CSIRO Publishing

Australian Journal of Agricultural Research

VOLUME 52, 2001

A journal for the publication of original contributions
towards the understanding of an agricultural system

All enquiries and manuscripts should be directed to:

Australian Journal of Agricultural Research
CSIRO Publishing
PO Box 1139 (150 Oxford St)
Collingwood, Vic. 3066, Australia

Telephone: +61 3 9662 7628
Fax: +61 3 9662 7611
Email: ajar@publish.csiro.au

CSIRO
PUBLISHING

Published by CSIRO Publishing
for CSIRO and the Australian Academy of Science

www.publish.csiro.au/journals/ajar

Aust. J. Agric. Res., 2001, **52**, 955–961

Contributions of soil and crop factors to plant available soil water capacity of annual crops on Black and Grey Vertosols

Z. Hochman[A], *N. P. Dalgliesh*[A], *and K. L. Bell*[B]

[A]CSIRO/APSRU, PO Box 102 (203 Tor Street), Toowoomba, Qld 4350, Australia.
[B]Queensland Department of Primary Industries, PO Box 102 (203 Tor Street), Toowoomba, Qld 4350, Australia.

Abstract. Improved methods for field measurements of plant available soil water capacity (PAWC) of Black and Grey Vertosols in Australia's north-eastern grain region were employed to characterise 83 soil–crop combinations over 7 depth intervals to 180 cm. Soil sub-order was shown to influence all components of PAWC (means of 224 and 182 mm in Black and Grey Vertosols, respectively) with drained upper limit (DUL), bulk density (BD), and crop lower limits (CLL) showing clear separation between soil sub-orders and a trend with soil depth. In addition to soil sub-order and soil depth effects, CLL showed crop effects such that expected PAWC of various crops when adjusted for soil sub-orders were: cotton 240 mm; wheat 233 mm; sorghum 225 mm; fababean 209 mm; chickpea 197 mm; barley 191 mm; and mungbean 130 mm. A total of 549 measured CLL values were used to develop a predictive model for estimating CLL from the soil sub-order, depth, DUL, and crop by predicting a CLL as a function of DUL and a depth-dependent variable for each crop–soil sub-order. The model CLL = DUL * (a + b * DUL) explained 85% of observed variation in the measured data with no significant bias between observed and predicted data. While properly measured data would be more reliable than estimated data, where specific site accuracy is less critical, this model may be used to estimate PAWC with an acceptable degree of accuracy.

Additional keywords: drained upper limit, crop lower limit, bulk density, predictive model, simulation.

Introduction

The concept of the soil as a water reservoir for plant growth is useful for calculating soil water balance and its impact on crop production. This concept is also central to many crop and cropping systems simulators. The potential of cropping systems simulation models to contribute to farmers' learning and decision making depends to a large degree on the ability of such simulators to perform credibly when locally specified and tested against farmers' experiences (McCown *et al.* 1998; Hochman *et al.* 2000). Past attempts to use modelling and simulation to account for yield variations in the field have failed, at least in part, due to the impracticality of obtaining data for such parameters as the water supplying traits of soils (e.g. Boote *et al.* 1996).

Available soil water is defined as the difference between the highest measured volumetric water content in the field (after drainage) and the lowest measured water content when plants are very dry and leaves are either dead or dormant (Ritchie 1981*a*). Plant available water capacity (PAWC) is the maximum amount of stored soil water that is available for plant growth. Field determination of PAWC requires measurement of 2 parameters: (*i*) drained upper limit (DUL), or the volumetric water content in the field after thoroughly wetting the profile and then allowing water to drain to a steady state under gravity; and (*ii*) crop lower limit (CLL) which may be defined as the volumetric soil water retained by the soil after a healthy crop, with uninterrupted root development, has reached maturity under soil water limited conditions.

Annual crops differ in their capacity to exploit water at depths. They also differ in their rooting pattern (e.g. taproot compared with fibrous rooting systems) and the length of time to maturity. Consequently, different CLL values might be expected for different crop species grown on the same soil. Yet, current knowledge of the relationships between root architecture and root function and the relative importance of the rate of water extraction compared with the duration of extraction (Passioura 1988; Gregory 1996) does not allow modellers to infer CLL without empirical data.

