990) initiated growth, and quite accurately predicted the time of divergence of *Et* from that predicted for a clean fallow (Fig. 6).

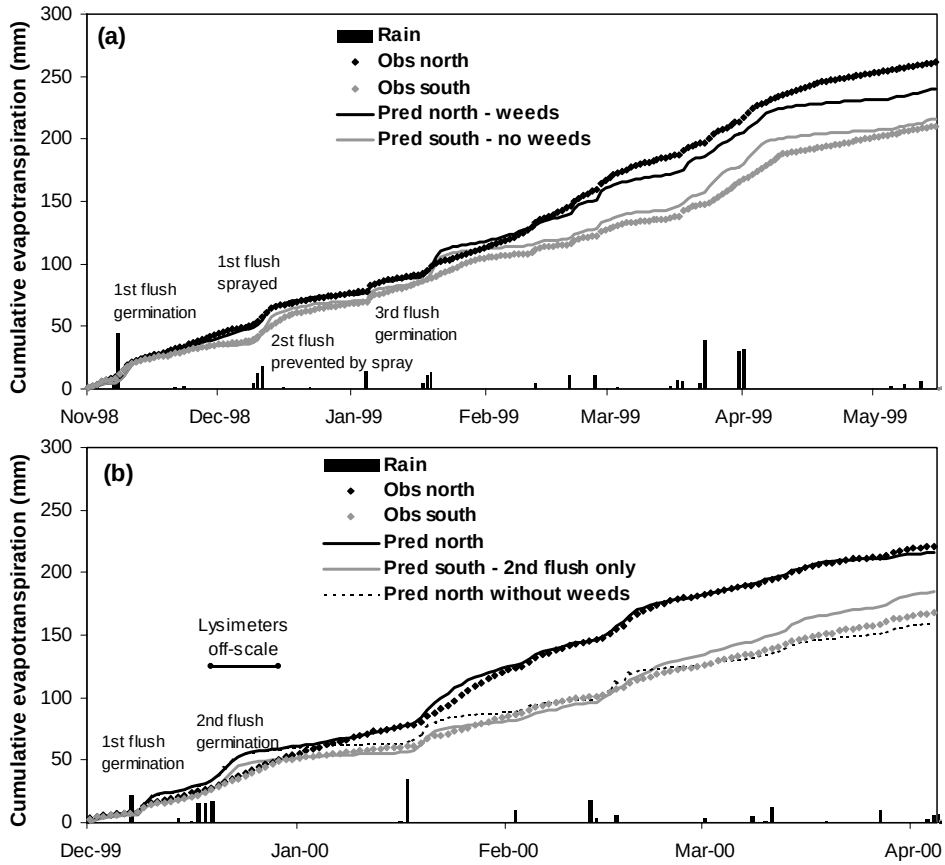

Figure 6: Observed (symbols) and predicted cumulative *Et* during the (a) 1998-1999 and (b) 1999-2000 summer fallows. Simulations assuming less weeds on the south lysimeter and nominal weed densities described the different *Et* patterns quite well. Default APSIM weed parameters were used without further optimisation because of lack of detailed observations of weed type, leaf size, etc. The assumed spray of weeds in December 1998 was inferred from daily *Et* data. A possible third flush of weeds in January2000 did not seem to be supported by the *Et* data.

Simulation of the 9-year evapotranspiration record

Given the sensitivity of the measured water balance components to management, and given the uncertainty about the exact conditions in most years (because the necessary observations were not always made), it is impossible to correctly simulate the full field measurement period in detail based on the available information. Cumulative evapotranspiration (*Et*) predicted for each period by a "best bet" simulation is shown in Fig. 7. This simulation reflects our best estimates of weather, crop, surface residue and weed conditions in the various season. Errors in these assumptions will impact not only on the period in question, but may carry over into subsequent periods of the continuous run. There is, however, no basis for resetting soil water content. TDR measurements were only made in the south lysimeter, and did not cover the full simulation period. Simulation of the summer fallows has already been discussed above. The other seasons are discussed below.

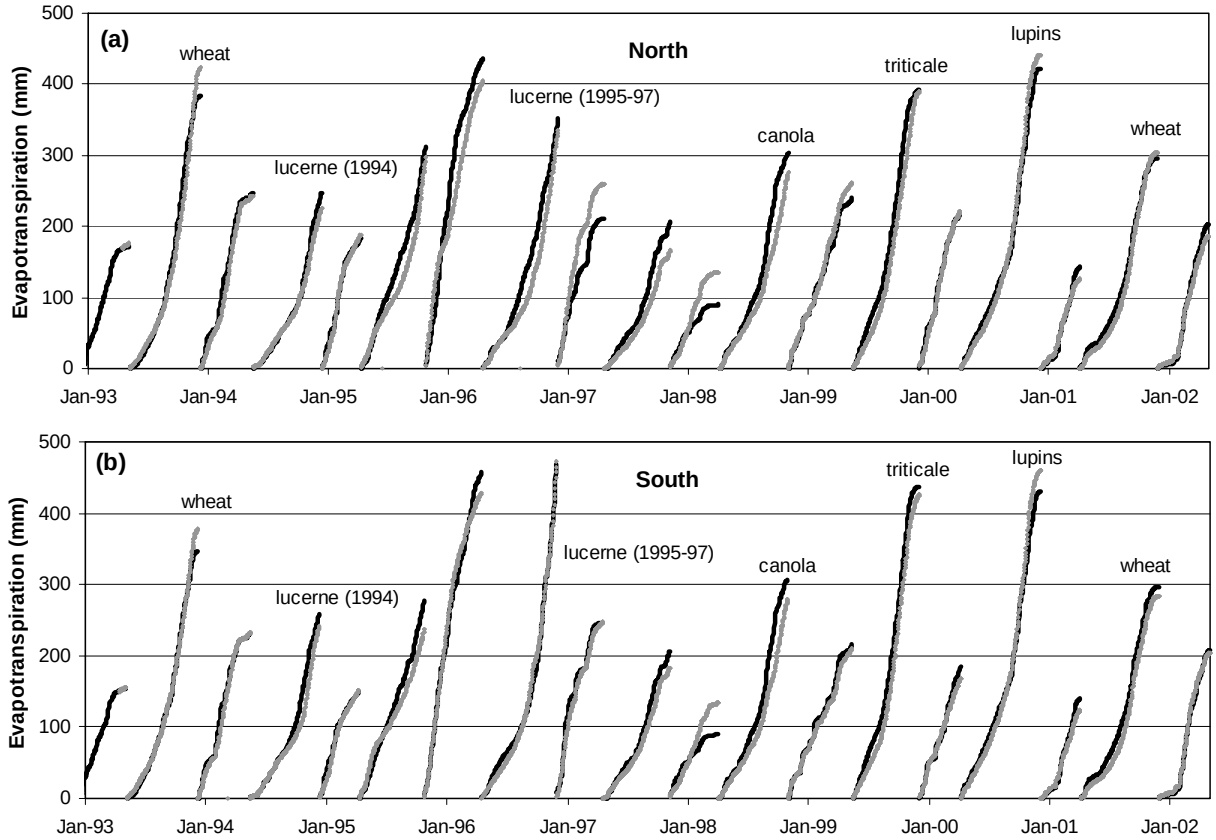

Figure 7: Observed (grey symbols) and predicted (black line) cumulative *Et* for the different periods of the CSU experiment as defined in Table 2.

Simulation of lucerne

The lucerne phase from 1994-1997 was the period for which the agreement between model predictions and measurements was poorest, but it was also the period where plant conditions were the least well defined. The lucerne was weedy, and did not always perform well, as is evident from the need to replant it twice (Fig. 2). As it is not known what factors caused the reduced performance, the model cannot include them in its predictions. The replantings used plants grown in a glass house rather than seeds, in order to match the lucerne in the paddock as closely as possible. This presented a difficulty for the model, which can only simulate annual crops and lucerne from sowing. If lucerne was sown in the model as seed on the date of replanting, the simulation would lag behind in crop phenology as well as provide less crop cover, affecting predictions of both evaporation from the soil surface and transpiration. If the replanting was ignored in the model, the simulations would take up deep water that new plants would not have access to. To address this issue for the 1996 replanting, we re-sowed lucerne in the model in early May, so that it was established by the replanting date in late July. This improved the simulation, in particular reducing the overprediction of *Et*

in October 1996 that resulted if replanting was ignored. In late 1995, the *Et* data from the north lysimeter have a seasonal pattern that more closely resembles an annual crop than lucerne; daily *Et* peaked in mid-November at 6 mm/day, and then declined to 1 mm/day by mid-December (Fig. 2). Rye grass and poppies were observed in the paddock during this time, and may have also been present on the lysimeter. Trying to simulate this effect without any knowledge of germination time or densities would, however, become a fitting exercise and not contribute to model testing.

Simulation of annual crops

Wheat was grown in 1993 (cv. Janz) and 2001 (cv. H45), and Triticale (cv. Abacus) in 1999. Evapotranspiration (*Et*) during these cropping seasons was simulated quite well. Within the seasons there were some under- and overpredictions, but in general these balanced out (Fig. 7). The exception is the underprediction of *Et* at the end of the 1993 season. About a month before harvest the model crop suffered nitrogen stress for a period of about two weeks, which reduced the green leaf area significantly. It is unknown whether the model underpredicted the nitrogen supply, or overpredicted the effect of nitrogen stress of leaf senescence. No nitrogen data are available for the lysimeter monoliths and data from soil cores in the adjacent paddock cannot be used because of management differences. For example, no crop residues were left on the lysimeters after the 1992 harvest, whereas in the field residue remained on the surface until burned in late March. In addition, sheep grazed in the field during part the summer fallow, which would have affected the soil nitrogen dynamics as well. That the lysimeters sometimes suffered nitrogen stress is suggested by the need to transplant plants or apply supplementary nitrogen in the lysimeters. For example, on 9 September 1993 the south lysimeter was given an extra 41.4 kg/ha urea-N, presumably in response to nitrogen stress. The model predicted nitrogen stress in the two weeks prior to 9 September, but again either underestimated nitrogen supply, or overpredicted the effect of nitrogen stress on the crop. It caused only a slight, temporary underprediction of evapotranspiration, but as it came at a critical time, it also caused an overprediction of drainage (Fig. 3b).

Underprediction of nitrogen supply is quite possible, in view of the changes that needed to be made to some APSIM-SoilN2 parameters (see Section 3). There are also uncertainties introduced by the initialisation of the SoilN2 (fresh) organic matter pools at the start of the simulation in December 1992, and by the impact on nitrogen dynamics of weeds grown during the 1992-1993 fallow. It should also be noted that simulations of the lysimeters are expected to be more sensitive to uncertainties in soil nitrogen supply than simulations of crops in the field due to the lack of nitrogen input from decomposing crop residues.

Crop performance was generally simulated well, as illustrated here by the predictions of biomass and nitrogen uptake by above ground biomass for the 1993 crops (Fig. 8). While the comparison between observed and predicted can strictly speaking only be made for the final sampling at harvest (star symbol for lysimeter crops), the comparison with data from the field crop (open and closed black symbols) confirms the right progression during the season. While biomass was predicted well, predictions of leaf area index (LAI) tended to be too high, especially around anthesis. This is currently being looked into in more detail.

Simulation of the 1998 canola crop in the lysimeters was difficult because, judged from final biomass and yield, the crop performed worse in the lysimeters than in the field for some reason. The simulation results more closely resembled those for the field, because the cause of the underperformance in the lysimeters was not known. This resulted in an overprediction of *Et* for the lysimeters. Water use by the lupin crop in 2000 was underpredicted. This does not seem to be related to stress, and it is suspected that the predicted phenological development was too rapid. No tested phenology parameters were available for the variety of lupin grown at CSU. There is also a suggestion, based on TDR measurements in the south lysimeter, that the lupins may have extracted water from deeper in that lysimeter than in the field, and deeper than other crops. Because the field data were used to set the maximum rooting depths in the model, this would lead to an underprediction of *Et*.

Early season soil evaporation

One aspect of the evapotranspiration predictions requires further attention. In a number of growing seasons the model overpredicts soil evaporation in early winter following sowing of the crop (e.g. Fig. 7, GS 1995, GS1998, GS1999, GS2001). It is likely that the tillage and sowing operations caused soil surface changes that are not currently captured by the model. As the tillage and sowing operations were poorly defined and the surface conditions, including residue cover, before and after the operations not well described, this could not be further assessed. Encouraging, however, is that in 2001, when conditions were well described, the model correctly simulated the effect of removal of weed residues at sowing (Fig. 4).

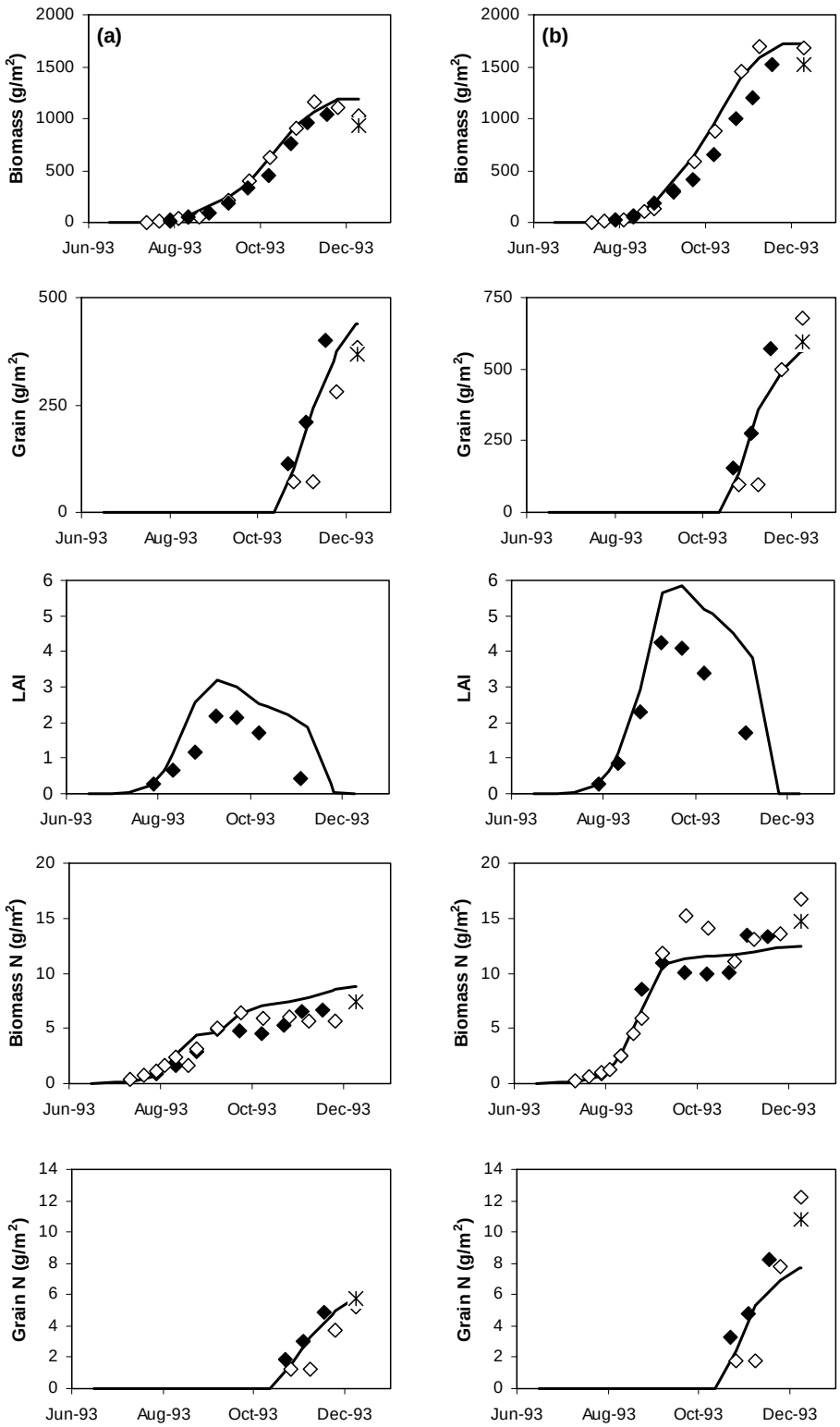

Figure 8: Observed crop biomass, crop yield, LAI, crop N uptake in biomass and grain for the 1993 wheat season (open and closed diamond shape symbols represent averages of two different field assessments, star symbol represents lysimeters) and predictions for lysimeter treatments; (a) south, (b) north.

Drainage

Measured and predicted drainage from the lysimeters is summarised in Table 3 for the seasons in which it occurred. In growing season 1993 (period 2) the incorporation of different weed growth described in an earlier section was effective in simulating the delayed and smaller drainage from the north lysimeter compared with the south (Fig. 3b). The total amount was predicted well for the south, but was underpredicted for the north, possibly because of incomplete information about the weeds. Overall, however, the agreement was pleasing.

During the 1993-1994 summer fallow (period 3) no drainage was collected from the lysimeter, but the model predicted that it occurred. It is possible that small amounts were missed due to the infrequent visits to the site during this time, or that the amounts were too small to initiate drainage from the lysimeters (a water table must be created at the base of the lysimeters before drainage occurs). It is also possible that the model overpredicted drainage due to underpredicting late water use of the preceding wheat crop.

In period 6 (GS 1995), the assumption that lucerne was more effectively removed from the south lysimeter than from the north lysimeter in early 1995, for reasons described in an earlier section, resulted in prediction of the different amounts of drainage from the two lysimeters (Fig. 3d, Table 3). Total drainage for this period was underpredicted, most likely as a result of the overprediction of *Et* after sowing of the (initially failed) lucerne. The underprediction by the model in period 7 (Table 3) probably relates to the overprediction of *Et* in 1995 when the initial lucerne sowing failed (Fig. 2, 7).

There is some uncertainty about the value for drainage measured following irrigation of the south lysimeter in November 1996 (period 8) because of a mismatch of 11 mm in the lysimeter water balance on the day of the irrigation. Therefore the actual drainage for this event could be as low as 32 mm. Some of the imbalance is attributable to leakage from the lysimeter collection tank which was observed but not able to be measured. Even if the actual value was 32 mm, however, it was significantly higher than that predicted. While *Et* from the south lysimeter was predicted well during the 1996 growing season, it is likely that the earlier overpredictions in 1995 and early 1996 (due to crop performance issues) created too much of a buffer. It is also possible that the large irrigation rate (195 mm in 3 hours; higher than the saturated hydraulic conductivity of the least permeable layer – see Appendix A) caused bypass flow down the small gap that exists between the soil monolith and the lysimeter container.

After a number of years with below average rainfall, the next drainage predicted by the model did not occur until September 2000 (period 18). No drainage was measured from the lysimeters, but in the field in spring 2000 there was an accumulation of water below 1.8 m of between 11 and 26 mm (average of 16 mm) based on NMM measurements. Data from TDR probes installed in the south lysimeter showed clear evidence of the transmission of a drainage pulse between 1.2 and 1.7 m in September and October, and approximately 10 mm drained past 1.8 m, even allowing for the possibility of some storage between 1.7 and 1.8 m. This combined evidence suggests that drainage did occur and but was lost by leakage from the collection tank and therefore not observed. Leakage from the collection tank had previously been observed and repaired in 1996, but further corrosion may have occurred in the intervening period.

Despite the differences described above, the total measured and simulated drainage for the whole 9½ year simulation period agreed fairly closely for both lysimeters (Table 3). In particular, the model captured the different drainage behaviours of the two lysimeters. That the totals agreed well, while individual periods differed, can be explained by the carry-over effects between seasons described in preceding sections. When the model over-predicts *Et* relative to the measurements in one season, it often under-predicts in the following season, and vice versa.

Table 3: Measured and predicted drainage (mm) from the lysimeters (1.8 m).

	Period	2	3	6	7	8	18	
	Season	GS 1993	OS 1993-94	GS 1995	OS 1995-96	GS 1996	GS 2000	Total
Measured	N lysimeter	36	-	33	0	0	0	69
	S lysimeter	63	-	75	16	43	0	197
Predicted	N lysimeter	25	2	18	0	0	13	59
	S lysimeter	65	17	65	5	13	16	177

Impact of rainfall record on predicted drainage.

As discussed in the beginning of this section, there were often large differences between the lysimeter rainfall record and that measured in nearby rain gages (Table 2). In addition there were often significant differences between these records and that for the Forest Hill station (Bureau of Meteorology station 72150) located 16 km from the CSU site. The differences were particularly striking during the 1993 growing season, when the lysimeters received 427 mm, while the nearby station 73127 run by the NSW Department of Agriculture Research Station received 469 mm and Forest Hill 525 mm. The impact of using these three different rainfall records on the predicted drainage is shown in Table 4. A large proportion (up to 70%) of the "extra" rainfall at stations 73127 and 72150 appeared in the drainage term, as the crops were not water stressed in the 1993 season.

Table 4: Rainfall and predicted drainage for the two lysimeters (1.8 m) during the 1993 growing season (7 May – 8 December) for different rainfall records.

Source of rainfall data:	Lysimeter record	Station 73127 (NSW Agric.)	Station 72150 (Forest Hill)
Rainfall (mm)	427	469	525
Predicted drainage for North lysimeter (mm)	25	53	58
Predicted drainage for South lysimeter (mm)	65	96	116

Soil nitrogen

As discussed above, soil nitrogen was not measured in the lysimeters. The accompanying field simulations simulated soil nitrogen quite well, as illustrated in Figure 9 for soil nitrate in 1993 (the season with most frequent measurements). The simulations of nitrate in the lysimeters (dotted line in Figure 9) illustrate the large impact that different residue management and weed dynamics have on nitrogen supply for the crop.

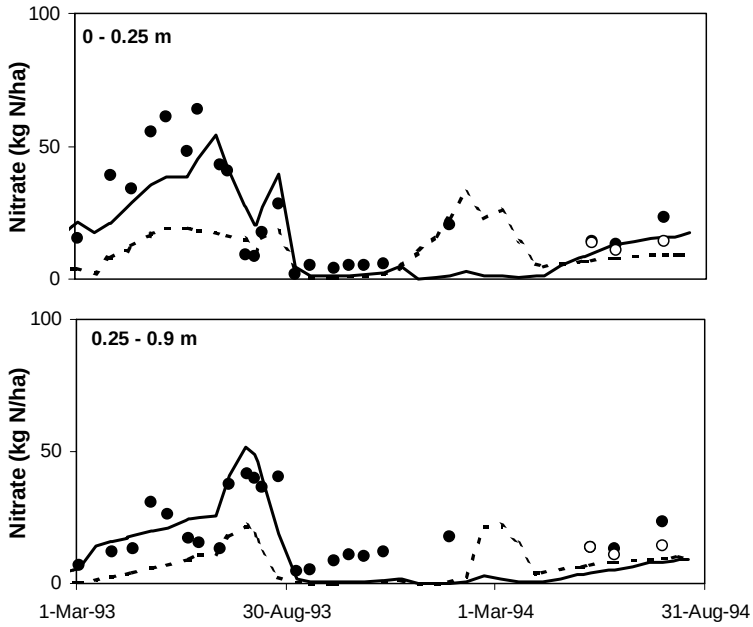

Figure 9: Observed (symbols) and predicted (continuous line) nitrate in the field of CSU Paddock 14 (north). Dotted line represents accompanying simulation of north lysimeter where crop residues were removed at harvest (both 1992 and 1993 crops). The increase in nitrate in the lysimeter in February 1994 relates to the absence of surface residues that would immobilise nitrate, and the subsequent decrease during March is a consequence of uptake by weeds.

