Soil Water Measurements at the Murrumbidgee Grain & Graze Coolamon Focus Farm, 2005/06

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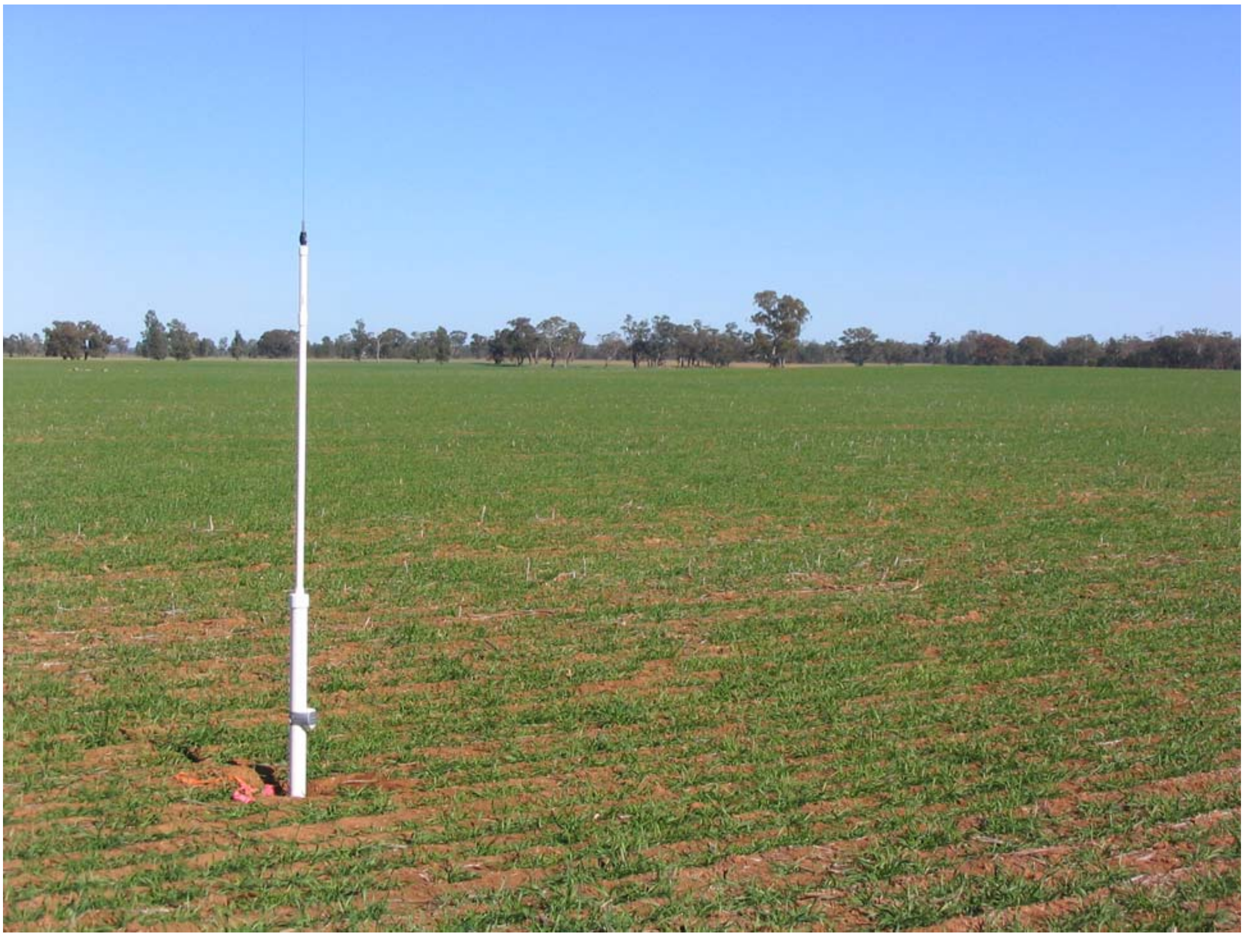

CSIRO Land and Water Science Report 17/06

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Cover Photograph:

Description: Wireless logger antenna in the *grain-only wheat* paddock of the Coolamon Focus Farm, August 2005
Photographer: Warren Bond

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Acknowledgements

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Executive Summary

In April 2005, soil water sensors were installed in the five paddocks of the Coolamon Focus Farm project of Murrumbidgee Grain & Graze. This project aims to monitor production and sustainability indicators across a range of mixed farming enterprises: perennial pastures, annual pastures, native pastures and cereals (grazed and ungrazed). Watermark® gypsum blocks were chosen for the soil water sensors because they are relatively inexpensive and easy to install. They were connected to CSIRO wireless microloggers that measured and stored the results as well as transmitting the results several times each day to a central base station. This base station then forwarded the results to a publicly accessible web page every morning before 3 am (www.clw.csiro.au/MoistureWeb/GrainGraze/Raywood).

The 2005 winter rainfall caused wetting to at least 1.2 m in all paddocks. Wetting was deepest under *annual pasture*, which was much wetter at the start of winter than other paddocks, and under the *native woodland*. The latter is attributed to a low rate of water use by native vegetation during the winter months. It may also be aided by the better soil structural conditions at the surface and throughout the soil that would be expected under undisturbed native woodland than under intensively farmed paddocks.