Existing methods for estimating PAWC indirectly from particle size analysis (e.g. Littleboy 1997) are useful where soil survey data are available. However, they fail to distinguish differences in CLLs of different crops. They are also expensive to measure given that particle size has to be determined for several depth layers.

10.1071/AR01004 0004-9409/01/100955

The only significant study of the effect of crop type on CLL found relatively small differences among annual crops, particularly in the upper portion of the soil profile where root density is high (Ratliff *et al.* 1983). These authors measured CLL directly by sequential soil water measurements throughout the rooting zone. Their method relied on measurements capturing soil water content of crops that have undergone severe water stress. With this approach severe stress may not occur when data are required. Additionally, the crop may not have a fully developed rooting system at the time of stress and not be able to exploit all the water in the profile that is potentially available to a crop with fully developed roots.

In this paper we set out to explore the possibility of a cost-effective method for determining the PAWC of farmers' soils and crops given the need for this information to be used as input parameters for simulating a specific crop at a paddock scale. Measurements of DUL, CLL, and BD were taken at regular depth increments to 180 cm on 21 Grey Vertosols and 15 Black Vertosols (Isbell *et al.* 1997).

CLL values were determined for wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), chickpea (*Cicer arietinum* L.), fababean (*Vicia faba* L.), mungbean (*Vigna radiata* (L.) Wilczek), grain sorghum (*Sorghum bicolor* (L.) Moench), and cotton (*Gossypium hirsutum* L.) crops.

We outline the methods used and describe the database of soils for which PAWC has been characterised in the Australian north-eastern grain region. To address the difficulties in determining CLL, especially where values are required for a number of crops, the possibility of developing a predictive model of CLL for commonly grown crops in the north-eastern grain region was investigated.

Materials and methods

The methods used to determine DUL and CLL were similar to those described by Ritchie (1981*b*) and by Ratliff *et al.* (1983). They were, however, adapted to overcome the problems of slow water infiltration inherent to the swelling heavy clay soils of this study (Williams 1983), and to avoid some shortcomings associated with opportunistic determination of CLL. The methods used in this research are briefly described below. For a more comprehensive description of these methods see Dalgliesh *et al.* (1998) and Dalgliesh and Foale (1998).

Determining DUL

In principle, DUL is determined by wetting up an area of soil until it has reached saturation, allowing time for drainage, and then sampling soil water content. As a Vertosol never stops draining, it is necessary to use some judgment to determine when drainage is negligible enough to be at DUL. In heavy clay soils where drainage is inherently slow the drained upper limit is more difficult to determine. A standard procedure was adopted in which a trickle irrigation system was established under plastic sheeting (using 100 μm builder's plastic) in a 16-m^2 area. To avoid surface ponding, water was applied through the trickle system under gravity at 200 L per week. A neutron moisture meter (NMM) access tube was inserted in the centre of the trickle system to a depth of 180 cm to allow regular monitoring of the progress of water drainage through the profile.

In some soils the estimation of steady state (using a NMM) is difficult; as the profile nears DUL, the increase in soil water content becomes smaller than the precision of water content measurements with the NMM. Thus, to confirm DUL in such soils, a portable, electronic tensiometer (Watson 1967) was used to check pore water pressure in a test core prior to the main destructive sampling. The core, of 50 mm diameter, was removed from the sampling tube, wrapped in plastic sheeting, and kept in the shade to avoid condensation and evaporation. Small diameter (4 mm) holes were bored at right angles to the length of the core at set points along its length equating to the mid-points of the standard depth intervals used in routine sampling. The ceramic probe of the tensiometer was inserted and the tensiometer was allowed to equilibrate (2–5 min) before pore water pressure was read from the counter. Where pore water pressure was at or above –10 kPa, the soil was considered to be at DUL and ready for sampling. Three soil core samples were taken at each site and divided into 7 depth increments: 0–15, 15–30, 30–60, 60–90, 90–120, 120–150, and 150–180 cm.