Summary

Differences in off-season *Et* and the amount and timing of drainage between the two lysimeters have illustrated the important impact of weed growth and residue cover on the water balance. Variability in both of these can therefore make a considerable contribution to the variability of drainage both within and between paddocks. It is therefore critical that management factors such as these be well described in order for any model to correctly simulate the water balance. Importantly, it was found that, when provided with the correct inputs, APSIM was sufficiently sensitive to be able to reproduce the effects of these factors on the water balance. It also accurately simulated soil water redistribution and evaporation from bare soil following summer rainfall.

Given the sensitivity of the measured water balance components to management, and given the uncertainty about the exact conditions in most years (because the necessary observations were not always made), it is impossible to exactly simulate the full field measurement period based on the available information. The poorest predictions of *Et* occurred during the lucerne phase when lack of sufficient information on lysimeter and surface conditions and lucerne growth performance was limiting. This was unfortunate, as it limited its use for model testing severely. Overall, however, the model can simulate this extensive data set quite well provided sufficient information is available to describe the conditions of the lysimeters.

Although measured and simulated drainage did not always agree in individual seasons, the total measured and simulated drainage for the whole 9½ year simulation period agreed fairly closely for both lysimeters (Table 3). As well as being influenced by the correct description of weed growth and residue cover, it was shown that the amount of drainage simulated was sensitive to the rainfall record used. This will be further explored in later sections.

Simulation of this data set identified several issues that require further investigation, including modelling the phenological development of lupins, weed senescence, nitrogen uptake by weeds, and wheat nitrogen stress. The difficulty of simulating evaporation from bare soil following cultivation and sowing is also an issue that requires further study.

4.2 CSU Paddock 12

Description of experimental data and model parameterisation

The data available from this paddock are summarised in Table 1. This data set is particular useful in that it allows assessment of the establishment of lucerne and the accompanying advance of the root water uptake front. By the end of the lucerne phase the root water uptake front was found to have reached 5.5 m.

The simulations used soil properties and other model parameters that were the same as those in the neighbouring Paddock 14 unless otherwise mentioned. The soil classification of Eutrophic Red Kandosol (Isbell, 1996) is also the same.

Between emergence and grain filling, the increase in root depth in the APSIM lucerne module is calculated from a daily maximum rate (10 mm/day) multiplied by an exploration factor *(xf)* and a soil water availability factor for the layer that the deepest roots are currently passing through. In the absence of any independent parameterisation data, we left the exploration factor *xf* at its maximum of 1.0. This may be an overestimate if soil properties at depth change significantly and cause root advance to be physically limited. Note that xf does not define the water uptake profile. Soil water uptake is determined by crop demand, soil water availability, soil hydraulic properties and the root length density predicted by the model.

Model evaluation

Measurements of water content (4 replicates; neutron moisture meter method) were made from August 1998 to 3 m depth, and from 19 April 2000 to 6 m depth. The data are presented as changes in water content relative to the water content on 9 Jan 2002 (Fig. 10). This removes the effect of variability in absolute water content between the measured replicates and provides a more stringent test of the model against the less variable water content changes.

The 1998 triticale crop was simulated using the wheat module. Its draw down of soil water to 1.1m depth was predicted well by the model. A late rainfall event (65 mm in mid-November) could not, however, be utilised as fully by the model crop as by the real crop. Possible reasons include an overestimated leaf senescence reaction to water stress, a later maturity for triticale than for wheat, or the presence of weeds which could have used the water. The sensitivity of leaf senescence to stress is being further explored.

Water content changes under lucerne (sown in July 1999) were generally simulated well to 3 m depth (Fig. 10, Fig. 11a). In October 1999 the model overpredicted soil water storage (1.3 – 3.0 m) by 10 mm (Fig. 11a), mainly due to overprediction of soil water contents at 2.0 and 2.2 m depth (data not shown). Possible reasons for the overprediction include overestimation of storage capacity of these layers (because soil characterisation at these deeper depths is based on minimal information), underprediction of water use, uncertainty in rainfall, or the lack of any predicted runoff (no experimental observations of runoff were made). During the first summer, the model lucerne dried out the profile to 1.8 m and also started accessing water down to 2.3m. Early the next summer, lucerne used significant amounts of water from depths to 5.5 m. Up to the 3 m depth the rate of uptake was supported by the experimental data, but below 3 m uptake appears to have been slower, although very variable between replicates (Fig. 10, Fig. 11b). It is unclear why the model and data deviate below 3 m, when they corresponded so well down to 3 m. One possible reason is overestimation of the hydraulic conductivity at depth, where little information on soil properties is available. However, when model sensitivity to this was evaluated using a ten-fold reduction in hydraulic conductivity, there was little difference in uptake.

Changing soil properties with depth may cause a change in the rate of root advance. The soil is quite layered and variable at depth, and the 15 bar water contents are greater below 3 m suggesting an increase in clay content and/or bulk density, which could impact the potential root growth rate. If this was the case, the lucerne roots might not have reached 3.5 m by early summer 2000, as currently predicted by the model. Adjusting the *xf* factor down to 0.6 below 2.3 m improved the simulations (Fig. 11b), although we do not have independent support for this change. Another possibility is that the model lucerne gets too little of its water requirements from the surface layers. This would be an interplay between soil conductivities and root length densities in surface and deeper layers. The model does not specify any preference for uptake from the shallow depths, other than through having a higher root length density in the surface. Another possibility is overprediction of water use by lucerne in November 2000. We have noticed that the transpiration efficiency method used by APSIM can result in too high water demands when the vapour pressure deficit and radiation levels are both high. This appears to have been the case for a week in November 2000. Preliminary work on this problem has suggested that over the long term (1957-2001) this problem only had a small impact on

predicted seasonal *Et* and drainage (Wang et al. 2003 in progress). Finally, it is also possible that the lucerne phenology is not simulated correctly. Further work will try to explore these different hypotheses, because correctly predicting the timing of water extraction by lucerne at depth will be important for applications of the model, such as predicting optimal lucerne phase length. Currently the model predicts the emptying of the soil water store between 1.3 and 3m quite well (Fig. 11a), but is between 6 and 12 months too early with emptying that between 3 and 6 m (Fig. 11b).

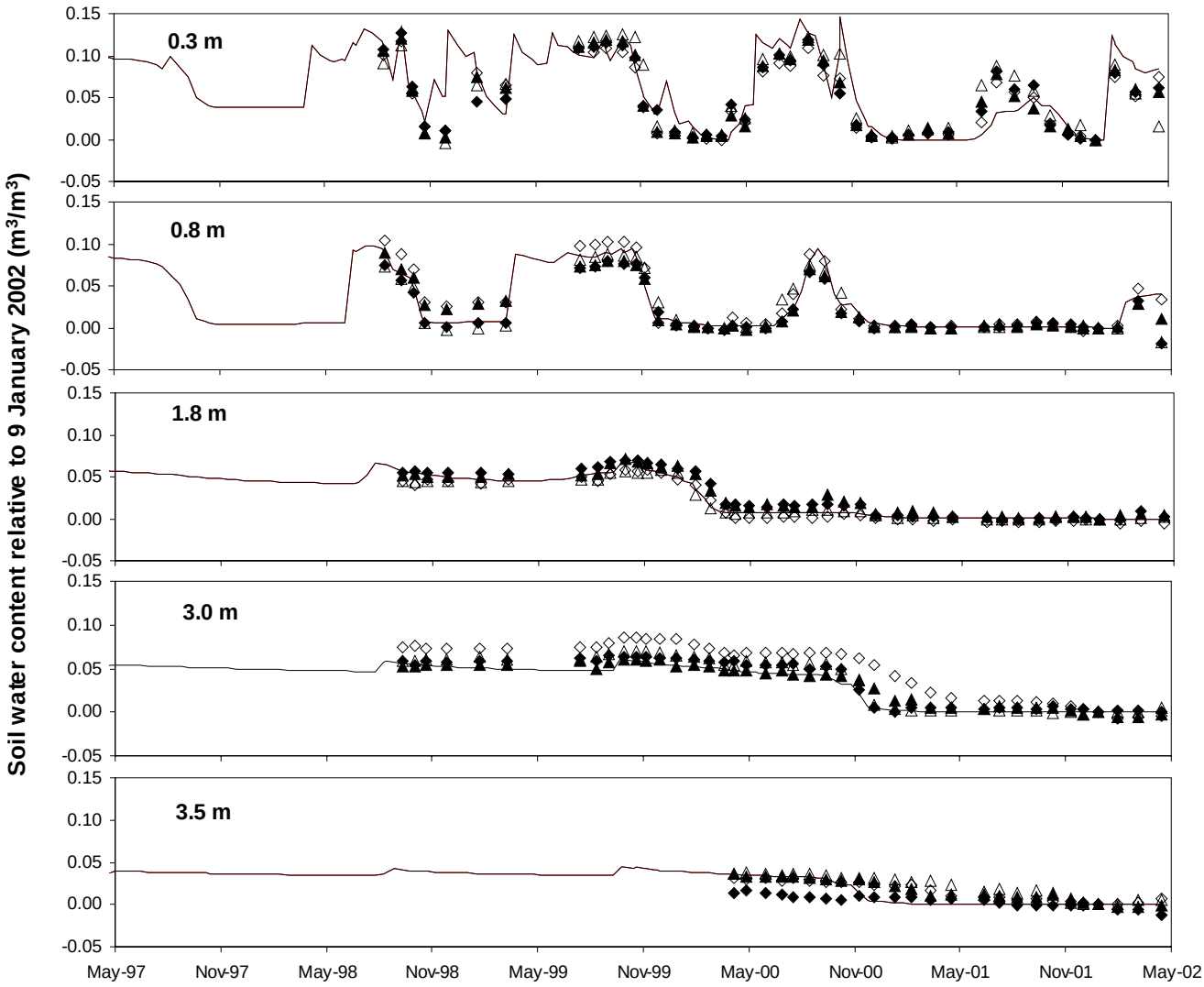

Figure 10: Measured (symbols) and predicted water contents at selected depths, all expressed relative to the water content on 9 Jan 2002.

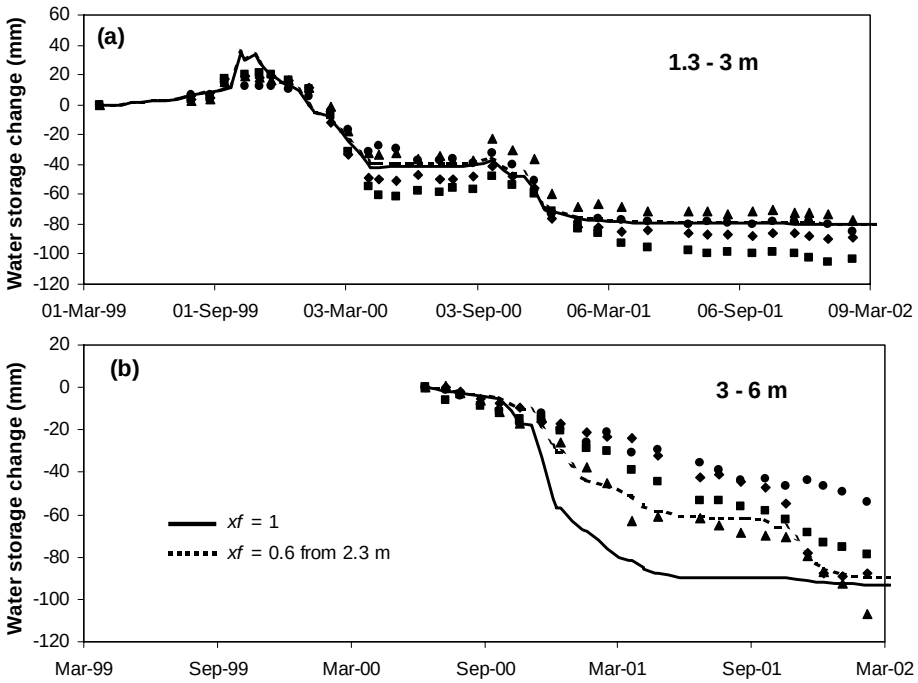

Figure 11: Observed (symbols) and predicted water storage change for (a) 1.3 – 3 m and (b) 3 – 6 m; xf = 1 continuous line, xf = 0.6 from 2.3 m dashed line.

Crop and lucerne biomass

The above-ground biomass of the canola and triticale crops grown in Paddock 12 was simulated well (Fig. 12). The peak leaf area index was overpredicted slightly, as for Paddock 14 (Section 4.1). Total N uptake by biomass was slightly overpredicted, but the progression during the season was simulated well. The late increase in biomass N of the triticale crop relates to an overprediction of grain N during the weeks of water stress. Biomass of lucerne was less well predicted (Fig. 13). The model overpredicted biomass production while the lucerne roots were extending and had easy access to water. This matter is being looked into, but unfortunately the data set for P12 has too little detail about lucerne stem numbers and phenology to allow detailed evaluation.

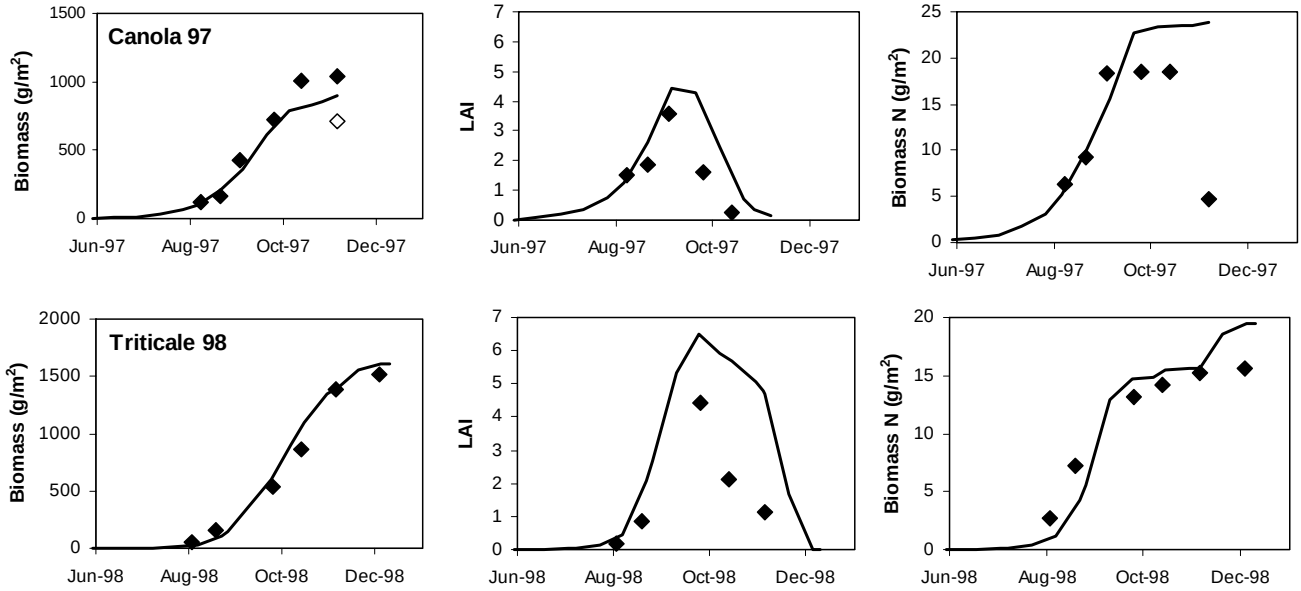

Figure 12: Observed (symbols) and predicted (lines) crop biomass, leaf area index (LAI) and N uptake by biomass for Canola in 1997 and Triticale in 1998 on CSU Paddock 12.

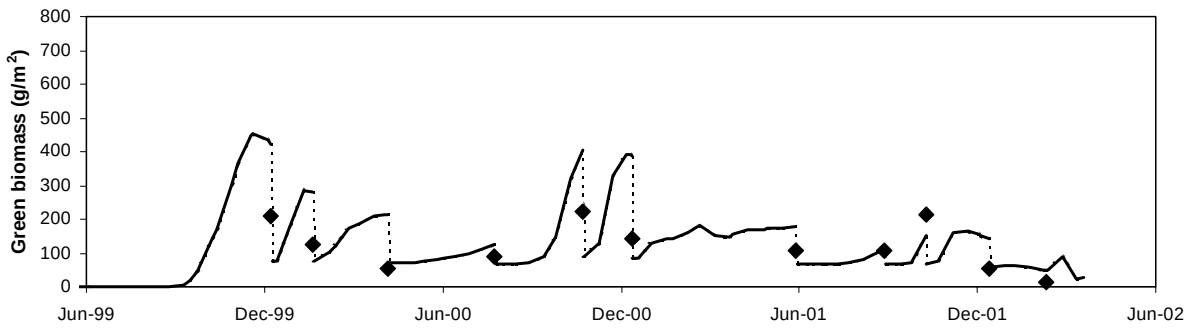

Figure 13: Observed (symbols) and predicted (lines) green lucerne biomass. Vertical drops in predicted line represent the harvests.

Summary

In conclusion, water content changes under wheat and the first 18 months of establishing lucerne were predicted well. Further work is needed to assess the root water uptake by lucerne at depth (> 3 m), as well as its phenology and biomass production in view of these deep root profiles. This data set is one of the few, if not the only one, documenting the root water uptake to depth of establishing lucerne. The ability of the lucerne module to simulate uptake to 3 m very well, is encouraging.

4.3 Rutherglen

Description of the experimental data and model parameterisation

This data set was collected to determine water losses, water storage capacities, and drying and wetting patterns under lucerne, annual crops, annual pasture, and various lucerne phase treatments (Ridley et al. 2001). One of the aims was to evaluate the effect of the duration of the lucerne phase (2, 3 or 4 years) on the number of annual crops that could subsequently be grown before drainage losses were likely to occur. All experimental treatments, except annual pasture, were simulated as part of the evaluation of APSIM (Table 5). Although the experiment started in 1993, neutron moisture meter (NMM) measurements of soil water content were not made until mid 1995. Simulations were started in 1993, because initialisation with an established lucerne crop would have introduced too many uncertainties. For the continuous cropping (CC) treatment, however, this meant that guesses had to be made about crop density, performance, and harvest time in 1993-1994, as well as surface cover during the summer fallows.

Table 5: Treatments of the Rutherglen data set simulated as part of the evaluation of APSIM

Treatment	Description
CC	Continuous cropping: wheat cv. Katunga in 1993, lupins cv. Gungurru in 1994, wheat cv. Katunga in 1995, canola cv. Oscar in 1996, wheat cv. Swift in 1997, wheat cv. Goldmark in 1998, canola cv. Pinnacle in 1999
CL	Continuous lucerne, cv. Pioneer 69
2L95	2 years lucerne, sown in 1993, cropped 1995-1997 as CC, re-sown to lucerne in autumn 1998
3L96	3 years lucerne, sown in 1993, cropped from 1996-1999 as CC
4L97	4 years lucerne, sown in 1993, cropped from 1997-1999 as CC
2L96	2 years lucerne, sown in 1994, cropped from 1996-1999 as CC
3L97	3 years lucerne, sown in 1994, cropped from 1997-1999 as CC

The soil at the site is classified as a Eutrophic Brown Chromosol (Isbell, 1996). Simulations used the water balance module SoilWat2, which was parameterised as follows: the lowest observed soil water contents under continuous lucerne were used for the lower limit; independent measurements of field capacity were used for the drained upper limit; and water contents measured a few days after a large rainfall event that flooded the site and wetted the whole profile were used for saturation. Based on observed soil water contents the maximum root depth for the annual crops was set to 1.2 m, and for lucerne to 3.6 m. The curve number for bare soil and average antecedent rainfall was estimated at 75 Littleboy (1997). Other model parameterisation was based on site specific measurements, where available (e.g. bulk density, pH). As tested phenology parameters for the wheat varieties Katunga, Swift and Goldmark, were not available, the first independent estimates were adjusted, but not optimised, to approximately match the reported anthesis dates. Management operations reflected the descriptions of the experiment by Ridley et al. (2001) and Hirth et al. (2001), supplemented with further details that were obtained through personal communication. Weeds were allowed to grow during the 1998-99 summer fallow in the CC treatment, reflecting the findings by Ridley et al. (2001) that summer grass (*Digitaria sanguinalis* (L.) Scop.) extracted water during that period.

The NMM measurements were replicated four times. These show that field variability was in some cases significant, and more marked in the phase cropping treatments (Fig. 14). The four replicates, rather than the average, were therefore included in the comparisons with model outputs in order to assess model performance against the range of field behaviour. Data for the CC and CL treatments came from two different sets of NMM access tubes; 2.7 m deep access tubes until 23 April 1997 and 5.5 m deep access tubes from 30 May 1997. These changes caused discontinuities in some replicates and at some depths, but the effects were generally small, especially given the variability across the paddock.

Drainage past 1.8 m was estimated by Ridley et al. (2001) at times when soil water potential measurements indicated that the soil profile was at or above field capacity. Changes in soil water storage were calculated from average monthly NMM measurements (for each treatment) and combined with Penman-Monteith reference crop *Et* to estimate drainage from the water balance. As runoff was not measured it was assumed to be zero. In periods where runoff coincided with drainage, the water balance calculations therefore effectively resulted in values of water excess (drainage + runoff). Any runoff events that occurred when there was no drainage would, however, been missed.