Prior to harvest, drying of the soil under the *wheat* crops had occurred to a depth of about 1.2 m. This is comparable to the maximum effective rooting depth of wheat and other cereals observed at other sites with similar soils in the Wagga Wagga region. However, the wheat left accessible water behind in the soil. After harvest, the *wheat* paddocks re-wet to some extent with the summer rainfall but at the end of April 2006 they were drier at all depths down to and including 1.2 m than at the same time in 2005. This reflects the better water extraction ability of wheat compared to the canola grown in 2004.

In contrast, the *annual pasture* only dried the soil to 0.6 m. This reflects the shallow rooting depth of most annual pasture species. The soil above 0.6 m re-wet over summer, but there was little change below 0.6 m. At the end of April 2006 this paddock was much wetter at all depths than at the same time in 2006. It is very likely that water was penetrated deeper than 1.6 m under this paddock, contributing to groundwater recharge, the only paddock in 2005/06 where this occurred.

The *perennial pasture* dried the soil strongly after winter, down to 1.4 m at the time the wheat was harvested in December 2005, and down to 1.6 m by April 2006. By April 2006 the soil at all depths was at least as dry as at the same time in 2005. In particular it can be seen that there has been effective water use at 1.4 and 1.6 m in 2006 compared with 2005.

Similarly, the *native woodland* actively extracted soil water down to at least 1.6 m. All depths at 1 m and above were at least as dry in April 2006 as at the same time in 2005, but below that the soil remains wetter, although not by very much.

Wheat was the most effective user of water in winter and spring. Grazing had little if any effect on water use of the wheat crops. Lucerne and native vegetation used less water in this period because they tend to grow less vigorously at that time of the year, while *annual pasture* was limited by its shallow rooting depth and lower leaf area.

Over summer and autumn, water accumulated in the soil under *wheat* and *annual pasture* when rainfall occurred in amounts greater than 20 to 30 mm per day, while *perennial pasture* and *native woodland* continued to dry the soil.

Of the five contrasting land uses, *annual pasture* used the least soil water. This resulted in lower production of dry matter and a greater risk of groundwater recharge.

Table of Contents

1. Background and Introduction

Five focus farms (Coolamon, Temora, Euroley Bridge, Tarcutta and Lockhart) were established by Murrumbidgee Grain & Graze in 2005 to monitor production and sustainability indicators across a range of mixed farming enterprises: perennial pastures, annual pastures, native pastures and cereals (grazed and ungrazed).

Monitoring included dry matter, feed quality, ground cover, water use & biodiversity to determine the impact of management decisions on productivity and the natural resource base. The Focus Farm monitoring was undertaken in conjunction with the 'Best Management Practices for Dryland Agriculture' project (Murrumbidgee CMA and NSW DPI). Results from the main project are reported elsewhere (e.g. "Grain & Graze Focus Farm Facts" at www.farmlink.com.au/results3.htm.

CSIRO Land and Water was commissioned to supply daily soil water monitoring under each of the five paddocks at the Coolamon Focus Farm to compare water use between different land uses. This report describes the measurements and results from the 2005/2006 season up to 30 April 2006. Four main aspects of the results are discussed:

- depth of penetration of the winter rainfall
- depth of soil drying by the crops
- comparison of water use between treatments
- soil water behaviour in summer and autumn

The data can be viewed at www.clw.csiro.au/MoistureWeb/GrainGraze/Raywood

Monthly reports of the other monitoring results can be found at www.farmlink.com.au/results3.htm

2. Overview of the Methodology and Supporting Information

2.1. Location and Treatments

Soil water measurements were made in the five paddocks selected for monitoring on the Coolamon Focus Farm property "Raywood", 12 km north of Coolamon, NSW, as part of the 'Best Management Practices for Dryland Agriculture' project. These paddocks were spread out over an area of 5 x 2.5 km, as shown in the map in Fig. 1.

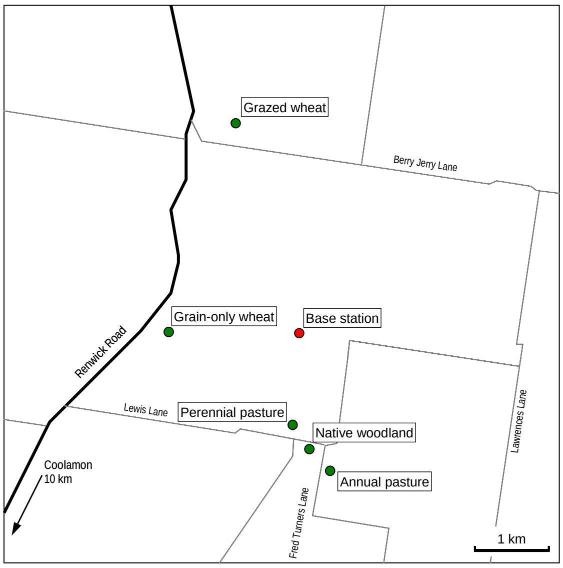


Fig. 1. Location of the paddocks monitored and the central base station.

The paddocks selected for monitoring contained *grain-only wheat*, *grazed wheat*, *annual pasture*, *perennial pasture*, and a remnant native woodland pasture. Relevant details of the paddocks' histories and management during 2005 are summarised below. (extracted from the "Coolamon Focus Farm Facts" prepared by Damien Doyle and Sheila de Lange (see "Grain & Graze Focus Farm Facts" http://www.farmlink.com.au/results3.htm)

Grain-only wheat.