Bulk density

Bulk density is required to convert measured gravimetric water content to volumetric water content. In soils that exhibit shrink/swell characteristics BD varies with water content and is difficult to determine in the field by direct measurement of volumes and weights. To overcome this difficulty BD was calculated at DUL using the relationship that exists between measured BD and gravimetric water content (Gardner 1988), using the formula:

$$\text{BD (g/cm}^3) = (1 - e) / (1 / ad + \theta g) \qquad (1)$$

where θg is gravimetric water content (g/g) at DUL; ad is absolute density of the solid matter in the soil (ad is assumed = 2.65 g/cm^3); e is air-filled porosity at θg (e is assumed to be 0.08 and comprising soil water content at saturation – DUL = 0.05, plus total porosity – soil water content at saturation = 0.03). Samples were obtained with coring tubes of 50 mm diameter that were pushed into the soil using hydraulics. As some compression of cores is unavoidable, core lengths were measured and compared with depth of sampling. Compensation for compression was made by assuming that it was uniform with respect to depth.

Crop lower limit

In order to induce a crop to use all the soil water that it was capable of extracting, and to avoid re-wetting of a profile due to late rains, a rain-exclusion tent was erected over a portion (3 m by 3 m) of the vigorously growing crop at around the time of flowering and was left in place until the crop reached maturity. The rain-exclusion tents featured a clear plastic top to allow light to infiltrate to the crop. To facilitate flow of moist air out of the tent, 2 sides of the tent were left open from the ground to a height of 50 cm, and air vents were placed near the apex at both ends. Trenches were used to prevent run-off water from entering the tent area.

To confirm that the potential rooting zone of the soil profile was wet prior to crop extraction, and that crop roots accessed water from a particular part of that zone, gravimetric water content was determined at the time of installation of the rain-exclusion tent. Pre rain-exclusion soil water was then compared with the final soil water content obtained, by taking 3 sample cores in the centre of the central crop inter-row space, at crop maturity, to determine extraction patterns.

Statistical analyses

In all, 577 CLL and 266 DUL and BD data values from up to 7 depths of 83 crop–soil combinations were available for analysis. The aim of analysis was to identify the factors that contribute to variations in PAWC and to derive a model to be used as a predictive tool to determine the CLL of specific crops when the DUL of any Grey Vertosol or Black

Vertosol is known. Although a number of models were tested, the best predictive model was based on the ratio of CLL to DUL. The CLL/DUL ratio was modelled against DUL and depth for each soil sub-order and crop.

Repeated measures analysis of DUL, BD, CLL and PAWC across depths was undertaken by using GENSTAT's residual maximum likelihood (REML) procedure to model the correlation across depths and to handle the imbalance in the data (GENSTAT 5 Committee 1997). Heterogeneity of variances across depths was tested using the change in deviance and found to have a significant effect on the models for all 4 variables.

Sites were used as the subject term for DUL and BD. Depth, soil sub-order, and their interaction were fitted to the model and all terms were found to be highly significant ($P < 0.003$). Each crop–soil combination was used as the subject term for CLL and PAWC. Soil, depth, crop and their interactions were fitted to the model and then non-significant terms were dropped using backward elimination. Due to the heterogeneity of variances, standard error of differences and least significant differences (l.s.d.) were calculated to compare treatments for each depth separately. A significance level of $P = 0.05$ was used in all testing.

To predict CLL, the CLL/DUL ratio was modelled for each combination of soil sub-order and crop by fitting depth, DUL, and their interaction and a correlation across depths using the REML procedure in GENSTAT. In some cases there was no data or only 1 replicate so no model was fitted. There was no significant heterogeneity of variances of CLL values across depths. A model predicting CLL with depth and DUL suited most crop–soil sub-order combinations. The CLL estimates were determined using a linear regression approach.

The internal consistency of the derived model was tested for goodness of fit by regressing predicted against measured values, omitting those crops that had only 1 site for a given soil group.

Results and discussion

Field measurement data were collated in a database published (along with site grid references and data from other soil sub-orders) as a booklet that was inserted in the folder of the Dalgliesh and Foale (1998) manual. Updated versions of the database may be downloaded from the internet at: www.farmscape.tag.csiro.au

Analysis of soil sub-order and depth showed significant differences ($P < 0.001$) in DUL values and a soil sub-order × depth interaction was also significant ($P = 0.002$). Similarly, soil sub-order, depth, and soil sub-order × depth interactions showed significant ($P < 0.001$) differences in BD values. The main factors influencing CLL values were soil sub-order, depth, and crop type ($P < 0.001$) as well as the soil sub-order × depth and crop × depth interactions ($P < 0.001$). Similarly, PAWC was influenced by soil sub-order, depth, and crop type ($P < 0.001$) as well as the crop type × depth ($P = 0.002$) and soil sub-order × depth ($P = 0.004$) interactions. Importantly, there was no significant crop type × soil sub-order interaction for any of the variants.