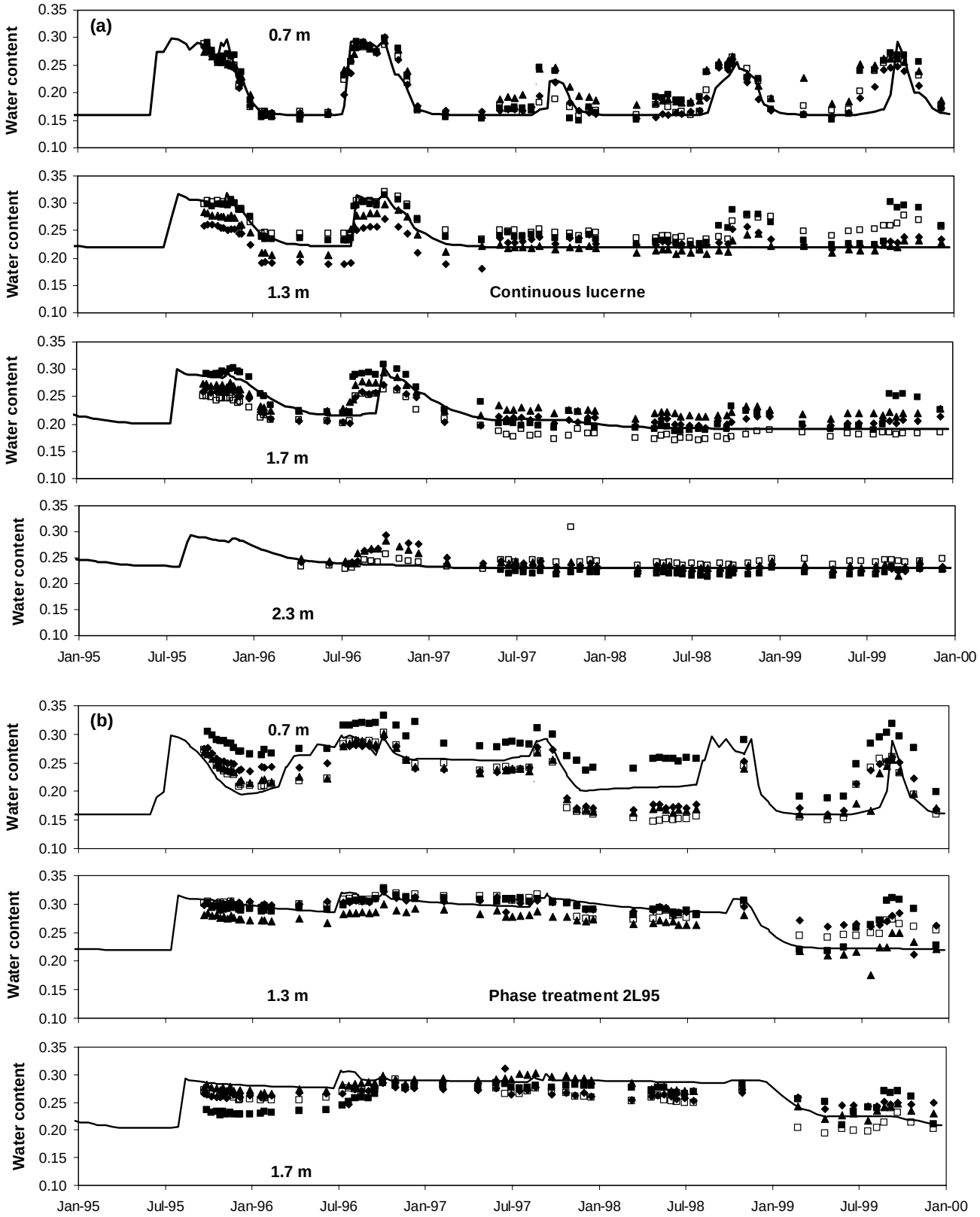

Figure 14: NMM data and model predictions for selected depths; (a) continuous lucerne, (b) phase treatment 2L95.

Model evaluation

One feature of the data set highlighted by Ridley et al. (2001) is the annual drying of the profile (0-1.8 m) to the lower limit by lucerne and the more variable water deficit created under annual crops. The model correctly captures these dynamics. Figure 15 shows that despite the model being parameterised with the same lower limits for lucerne and for annual cropping, crops only use all the available water in the root zone (0-1.2 m) towards the end of the dry 1997 growing season. During the other seasons there was enough in-season rainfall to meet crop demand and less water was extracted from the soil store.

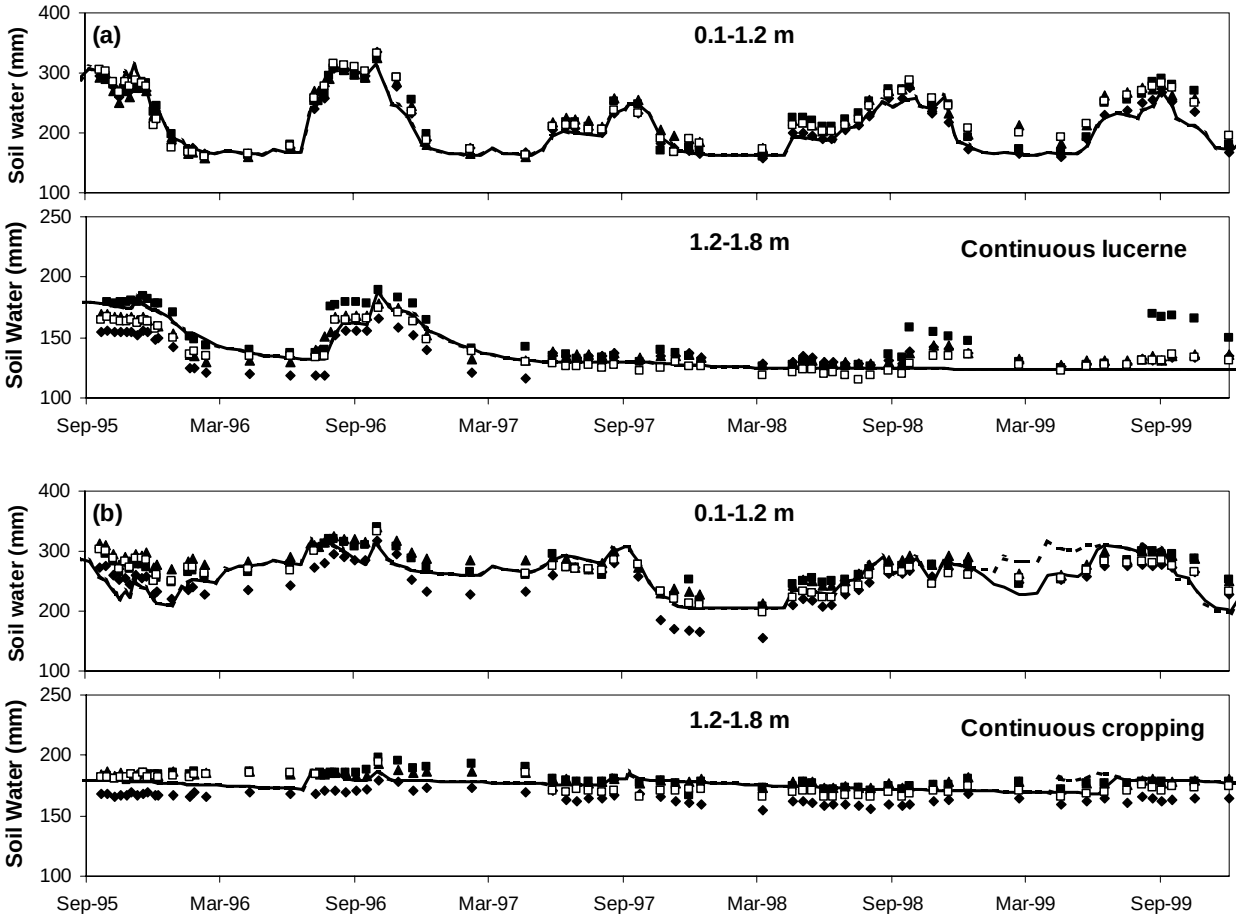

Figure 15: Observed (symbols) and predicted (continuous line) water storage changes under (a) continuous lucerne and (b) continuous cropping; simulation without summer weeds in 1998-99 as a dashed line.

Prediction of water excess (runoff + drainage past 1.8 m) also agreed fairly closely with the estimates of Ridley et al. (2001), especially for the continuous cropping and continuous lucerne treatments (Fig. 16). The amounts of runoff predicted by APSIM were small (10, 7, 3 and 3 mm under continuous cropping for 1996, 1997, 1998, and 1999, respectively). The different amounts of water excess under cropping and lucerne in 1996 were simulated well, as were the two additional events under cropping in 1997 and 1999. While the 1997 event was slightly overpredicted and the 1999 event was predicted to start earlier, the water balance calculations of Ridley et al. (2001) appear to have missed some rapid drainage events (brief periods of field capacity) that occurred in between NMM measurement dates (22 August – 24 September 1997 and in June-July 1999). In 1999 this was offset by higher predicted *Et* for the period between 25 August - 7 September 1999. Apparent discrepancies in 1997 (CL) and 1998 (CC and CL) are a consequence of runoff-only events, which were predicted by the model but not captured in the calculations of Ridley et al. (2001).

At first glance drainage in the phase treatments seems to be predicted less well than the continuous cropping and lucerne treatments (Table 6), with no difference predicted between 2L96 and 3L96 in 1996 and 1999, and overpredictions in 1997 (2L95, 2L96, 3L96) and 1999 (2L96, 3L96). A number of factors appear to be responsible for these discrepancies. In 1996 canola performed better in the phase treatments (2L95, 2L96, 3L96) than in the continuous cropping treatment, even though only the 2L95 treatment contained increased

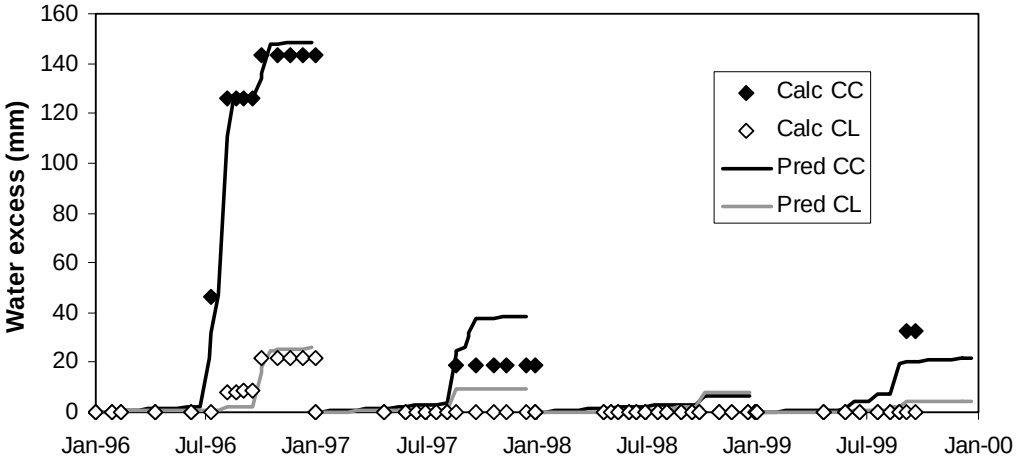

Figure 16: Water excess (runoff + drainage at 1.8m) predicted by APSIM for the continuous cropping and lucerne treatments, compared with water balance calculations by Ridley et al. 2001.

levels of soil nitrogen at sowing (Hirth et al. 2001). The better performance was reflected in increased late water use. It is unclear what caused the better performance. The only other piece of information is that the crop flowered rather late (by about 4 weeks compared with the 1999 canola crop), which may have been related to the flooding experienced at the site in early October (J.R. Hirth, pers. comm.). Without the information required to predict differences in water and nitrogen supply, the model was unable to predict either the differences in crop performance or in water use, so that predicted drainage in 1997 in the 2L95, 2L96 and 3L96 treatments was similar to that of the CC treatment.

The observed differences between 2L96 and 3L96 in 1996 and 1999 could not be explained by the model on the basis of a different length of lucerne phase. It is possible that differences in the effectiveness of lucerne removal played a role in causing the observed drainage differences in 1996, especially given that the 2L96 and 3L96 needed to be disced immediately prior to sowing to kill surviving lucerne crowns. As the subsoil (1.2-1.8 m) under 3L96 stayed drier throughout the experiment, this effect may have carried over into 1999.

A factor that does warrant further investigation is the nitrogen stress experienced by crops in the 2L96 and 3L96 phase treatments in 1998 and 1999. This appears to occur in September/October when the crops have used the mineral nitrogen that was available at sowing, and it causes some water flow beyond the crop rooting zone in November 1998 and drainage in September 1999. In the continuous cropping treatment the crops benefited at this time from the additional fertiliser applied (50 kg N/ha in 1998 and 10+50 kg N/ha in 1999), but the phase treatments relied on soil mineralisation alone. This makes these treatments more sensitive to correct parameterisation of the SoilN2 module. It is possible that the increases of the *rdhum* and *rdbiom* parameters (see Section 3) were not sufficiently large, causing an underprediction of nitrogen mineralisation. It is also possible that the crop modules overpredicted the effect of nitrogen stress on the crop. Unfortunately none of the experiments contained soil nitrogen data of sufficient detail to check this out.

For the 2L95 treatment that had just gone into lucerne APSIM predicted one 37 mm drainage event that was not reported by Ridley et al. (2001). This event occurred at a critical time (early October 1998), just before lucerne growth was predicted to speed up. Unfortunately, this coincided with a time that NMM measurements for this treatment were not made (between 21 August and 30 October 1998), and therefore estimates of drainage were not available. Whether the speed of lucerne development predicted by the model was too slow could therefore not be tested. This drainage prediction is consistent, however, with the observation by Hirth et al. (2001) that biomass water use efficiency of lucerne was less than annual crops over the winter period, so that drainage under establishing lucerne would have been possible, even though there was no drainage in the cropped treatments sown at the same time.

Finally, it should be noted that the water balance calculations of Ridley et al. (2001) used average values for soil water storage based on the four replicate NMM measurements, masking variability between treatments. The storage changes in the individual replicates differed by up to 15 mm for the six drainage events in the continuous cropping treatment. The average deviation from the average storage change was 3.2 mm. An indication of the field variability can also be obtained from comparing the CL and 4L97 treatments in 1996 (Table 6), at which point these treatments were still replicates.

Table 6: Water excess (runoff + drainage at 1.8m) predicted by APSIM, compared with water balance calculations by Ridley et al. 2001. Runoff only events are excluded from the comparison

	Water balance calculations using NMM					APSIM prediction				
	1996	1997	1998	1999	Total	1996	1997	1998	1999	Total
CC	143	19	0	32	194	146	38[d]	4	18	206
CL	22	0	0	0	22	25	1	1	0	27
2L95	125	8	-[a]	0	133[b]	138	34[de]	30	0	172[b]
2L96	33[f]	0	0	26[f]	59	8[f]	37[de]	4	35[df]	84
3L96	6[f]	0	0	0[f]	6	2[f]	26[de]	4	35[df]	69
3L97	-[a]	0	0	0	0[c]	28	1	1	0	2[c]
4L97	27[g]	0	0	0	27	25	1	1	0	27

[a] Estimate unavailable due to incomplete NMM measurement record
[b] 2L95 total excludes 1998
[c] 3L97 total excludes 1996
[d] Includes rapid drainage events in between NMM measurements
[e] Consequence of not predicting late water uptake in 1996; see text.
[f] Treatment differences (2L96 vs 3L96) not explained by the difference in length of lucerne phase; see text.
[g] Replicate of CL treatment in 1996

While drainage past 1.8 m in the CL treatment was predicted satisfactorily, the modelled soil wetting resulting from early winter storms did not always reach the depths suggested by the experimental data. For example, in Fig. 14a the 1998 and 1999 water content maxima at the 1.3 m depth were under-predicted. This appears due to overprediction of evaporation from the soil surface, attributed to overprediction of the rate of surface residue decomposition. Predicted C:N ratios of the lucerne residue seem on the low side, which would enhance its decomposition. There is unfortunately no data available to confirm this hypothesis. It is a problem that would mainly show up in the (early) winter months when evaporation is driven by atmospheric demand and crop cover is minimal or non-existent. Residue cover is an important factor controlling soil evaporation at that time (as demonstrated in Fig. 4). This issue requires further investigation.

The fast drying of the profile to 1.8 m by the end of the first year of lucerne was correctly reflected in the model using the standard rate of 10 mm/day for the advance of the maximum rooting depth (see Section 4.2). Unfortunately, the experimental data did not provide any information about root water uptake advance below 1.8m. By the time deep NMM tubes (to 5.5 m) were installed in the CL treatment, the profile drying by lucerne had already reached its maximum depth (3.6 m). In the SoilWat2 module used for the Rutherglen simulations, water uptake is limited by an empirically derived parameter *kl*, incorporating both plant and soil factors. It represents the fraction of available soil water that can potentially be taken up from a soil layer in one day. Without any information available for independent parameterisation, we set up a profile that gradually reduced the uptake fraction from 0.08 in the surface 0.6 m, down to 0.01 for 1.4 m and below. This was found to work well for the CL treatment, which was simulated first and the parameterisation was not changed for the other treatments.

While the focus of the model evaluation was on the water balance, simulation of soil nitrogen and crop performance were tested as well. The annual measurements of soil nitrogen in autumn were not frequent enough to examine any patterns, but predicted values generally agreed closely with measurements (e.g. Fig. 17). The model only did not always predict the (net) mineralisation of soil nitrogen in the surface 0-0.2 m following the removal of lucerne very well. In 1999 this was also true for the continuous cropping treatment if weeds were simulated during the summer fallow. It is possible that too much nitrogen was taken up by the weeds. Predicted biomass in the continuous cropping treatment was satisfactory (Fig. 18a, observed values at anthesis), which is encouraging as it reflects crop water use. Only the 1999 canola crop was underpredicted by more than 10%, apparently due to underprediction of nitrogen availability (as discussed above). Yield (Fig. 18b) and N uptake (data not shown) were reasonably well predicted most of the time, but slightly over predicted in 1996, slightly underpredicted in 1997 and overpredicted in 1998. The latter presumably reflects the fact that the model does not currently include the ability to simulate the effect of the severe frost observed in late October 1998 (Hirth et al. 2001). In the phase treatments results were similar with underprediction of canola biomass (1996, 1999) and overprediction of 1998 wheat yield.

Lucerne biomass was predicted less satisfactorily with overpredictions similar to CSU Paddock 12 (data not shown). As explained in the previous section this area needs more work, both in view of simulating phenology during summer and in dealing with a deep rooting profile.

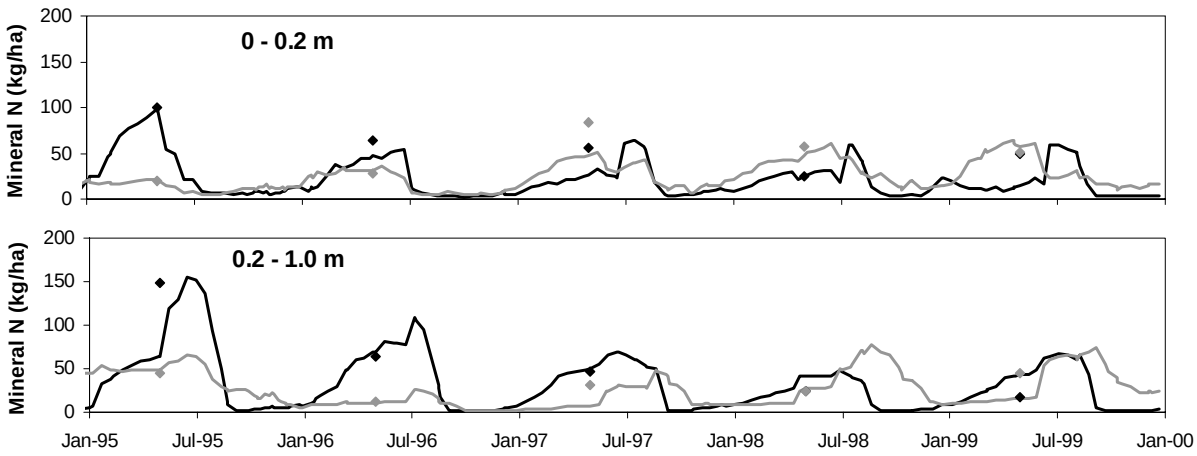

Figure 17: Observed average (symbols) and predicted (lines) mineral N in surface (0-0.2 m) and subsurface (0.2-1.0 m) under continuous cropping (black) and continuous lucerne (grey).

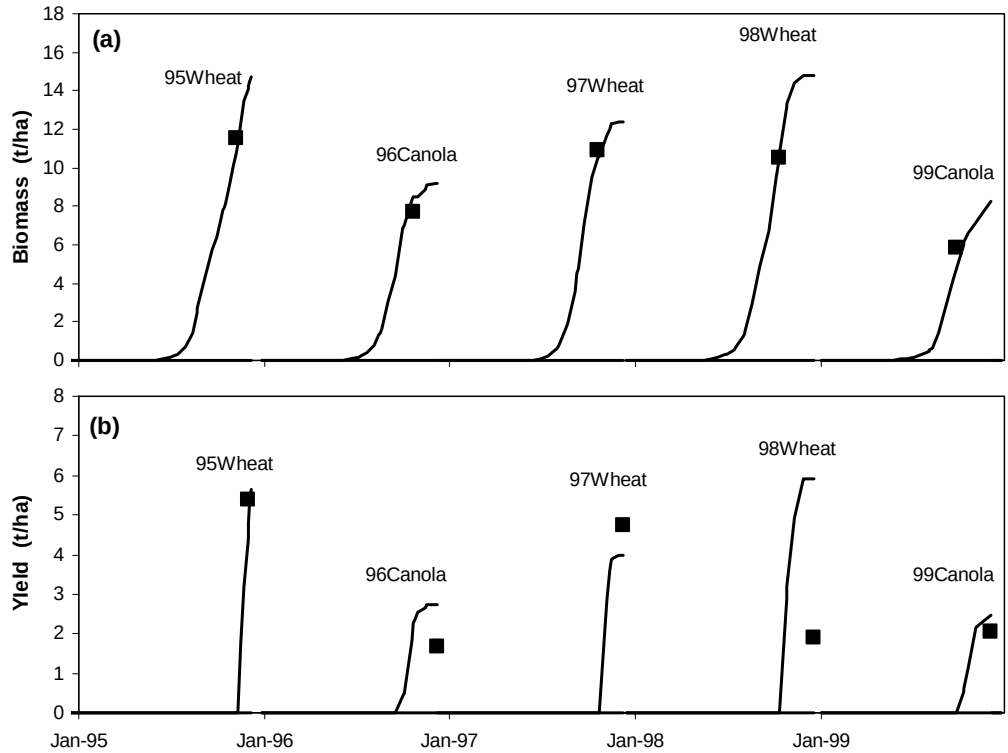

Figure 18: Observed average (symbols) and predicted (lines) crop biomass and crop yield; biomass measurements were made at mid-anthesis (wheat) or 50% flowering (canola).

Summary

The model simulated the water balance measurements from the field experiments quite well. There was close agreement between the measured and predicted soil water contents, and key features of the water content changes were accurately simulated. The estimated and simulated drainage (or excess water) values also agreed quite well. Simulation of this data set did identify several issues that require further investigation, including lucerne biomass prediction, decomposition of lucerne residues, nitrogen supply from soil nitrogen mineralisation, and the effect of N stress on crops.

4.4 Temora

Description of experimental data and model parameterisation

The Fergusons Lane data set was collected to evaluate the effect of lucerne on soil water dynamics and in particular on its ability to reduce the risk of water logging through creation of a dry soil buffer. For this purpose lucerne established in 1996 was removed in three sequential years (1998-2000) and replaced by canola or wheat. These six treatments (Table 7), along with a continuous lucerne "control" treatment were simulated as part of the APSIM evaluation.

Table 7: Temora rotations simulated as part of APSIM evaluation (L = lucerne, C = canola, W = wheat).