This paddock had been sown to canola in 2004. Wheat (*cv. Rosella*) was sown dry on 4th May 2005.

Although intended as a grain-only treatment, the scarcity of feed in winter and spring meant that it was grazed from 15th July to 1st August with 3.2 ewes/ha, and from 15th August to 15th September with 3.5 40 kg Merino lambs/ha. Stock were removed when the first nodes formed on the wheat.

Grazed wheat.

This paddock had also been sown to canola in 2004. It was sown dry with wheat (*cv. Rosella*) on 27th April 2005.

It was grazed from 17th July to 7th August with 6.6 ewes/ha, and again from 9th August to 6th September with 1.6 merino wether lambs/ha. Stock were removed when the first wheat nodes formed.

Annual pasture.

This paddock is predominantly sub clover and has been under annual pasture for more than 5 years.

The paddock has been grazed more or less continuously since establishment of the project whenever there was sufficient feed. On 18th October it was sprayed to control grass weeds and improve the sub clover establishment and then grazed with 8 merino ewes/ha.

Perennial pasture.

This paddock was sown with a lucerne/chicory mix in Spring 2004.

From 18th to 22nd July it was grazed at a rate of 23.5 wet ewes/ha. From the 23rd July to 2nd September it was grazed at a rate of 3.4 lambing ewes/ha. From 2nd September to 10th of October it was grazed with 2.7 lambing merino ewes/ha. It was grazed heavily from the 31st October to 16th of November with 15 merino lambs/ha. It was then grazed regularly at 16 dse for about 10 days per month for the rest of the reporting period.

Native woodland.

The native pasture is a remnant woodland area that is not open to grazing. The pasture is comprised mainly of Kangaroo grass and *Austrostipa* species, with introduced annual grasses and weeds making up about 1% of the paddock.

2.2. Soil Water Measurements

The chosen soil moisture sensors were Watermark® gypsum blocks. These have the advantages of low cost, and ease of installation at depths up to 2 m or more. The main disadvantage is that these sensors measure soil water potential, rather than soil water content, and soil water potential cannot be directly related to soil water storage in mm of water without site calibration. Nevertheless, much useful information can be obtained, as described later in this report, at a substantially lower cost compared with more quantitative measurements of soil water content. A guide to interpreting these measurements is attached in Appendix B.

Sensors were installed in April 2005 (prior to sowing of the cropped paddocks) at one location in each paddock, adjacent to the transect along which soil and pasture sampling was carried out. The sensors were installed at depths from 0.2 m to 1.6 m below the soil surface at 0.2 m intervals.

Each set of sensors was connected to a data logger buried below the soil surface adjacent to the sensors. The data loggers measured the sensors four times each day and, using radio telemetry, the results were transmitted to a central base station receiver located at the farm sheds (Fig. 1). This in turn communicated daily by cdma telephone link to a computer at the CSIRO Laboratories, from where the data were uploaded daily to the website. By this means, data from the previous day were usually available by 3 am each morning.

A more detailed description of the methodology can be found in Appendix A. In addition, some notes on interpreting the measurements are attached in Appendix B.

The complete data set for each plot is presented in Appendix C.

Full details of the methodology, results and a running commentary on them can be found at: www.clw.csiro.au/MoistureWeb/GrainGraze/Raywood/

2.3. Rainfall and Dry Matter Production

Interpretation of the soil water measurements is aided by knowing the rainfall and the crop response. Rainfall data measured on the "Raywood" property has been collated by Damien Doyle (see "Grain & Graze Focus Farm Facts" http://www.farmlink.com.au/results3.htm), and is presented in Fig. 2. Although the usual estimate of crop growth is dry matter production, in this case we use "green feed on offer", which was measured as part of the 'Best Management Practices for Dryland Agriculture' project. This was extracted from "Grain & Graze Focus Farm Facts" (http://www.farmlink.com.au/results3.htm) and is presented in Fig. 3.

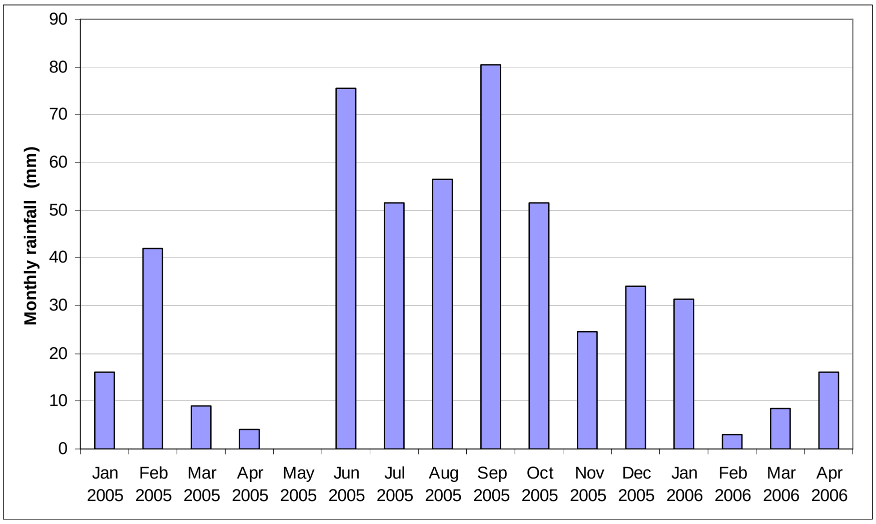


Fig. 2. Rainfall measured at Raywood between January 2005 and April 2006 (courtesy Ian Jennings).