Table 1 shows the mean values of BD, DUL, and PAWC for Black and Grey Vertosols for depth × soil sub-order after adjustment for non-orthogonal crop influences on PAWC. The tendency of Black Vertosols to have lower BD and higher DUL than Grey Vertosols at all depths was clearly shown. The low l.s.d. values in these data indicate that soil sub-order and depth are good predictors of these parameters. The higher PAWC values of Black Vertosols at all depths (total PAWC = 224 mm) confirm similar results reported by Littleboy (1997) that they store more water than Grey Vertosols (total PAWC = 182 mm). The higher l.s.d. values observed for PAWC may be due, at least in part, to it being a function of 2 variables (DUL and CLL). Figure 1 shows adjusted mean DUL values as a function of soil depth with their respective mean CLL values for all crops on Black and Grey Vertosols. In both soil sub-orders, CLL increased with depth. However, the differences between CLLs and DULs on the Black Vertosols were greater than the Grey and persisted to a greater depth.

Ratliff *et al.* (1983) reported an average of 12.9 cm^3/cm^3 of PAWC between 30 and 120 cm depth for clay soils in the USA, although they found little evidence of increase in PAWC with texture fineness increases from silt loam to clay. The higher clay content of soils in the current study may explain the different observations. The higher values and the more pronounced trend for reduced PAWC with depth in the current study may also relate to the shrink–swell properties of the Vertosols. Possibly, the lower BD of Black Vertosols (rather than their higher clay content) contributed to their

Table 1. Comparison of drained upper limit (DUL, % volume), bulk density (BD, g/cm^3), and plant-available water capacity (PAWC, mm) of Black and Grey Vertosols

Depth (cm)	BD			DUL			PAWC		
	Black Vertosol	Grey Vertosol	l.s.d.	Black Vertosol	Grey Vertosol	l.s.d.	Black Vertosol	Grey Vertosol	l.s.d.
0–15	1.06	1.39	0.073	51.1	39.3	2.8	36.0	26.2	2.7
15–30	1.11	1.40	0.073	50.3	39.4	2.8	29.4	24.2	3.0
30–60	1.12	1.39	0.065	49.9	39.4	2.4	49.7	46.6	4.4
60–90	1.12	1.42	0.065	49.6	38.6	2.4	44.5	38.3	4.9
90–120	1.16	1.43	0.067	48.1	38.1	2.5	32.1	27.1	4.7
120–150	1.21	1.44	0.073	46.4	37.6	2.7	20.7	14.2	5.2
150–180	1.24	1.44	0.083	45.1	37.2	3.0	11.3	4.9	5.1

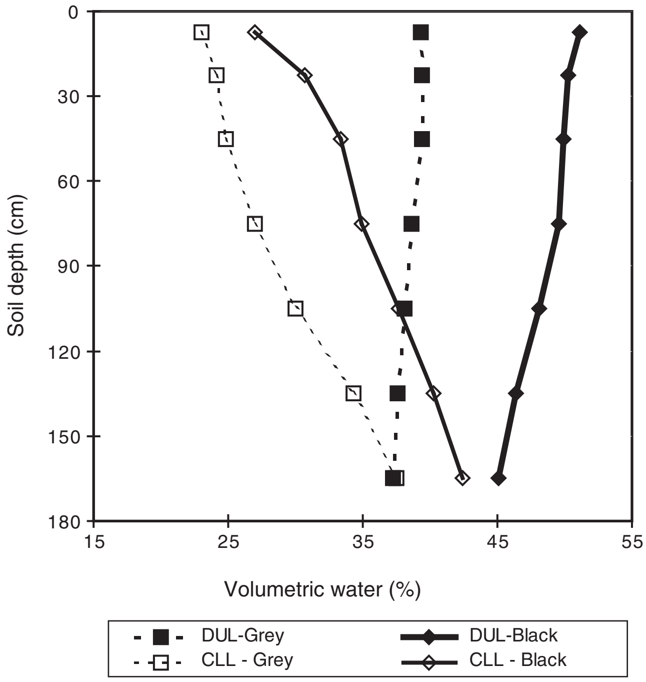

Fig. 1. Adjusted means of drained upper limit (DUL) and crop lower limit (CLL) values of all crops on Black and Grey Vertosols.