Rotation	1996	1997	1998	1999	2000
LLLLL	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne
LLCWC	Lucerne	Lucerne	Canola	Wheat	Canola
LLWCW	Lucerne	Lucerne	Wheat	Canola	Wheat
LLLCW	Lucerne	Lucerne	Lucerne	Canola	Wheat
LLLWC	Lucerne	Lucerne	Lucerne	Wheat	Canola
LLLLC	Lucerne	Lucerne	Lucerne	Lucerne	Canola
LLLLW	Lucerne	Lucerne	Lucerne	Lucerne	Wheat

The soil at the site is classified as a Subnatric Red Sodosol (Isbell, 1996). Continuous simulations started with the sowing of lucerne in 1996, even though comparison with measurements was not possible until 1998 when data collection started. Parameterisation of the model was based on local measurements (pH, bulk density, organic C, C:N ration, etc.) and used observed water contents and measured water retention curves to derive upper and lower limits for the water balance module SoilWat2. The maximum effective rooting depth of the crop (1.2 m) was deduced from the NMM data. The rooting depth of lucerne could not be assessed using the NMM data because it was deeper than the maximum measurement depth (1.8 m). It was assumed to be 2 m but in view of the findings at CSU Paddock 12 and Rutherglen, that could be an underestimate. Locally measured rainfall data differed a little from that of the nearest Bureau of Meteorology station (073038 Temora Agricultural Research Station, latitude: 34°25'S, 147°32'E; ~ 12 km from the field site) (Fig. 19). As parts of the local record were missing and needed to be infilled from station 073038, this introduced uncertainty in the model input. Simulations were therefore run with both records to indicate the resulting uncertainty.

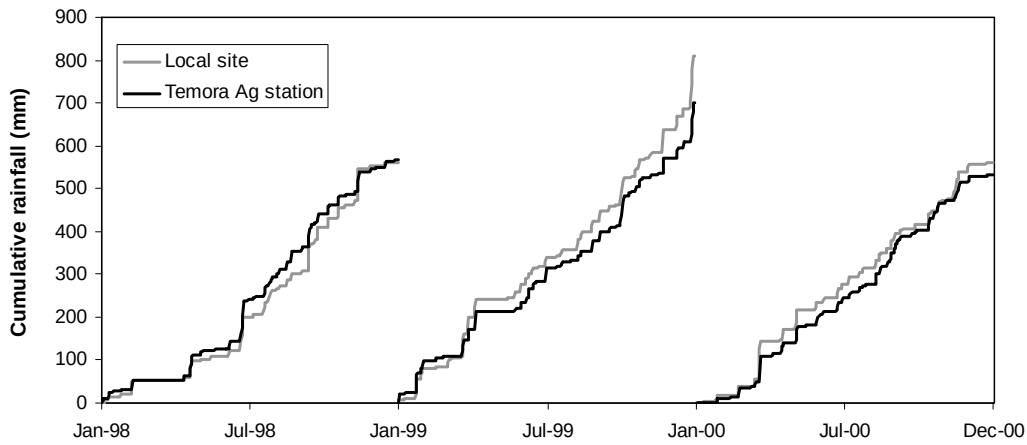

Figure 19: Cumulative annual rainfall from local site (infilled when necessary) and Temora Agricultural Research Station.

Soil water contents in the treatments were measured by the neutron moisture meter method (four replicates, monthly readings). Variability between replicates of the absolute water content was large. There were also a number of switches between the plots that were used to characterise certain treatments, as well as replacement of NMM access tubes, so that for a number of treatment replicates there was no continuous record identifiable with a specific access tube. These two features of the experimental work mean that it is not possible to identify changes in soil water storage with confidence for some treatments. This presented difficulties when comparing the data with model predictions.

As a result of site variability and discontinuities in the NMM records discussed above, changes in soil water storage during the phase transitions were not well characterised by the experimental data. The experimental data suggested that by the time of the first measurements (September 1998 for LLCWC and LLWCW, prior to sowing in 1999 for LLLCW and LLLWC and prior to sowing in 2000 for LLLLC and LLLLW) the soil had already significantly wet up (Fig. 20). The magnitude of this change is uncertain due to a discontinuity in the record (different plots or NMM tubes were used for the measurements before and after the transition). The spatial variability is also obvious from the comparison of the LLLCW and LLLWC treatments in April 1999 and the LLLLW and LLLLC in May 2000 (Fig. 20), as these were times when they were still replicate treatments. Model testing of these transitions was therefore limited to a qualitative assessment.

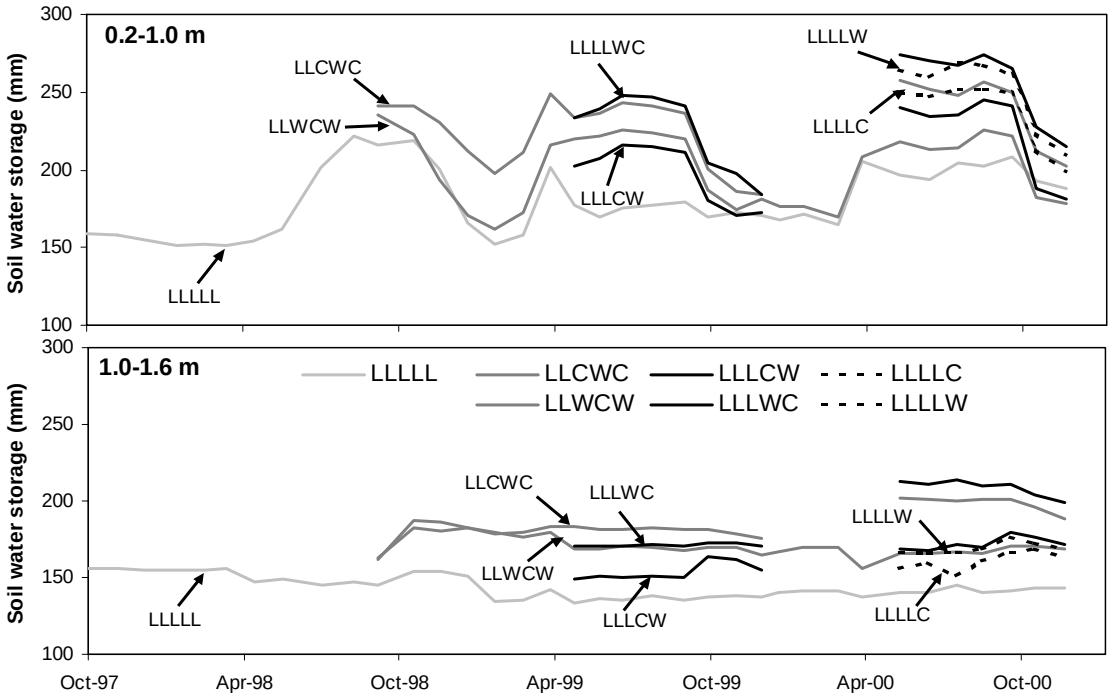

Figure 20: Observed average soil water storage patterns (0.2–1.0 and 1.0–1.8 m) under the different treatments.

Model evaluation

Considering the uncertainties in the data sets, the model did a satisfactory job simulating the soil water dynamics, as shown, for example, in Fig. 21 and 22 for the LLLLL and LLCWC treatments. Use of the Temora Ag station rainfall record resulted in a larger predicted increase in water storage in the subsoil (1.0 to 1.6 m) in October 1998, as a result of higher rainfall in July. Using the local rainfall record, the model predicted a more gradual increase in subsoil water storage, which was not really supported by the NMM data (subject to discontinuities in the records), particularly for the LLCWC treatment.

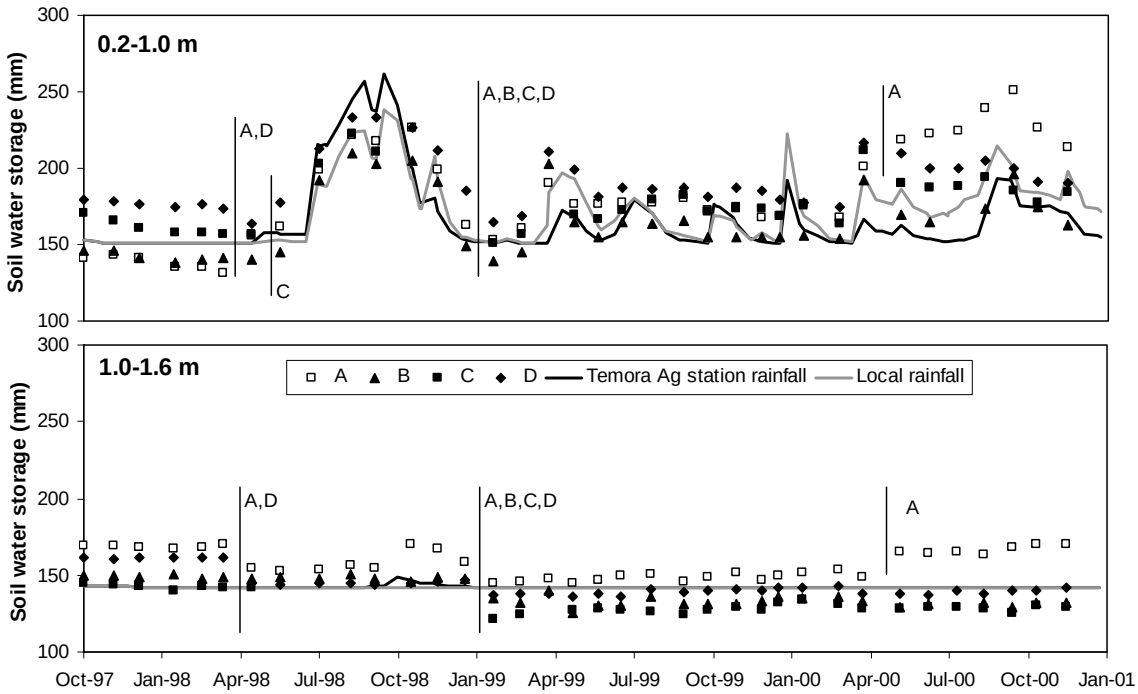

Figure 21: Observed (replicates A - D) and predicted soil water storage under the LLLLL treatment; black line = Temora Ag station rainfall, grey line = local rainfall; vertical lines indicate changes in access tubes and plots.

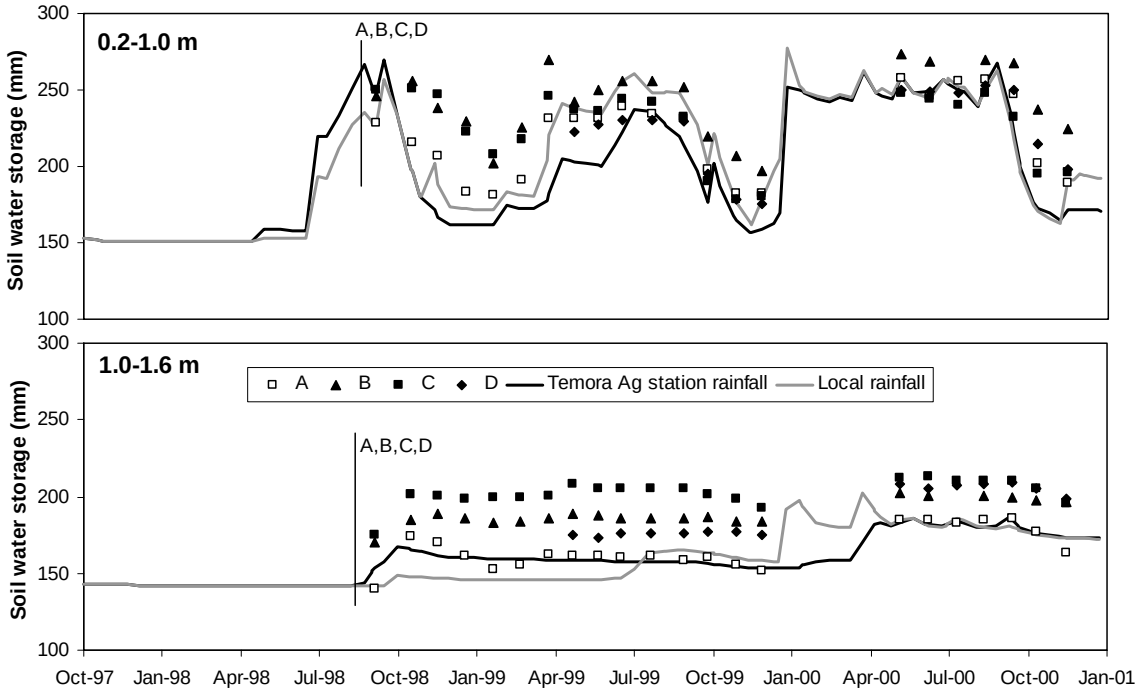

Figure 22: Observed (replicates A - D) and predicted soil water storage under the LLCWC treatment; black line = Temora Ag station rainfall, grey line = local rainfall; vertical lines indicate changes in plots.

During the summer fallow of 1999-2000, the NMM data for most of the treatments indicated significant wetting of the profile. This occurred to a lesser extent in the LLLCW treatment and barely at all in the LLWCW treatment. Initially the experimental team suspected that these treatments were related to a less dense stubble cover and increased evaporation from the soil surface. Simulations of these treatments with and without stubble suggested that stubble cover could not explain the difference in observed soil water storage. The simulations were then used to check whether weeds or resprouting of canola, both triggered by

above average December rainfall, could explain the water use of these treatments during summer. Introduction of weeds, resulted in a reduction of soil water contents, but the effect was later than observed. As shown in Fig. 23, predictions were significantly improved after allowing for canola resprouting. Field notes from a technical officer later confirmed that LLWCW and LLLCW plots had indeed experienced canola resprouting, although to varying extents. This illustrates how modelling can help interpret experimental data.

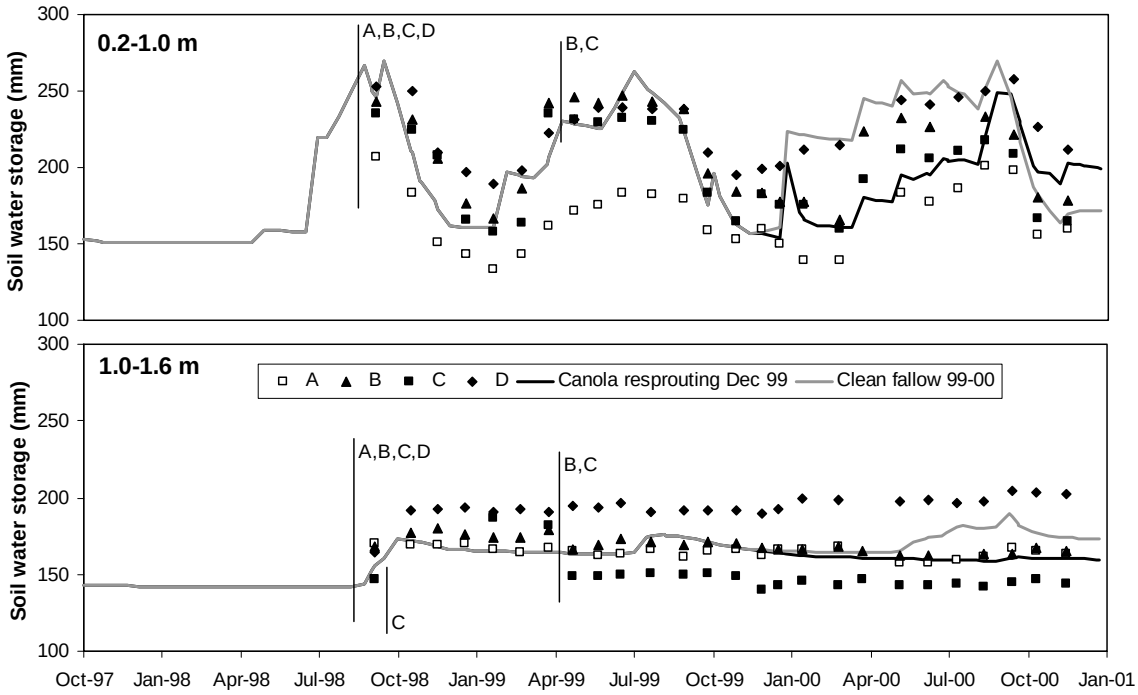

Figure 23: Observed (symbols) and predicted soil water storage under the LLWCW treatment; grey line = clean fallow, black line = canola resprouting in Dec 1999; vertical lines indicate changes in access tubes and plots (Temora Ag Station met file

Soil nitrogen in the surface (0-0.1 m) was simulated reasonably well, but in the subsoil (0.1-1.0 m) the flush of N following removal of lucerne was overpredicted and occurred too early (Fig. 24). While uncertainty about grazing of the cut lucerne plays a role in this, we suspect it is related to underprediction of C:N ratios of lucerne surface and/or root residue. This speeds up residue breakdown, so that N is available sooner. The overprediction appears to be less marked when the model lets lucerne be cut upon first flowering. It is possible that the relatively shallow rooting assumed in the Temora simulations (2 m) caused an overprediction of water stress and that this may have influenced lucerne senescence and/or the nitrogen concentrations of senesced material. Unlike at CSU and Rutherglen, there was no removal of lucerne residue at harvest time, except for one or two grazing events, so that the soil nitrogen data are more sensitive to correct prediction of lucerne biomass and residue C:N ratio. Soil nitrogen predictions in 2000 for the LLWCW and LLLCW treatments were found to be quite sensitive to the simulation of canola resprouting in December 1999. There is some support for this in the field data, because both measurements of soil nitrogen (85.8 ± 45.7 kg N/ha in 0-1.0 m layer) and the density of resprouted canola were quite variable. Further research (field measurements and modelling) in the area of residue decomposition during the summer fallow period would, however, be desirable.

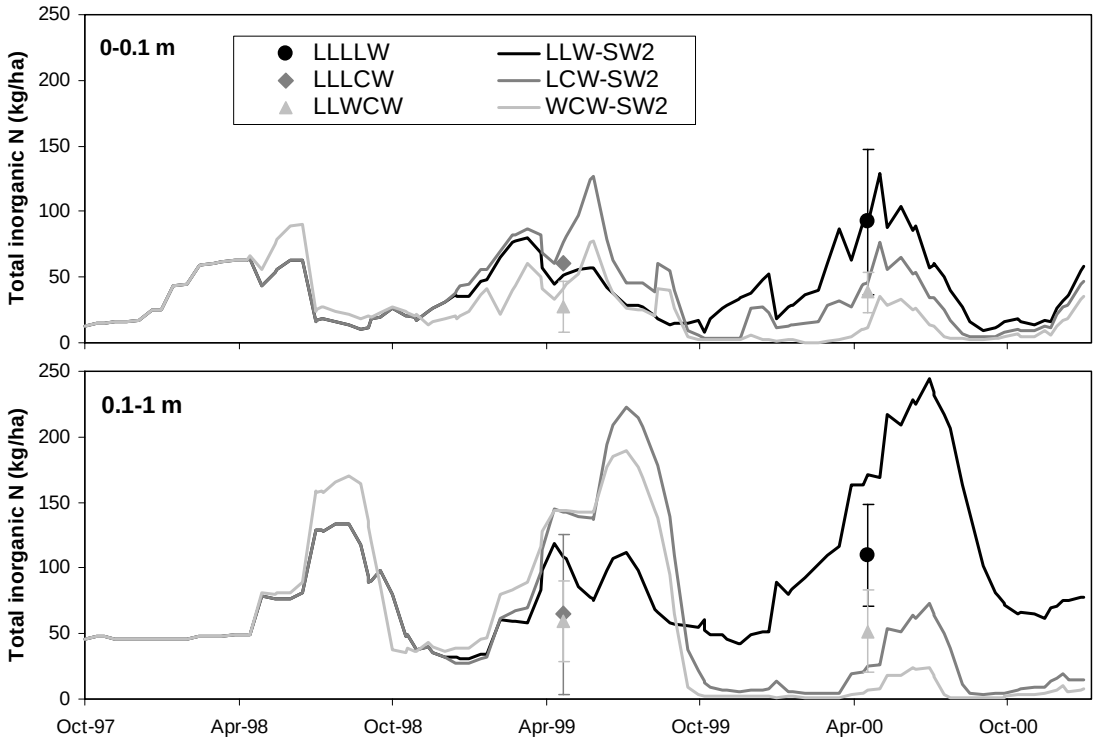

Figure 24: Observed average (symbols) and predicted total inorganic nitrogen for surface and subsurface soil of selected treatments. Standard deviations (of 3-4 replicate measurements) are shown as error bars.

Given the uncertainties in N mineralisation, the crop yields and biomass were predicted quite well. Predicted values were generally well within the measured ranges, except for 1999 when canola yields were overpredicted (Fig. 25). Lucerne biomass was predicted reasonably well, especially given that dates of some of the biomass cuts were a little uncertain (Fig. 26). However, we feel that the model is not yet predicting lucerne phenology during dry summer fallows adequately.