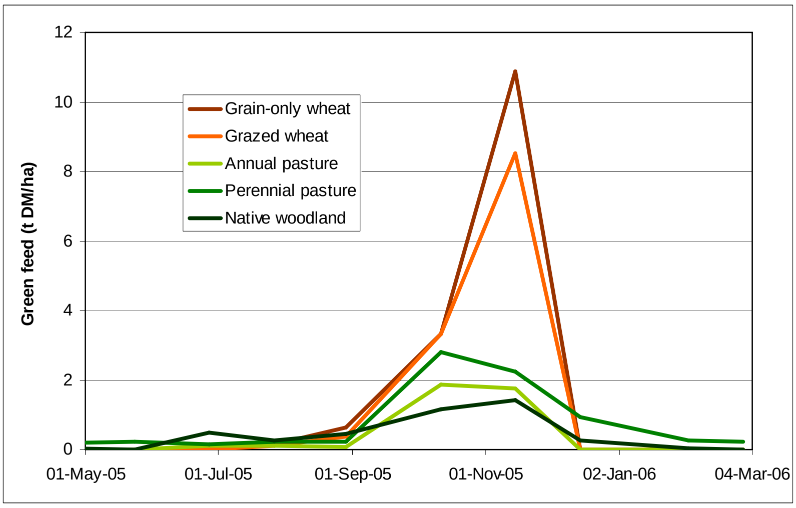


Fig. 3. Green feed on offer in each paddock throughout 2005 (data from Sheila de Lange and Damien Doyle, "Grain & Graze Focus Farm Facts", www.farmlink.com.au/results3.htm).

3. Pre-Season Soil Moisture and Winter Wetting

Immediately after the installation of the soil moisture sensors there was a period of equilibration as the sensors adjusted to the soil conditions. In most cases the sensors, which were wet before installation, were wetter than the soil and therefore steadily dried before reaching a stable, constant state of dryness. This effect was most obvious under the *native woodland* (see Appendix C) where the soil was initially very dry at all depths. Most sensors had equilibrated with the soil by the end of May, just in time for the arrival of the rain on 10 June.

The arrival of winter rainfall at individual depths can be seen quite clearly in the data traces (see Appendix C). This is illustrated in Fig. 4 for the *grain-only wheat* paddock. The first wetting at 0.2 m (16 Jun), in response to the commencement of rainfall on 10 June, was abrupt and followed soon after by wetting at 0.4 m (20 June). As the rainfall continued, wetting occurred deeper in the soil: 0.6 m (28 June), 0.8 m (9 July), 1.0 m (26 July) and 1.2 m (20 Aug). As the wetting front penetrated deeper the rapidity of the response decreased and the wetting pattern became broader. In the *grain-only* paddock wetting did not occur at 1.4 or 1.6 m. The gentle wetting trend from August onwards at both those depths (clearer in Appendix C) is attributed to soil warming and the effect of the increasing temperature causing the sensor output to indicate an apparent wetting (as described in Appendix B).

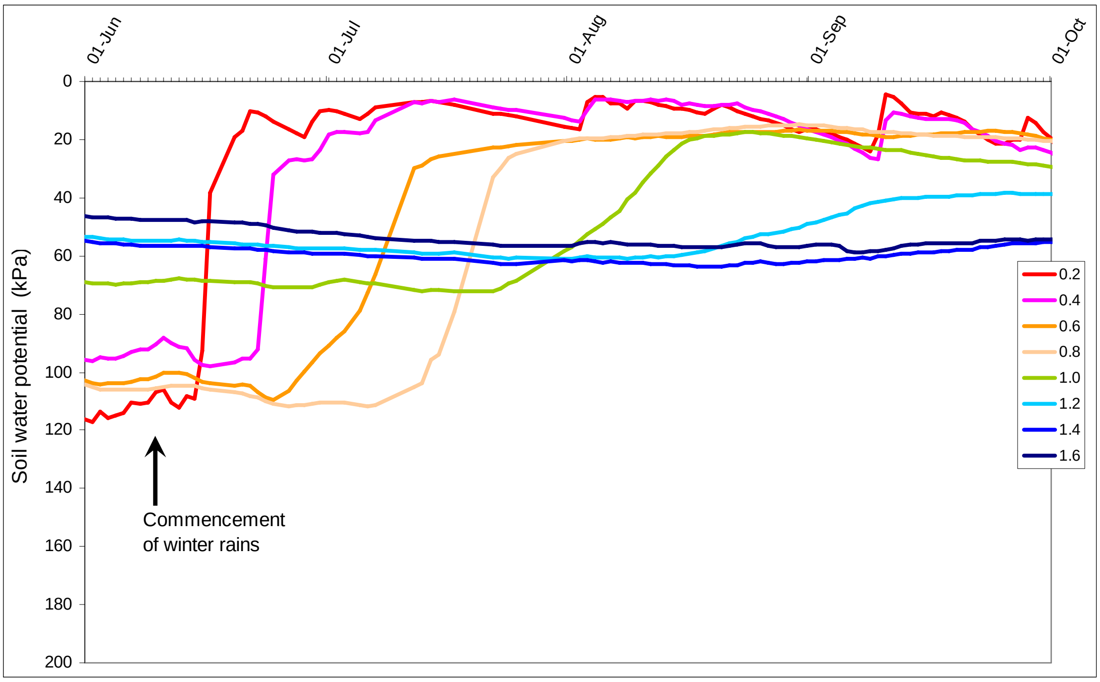


Fig. 4. Soil water potential data for the grain-only paddock, showing profile wetting during winter and spring.