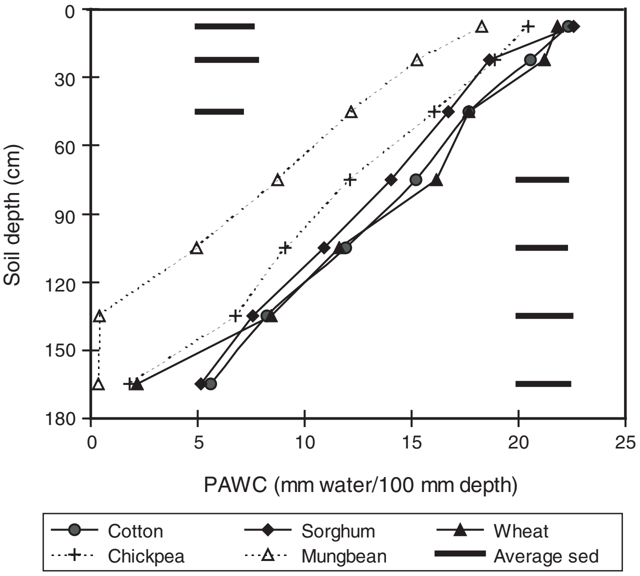

Fig. 2. Adjusted means of plant available water capacity (PAWC) values of 6 crop types on Black and Grey Vertosols.

greater PAWC. Other factors that might explain differences in PAWC between and within soils include texture, structure, and clay mineralogy (Williams *et al.* 1983; Gaiser *et al.* 2000) as well as salinity, sodicity, acidity, nutrient deficiency, and the positive and negative influences of various soil biota.

Mean values of PAWC of different crops grown on both Black and Grey Vertosols, as adjusted for the unbalanced nature of crops and soils in the data set, are shown in Table 2. These data show the effect of crop type and soil depth on PAWC. Total PAWC of the various crops added up to: cotton 240 mm; wheat 233 mm; sorghum 225 mm; fababean 209 mm; chickpea 197 mm; barley 191 mm; and mungbean 130 mm. At the $P = 0.05$, PAWC of cotton is greater than that of barley, chickpea, and mungbean. All crops except barley have significantly higher PAWCs than mungbean.

Figure 2 shows the depth profile of mean PAWC (expressed here as mm water/100 mm soil depth to remove the artefact due to different depth intervals) of various crops after adjusting for site and soil differences. Of the 5 crops shown (barley and fababean were omitted to reduce visual clutter) cotton and sorghum have the highest PAWC throughout the soil profile. Wheat is similar to cotton and sorghum to the 120–150 layer but has a lower PAWC in the 150–180 cm layer. Compared with cotton, sorghum, and wheat, the legume crops have lower PAWC values especially

Table 2. Adjusted means of plant available water capacity (PAWC, mm) of 7 crop types grown on Black and Grey Vertosols

Number in brackets indicates for each crop the number of soils on which PAWC was determined. Within rows, values followed by the same letter are not significantly different (at $P = 0.05$)

Depth (cm)	Cotton (25)	Sorghum (19)	Wheat (18)	Barley (5)	Fababean (4)	Chickpea (8)	Mungbean (3)
0–15	33.4a	33.9a	32.7a	26.7b	32.0ab	30.7ab	27.5ab
15–30	30.8a	28.0ab	31.8a	22.9b	28.3ab	28.3ab	22.9b
30–60	53.1a	50.2a	53.1a	46.8ab	47.6ab	48.2ab	36.5c
60–90	45.7a	42.1ab	48.5a	42.6ab	42.8ab	36.4bc	26.2c
90–120	35.8a	32.8ab	34.8ab	27.6abc	25.7abc	27.3bc	14.9c
120–150	24.6a	22.7a	25.2a	19.4a	19.1a	20.3a	1.2b
150–180	16.9a	15.5ab	6.6cd	5.2bcd	13.1abcd	5.5cd	1.1d
Total	240a	225ab	232ab	191bc	208ab	196b	130c