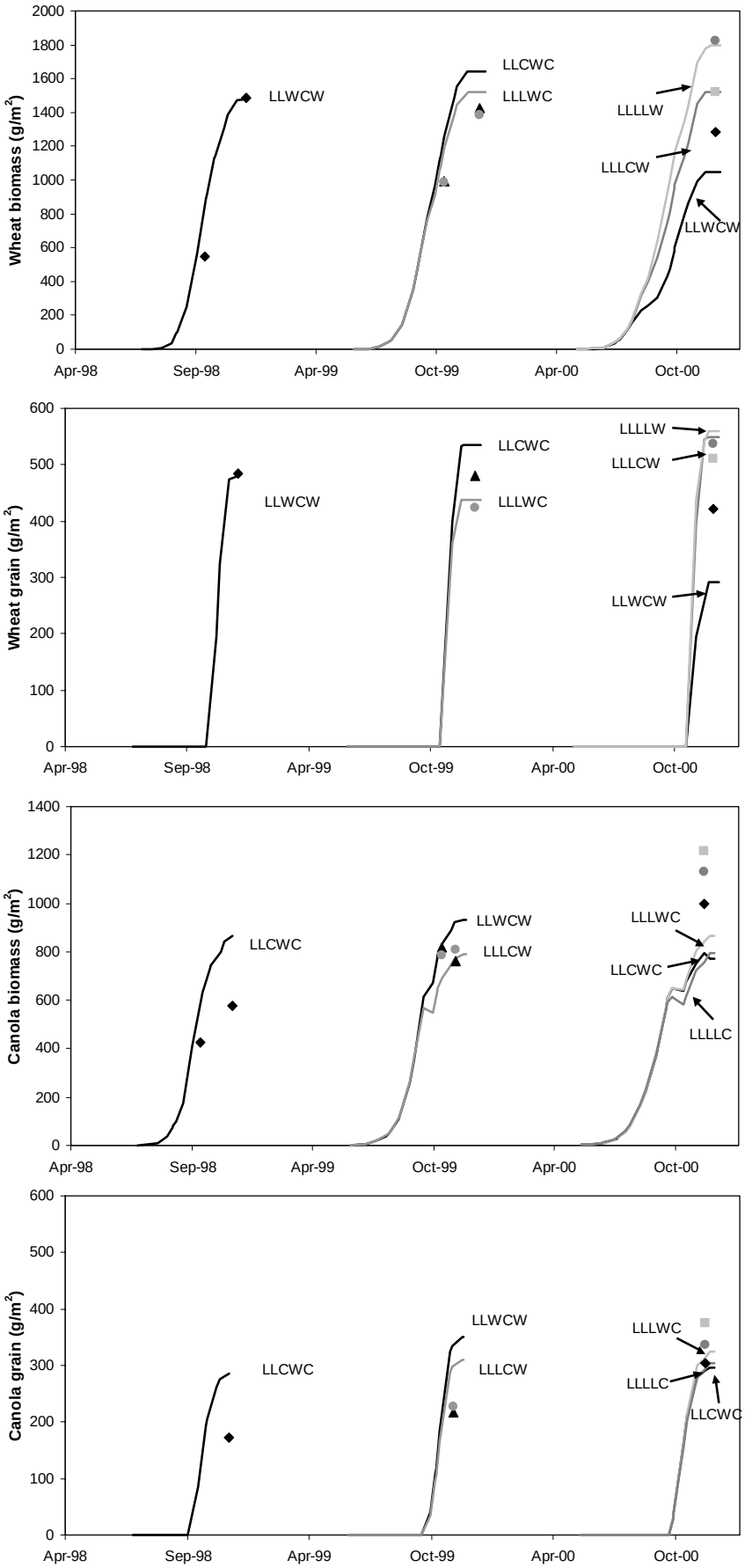

Figure 25: Observed (symbols, average of 4 replicates) vs. predicted crop biomass and yield

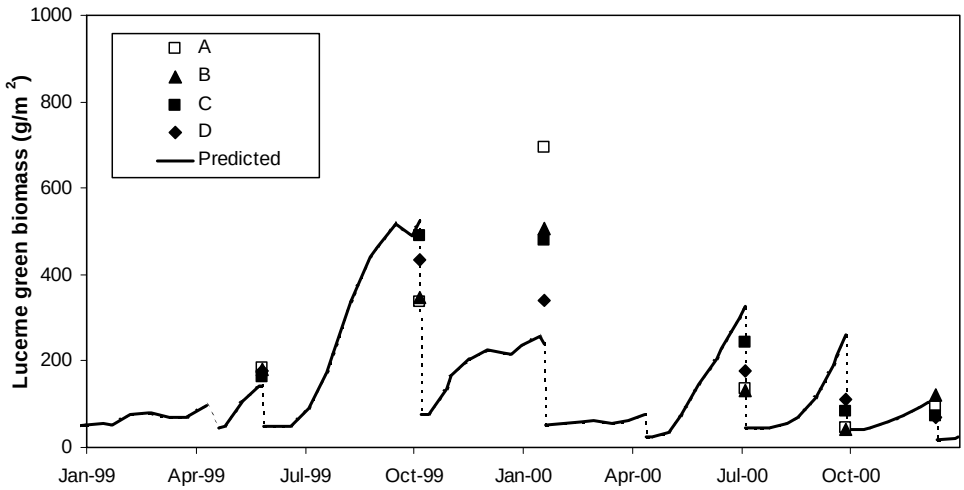

Figure 26: Observed vs. Predicted lucerne biomass

Summary

Considering the uncertainties in the data sets, the model did a satisfactory job simulating the soil water dynamics. The important effects of rainfall, weed growth and residue cover were again identified, as well as the need for having continuous water content measurements to facilitate model testing. Soil nitrogen in the surface (0-0.1 m) was also simulated reasonably well, but in the subsoil (0.1-1.0 m) the flush of N following removal of lucerne was overpredicted and occurred too early (Fig. 24). While uncertainty about grazing of the cut lucerne plays a role in this, we suspect it is related to an underprediction of C:N ratios of lucerne surface and/or root residue. The experimental dataset was, unfortunately, not detailed enough to evaluate the residue decomposition and soil nitrogen dynamics following lucerne removal, and there are still concerns about prediction of lucerne phenology and biomass during dry summer fallows. Continued investigations are needed to address these issues.

5 APSIM as an analysis tool

The sensitivity of APSIM to management actions reflects the reality of the water balance, and therefore is an advantage for its use in simulation analyses to evaluate options for cropping systems and agronomic practices. The results of such analyses will be strongly dependent on the conditions of the chosen scenario, as are the results of field experiments. Scenario analysis using models offers two advantages over field experiments: sensitivity to management can be evaluated in isolation from other effects, and by using historical weather records the results are not restricted to the weather conditions experienced during the few years of a field experiment.

As an illustration of the uses of model scenario analyses, we present one example from each of the evaluation sites. These demonstrate the various applications of models, namely (1) extending experimental results by sampling a longer weather data set, (2) exploring consequences of management changes, (3) assessing sensitivity of field results to management, and (4) providing a guide for measurement and interpretation.

5.1 Example 1: Testing the conclusions of a field experiment (Rutherglen)

On the basis of the soil water deficits measured to 1.8 m under the different treatments, Ridley et al. (2001) concluded that two years of lucerne were insufficient to guarantee more than 1 cropping year with minimal drainage and that having at least 3 years of lucerne would give a better chance for growing 3 or 4 annual crops before the profile had refilled. As acknowledged by Ridley et al. (2001), these conclusions could be influenced by the fact that both 2-year lucerne treatments (2L95, 2L96) started with a wet cropping season while the 3- and 4-year lucerne treatments (3L97, 4L97) had three average to dry cropping years. Simulation analysis can be used to extend the experimental results by sampling a larger weather record. In this case such an analysis allows an evaluation of the influence that the particular sequence of wetter and drier years during the field experiment had on the conclusion above. The conclusion of Ridley et al. (2001) was also based on soil water deficits measured to only 1.8 m, and modelling allows us to evaluate the benefits of the additional soil water deficit created by lucerne between 1.8 and 3.6 m.

Four simulation scenarios were considered, each running for 8 years:

- CC: Continuous wheat (8 years)
- 1L: 3 years of wheat followed by 1 year of lucerne and 4 years of wheat
- 2L: 2 years of wheat followed by 2 years of lucerne and 4 years of wheat
- 3L: 1 year of wheat followed by 3 years of lucerne and 4 years of wheat

These scenarios were repeated 38 times by starting them every year from 1957 to 1994. Historical weather data were sourced from the SILO Patched Point Dataset (Jeffrey et al., 2001). Management conditions were based on those of the field experiment; lucerne was managed for a hay forage crop in winter and grazed in summer. As in the experiment, lucerne was removed shortly before cropping, in this case on a fixed date (1 April), being 4 – 10 weeks prior to the sowing date of wheat determined by the model according to rainfall conditions (within a 25 April to 15 June sowing window). Nitrogen fertiliser was only applied to the continuous wheat treatment and to the wheat crops prior to lucerne sowing. Rather than looking at the total soil water deficit from 0 to 1.8 m, we focussed on the 1.2 – 1.8 m layer, which was below the root zone of the annual crops and dewatered only by lucerne. In addition we looked at the 1.8 – 5m layer (lucerne rooting to 3.6m), recording for both layers the time it took to refill to field capacity (drained upper limit). Simulations were run both with and without weeds in the summer fallow periods, which were germinated according to the scheme of Fischer et al. (1990) (see section 4.1).

For the scenario with summer weeds, three years (3L) instead of two years (2L) of lucerne increased the longevity of the soil water deficit in the 1.2-1.8 m layer in only 4 out of 38 runs. For 2 of these, the refilling of the soil was delayed by only 1 month, so that a third year of lucerne allowed an extra season of cropping in only two runs. Without summer weeds the longevity of the soil water deficit was increased (3L vs. 2L) in only 2 out of 38 runs; neither of which allowed an extra crop. The average longevity (3L with summer weeds) was 16 months, but with a large range from 3 to 40 months. The limited benefits of adding an extra year of lucerne on the longevity of the soil water deficit to 1.8 m is related to the fact that usually lucerne had largely dried out the profile to 1.8 m by the end of the first summer, as was observed in 1999 for treatment 2L95 of the field experiment (Fig. 14). The simulation results therefore suggest that the findings of the field experiment were influenced by the particular sequence of wetter and drier years.

A greater advantage of a third year of lucerne would be expected through increasing the soil water deficit at depth (> 1.8 m). For the scenarios simulated here a third year of lucerne allowed an extra year of cropping in 10 out of 38 runs (26%) if summer weeds were included in the cropping phase and an extra year of cropping in 9 out of 38 runs (24%) for the scenario without summer weeds. Weeds increased the longevity of the soil water deficit by an average of 3 months. Following a three-year lucerne phase with weeds growing during summers of the cropping phase there were 14 out of 38 runs in which the soil water deficit lasted more than 3 cropping seasons, and 6 runs in which it lasted more than 4 cropping seasons. Without weeds, the values changed to 10 and 1, respectively.

These results are subject to a number of assumptions, including the exact scenario conditions simulated (such as the late removal of lucerne), the maximum lucerne rooting depth, the rate of root advance past 1.8 m by lucerne (which could not be verified at this site), and the properties that determine the storage capacity of the deeper layers. For example, if lucerne was removed on 1 December instead of 1 April (scenario with summer weeds in the cropping phase), partial refilling could already occur during the summer fallow after lucerne removal, causing the longevity of the soil water deficit to be less than for April removal. This change in the management scenario increased the advantage of a third year of lucerne. When evaluated to 1.8 m depth, the extra year of lucerne removed in December resulted in an extra season of cropping in 3 runs (compared with 2 for April removal) and when evaluated to 5 m depth it allowed an extra year of cropping in 19 out of 38 runs (compared with 10 for April removal). This suggests that recommendations for the length of the lucerne period, should be linked with the timing of lucerne removal.

Long-term average drainage

The small differences in refilling of the 1.2-1.8 m layer between scenarios with two or three years of lucerne and the larger differences between refilling of the 1.8-5 m layer are reflected in the values of predicted long-term average drainage past 1.8 m and 5 m (Table 8). Long-term average drainage in the four cropping years after two or three years of lucerne differed by at most 1 mm at 1.8 m depth, but by up to 9 mm/year at 5 m depth. By the fourth year after lucerne, long-term average drainage at 1.8 m was almost the same as for continuous cropping, but there was still a benefit from lucerne of reduced average drainage past 5 m. It is also clear from these predicted drainage values that water deficits created after only 1 year of lucerne were less effective in delaying drainage than the 2L and 3L scenarios, especially at 5 m depth, due to the roots not accessing water below 1.8 m.

Table 8: Predicted long-term average drainage at 1.8 m and 5 m for the first four cropping years after a lucerne phase of 1, 2, or 3 years of lucerne (1L, 2L, 3L), and for continuous wheat cropping (CC, 5th - 8th year of 8-year run). Weeds were allowed to germinate during summer fallows if there was sufficient rainfall between crop harvest and 31 March. Lucerne was removed on 1 April.

	1.8 m				5 m			
Scenario	1st year	2nd year	3rd year	4th year	1st year	2nd year	3rd year	4th year
1L	23[a]	80[b]	98[c]	102[d]	22[a]	74[b]	94[c]	101[d]
2L	19[a]	75[b]	96[c]	101[d]	3[a]	38[b]	71[c]	93[d]
3L	18[a]	74[b]	95[c]	101[d]	2[a]	29[b]	62[c]	87[d]
	5th year	6th year	7th year	8th year	5th year	6th year	7th year	8th year
CC	103[a]	104[b]	106[c]	104[d]	103[a]	104[b]	106[c]	104[d]

[a] 1961-1998, [b] 1962-1999, [c] 1963-2000, [d] 1964-2001

At first sight the predicted long-term average drainage for the continuous cropping scenario with summer weeds (e.g. 104 mm/year, 1964-2001; Table 8) may seem high compared with the average of 49 mm/year obtained by Ridley et al. (2001) for the last four years of the experiment (CC treatment). Weather conditions in the 4-year period of the field experiment that were significantly different from the long-term average conditions appear to be the main reason for the 61 mm difference in predicted drainage. The average annual rainfall was 609 mm/year between 1964 and 2001, but was only 548 mm/year in the period when field measurements were made from 1996 to 1999. It is not unexpected that the difference in rainfall would appear as drainage, because the crops are generally not severely water stressed at annual rainfalls of 548 mm and above. Model predictions for the specific years of the field experiment are consistent with the values derived from field measurements (Table 9). For the long-term continuous cropping (CC) scenario (wheat 1992-1999) average annual drainage at 1.8 m predicted by the model in the period 1996-1999 was 38 mm, 22% lower than the value derived from field measurements. Predictions for the individual years are slightly different

from those calculated for the experiment, due to the different management conditions of the simulation scenario. When wheat was replaced by canola in the simulation scenario in 1996 and 1999, and weeds controlled in the summer fallows of 1995/96, 1996/97, and 1997/98, as in the experiment, then the drainage numbers were very close to the field measurements (Table 9).

Table 9: Predictions of drainage at 1.8 m under continuous cropping at Rutherglen (1996-1999).

	1996	1997	1998	1999	Average
Ridley et al. (2001) based on field measurements	143 mm	19	0	32	49
Experimental simulation (see Section 4.3)	139	32	4	18	48
CC scenario (wheat 1992-1999)	123	4	3	20	38
CC scenario with canola 1996 & 1999, minus weeds in 1995/96, 1996/97, 1997/98	147	23	4	23	49

The model predicts larger drainage during other, wetter periods of the historical record than during 1996 to 1999. The 3-year running average of the deviation from the long-term (1964-2001) mean annual rainfall and drainage (Fig. 27) highlights the very wet years in the mid 1970s, and the wet period in the late 1980s and early 1990s. These periods match trends in water table changes recently reported by GRDC funded project GS01 (Richard Cresswell, pers. comm. February 2003). That project found that water table rises in the cropping area of the SW slopes of NSW coincided with significantly wet climatic periods, such as the 1950s, mid-1970s and late 1980s (Cresswell, 2003). Figure 27 also illustrates that measurement and simulation of different short periods (< 5 years) may result in very different estimates of drainage.

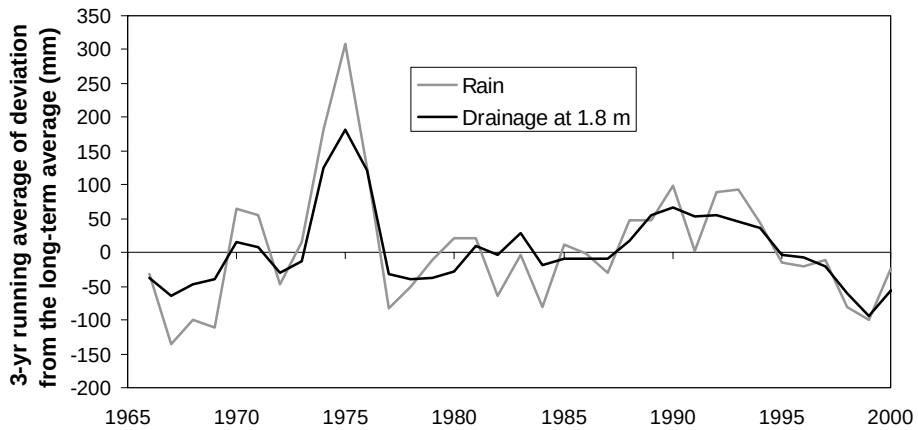

Figure 27: Simulated deviation in rainfall and drainage (at 1.8 m) from the average under continuous wheat from 1964 to 2001 (3-year running average is the average of values for the 3 preceding years to account for the cumulative effect of rainfall history on drainage).

There remains some uncertainty about the partitioning of water excess into runoff and drainage, especially in years of extreme rainfall. The model's ability to predict runoff could not be tested in any of the data sets as no runoff data were collected, and conditions were not conducive to large amounts of runoff. Average runoff predicted for 1964 – 2001 under continuous cropping was 13 mm/year, which seems reasonable for the low sloping land at the experimental site (< 0.05% slope) with an estimated bare soil curve number for average antecedent rainfall conditions of 75. When the curve number was varied between 72 and 78, which represents the uncertainty in this parameter for this site, predicted runoff varied between 10 and 17 mm/year.

It is possible, however, that runoff was underpredicted in very wet years such as 1973 and 1974 (978 and 1027 mm annual rainfall, respectively). In these years saturation excess runoff could become significant, whereas the curve number technique employed by SoilWat2 only accounts for infiltration excess runoff (predicted to be 22 and 64 mm under continuous cropping with a curve number of 75 for 1973 and 1974, respectively). In an attempt to estimate the importance of saturation excess runoff, we re-parameterised the model to simulate a perched water table on top of the B horizon. This feature was implemented in the SoilWat2 module in APSIMv2.1 and is described in Asseng et al. (1997). It introduces a parameter *mwcon*, which restricts cascading flow through a layer (the 0.2 – 0.3 m layer in the current example). Maximum water flow through this layer is then a function of drainable porosity and a drainage coefficient for the soil

matrix, resulting in a value of 4.2 mm/day for the simulations reported here. As no hydraulic conductivity measurements were made at the site, it is unknown how well this value compares with reality.

In the simulation of the experimental period, the effect of these changes on drainage and runoff was minimal in the experimental simulation (1996-1999, Table 10). The only change to runoff was predicted in late September/early October 1996, matching field observations of temporary flooding during this period (Ridley et al. 2001). As the calculations of drainage by Ridley et al. (2001) assumed no runoff and obtained drainage by closing the water balance, it cannot be established whether the simulations with a perched water table reflect the partitioning of water excess better. Certainly the comparisons of predicted and observed water contents could not differentiate between the two parameterisations, except that the observed rapid wetting up of the whole profile (to 2 m depth) on 3 October 1996 could not be simulated if the model was parameterised with a perched water table.

Table 10: Predicted runoff and drainage (at 1.8 m) for the CC experimental treatment at Rutherglen with and without simulation of a perched water table.

Parameterisation	1996		1997		1998		1999	
	Runoff	Drainage	Runoff	Drainage	Runoff	Drainage	Runoff	Drainage
no perched water table	10 mm	139 mm	7	32	3	4	3	18
perched water table	16	123	7	38	3	4	3	10

Inclusion of a perched water table in the long-term simulations increased average annual runoff from 13 to 18 mm/year and reduced the average drainage from 104 to 98 mm/year for the continuous cropping scenario with summer weeds in the cropping phase (1964-2001). In 1973 and 1974 the runoff was now predicted to be 29 and 133 mm, respectively, a doubling in the wettest year (1974). As shown in Fig. 28, there were large increases in runoff only in the wetter 10% of years and overall the effect on drainage was small compared with the effect of the presence of summer weeds. In terms of the original question as to whether a third year of lucerne would give a better chance for growing 3 or 4 annual crops before the profile had refilled, the results did not change appreciably. A third year of lucerne allowed an extra crop in 2 out of 38 runs (same as for the scenario without perched water table) when evaluated to 1.8 m depth, and in 9 out of 38 runs (compared with 10 out of 38) when evaluated to 5 m depth.

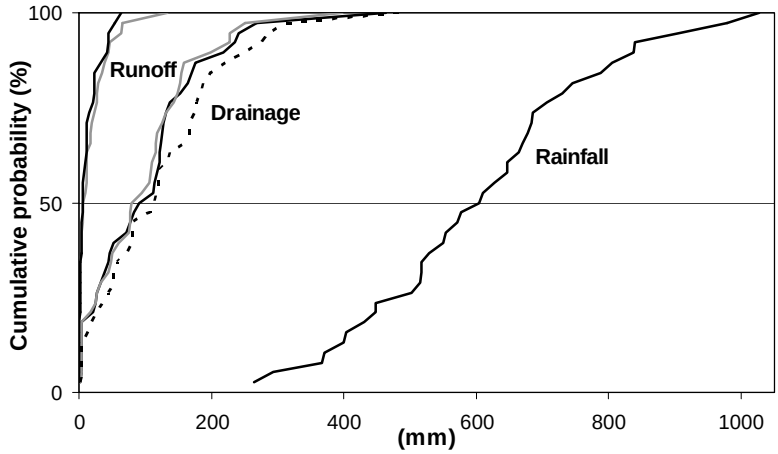

Figure 28: Cumulative probability distributions of rainfall, predicted runoff, and predicted drainage at 1.8 m depth under continuous cropping (1964-2001) for simulations with weeds (continuous lines) and without weeds (dashed line), and with (grey) and without (black) a simulated perched water table.

Finally, although it seems high, the average value of 98 - 104 mm/year drainage for an average rainfall of 609 mm/year is consistent with the range of recharge measurements reported by Petheram et al (2002) for annual crops. However, care should be taken in assuming that this value represents a large area of the Riverine plains because it is subject to the specific assumptions adopted in the simulation scenario, including soil type, crop sequence and management, as well as rainfall and slope. When evaluating deep drainage over large areas, the spatial distribution of rainfall, soils, slope, and land use across that area need to be taken into account. Further discussion on the interpretation and application of long-term simulation analyses can be found in Section 6 of this report.

Conclusion

Even though the long-term average drainage varies slightly as a result of parameterisation and management assumptions in the scenarios simulated here, the APSIM model allowed a useful assessment of the experimental findings in the light of longer term climatic variability and alternative timing of lucerne removal. While there is still some uncertainty about the exact magnitude of runoff, and therefore drainage, in years of extreme rainfall, the values of predicted long-term average drainage appear to be reasonable. The difference between long-term average drainage and the experimental estimate of drainage for the 1996 to 1999 period is a result of different average rainfall for these two periods.

5.2 Example 2: Exploring the possibility of improving the timing of phase farming (CSU)

Data from CSU and Rutherglen show that the rate at which the soil profile refills after a lucerne phase is highly dependent on weather conditions as well as crop and fallow management. For optimal management of phase farming, decisions about the timing of phase changes should take this into account. Here we use APSIM to explore the possibility of using simulations to identify field measurable parameters that could be used to help with tactical decision making.

Long-term scenarios were set up to reflect a wheat-lucerne phase farming system, with either fixed 3-year phases (fixed rotation) or conditional phase changes (tactical simulation). The simulations used soil properties from the CSU site and 42 years of historical rainfall data (1957-1998) from the nearby Australian Bureau of Meteorology station at the NSW Department of Agriculture Research Station (station 73127). Other meteorological data (solar radiation, maximum and minimum temperatures) were extracted from the SILO Patched Point Dataset (Jeffrey et al., 2001) for the same location. Sowing of both wheat and lucerne was conditional on rainfall within a sowing window between 1 May – 15 June, or sown "dry" on 15 June. Crop and fallow management reflected that of CSU Paddock 14 (north) in 1993, including the germination of weeds (single cohort) using the scheme proposed by Fischer et al. (1990). Wheat was fertilised at 137 kg N/ha/season (17 kg N/ha applied at sowing, the balance 62 days later) and 70% of crop residues were burned on 31 March with the remainder incorporated by tillage on 15 April. Lucerne was managed as a fodder crop and cut frequently upon flowering. At the end of the pasture phase it was removed on 15 December. In the simulations the roots of wheat (cv. Janz) were allowed to penetrate to a maximum depth of 1.2 m, whilst those of lucerne penetrated (conservatively) to a depth of 3 m.

For both the tactical and fixed-rotation simulations, the first six years of the simulation were identical (fixed rotation). The first five of these years were included to allow the simulation to stabilise and minimise artificial initialisation effects. These years were not included in the analyses that follow, which focused on the period 1962-1998 (36 years). In the fixed rotation, the simulations consisted of six cycles of six stages (first, second, third year wheat, first, second, third year lucerne). To ensure equal representation of the full weather record for every stage of the rotation cycle, the simulations were run six times in a staggered fashion (Table 11).

Table 11: Design of long-term simulations in Example 2 (W = Wheat, L = Lucerne); tactical rules explained in section on Tactical simulation.