The arrival of the wetting front at different depths is summarised for all paddocks in Fig. 5. In the two *wheat* paddocks and the *perennial pasture* paddock, the maximum depth of wetting was between 1.2 and 1.4 m, while under the *annual pasture* and *native woodland* wetting was observed all the way down to the deepest measurement depth of 1.6 m (and perhaps extended beyond that). The rate of wetting was quite similar in all paddocks, although wetting at 1 m under the *perennial pasture* was somewhat later than in the other paddocks. It also took longer for the wetting front to reach 1.6 m under the *native woodland* than under the *annual pasture*.

The depth of wetting is determined by a number of factors apart from the amount of rainfall, which was assumed to be roughly the same for all paddocks. These include how wet the soil was to start with, and how much of the rainfall was evaporated from the soil or used by vegetation. As can be seen from the "green feed on offer" graph (Fig. 3), there was very little difference in growth between the paddocks up to 1st September, during which time wetting occurred in each of the paddocks at more or less the same rate. After that, the *wheat* paddocks produced much more growth (and therefore, we would expect, water use) than the other paddocks until the crops senesced in November, so that more of the rain that fell in September and October (Fig. 2) was used and less available to move further into the soil. The *perennial pasture* produced almost as much growth in September as the *wheat*, which helps explain the shallower wetting in that paddock.

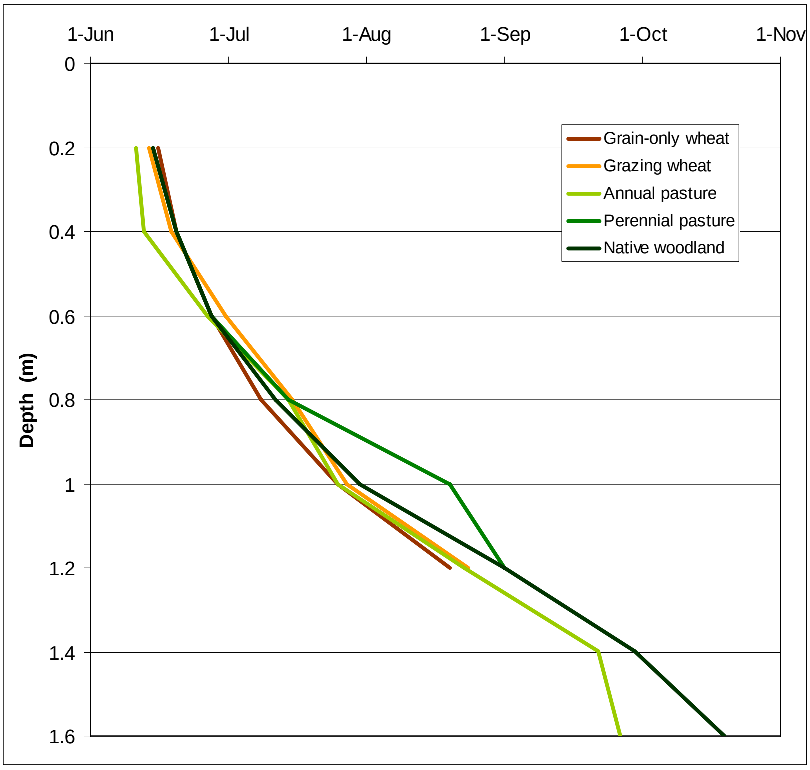


Fig. 5. Time of arrival of the wetting front at each measurement depth in each paddock.