Table 3. Fitted values for parameters *a* and *b* of the equation [predicted CLL = DUL * (*a* + *bDUL)] for Black and Grey Vertosols**

Values in parentheses are the standard errors

Crop	Depth centre (cm)	*a* Black Vertosol	*a* Grey Vertosol	*b* Black Vertosol	*b* Grey Vertosol
Cotton	7.5	0.832 (0.097)	0.853 (0.056)	–0.0070 (0.0019)	–0.0082 (0.0014)
	22.5	0.868 (0.093)	0.851 (0.056)		
	45.0	0.951 (0.092)	0.883 (0.056)		
	75.0	0.988 (0.092)	0.953 (0.055)		
	105.0	1.043 (0.089)	1.022 (0.054)		
	135.0	1.095 (0.087)	1.125 (0.054)		
	165.0	1.151 (0.086)	1.186 (0.053)		
Sorghum	7.5	0.699 (0.081)	0.818 (0.141)	–0.0038 (0.0016)	–0.0071 (0.0034)
	22.5	0.802 (0.079)	0.864 (0.141)		
	45.0	0.853 (0.079)	0.882 (0.140)		
	75.0	0.907 (0.078)	0.938 (0.138)		
	105.0	0.954 (0.076)	1.013 (0.137)		
	135.0	1.003 (0.074)	1.096 (0.137)		
	165.0	1.035 (0.072)	1.172 (0.138)		
Wheat	7.5	–0.124 (0.442)	0.660 (0.082)	0.0116 (0.0086)	–0.0032 (0.0020)
	22.5	–0.049 (0.453)	0.655 (0.082)		
	45.0	0.024 (0.445)	0.701 (0.082)		
	75.0	0.029 (0.443)	0.745 (0.081)		
	105.0	0.146 (0.427)	0.845 (0.080)		
	135.0	0.246 (0.408)	0.933 (0.080)		
	165.0	0.406 (0.396)	1.084 (0.079)		
Barley	7.5	0.516	0.847 (0.164)	1 rep only	–0.0051 (0.0040)
	22.5	0.586	0.866 (0.160)		
	45.0	0.644	0.835 (0.167)		
	75.0	0.665	0.872 (0.166)		
	105.0	0.777	0.981 (0.162)		
	135.0	0.854	1.036 (0.155)		
	165.0	0.988	1.152 (0.151)		
Chickpea	7.5	0.639	0.435 (0.104)	1 rep only	0.0029 (0.0025)
	22.5	0.628	0.452 (0.105)		
	45.0	0.736	0.481 (0.105)		
	75.0	0.772	0.595 (0.103)		
	105.0	0.812	0.668 (0.102)		
	135.0	0.835	0.737 (0.102)		
	165.0	0.888	0.875 (0.103)		
Fababean	7.5	No data	–0.467 (0.289)	No data	0.02455 (0.0067)
	22.5	No data	–0.451 (0.291)		
	45.0	No data	–0.396 (0.285)		
	75.0	No data	–0.336 (0.282)		
	105.0	No data	–0.190 (0.278)		
	135.0	No data	–0.134 (0.278)		
	165.0	No data	–0.084 (0.276)		
Mungbean	7.5	0.542	0.779 (0.236)	1 rep only	–0.0034 (0.0056)
	22.5	0.693	0.770 (0.237)		
	45.0	0.735	0.834 (0.229)		
	75.0	0.732	0.990 (0.218)		
	105.0	0.899	1.008 (0.210)		
	135.0	0.999	1.144 (0.266)		
	165.0	1.000	1.150 (0.276)		

at depths below 30 cm. Mungbean has the lowest PAWC at all depths with little evidence of water extraction below 120 cm depth. While root architecture cannot be ruled out as a contributing factor, the observed results are consistent with crop duration and rooting depth.