		Stabilisation		Preliminary years			36 years used in analysis (May 1962 – April 1998)						
Scenario	Run	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	..
Fixed Rotation	RW1	W	W	L	L	L	W	W	W	L	L	L	..
	RW2	W	L	L	L	W	W	W	L	L	L	W	..
	RW3	L	L	L	W	W	W	L	L	L	W	W	..
	RL1	L	L	W	W	W	L	L	L	W	W	W	..
	RL2	L	W	W	W	L	L	L	W	W	W	L	..
	RL3	W	W	W	L	L	L	W	W	W	L	L	..
Tactical Rotation	TW1	W	W	L	L	L	W	… (tactical rules)					
	TW2	W	L	L	L	W	W	… (tactical rules)					
	TW3	L	L	L	W	W	W	… (tactical rules)					
	TL1	L	L	W	W	W	L	… (tactical rules)					
	TL2	L	W	W	W	L	L	… (tactical rules)					
	TL3	W	W	W	L	L	L	… (tactical rules)					

Fixed rotation

In fixed rotation simulation run RW1 (first year wheat in 1962) there were eight periods (in 36 years) when there was drainage below 3 m: once during a first wheat crop, twice during a second wheat crop, once during a third wheat crop, twice during the summer fallow between the third wheat crop and sowing of lucerne, and twice during a first lucerne year (Fig. 29a). Long-term average drainage for this run was 21 mm/year. Average annual drainage over all 6 staggered runs was 22 mm/year (range 18 – 26 mm/year). Water storage in the 0-1.2 m layer was largely a function of rainfall, with fluctuations under lucerne just as large as under wheat (Fig. 29b). Hence this storage could not be used to predict the timing of phase changes. Analysis of water content fluctuations at 1.3 m – just below the root zone – showed that on all occasions increases in water content preceded the drainage events by sufficient time to allow a phase change (Fig. 29c). These

results suggest that for this particular scenario, the water content at 1.3 m could serve as a trigger for phase changes. Once the soil at 1.3 m starts to wet, lucerne should be sown in the following autumn to limit deep drainage. Similarly, once the soil at this depth is dry lucerne could be removed and a crop sown the next autumn. Note that in many cases wetting up at 1.3 m starts soon after commencing the wheat phase. This is probably influenced by the choice of 100% effective lucerne removal on 15 December. Later removal would reduce the risk of water storage over the summer fallow and delay wetting up of the profile.

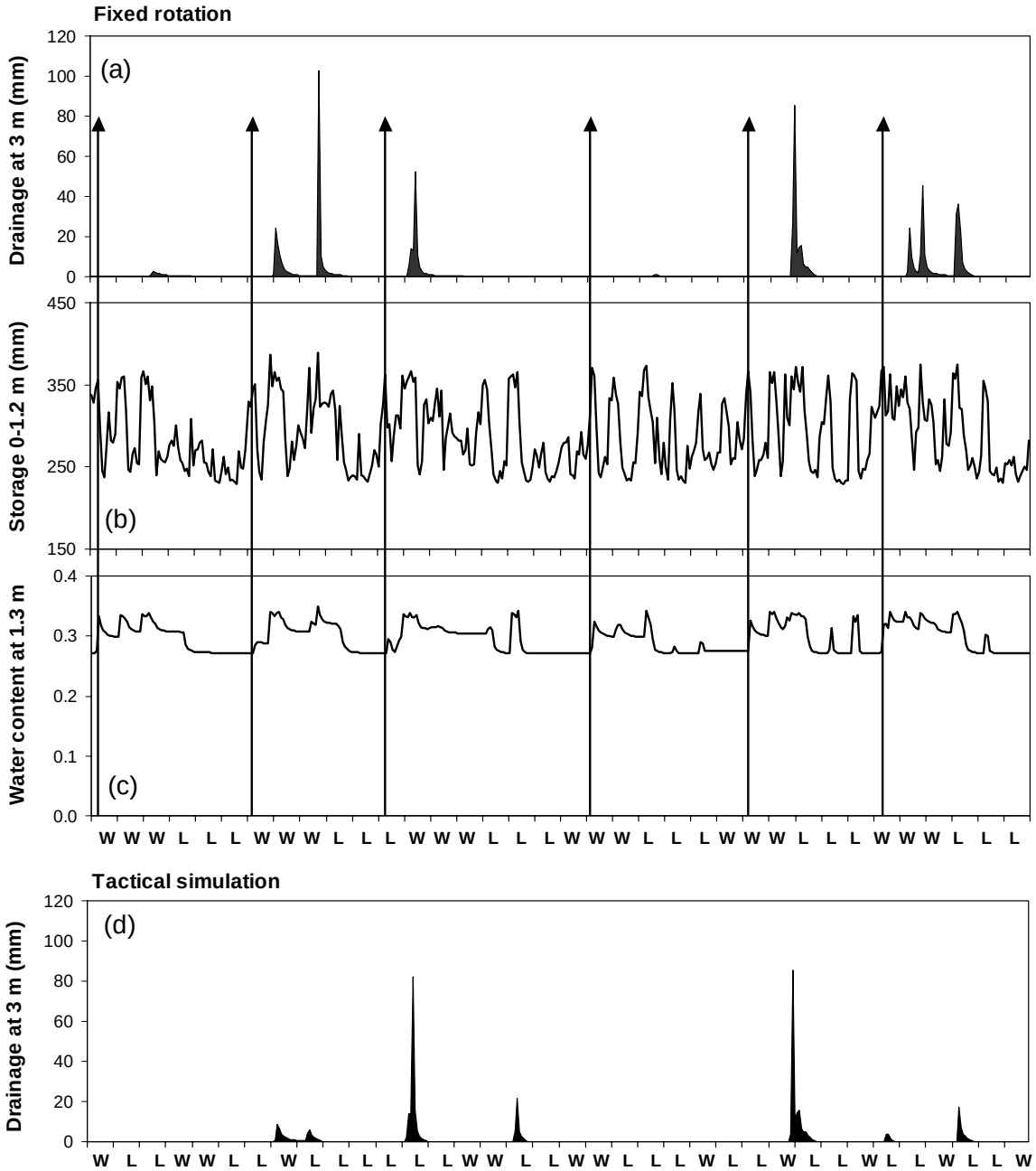

Figure 29: Drainage and soil water dynamics under fixed rotation (a-c) and (d) drainage predicted for the tactical simulation using soil water content at 1.3 m as a trigger for phase changes. The x-axis shows the phase in each year from 1962 to 1997 (W = wheat, L = lucerne). Arrows show timing of first wetting up at 1.3 m depth.

Tactical simulation

Tactical use of phase farming to control drainage at 3 m was explored by using the water content at 1.3 m as a trigger for phase changes. In years when the soil at this depth had started to wet by the 1st of March, lucerne was sown (on the date determined by the sowing rules) instead of wheat, and when water extraction by lucerne had dried the soil at 1.3 m to its lower limit, lucerne was removed (on 15 December) and wheat sown

in the following autumn. The results of the tactical simulation (TW1) showed that two of the drainage periods in the fixed rotation simulation were completely eliminated and that drainage was significantly reduced during the four of the other periods (Fig. 29d). Drainage during the remaining two periods (1974, 1989) was still significant, but inevitable given the very large amount of rainfall during the preceding months. Long-term average drainage was reduced to 12 mm/year (run TW1). The average drainage of all 6 staggered tactical runs was 14 mm/yea, a 37% reduction from the average of the fixed rotations.

Two small drainage events were introduced in tactical run TW1 (in 1978 and 1992) that were not present in the fixed run RW1. This illustrates the impact on drainage of the combined effects of seasonal rainfall variability with the type of crop in the ground at the time of above average rainfall and demonstrates the need to evaluate all 6 staggered runs when determining the average effectiveness of management changes.

The 37% reduction in drainage in the tactical runs came at the cost of the number of wheat crops grown (12 to 13 crops vs. 18 in the fixed rotation), because the wheat phase was generally shortened. The reduction in the number of cropping years will contribute to the reduction in deep drainage. In order to explore the effect of the phase timing alone, the tactical simulation was adjusted to use a less stringent trigger which allowed a similar number of cropping years to the fixed rotation. Using soil water change at 1.7 m as the trigger for phase changes, the number of annual crops was increased to 17 or 18. Average drainage for all 6 staggered runs was 17 mm for this scenario, a reduction of 23% compared with the fixed rotations. Thus the tactical distribution of cropping years did reduce deep drainage compared with the fixed rotation.

Another way to maintain the larger drainage reduction without reducing the number of cropping years would be to sow the first year of each lucerne phase under an additional crop. The ability of APSIM to simulate undersowing is currently being evaluated so that we have not yet tested this hypothesis, but experimental evidence suggests that the benefits of the lucerne phase will still be attained. The lucerne phase in the tactical runs was usually only two seasons, except in the wet early seventies. In reality the shortened phases may not be acceptable for economic and practical operational reasons. This and other factors such as varying the length of fallow period, fertility, and economics need further analysis.

Conclusion

The example illustrates the role that simulation analysis can play in helping develop practical decision rules for phase changes, and in guiding the development of appropriate measurement programs. It showed, for example, that measurements within the root zone of annual crops are unlikely to useful for timing phase changes and that measurements within 0.4 – 0.5 m below the root zone of annual crops are more promising. Our GRDC project CSO00004 (Objective measures for managing the risk of deep drainage) will elaborate on these analyses, test them in the field, and will develop guidelines for installing and interpreting simple, farmer-friendly soil moisture sensors.

5.3 Example 3: Evaluating the effect of lucerne on water logging over the long term (Temora)

The Temora (Fergusons Lane) data set was collected to evaluate the ability of lucerne to reduce the risk of water logging. Long-term simulations using historical weather data were carried out to evaluate this, based on the LLLWC and LLLCW treatments (Table 7). The 8-year simulation scenario consisted of 1 year of wheat followed by 3 years of lucerne and 4 years of wheat-canola rotation, and was started every year from 1957 to 1994, effectively repeating the field experiment 38 times. With the focus on soil water storage in the top 0.6 m where water logging is observed, only the first crop after lucerne was evaluated. Lucerne was cut at flowering, and annual crops were well fertilised to avoid any possibility of them running out of nitrogen during the simulations, thus representing best practice.

The simulations confirmed that lucerne phases reduced the risk of water logging, by keeping the soil drier during the summer fallow and creating a buffer for soil water storage in years with above average rainfall during the early months of the growing season. The magnitude of the buffer and percentage of years that this avoided water logging were sensitive to the timing of lucerne removal and the management of the fallow period prior to cropping.

If lucerne was removed with 100% success on 1 April, and the fallow was subsequently kept free of weeds, the soil water storage to 0.6 m was predicted to be, on average, 32 mm less than following cropping and a weed-free summer fallow. In 7 years out of the 38 tested (1961-1998) the advantage of lucerne had been lost (<5% of maximum buffer left). If, however, lucerne was removed on 1 January, this buffer was reduced to 16 mm and in 13 years out of the 38 tested the advantage of lucerne had been lost.

In reality, weeds usually do grow during the summer fallow and even if subsequently grazed or sprayed out they do increase evapotranspiration for that period. To estimate their impact, we allowed weeds to germinate according to the scheme of Fischer et al. (1990). This reduced the long-term average (1961-1998) soil water storage at sowing by 8 mm (continuous crop treatment). The phase cropping treatment with lucerne removal in January was also 8 mm drier at sowing if weeds were allowed to germinate in response to sufficient rainfall during the period from January until sowing. These results emphasize that conclusions about the effectiveness of lucerne are very sensitive to fallow and weed management. Similar factors, such as the success of lucerne removal, may be responsible for the observed differences in water storage between the Fergusons Lane treatments LLWCW and LLCWC in 1998 and LLLCW and LLLWC in 1999.

Conclusion

Model simulations confirmed the conclusions from the field experiments that inclusion of lucerne phases kept the soil profile drier, reducing the risk of water logging in winter. The simulations showed, however, that the magnitude of the effect was dependent on timing of lucerne removal and subsequent fallow management. The results will depend on lucerne management (hay or grazing) and timing of lucerne removal. While the analysis presented here focused on the 0 - 0.6 m layer, the drying of the profile to deeper depths (past cropping root zone) by lucerne may also reduce the risk of water logging due to subsurface flows coming from off-site. Of course, the lucerne phase has the added benefit of impacting favourably on nitrogen supply for subsequent annual crops, but an evaluation of that was not the purpose of these simulations.

6 Discussion

As mentioned in the Introduction, concerns have been expressed by some readers of earlier reports that APSIM simulations overpredicted deep drainage. These concerns stem largely from comparisons made by those readers between results from long-term simulation analyses and experimental assessments in the NSW-Vic slopes agroecological zone. Simulation results, such as 84 and 185 mm/year deep drainage under continuous wheat for analyses presented by Dunin et al. (1999), and 89 and 101 mm/year deep drainage under continuous wheat for analyses included in Keating et al. (2001), were considered too high, given findings from field studies of 49 mm/year at Rutherglen (Ridley et al., 2001) and 25 mm/year (Dunin et al. 1999) or 39 mm/year (Dunin et al. 2001) at Wagga Wagga (CSU).

In Section 5.1 we illustrated the effect that differences between weather conditions during measurement periods and the average conditions of long-term simulations can have, and that comparisons need to be made for the same period and the same management conditions before conclusions can be drawn about the accuracy of APSIM's predictions. In this section we further illustrate the impact of choices in the simulation scenarios on the predicted deep drainage and discuss the appropriateness of these comparisons between specific field studies and long-term simulation scenarios.

6.1 Scenario choices and variability in long-term average predicted drainage

All long-term simulation scenarios require specific choices of soil type, weather record, and management options as inputs. As has been illustrated in Section 5, these choices impact on the predicted water balance, just as they influence the water balance in the field. Before discussing the comparison of long-term simulation results with short term experimental drainage estimates, it is useful to explore the implications of the choice of inputs on drainage estimates a little further, with specific reference to the choices used in the simulations of Dunin et al. (1999) and Keating et al. (2001) which have been criticised.

We have chosen as the baseline scenario in Table 12 a long-term (1962-1998) simulation of continuous wheat at CSU, using the same soil properties, and assumptions about wheat management as in the example in Section 5.2. This scenario produced an average drainage at 1.8 m depth of 54 mm/year. This value is much lower than the results of Dunin et al. (1999) and Keating et al. (2001) cited above, and appears to contradict them. However, the simulations of Dunin et al. (1999), for example, were carried out with different soil properties, a different rainfall record, and lower fertiliser input (67 kg N/ha/year instead of 137 kg N/ha/year). They also assumed perfect weed control and no residue removal. The impact on the simulation output for each of the different inputs used by Dunin et al. (1999), separately and combined, is illustrated in Table 12.

We have already shown in Section 4.1 for the simulations of 1993 and 1995 CSU lysimeter data (Table 4), that using different rainfall records can have a large impact on predicted drainage. The Wagga Wagga weather data that were used in the simulations of Dunin et al. (1999) come from Bureau of Meteorology station 72150 at Forest Hill, approximately 16 km east of the CSU site. Its average rainfall for 1962-1998 is 19 mm higher than at station 73127 adjacent to the CSU site (589 mm vs. 570 mm). In the simulations, much of the extra rainfall became drainage because the annual crops were seldom water stressed in years with rainfall sufficient to cause deep drainage. So while the long-term average rainfall was only 3% more at Forest Hill, the increase in predicted drainage was 26 % for the baseline scenario (Table 12).

The effects of different weed and residue management, separately and combined, on the baseline scenario are shown in Table 12 for both rainfall records. Assuming perfect weed control resulted in an increase in drainage of 27 mm, while removing 90% of the residue at harvest (as happens for the CSU lysimeters) resulted in 19 mm less drainage than the baseline case. While some residue effects (e.g. standing vs mulched stubble) have not yet been tested in detail, this sensitivity of the model to management appears realistic. Similar sensitivities were observed in the experiments at CSU (differences between lysimeters, Fig. 2, 3; effect of residue removal in June 2002 Fig. 4), Rutherglen (effect of weeds in 1998-99, Fig. 15) and Temora (effect of resprouting canola in 1999-2000, Fig. 23).

Table 12: Long-term (1962-1998) average drainage (mm/year) at 1.8 m and (in parentheses) average yield (t/ha) for a scenario of continuous wheat using different weather records, management options, and soil hydraulic characteristics.

Drainage (mm/year) *Yield (t/ha)*	Eutrophic Red Kandosol					Mesotrophic Red Kandosol
Weather record	baseline scenario[a]	no weeds[b]	10% residues[c]	10% residues no weeds[d]	no weeds low fertiliser[e]	no weeds low fertiliser[e]
NSWAG	54 *(4.2)*	81 *(4.3)*	35 *(4.1)*	47 *(4.2)*	88 *(3.7)*	154 *(3.8)*
Forest Hill	68 *(4.4)*	94 *(4.4)*	47 *(4.3)*	63 *(4.3)*	107 *(3.6)*	173 *(3.7)*

[1] Eutrophic Red Kandosol has soil hydraulic characteristics as described in Section 4 (CSU) and Appendix 1 of this report.
[2] Mesotrophic Red Kandosol has soil hydraulic characteristics as used by Bond et al. (1998) and Snow et al. (1999a).
[a] Scenario based on that described in Example 2 (Section 5); continuous wheat (var. Janz), 137 kg N/ha/yr, summer weeds (single cohort 15/m^2 rooting to 0.6 m germinating in response to rainfall), 70% of surface residues burned on 31 March, remainder incorporated through tillage on 15 April, 1 May – 15 June sowing window
[b] Like scenario a, but without summer weeds
[c] Like scenario a, but with 90% of surface residue removed at harvest (similar to lysimeters)
[d] Like scenario c, but without summer weeds
[e] Like scenario b, but with only 67 kg N/ha/yr fertiliser

The effect of soil type can be even more dramatic. The soil properties at CSU (Section 4.1) and those reported by Bond et al. (1998) for another Red Kandosol in the region – both of which were used by Dunin et al. (1999) – are very different. The soil at CSU is less permeable, which is reflected in its classification at the Great Group level (Isbell, 1996) as Eutrophic (base status > 15 mol$_c$/kg clay) compared with Mesotrophic (base status ≤ 15 mol$_c$/kg clay) for the Kandosol described by Bond et al. (1998). The difference in permeability and storage – a consequence of different clay percentages – has a large impact on long-term average drainage (Table 12).

The results presented in Table 12 are very similar to those of Dunin et al. (1999) and Keating et al. (2001) when the same input assumptions are used. They are not identical because of changes to the model between the version used then and the current version. They also show that there is no single value for long-term average drainage for continuous wheat grown in the Wagga Wagga region. Much depends on the precise soil type, rainfall, and crop and fallow management. The assumptions chosen for the earlier simulations yield results at the higher end of the range that would be expected as a result of different management options. Since the earlier studies, improved understanding of the important processes affecting drainage that need to be included in long-term simulations has resulted in specification of scenarios that are more aligned to local practices and have less drainage than earlier predictions.

What then is the value of these scenario analyses, if the predicted long-term average drainage can vary so much? The answer lies in using the results in a relative sense. While the long-term average drainage in the Rutherglen simulation analyses (Section 5.1) was different for the scenarios with and without weeds during the summer fallow, that did not affect their usefulness for extending the conclusions of the field experiment. Whether weeds were included or not, the conclusions were the same. Similarly the conclusions from the simulation analyses in Section 5.2, that most promising parameters for timing phase changes would be located just below the root zone of annual crops, are not affected by the exact choice of scenario.

It is, nevertheless, important to test the sensitivity of simulation analyses to alternative choices of relevant scenario conditions, and thereby explore the range of possible outcomes. Such a sensitivity analysis is useful to assess the relative impacts of different management options, something which is difficult to achieve through experimentation alone. For example, the alternative management of December instead of April removal of lucerne in the Rutherglen simulation analyses, did have an impact on the benefits of a third year of lucerne and adds another dimension to the question of ideal length of the lucerne phase (Section 5.1).

6.2 Comparisons of long-term simulation analyses with drainage estimates obtained from field measurements

The large impact of the choice of specific model scenario on predicted deep drainage suggests that comparisons of long-term simulation results with experimental estimates of drainage will be difficult. A number of observations made in Sections 4, 5 and 6.1 of this report confirm this.

In Section 4.1 it was shown that rainfall for the lysimeters was often less than that of the nearby station at the NSW Department of Agriculture Research Station (station 73127), let alone the station located at Forest Hill 16 km away. In 1993 the differences were particularly large and, as shown in Table 4, choice of rainfall record affected the amount of drainage predicted. More generally, when experimental drainage estimates are compared with long-term drainage predicted in simulation analyses, the rainfall during the experimental period must be representative of the long-term rainfall record used in the simulations. If that is not the case, quite different values of drainage may be obtained that do not say anything about the model's ability to predict drainage. This was demonstrated by comparing the average drainage for the Rutherglen experimental period (1996-1999) with that of a long-term (1964-2001) simulation (Section 5.1). Even a small difference in rainfall will have a disproportionate impact on the drainage term.

As shown in Section 6.1, the hydraulic properties of the soil at the location of the field study and that of the soil used in the simulations must be similar; both storage properties and hydraulic conductivity are important. Soil classification alone will often not be sufficient to establish this. As seen in Table 12, there were striking differences in predicted water balance between two soils both classified as Red Kandosols.

The cropping systems in the field study and the simulation must also be similar. Although it has been done by some people, it is not valid to compare drainage estimates from a long-term simulation of continuous wheat with measurements of drainage under a lucerne-wheat phase system, even if drainage is evaluated at the bottom of the wheat root zone (ignoring the deeper uptake by lucerne). This is shown in Table 13 for the simulation scenarios used in Example 2 of Section 5. The active water use by lucerne during the summer months reduces water storage over summer and keeps the soil in crop root zone drier. This was shown quite convincingly in Fig. 15, where both measured and modelled soil water storage in the 0.1 – 1.2 m layer at Rutherglen under continuous wheat and continuous lucerne were contrasted.

Table 13: Predicted long-term (1962-1998) average net flow and drainage (mm/year) under continuous wheat (baseline scenario with NSWAG rainfall from Table 12) and the fixed wheat-lucerne rotation of Example 2, Section 5.

	Flow past 1.2 m*	Flow past 1.8 m*	Drainage past 3.0 m
Continuous wheat	58	54	54
Fixed rotation	44	33	22

* This does not take into account subsequent extraction of this water by lucerne from below 1.2 or 1.8 m depth in the fixed rotation.

At CSU the presence of lucerne during the summer was shown to reduce drainage during the winter/spring in 1995 (north vs south lysimeter, Fig. 3). Given that both CSU and Rutherglen experienced above average rainfall in 1995 and 1996 and that lucerne reduced drainage quite significantly in 1996 at Rutherglen, it is quite likely that the lack of drainage during the 1996 winter/spring at CSU was caused by the presence of lucerne. Therefore, the drainage record from the lysimeters at CSU is reflective of a phase system, and cannot be compared with simulations of drainage under continuous cropping.

Finally, management must be similar for the long-term simulations and the experimental period for a valid comparison to be made. Results from a lysimeter with barely any crop residues left after harvest cannot be compared with a long-term simulation in which residues were left on the surface until some time in March or April. Similarly the impact of weed management can be significant, as shown in both the experimental data (CSU 1993 drainage, CSU cumulative *Et* for various summer fallows, Rutherglen soil water during 1998-99 summer fallow, Temora soil water during 1999-2000 summer fallow) and the simulations (e.g. Table 12 above).