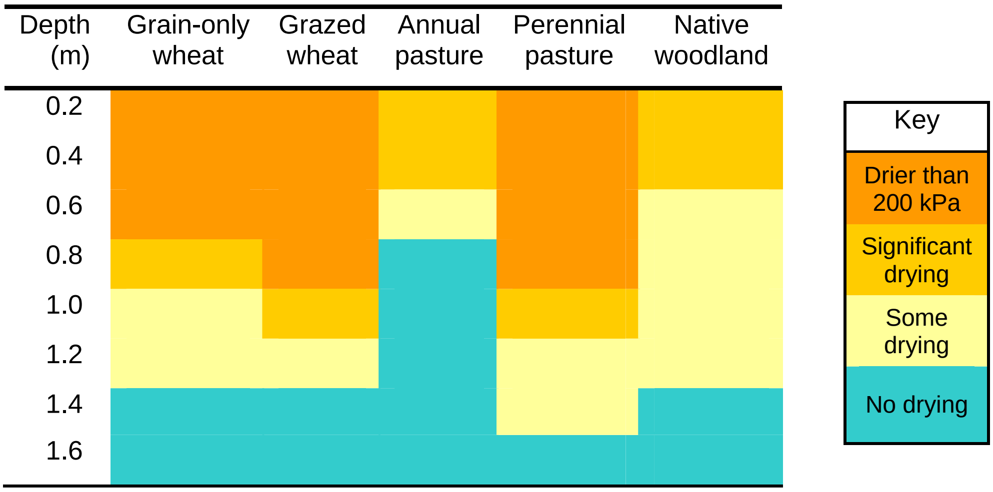
The *annual pasture* paddock was the wettest coming into the winter at depths below 40 cm (see Appendix C), so had less capacity to store the winter rainfall. It is therefore not surprising that this paddock wet all the way to 1.6 m and reached that depth earlier than the *native woodland*. The deep wetting of the soil under the *native woodland* is attributed in a low rate of water use during the months when most of the rain fell. It may also be aided by better soil structural conditions at the surface and throughout the soil that would be expected under undisturbed native woodland than under intensively farmed paddocks. The wetting results are consistent with measurements of water storage patterns under native vegetation in the Lester State Forest just to the south-west of Coolamon (Bond et al., unpublished data).

4. Soil Drying in the Growing Season

The soil water potential data also give a clear indication of how deep in the soil profile drying occurred. Unfortunately the WaterMark® sensors used for the measurements are capable of measuring accurately to only 200 kPa, which is somewhat less than the notional maximum crop drying potential (or "wilting point") of 1500 kPa. While the data therefore do not allow any statement about complete drying at a particular depth, they do indicate whether or not roots have reached that depth as evidenced by a sharp increase in the rate of drying.

Table 1 summarizes the results of applying this criterion to the data in Appendix C up to 1st December 2005, which is after senescence of the crops and just prior to 30 mm rainfall on 2nd December. There was evidence of drying by roots down to 1.2 m under all paddocks except the *annual pasture*, while under *perennial pasture* drying was observed down to 1.4 m. There was no evidence of drying at 1.6 m. An effective depth of root water extraction of 1.2 m by the *wheat* is comparable to that observed at other sites with similar soils in the Wagga Wagga region for a range of crops over a number of years. As will be seen below, the *perennial pasture* and *native woodland* went on to extract water from deeper in the soil during summer. Based on experience in the Wagga Wagga region (Bond et al., unpublished data), lucerne and native woodland would not be expected to extract water from much deeper than annual crops in a wet winter/spring such as we had in 2005.

Table 1. Extent of soil drying at the different measurement depths in each paddock up to 1st December (prior to December rainfall).



Depth (m)	Grain-only wheat	Grazed wheat	Annual pasture	Perennial pasture	Native woodland
0.2	🟧	🟧	🟨	🟧	🟨
0.4	🟧	🟧	🟨	🟧	🟨
0.6	🟧	🟧	⬜	🟧	⬜
0.8	🟨	🟧	🟦	🟧	⬜
1.0	⬜	🟨	🟦	🟨	⬜
1.2	⬜	⬜	🟦	⬜	⬜
1.4	🟦	🟦	🟦	⬜	🟦
1.6	🟦	🟦	🟦	🟦	🟦

Key	
🟧	Drier than 200 kPa
🟨	Significant drying
⬜	Some drying
🟦	No drying

It is interesting that the crops left accessible soil water behind in the soil, as evidenced by the fact that the soil water potential was only drier than 200 kPa to 0.6 m under the grain-only paddock and 0.8 m under the grazed paddock. This is probably because of the larger in-season rainfall which extended through to November.

5. Seasonal Comparison of Soil Wetting and Drying

Another way of comparing the soil water storage and use in the different paddocks is to compare the soil water potential profiles (distribution of soil water potential with depth) before, during and after the growing season. For this purpose, I have chosen data from three days to compare for each paddock: "pre-season" (1 June), "mid-season" (15 September) and "end-of-season" (1 December). There is a detailed discussion below which compares the 5 paddocks on each of those days (Fig. 7 - 9). To start with, however, there is a quick summary of each of the paddocks compared on those 3 days (Fig. 6). Both ways of looking at the data are useful and shed light on the contrasting soil water behaviour under different vegetations.

In viewing these results it should be remembered that 0 kPa is saturated soil, 10 to 20 kPa is "drained upper limit" or "field capacity", and 200 kPa is dry soil, though not so dry that crops can’t continue to extract some water. For more details on interpretation, see Appendix B.