Using and testing the CLL prediction model

The model selected for predicting CLL was of the general form of Eqn 2:

$$\text{Predicted CLL} = \text{DUL} * (a + b * \text{DUL}) \qquad (2)$$

where for each crop × soil-suborder combination, *a* changes for each depth and *b* remains the same.

Fitted values for *a* and *b* are provided in Table 3. Interestingly, the slopes (*b* value) of some crops (e.g. wheat) are not significantly different from zero, while slopes of other crops are either significantly negative (e.g. cotton) or significantly positive (e.g. fababean). A detailed study of the relationship between soil and root characteristics would be needed to explain these differences.

To test the model's goodness of fit, measured CLLs in the database were compared with predicted CLLs using Eqn 2 and reading *a* and *b* values from Table 3. Figure 3 shows the regression of predicted CLL versus actual CLL. The regression equation was:

$$\text{Actual CLL} = -0.015\ (0.521) + 1.0005\ (0.0178) \times \text{Predicted CLL}$$

where the values in brackets are the standard errors of the parameters; 549 values were used in the regression. The adjusted R^2 is 85.3% and the regression is highly significant ($P < 0.001$). The intercept is not significantly different from zero ($P = 0.977$) and the slope is not significantly different from 1 ($P = 0.978$). These results indicate no significant bias in the predictions across the range of CLL.

Conclusions

Application of improved methods for determining PAWC, and the availability of a relatively large set of data of crop-soil combinations, has provided an opportunity for a more rigorous analysis of soil and crop factors than any previously undertaken. This analysis showed clear differences between Grey and Black Vertosols in their BD, DUL, and, averaged over all crops, CLL and PAWC values. In contrast to the findings of Ratliff *et al.* (1983), important differences in CLL values of different crop types were demonstrated throughout the depth profiles of each soil sub-order.

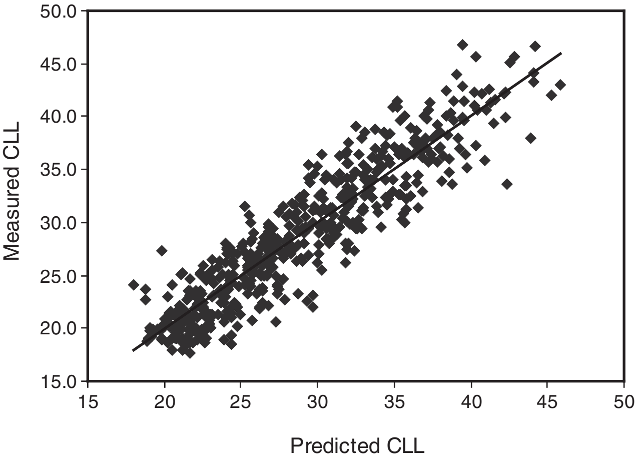

Fig. 3. Comparison of measured and predicted crop lower limit (CLL) values of all crop–soil combinations.

This research has produced a predictive model for calculating CLL values for most crops of economic importance grown on Grey and Black Vertosols in the Australian north-eastern cropping region. The model requires input data of DUL, layer depth, soil sub-order, and crop type. It accounts, without bias, for 85% of variation in the data. This result shows the robustness of the model in determining CLL, given that there were probably significant differences in other soil (e.g. salinity and sodicity) and agronomic (e.g. crop varieties and row spacing) factors.

While reliably measured data are always preferred to estimated data, the costs as well as the benefits of obtaining measured data should be considered against the aims of any crop modelling effort. Depending on the importance placed on specific site accuracy this research allows the modeller 3 options: at the highest level of accuracy requirement, data may be measured according to the field methods used to obtain the data for this study; at the next level of required accuracy, BD and DUL may be measured while CLL is calculated from the model; at the lower level of accuracy, only soil sub-order need be known with CLL calculated using mean BD and DUL of the appropriate soil sub-order.

Improvements to the predictive CLL model may follow from re-analysis once more data are added to the database for crops that are less well represented. Data from other soils may also facilitate modelling CLLs on soils other than Vertosols.