The requirements of similarity in rainfall records, soil type, cropping system, and field management have been largely ignored in the comparisons of long-term predicted drainage with experimental observations that most criticisms of APSIM's ability to predict drainage have been based on. We have shown that such comparisons are inappropriate and hence that these criticisms are unfounded.

Several of the dilemmas that are faced when comparing experimental results with model predictions extend to the way that experimental results are generalised. Extrapolation of experimental measurements of drainage to estimate long-term drainage, or the leakiness of a particular farming system in a particular area, requires an assessment of the impact of rainfall, soil type, and management. In most cases that will not be a straightforward matter. In fact this is where the power of combining measurement and modelling lies. Predictions using a satisfactorily tested model do provide the ability to extrapolate from experimental results.

7 Conclusions

The evaluation of APSIM reported here was based on data from four detailed experiments that were characterised by frequent soil water measurements. Although the data sets were comprehensive, the model evaluation was still affected by data limitations, including rainfall uncertainty (CSU, Temora), discontinuous water content records (Temora), and insufficiently detailed records of management operations (all sites). The latter was particularly true for the periods between growing seasons. All four data sets included periods in which the measured water balance was sensitive to management of the residues and weeds in the summer fallow (e.g. Fig. 3, 5, 23). The model exhibited similar sensitivity to management, with evapotranspiration and drainage predictions responding accurately to management actions such as removal of surface residue and weed growth (Fig. 3, 5). This is reassuring but means that for accurate model testing the operations record needs to be very detailed and include observations about weed growth and composition, surface residues, as well as crop performance. In the four data sets simulated, this detailed information was not always available, sometimes introducing significant uncertainty (e.g. Fig. 2, 23).

Despite these uncertainties, the model was found to do a good job of simulating the soil water dynamics under the various systems. Particularly good agreement was found for simulations of water storage and evapotranspiration during the 2001-2002 summer fallow in the lysimeters at CSU (Fig. 4, 5), drainage during the 1993 and 1995 growing seasons in the lysimeters at CSU (Fig. 3), and drainage for the continuous cropping and continuous lucerne treatments at Rutherglen (Fig. 16). Another highlight was that soil drying after the first summer of (re-)sown lucerne at Rutherglen was simulated well (Fig. 14) and that the model predicted similar drying to 1.8 m in the first season at CSU (Fig. 10, 11). This was especially encouraging since in the latter simulations, which used the APSWIM water balance model, uptake was governed by the root length densities predicted by the model, rather than limited by the user defined *kl* factor in SoilWat2. At the CSU site water uptake by lucerne down to 3 m in CSU paddock 12 (Fig. 11a) was predicted well. Below 3 m the predicted uptake was faster than the measured uptake, although the measured uptake was quite variable between replicates (Fig. 11b). Further evaluation against more data sets is required.

Drainage predicted by the model was in good agreement with measurements where available. Predicted and measured drainage summed for the whole 9½ year simulation period at CSU agreed fairly closely for both the north and south lysimeters, with the model correctly reflecting the different drainage behaviours of the two lysimeters (Table 3). At Rutherglen treatment differences were also largely reflected well by the model.

While the focus of the evaluation was on water balance predictions, simulations of crop biomass and yield were generally within the measurement error. Lucerne biomass was less well predicted, particularly in situations where water was readily available. Simulations of soil nitrogen were also quite good, but further testing is required, given the limited data included in these data sets and the need to change some of the model constants. The same applies to the decomposition of surface residues over the summer fallow.

The detail needed for model testing does not prevent the model's use in long-term simulation analyses. The model's sensitivity to management is similar to that observed in the experiments and simulation results are expected to correctly represent the chosen scenarios. Results of long-term simulation analyses should not necessarily be expected to agree with field observations from any particular site, however. Differences may result from differences in cropping sequences (Sections 5.1, 6.2), differences in management of surface conditions (Section 6.1), differences in average rainfall during the measurement period compared with the long-term simulation period (Sections 5.1, 6.1), or differences in soil properties (Section 6.1). Instead, the results of any simulated scenario need to be considered as one possible outcome that is realistic for that site (provided realistic management options have been chosen) and the sensitivity of the results to management changes used to evaluate the impact of management options. Long-term simulation analyses can then be used for a range of applications, as illustrated in the three examples in Section 5, namely: (1) extending experimental results by sampling a longer weather data set, (2) exploring consequences of management changes, (3) assessing sensitivity of field results to management, and (4) providing a guide for measurement and interpretation.

The results presented in Table 12, show that the simulation analyses in Section 5 are consistent with the earlier drainage predictions by Dunin et al. (1999) and Keating et al. (2001). While the model and its parameterisation have been refined over the past few years, the estimates of long-term drainage in response to given input scenarios have not been affected significantly. The detailed model evaluation has, however, led to improvements in various modules and of their parameterisation that have contributed to the successful simulations of experimental data. Combined with improved understanding of the important processes

affecting drainage that need to be included in long-term simulations, this has significantly increased our confidence in the long-term drainage values obtained in simulation analyses.

The evaluation process also led to the identification of current limitations of the model, suggesting areas that need further model improvement (see Section 4). This has been a useful outcome of the project.

Acknowledgements

Funding for the evaluation of APSIM was provided by CSIRO, GRDC, and Land and Water Australia. The experimental data were collected as part of projects contributed to by GRDC (Projects CSO197, DAV219, CSP243), Land and Water Australia (Projects CPI5, CDS20), CSIRO, and Agriculture Victoria. We acknowledge the technical assistance of the staff on the various projects. Simulation analyses were supported by GRDC Projects CSO197 and CSO 00004, and built on earlier simulations carried out as part of Land and Water Australia Project CTC11. We thank C.J. Smith, F.X. Dunin, A.M. Ridley, J.R. Hirth, M.B. Peoples, M.H. McCallum for sharing their experimental data with us, M.J. Robertson, M.E. Probert, N.I. Huth, J.N.G. Hargreaves, I. Farre, S. Asseng, and E. Wang for providing updated versions of the APSIM model and/or feedback on parameterisation, B.A. Keating for input into the earlier long-term simulation analyses, J.M. Lilley and R.A. Richards for suggestions on wheat cultivar parameters, N.J. McKenzie and D.W. Jacquier for soil profile descriptions of the CSU and Temora sites, and E.J. Kladivko, M.E. Probert, M.J. Robertson, and F.X. Dunin for comments and suggestions on the manuscript.

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Appendix A: Soil hydraulic properties for CSU

Data sources

Soil properties at the CSU site have been measured in a number of ways since 1993. Most of this work has been in paddock P14, but some has also been carried out in P12. As will be discussed below, there are no differences between properties for P12 and P14 that are greater than the differences within each paddock, so a combined set of soil properties has been put together.

The data fall into two categories: those collected from purpose-designed sampling, and those obtained indirectly from samples collected for other purposes. The latter are primarily bulk density values.

The data sources are summarised below.

Source	Date	Paddock	Measurements made
Push tube sampling	1993/94	P14	Bulk density
Small core sampling	1993/94	P14	Bulk density, water retention, saturated hydraulic conductivity
Bulk soil sampling	1993/94	P14	1500 kPa water content, particle size, mineralogy
Push tube sampling	1997/01	P12, P14	Bulk density
Internal drainage experiment	1999/00	P14	In situ water retention, hydraulic conductivity-water content relation
Soil description pits (and core sampling)	2000	P12, P14	Full pedological description, water retention, near-saturation hydraulic conductivity, particle size, mineralogy
Deep core sampling	2001/02	P12, P14	Bulk density, 1500 kPa water content

Push tube sampling

Many push-tube core samples have been collected from the paddocks for chemical analysis. While individual sections of these core samples give unreliable estimates of bulk density because of the uncertainty about section length and compaction, when averaged over many samplings it is believed that these do give a reasonable estimate of the paddock bulk density profile. For P14 two separate sets of core samples were averaged – one for samples collected in 1993/1994 under the direction of Roland Poss, and one for samples collected subsequently from 1997 onwards under the direction of Chris Smith. For P12, samples were only collected from 1997 onwards.

Small core sampling and bulk soil sampling, 1993/94

Small cores (100 mm diameter by 75 high) were collected from a pit at depths of 0.05, 0.15, 0.40, 0.80, and 1.40 m. Four replicates were collected at each depth. These were used for the measurement of soil water retention and saturated hydraulic conductivity as described below under "Soil description pits".

Bulk soil samples were collected at depths of 0 –0.05, 0.05 – 0.10, 0.10 – 0.15, 0.15 - 0.25, 0.25 - 0.50, 0.50 - 0.70, 0.70 - 90, 0.90 – 1.10, 1.10 – 1.30, 1.30 – 1.50, 1.50 – 1.70, 1.70 – 1.90, and 1.90 – 2.00 m. These were used for measurement of 1500 kPa water content, particle size and mineralogy.

Internal drainage experiment

The unsteady drainage flux method, similar to that described by Green et al. (1986), was used to determine the hydraulic properties required by the model. Measurements were made in duplicate at a single site (2.5 x 2.5 m square) in P14. Soil water retention curves [$\psi(\theta)$] and hydraulic conductivity - water content relationships [$K(\theta)$] were obtained at 0.2 m intervals from 0.2 m to 0.8 m; $\psi(\theta)$ were also obtained at 0.1 m.

Soil description pits

Two pits were opened in May 2000, one in P12 and one in P14, to enable full morphological description and sampling for soil physical and chemical properties. Core samples were collected at four depths in each of the pits, selected according to the profile morphology. In P12 these depths were nominally 0.05, 0.4, 0.7 and 1.1 m, while in P14 they were 0.05, 0.4, 0.7 and 0.9 m.

At the shallowest depth in each pit, five replicate small cores (75 mm diameter by 75 mm high) were collected. The water retention data were obtained by equilibrating the small cores on suction plates at matric potentials -0, -10, -30, -50, -100, -300 and -600 cm of water. Disturbed sub-samples were then taken from these cores and equilibrated on pressure plates at -1000, -5000 and -15000 cm of water. Near-saturated (at 0 and –3 cm of water) hydraulic conductivity was measured on the cores prior to the water retention measurements using methods similar to those described by McKenzie et al. (2001).

At each of the other depths, four large undisturbed cores (225 mm diameter by 200 mm high) were collected using the method described by (McKenzie and Jacquier, 1996). These cores were used for laboratory measurement of hydraulic conductivity at saturation as described by McKenzie and Jacquier (1996) and at matric potentials of -1, -5 and -10 cm of water using the tension infiltrometer method described by McKenzie et al. (2001). Between two and four small cores (73 mm diameter by 75 mm high) were then collected from each of large cores. These were used for water retention measurements as described above.

Bulk soil was also collected from each depth and used for measurement of particle size, mineralogy (not discussed here) and 1500 kPa water content.

Deep core sampling

In 2000 and 2001, deep cores were collected using a hydraulic split-ring barrel sampler (100 mm internal diameter) mounted on a drilling rig. This allowed relatively undisturbed cores to be taken to a depth of 3 m; 0.2 m sections were cut from these cores centred on 1.5, 2.0, 2.5 and 3.0 m. These were used to estimate bulk density, and sub-samples were used to measure 1500 kPa water content.

At the same time, push tube samples were obtained at intervals of 0.5 m between 3.5 and 6 m, and in some cases 7 m. These were used to measure 1500 kPa water content.

Parameterisation of Hydraulic Properties

Soil water retention data were described by the *Campbell* [1974] form of the *Brooks and Corey* [1964] equation, using the smoothing function of *Hutson and Cass* [1987] to avoid the discontinuity at the air entry water potential, namely

$$(\theta/\theta_s) = (\psi/\psi_e)^{-1/b} \qquad \psi \le \psi_i$$

$$(\theta/\theta_s) = 1 - c\,\psi^2 \qquad 0 \ge \psi > \psi_i \qquad (1)$$

where θ is the volumetric water content, θ_s is the water content at saturation, ψ_e is the air entry water potential and b is an empirical constant. The Hutson-Cass parameters c and ψ_i are related to b and ψ_e as follows:

$$\psi_i = \psi_e\, a^{-b}$$

$$c = (1 - a) / \psi_i^2$$

$$a = 2b / (1 + 2b) \qquad (2)$$

Similarly, the hydraulic conductivity - water content relationship $K(\theta)$ was described by a generalised form of the equation of *Brooks and Corey* [1964] and *Campbell* [1974], namely

$$(K/K_s) = (\theta/\theta_s)^{b\,m} \qquad (3)$$

where K_S is the saturated hydraulic conductivity and m is an empirical constant related to the pore interaction factor p by $m = 2 + (2+p)/b$ [*Campbell*, 1974].

In some instances, the $K(\theta)$ relationship was characterised by a very steep decline in K with decreasing θ near saturation. This was attributed to macropore flow and the $K(\theta)$ relationship was then described by the sum of a matric component and a macropore component (Ross and Smettem, 1993). In this case $K(\theta)$ was described by

$$(K/K_S) = (K_s - K')\,(\theta/\theta_S)^{b\,m'} + K'\,(\theta/\theta_S)^{b\,m} \qquad (4)$$

where K' is the maximum value of hydraulic conductivity of the matrix once the macropores have drained and m' describes the rate of decline of hydraulic conductivity with water content in the macropore range. For consistency with the matrix component, m' is defined in terms of a macropore interaction factor p', by $m' = 2 + (2+p')/b$, although in practice m' is estimated directly from the near-saturation $K(\theta)$ data.

Application in APSIM

Soil hydraulic properties were compiled for 12 depths: 0.05, 0.20, 0.40, 0.70, 0.90, 1.10, 1.3, 2, 3, 3.5, 4, and 5 m, as described below. Bulk densities were ascribed to each of these soil layers using the average values for the site.

More nodes than this were used in APSIM, however. Soil properties were attributed to these additional nodes on the basis of the morphological description and the shapes of the neutron moisture meter profiles.

Depth of node (m)	Soil properties
0.00, 0.01, 0.02	Same as 0.05 m
0.10	Interpolated between 0.05 and 0.20 m
0.30	Same as 0.20 m
0.50	Interpolated between 0.40 and 0.70 m
1.50, 1.70, 1.90, 2.10	Used nominal 2 m properties
2.30	Used 1.3 m properties, as described on p. 59
2.50	Interpolated between 2.30 and 2.70 m
2.70, 2.90, 3.10	Used nominal 3 m properties
4.50, 5.00, 5.50, 6.00	Used nominal 5 m properties

Comment of differences between P12 and P14

As mentioned above, in most cases it was not possible to discern a systematic difference between the measurements from P12 and P14. The exception was the water retention data from the soil description pits at 0.4 m, where the P12 cores were significantly wetter at the wet end than those from P14. At –50 cm of water, for example, the average water content for the P12 cores was 0.346 compared with 0.316 for P14. This difference near the wet end is not borne out in the neutron moisture meter data collected from the two paddocks, however. The mean and standard deviation of the wettest measured water content at 0.4 m at each of the four measurement locations in the two paddocks is: P14 0.300 ± 0.015; P12 0.293 ± 0.013. In other words the two are not significantly different but if anything P12 is drier than p14. This pattern was also observed for other depths in the top 1 m. At these depths, differences between soil water extraction patterns of lucerne and annual crops are not expected to be different, particularly over winter when these observations were made, so the smaller water content in P12 is not expected to be caused by crop differences. It was therefore concluded that in this case the cores from P14 were more representative of both paddocks.

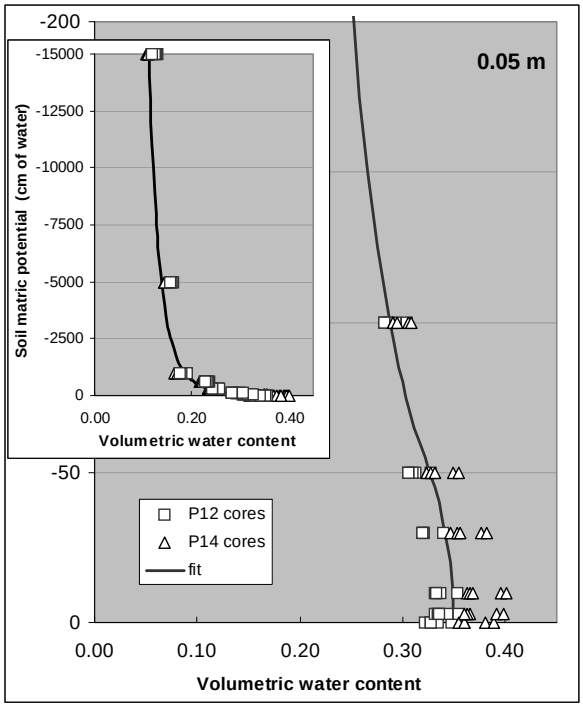
Bulk density and 1500 kPa water content

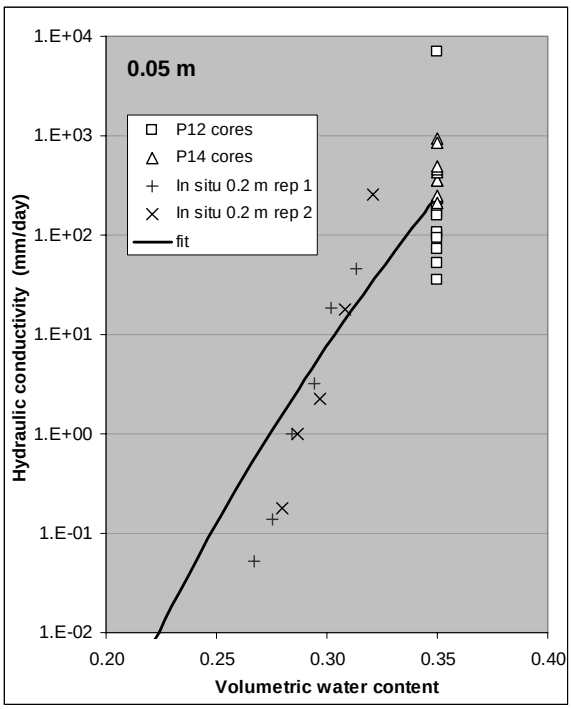
The average bulk density and 1500 kPa water contents obtained from the above data sources are shown in the table below. Note that the bulk density values below 3 m, where no data was available, were set equal to the average bulk density between 1 and 3 m.

Depth (m)	Bulk density (Mg/m^3)	Water content at 1500 kPa (m^3/m^3)
0.05	1.50	0.112
0.10	1.52	0.116
0.15	1.55	0.134
0.20	1.50	0.149
0.30	1.42	0.152
0.40	1.37	0.176
0.50	1.37	0.194
0.60	1.45	0.213
0.70	1.53	0.222
0.80	1.58	0.227
0.90	1.63	0.241
1.00	1.67	0.244
1.10	1.67	0.258
1.20	1.64	0.273
1.40	1.60	0.270
1.50	1.64	0.281
1.60	1.65	0.285
1.70	1.67	0.289
1.80	1.65	0.296
2.00	1.63	0.295
2.20	1.60	0.272
2.50	1.61	0.253
2.60	1.62	0.241
3.00	1.68	0.245
3.50	1.65	0.259
4.00	1.65	0.262
4.50	1.65	0.293
5.00	1.65	0.276
6.00	1.65	0.201

Hydraulic Properties for 0.05 m

Depths applied to: 0, 0.05 m





θ_s m^3m^{-3}	b	ψ_e cm of water	K_s mm/day	p
0.350	5.3	35	250	10

Soil water retention

Available data: cores from soil characterisation pits (0.01 – 0.08 m)

There was considerable scatter at the wet end of the measured soil water retention data. In keeping with the experience that small laboratory cores over-estimate saturated water content, the larger values were discounted. The curve was forced through the average15 bar value from the cores from P12 and P14.

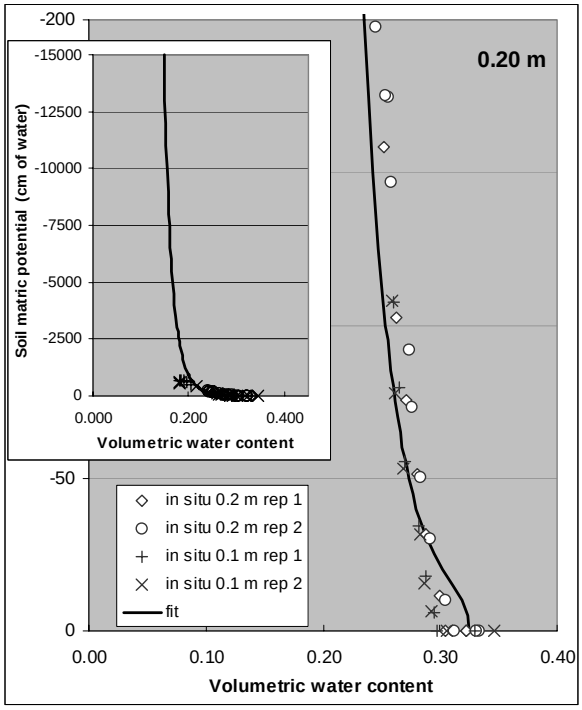
Hydraulic conductivity

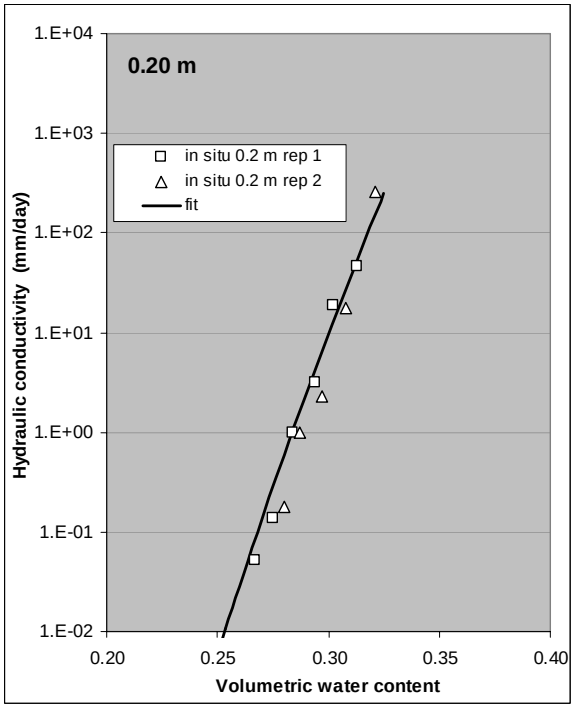
Available data: $K(\psi)$ (0, -3 cm of water) from cores from soil characterisation pits (0.01 – 0.08 m)
in situ $K(\theta)$ at 0.2 m from internal drainage measurements

There was considerable scatter of the wet end $K(\theta)$ values. K_s was set at the geometric mean of the values of K measured at 0 and –3 cm of water. In the absence of data at 0.05 m to indicate the steepness of the decay of $K(\theta)$, experience from other soils in the Wagga Wagga region suggested that a p value of 10 usually describes the decay well. This resulted the decay being less steep than that for the 0.2 m in situ data, which was considered to be appropriate.

Hydraulic Properties for 0.20 m

Depths applied to: 0.20, 0.30 m





θ_s m^3m^{-3}	b	ψ_e cm of water	K_s mm/day	p
0.325	9.3	10	250	20

Soil water retention

Available data: in situ internal drainage measurements (0.1, 0.2 m)
average 15 bar water content at 0.2 m (= 0.149)

There was little difference between the 0.1 and 0.2 m values, but considerable scatter at the wet end. The value of saturated water content was that found when the 0.2 m data were fitted with Eq. (1). The final curve was forced through the 15 bar value.