5.1. Comparsion within each paddock

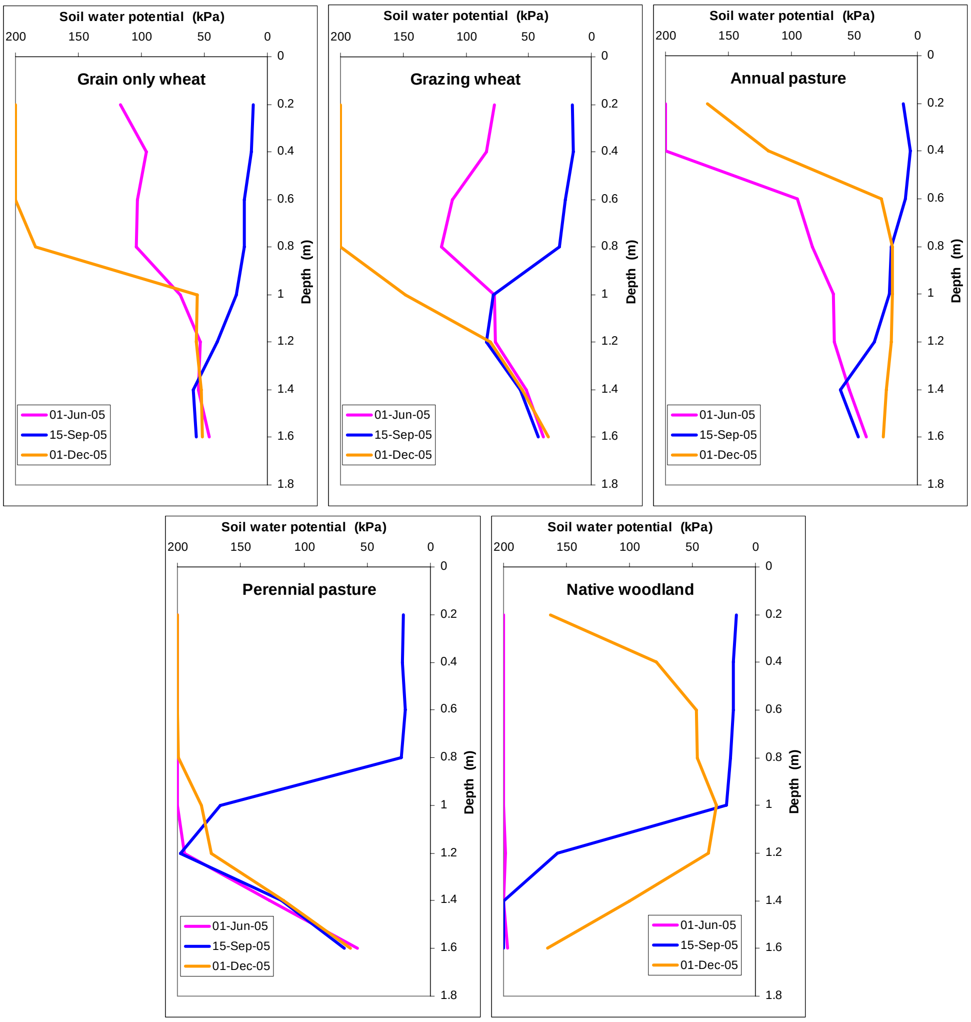


Fig. 6. Comparison of soil water status on 1st June (pre-season), 15th September (mid-season) and 1st December (end of season) in each of the five paddocks.

It can be seen clearly in Fig. 6 that between 1st June and 15th September significant soil wetting occurred down to 1.2 m under the *grain-only wheat* but only to 0.8 m under the *grazed wheat*. This water, plus water stored over the previous summer was extracted by the wheat crops, with the soil being dried effectively to 0.8 m under the *grain-only wheat* and to 1 m under the *grazed wheat*. The soil finished the season at about the same wetness as it started below 1 m under the *grain-only wheat* and below 1.2 m under the *grazed wheat*.

The soil under the *annual pasture* wet down to 1.2 m by 15th September, and continued to wet deeply after that. Some of the water stored down to 0.6 m had been used by the beginning of December, but some of this may also have moved deeper into the soil and contributed to the continued wetting of the soil at depth (to at least 1.6 m by 1st December). In contrast to the *wheat* and *perennial pasture* paddocks, the top meter of soil finished the year wetter than it started under the *annual pasture*. It is very likely that there was deep drainage under this paddock, with water irrevocably lost to the groundwater.

While a lot of water was stored over the winter and early spring under the *perennial pasture,* when it was not growing very vigorously, this was quickly used once the weather warmed up, so that the soil was almost as dry on 1st December as it had been on 1st June.

As with the *perennial pasture*, a considerable amount of water was stored before 15th September (down to 1.2 m) under the *native woodland*, and storage at deeper depths continued up to 1st December. At that time the soil was still much wetter than on 1st June, with serious draw-down of the stored water not starting until later in December. This is consistent with previous observations that native vegetation uses less water than crops during winter and spring, storing it for use in the summer months (Bond et al., unpublished data).

5.2. Pre-season (1st June)

This is immediately before the onset of the winter rains. It shows the net effects of rainfall, evaporation and water use over the summer period. It is also sufficiently long after the installation of the sensors (in April) for them to have stabilised and be representing true soil conditions.

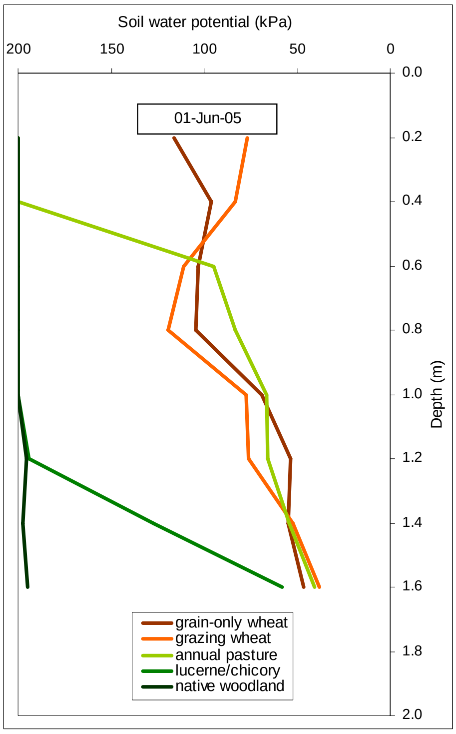


Fig. 7. Pre-season comparison of soil water status in each of the five paddocks.