Acknowledgments

This work was made possible by funding from the Grains Research and Development Corporation and the Cotton Research and Development Corporation. Mr S. Cawthrey and Mr B. Cocks, (CSIRO/APSRU); Dr M. Bange and Mr D. Richards (CSIRO Cotton Research Unit, Narrabri); Dr R. Connolly, Dr D. Freebairn, Mr G. Wockner, and Mr J. B. Robinson (QDNR/APSRU); Mr N. Christdoulu and Mr D. Lack (QDPI); and Mr C. Cole (NSW Agriculture) gathered soil characterisation data.

References

Boote KJ, Jones JW, Pickering NB (1996) Potential uses and limitations of crop models. *Agronomy Journal* **88**, 704–715.

Dalgliesh NP, Foale MA (1998) Soil matters-Monitoring soil water and nutrients in dryland farming systems. CSIRO/Agricultural Production Systems Research Unit, Technical Manual-ISBN 0 643 06375 7.

Dalgliesh NP, McCown RL, Bridge B, Probert ME, Cawthrey S (1998) Characterising soils for plant available water capacity – Challenges on shrink/swell soils. In 'Proceedings of the 9th Australian Agronomy Conference'. Wagga Wagga, 1998. pp. 793–794.

Gaiser T, Graef F, Cordeiro JC (2000) Water retention characteristics of soils with contrasting clay mineral composition in semi-arid tropical regions. *Australian Journal of Soil Research* **38**, 523–536.

Gardner EA (1988) Lecture 10—Soil Water In Understanding Soils and Soil Data, pp. 153–185. (Australian Society of Soil Science Inc., Qld Branch: Brisbane)

GENSTAT 5 Committee (1997) 'GENSTAT 5 Release 4.1 Reference Manual Supplement.' (Clarendon Press: Oxford)

Gregory PJ (1996) Root dynamics of cropping systems: major issues and research needs. In 'Roots and nitrogen in cropping systems of the semi-arid tropics'. (Eds O Ito, C Johansen, JJ Adu-Gyamfi, K Katayama, JVDK Kumar Rao, TJ Rego) pp. 285–289. (JIRCAS/ICRISAT: Patancheru, AP, India)

Hochman Z, Coutts JA, Carberry PS, McCown RL (2000) The FARMSCAPE experience—Simulations aid participative learning in risky farming systems in Australia. In 'Cow up a tree: Knowing and learning processes for change in agriculture. Case studies from industrial countries'. (Eds M Cerf, D Gibbon, B Hubert, R Ison, J Jiggins, M Paine, J Proost, N Röling) pp. 175–188. Coll. Science Update (INRA Editions: Paris)

Isbell RF, McDonald WS, Ashton LJ (1997) 'Concepts and rational of the Australian soil classification.' (CSIRO Publishing: Melbourne)

Littleboy M (1997) Spatial generalization of biophysical simulation models for quantitative land evaluation: a case study for dryland wheat growing areas of Queensland. PhD thesis, Department of Geographical Sciences and Planning, University of Queensland.

McCown RL, Carberry PS, Foale MA, Hochman Z, Coutts JA, Dalgliesh NP (1998) The FARMSCAPE approach to farming systems research. In 'Proceedings of the Australian Agronomy Conference'. Wagga Wagga, 1988. pp. 633–636.

Passioura JB (1988) Water transport in and to roots. *Annual Review of Plant Physiology and Molecular Biology* **39**, 245–265.

Ratliff LF, Ritchie JT, Cassel DK (1983) A survey of field-measured limits of soil water availability and related to laboratory-measured properties. *Soil Science Society of America Journal* **47**, 770–775.

Ritchie JT (1981*a*) Water dynamics in the soil-plant-atmosphere system. *Plant and Soil* **58**, 81–96.

Ritchie JT (1981*b*) Soil water availability. *Plant and Soil* **58**, 327–338.

Watson WW (1967) A recording field tensiometer with rapid response characteristics. *Journal of Hydrology* **5**, 33–39.

Williams J (1983) Physical properties and water relations: Soil hydrology. In 'Soils: an Australian viewpoint'. pp. 499–530. (CSIRO: Melbourne/Academic Press: Melbourne)

Williams J, Prebble RE, Williams WT, Hignett CT (1983) The influence of texture, structure and clay mineralogy on the soil water characteristic. *Australian Journal of Soil Research* **21**, 15–32.

Manuscript received 4January 2001, accepted 20 June 2001