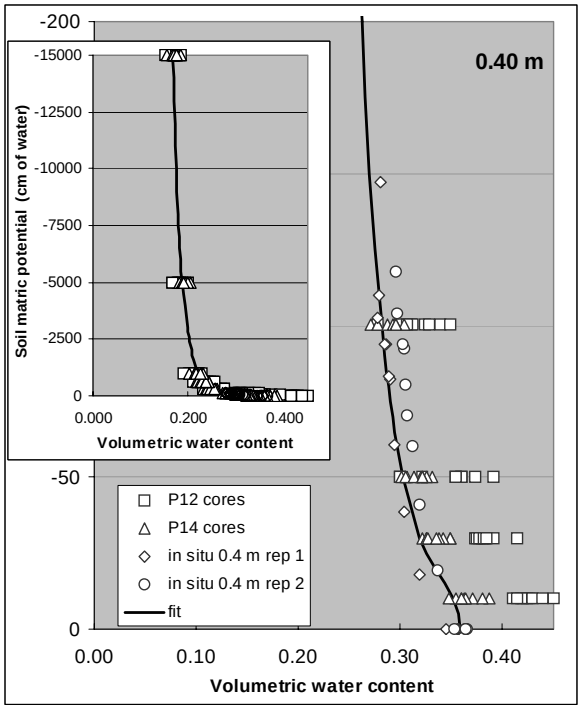
Hydraulic conductivity

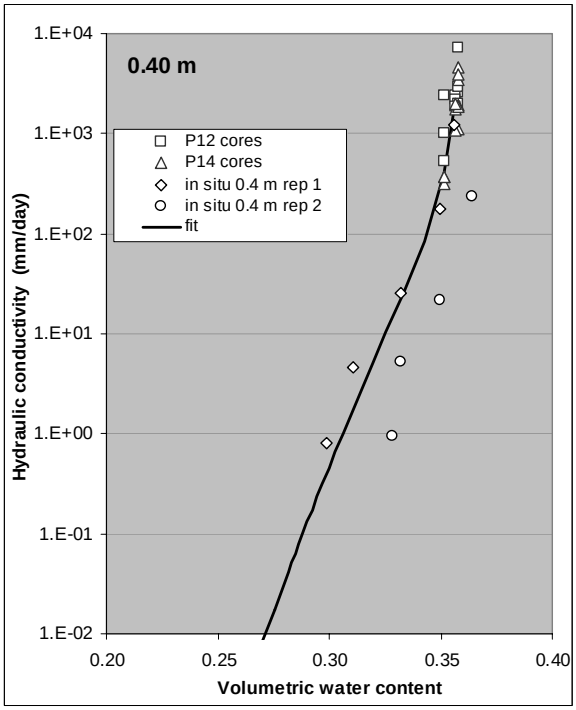
Available data: in situ $K(\theta)$ from internal drainage measurements (0.2 m)

The two replicates agreed closely with each other and supported using a value of K_s the same as for 0.05 m. To match the rate of decay of K with θ required p to be set at the larger value of 20.

Hydraulic Properties for 0.40 m

Depths applied to: 0.40 m





θ_s m^3m^{-3}	b	ψ_e cm of water	K_s mm/day	K' mm/day	p	p'
0.358	9.6	10	4000	400	17	129

Soil water retention

Available data: cores from soil characterisation pits (0.3 – 0.5 m)
in situ internal drainage measurements (0.4 m)

The soil water retention data from the P12 and P14 cores diverged somewhat at the wet end (0 to –100 cm of water), and the in situ measurements agreed more closely with the P14 core data. The final curve was based on a fit to the in situ and core data for P14, which set the value of saturated water content, but forced through the average 15 bar value from the cores.

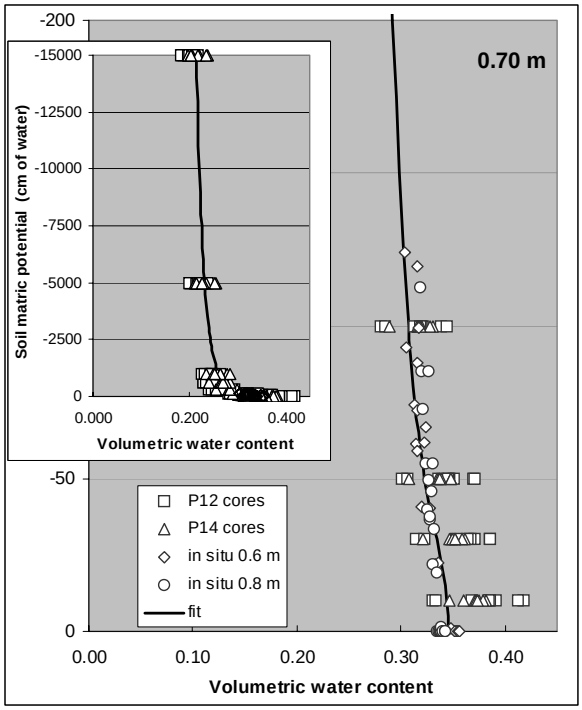
Hydraulic conductivity

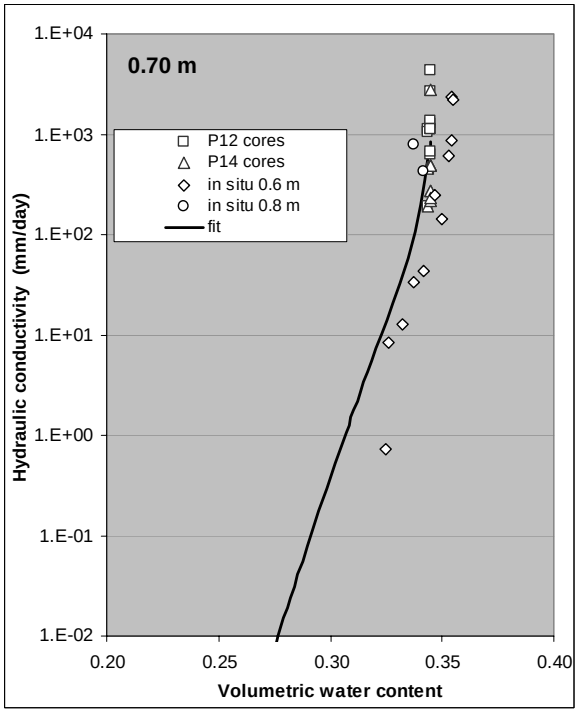
Available data: $K(\psi)$ (0, -1, -5, -10 cm of water) from cores from soil characterisation pits (0.3 – 0.4 m)
in situ $K(\theta)$ at 0.4 m from internal drainage measurements

The K values measured on the cores were somewhat larger than the in situ measurements, with the results for P12 being larger than for P14. The largest values of the in situ measurements (~1000 mm/day) were not too much smaller than the geometric mean of the values of K measured on the P12 and P14 cores at 0 and –1 cm of water. This latter value was used for K_s. The decline of K with decreasing θ for the in situ data was used to guide the final $K(\theta)$ curve. To account for the initial very steep decline in K, a macropore term was introduced as described by Eq. (4). Selection of the value of matrix conductivity K' was guided by the lowest two values of K measured in the cores.

Hydraulic Properties for 0.70 m

Depths applied to: 0.70 m





θ_s m^3m^{-3}	b	ψ_e cm of water	K_s mm/day	K' mm/day	p	p'
0.345	13.9	20	850	200	15	120

Soil water retention

Available data: cores from soil characterisation pits (0.6 – 0.8 m)
in situ internal drainage measurements (0.6, 0.8 m)

The soil water retention data from the cores diverged somewhat from the in situ data at the wet end (0 to –100 cm of water). The final curve was based on a fit to the in situ and core data, excluding extreme core values at the wet end.

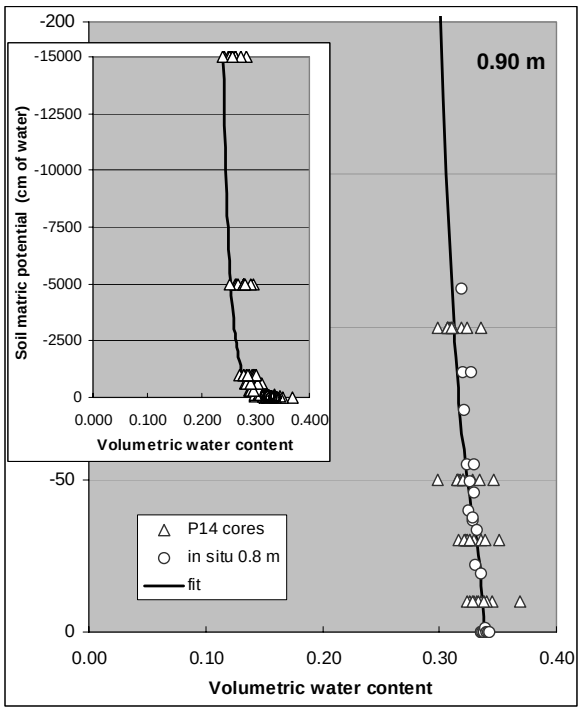
Hydraulic conductivity

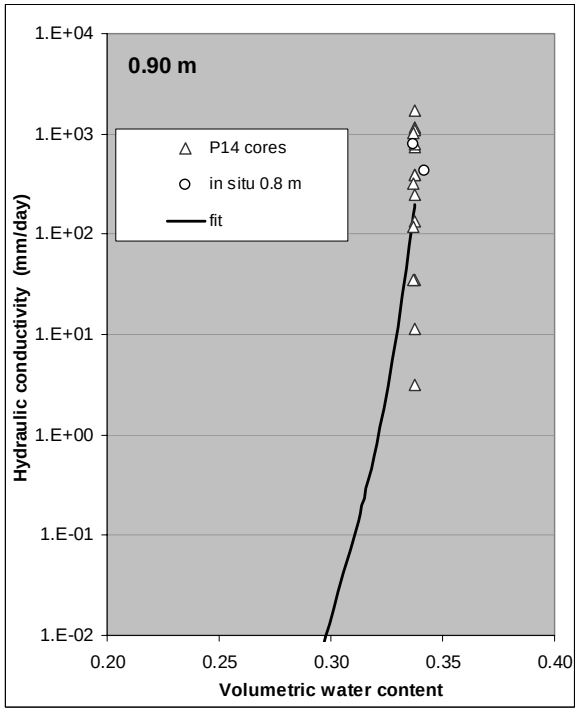
Available data: $K(\psi)$ (0, -1, -5, -10 cm of water) from cores from soil characterisation pits (0.6 – 0.8 m)
in situ $K(\theta)$ at 0.6 and 0.8 m from internal drainage measurements

There was a degree of overlap of the near-saturated values from all sources, although the largest values from the in situ data corresponded to slightly larger water contents. The value of K_s was once again set as the geometric mean of the values of K measured on the P12 and P14 cores at 0 and –1 cm of water. The decline of K with decreasing θ for the in situ data was used to guide the final $K(\theta)$ curve. A macropore term was used again and selection of the value of matrix conductivity K' was guided by the lowest two values of K measured in the cores.

Hydraulic Properties for 0.90 m

Depths applied to: 0.90 m





θ_s m^3m^{-3}	b	ψ_e cm of water	K_s mm/day	K' mm/day	p	p'
0.3375	19.3	22	200	10	15	89

Soil water retention

Available data: cores from P14 soil characterisation pits(0.8 – 1.05 m)
in situ internal drainage measurements (0.8 m)

The wet end was set by fitting to the core data, which was quite similar to the 0.8 m in situ data. However the 15 bar water content obtained in this way resulted in a smaller available water capacity than required to be consistent with the field neutron moisture meter observations. The final curve was therefore forced through the average 15 bar water content for the site (0.260 m^3m^{-3}).

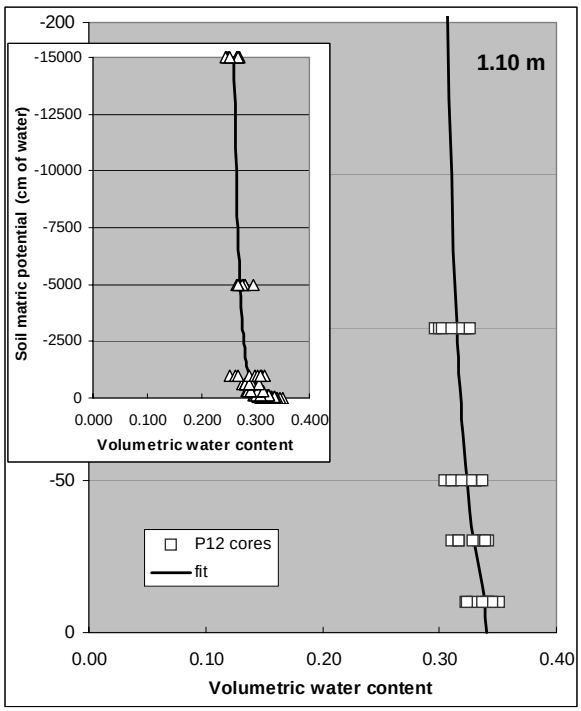
Hydraulic conductivity

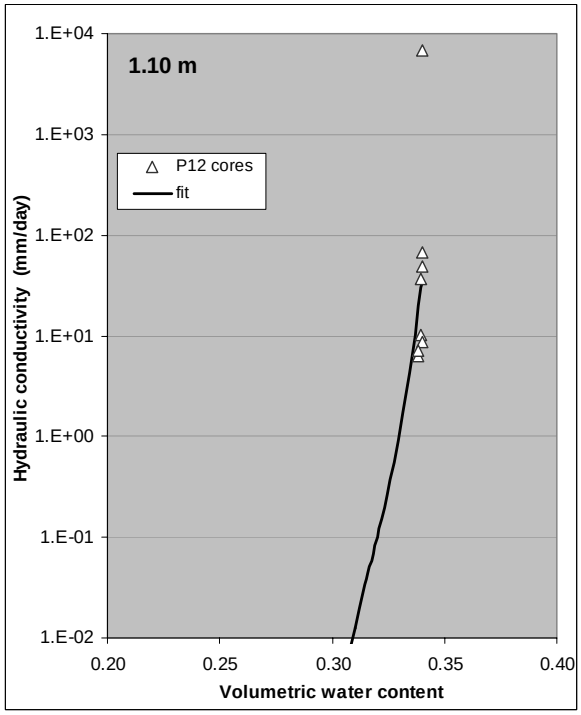
Available data: $K(\psi)$ (0, -1, -5, -10 cm of water) from cores from P14 soil characterisation pits (0.8 – 1.05 m)
in situ $K(\theta)$ at 0.8 m from internal drainage measurements

The value of K_s was set as the geometric mean of the values of K measured on the P14 cores at 0 and –1 cm of water. In the absence of other data, the decline of K with decreasing θ, p was based on that for 0.7 m; the resulting curve was a little steeper reflecting the larger value of b. A macropore term was used again and selection of the value of matrix conductivity K' was guided by the lowest two values of K measured in the cores.

Hydraulic Properties for 1.10 m

Depths applied to: 1.10 m





θ_s m^3m^{-3}	b	ψ_e cm of water	K_s mm/day	K' mm/day	p	p'
0.340	26.5	13	35	5	10	95

Soil water retention

Available data: cores from P12 soil characterisation pits(1.0 – 1.2 m)

The curve used was obtained by fitting the available data.

Hydraulic conductivity

Available data: $K(\psi)$ (0, -1, -5, -10 cm of water) from cores from P12 soil characterisation pits (1.0 – 1.2 m)

The value of K_s was set as the geometric mean of the values of K measured on the P12 cores at 0 and –1 cm of water. In the absence of other data, the decline of K with decreasing θ, p was set to 10, resulting in a slope slightly steeper than for 0.9 m.

Hydraulic Properties for 1.3 to 6 m

No measured soil hydraulic properties were available for depths greater than 1.1 m, except for 1500 kPa water contents. Properties were therefore determined using this limited information as described below. Properties were not prepared for every depth node in the simulations. The neutron moisture meter record and 1500 kPa water contents were used to determine depths likely to have similar properties, thus limiting the number of property sets derived as follows:

Nominal depth	Depths applied to
1.3 m	1.3, 2.3 m
2 m	1.5 to 2.1 m
3 m	2.7 to 3.1 m
3.5 m	3.5 m
4 m	4 m
5 m	4.5 to 6 m

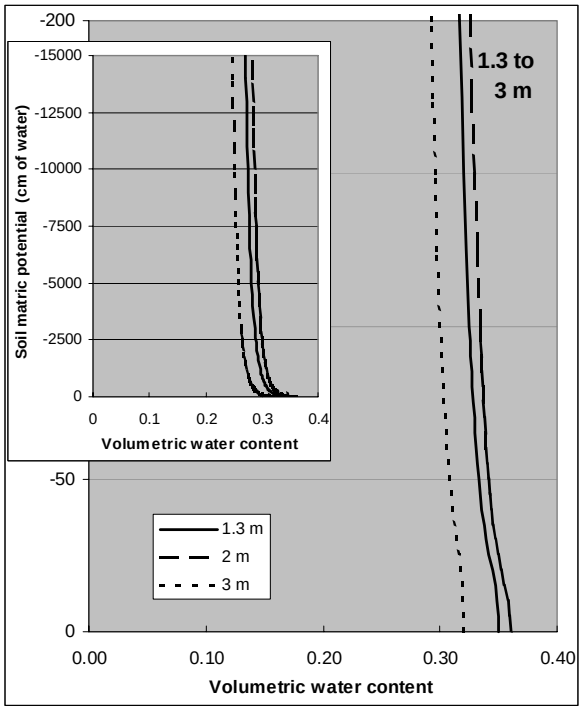
Soil water retention

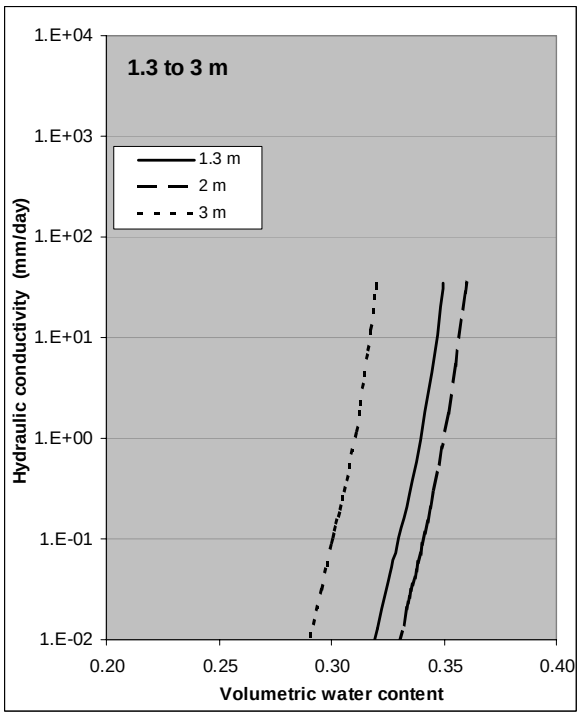
In the absence of other data at these depths, the soil water retention properties were fixed at lower end using the average 1500 kPa water contents for the site. The dynamic range of the neutron moisture meter observations was then used to set the field capacity. The dynamic range from P14 only reflected plant available water for depths <1.2 m because below that the soil was never dried to wilting point. Therefore data from P12, in which lucerne dried the soil to >5 m during the measurement period, was used for this. To obtain the final curves combinations of b, θ_s and ψ_e were somewhat arbitrarily chosen, but based on experience, to ensure the desired 1500 kPa water content and plant available water capacity.

Hydraulic conductivity

There was no data to guide the determination of $K(\theta)$ for these depths. Therefore the values of K_s and K' and p from 1.1 m were used for all deeper depths. The exponent $b\ m'$ was kept constant and the variation in p' determined by the variation in b.

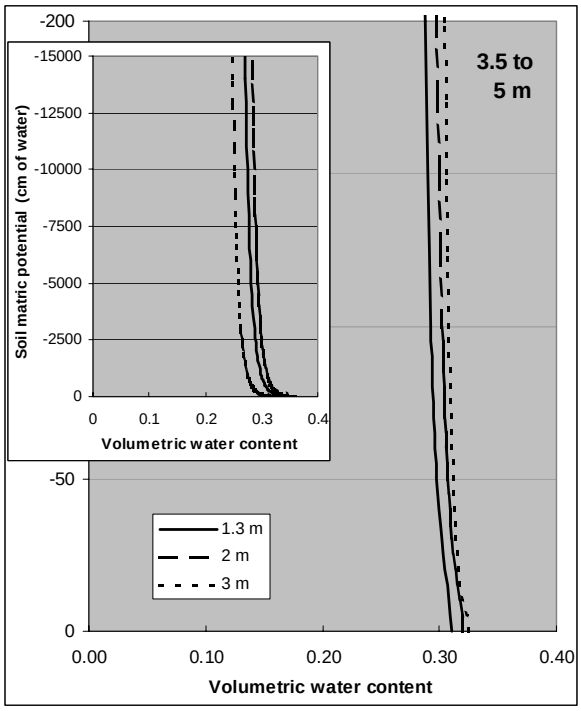
Hydraulic Properties for 1.3 to 3 m

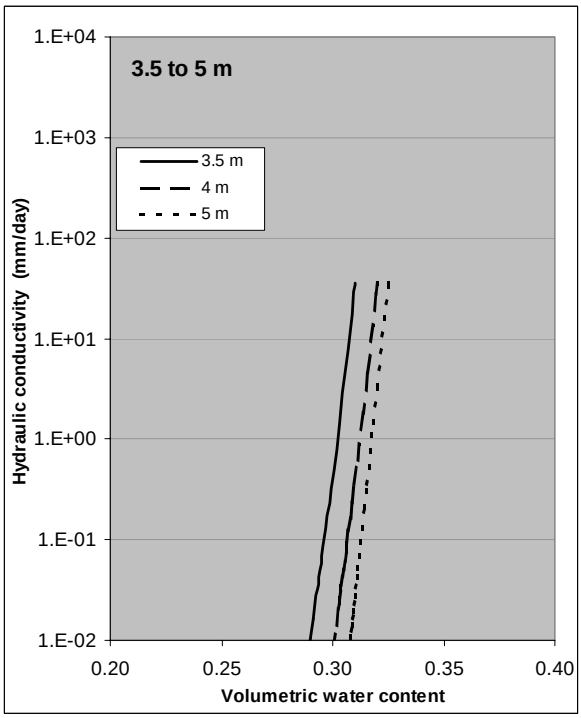




Depth m	θ_s m^3m^{-3}	b	ψ_e cm of water	K_s mm/day	K' mm/day	p	p'
1.3	0.350	27.5	13	35	5	10	93
2	0.360	30.5	10	35	5	10	97
3	0.320	26.0	19	35	5	10	106

Hydraulic Properties for 3.5 to 5 m





Depth m	θ_s m^3m^{-3}	b	ψ_e cm of water	K_s mm/day	K' mm/day	p	p'
3.5	0.310	40	10	35	5	10	78
4	0.320	45	8	35	5	10	68
5	0.325	60	4	35	5	10	38

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