The *native woodland* was at least as dry as 200 kPa (the driest the sensor can reliably measure) throughout the whole measurement depth. This would be expected; the combination of perennial species, including deep-rooted trees, should have dried out the soil to 1.6 m by the end of summer.

At the other extreme, the two *wheat* paddocks (which were under canola in 2004) were much wetter throughout the profile, getting wetter with depth. This is the combined effect of water left behind at depth by previous crops (for example it will be seen below that neither of the *wheat* crops dried the soil deeper than 1.2 m in 2005), and the accumulation of soil water over the summer after the windrowing of the canola in November 2004. There was 124 mm of rain between mid-November 2004 and February 2005 (Coolamon Post Office), some of which fell in large enough amounts to move deep enough into the soil and be retained.

The *annual pasture* is similar to the two cropped paddocks at 0.6 m and below, but dry in the top 0.4 m. At shallow depths the growth of annual pasture (or weeds), triggered by the summer rainfall events, dried the soil more effectively compared with the cropped paddocks, which had minimal weed growth and a stubble cover that minimised evaporation from the soil. Below this, water was left behind in the soil both during summer and during the previous winter; as can be seen in Fig. 9, even by December 2005 the *annual pasture* had not effectively dried the soil at 0.6 m and below. This is attributed to the typically shallow rooting depth (< ~ 0.6 m) of annual pasture species.

The *perennial pasture* (lucerne/chicory) paddock was dry to 1.2 m, approaching the same wetness as the crop and *annual pasture* paddocks at 1.6 m. This is expected for lucerne after its first summer. After a number of years of annual crops, the soil would have been expected to be similar to the cropped paddocks prior to sowing. At and below 1.6 m, this is still the case because the lucerne roots have not yet penetrated that deeply. Judging from the very effective drying to 1.2 m, the partial drying at 1.4 m, and the slightly drier soil at 1.6 m, the lucerne was gradually drying the profile deeper through the summer months.

5.3. Mid-season (15th September)

This is when most of the paddocks were at their wettest. This means that until 15th September rainfall exceeded evaporation and water use in all paddocks. Some depths in some paddocks may have been wetter on other days, however. Wetting continued at 1.2 m in both the *perennial pasture* and *native woodland* paddocks, for example, after this date.

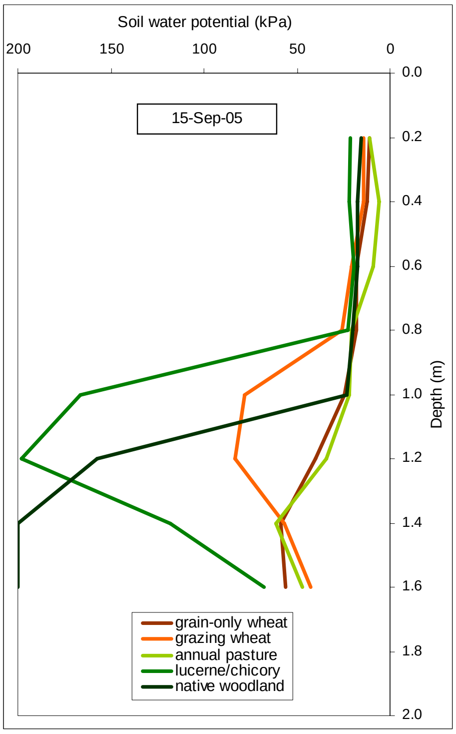


Fig. 8. Mid-season comparison of soil water status in each of the five paddocks.

All paddocks were very wet down to 0.8 m. Over the whole measurement depth, the wettest profile was under the *annual pasture*, closely followed by the *grain-only wheat*. The *grazed wheat* paddock was similar, but was slightly drier at 1.0 and 1.2 m. The *perennial pasture* and *native woodland* were clearly drier overall.

Although not clear from the graphs here, it was shown in section 3 that *grain-only* and *grazing wheat* both showed some wetting down to 1.2 m. Water reached at least 1.6 m under the *annual pasture*, 1.4 m under the *perennial pasture*, and 1.6 m under the *native woodland*. The *perennial pasture* and *native woodland* appear drier in the graph here mainly because they continued to wet at depth after 15th September.

These results are consistent with expectations. Wheat grows vigorously during late winter and early spring, while lucerne is at its least vigorous during these cold months. Thus *wheat* transpired more and used more of the rain, leaving less to move down deep into the soil and be stored. Previous observations (Bond et al., unpublished data) also suggest that native vegetation uses less water than a vigorous wheat crop during these months, similarly leaving more of the rain to be stored at depth in the soil. Growth and water use were also less vigorous for the *annual pasture* than for *wheat*.

5.4. End of season (1st December)

This is when the *wheat* paddocks were at their driest. It is after the *wheat* had senesced and ceased water use and a few days before the last significant rainfall of the year (which caused re-wetting of the soil in all paddocks).

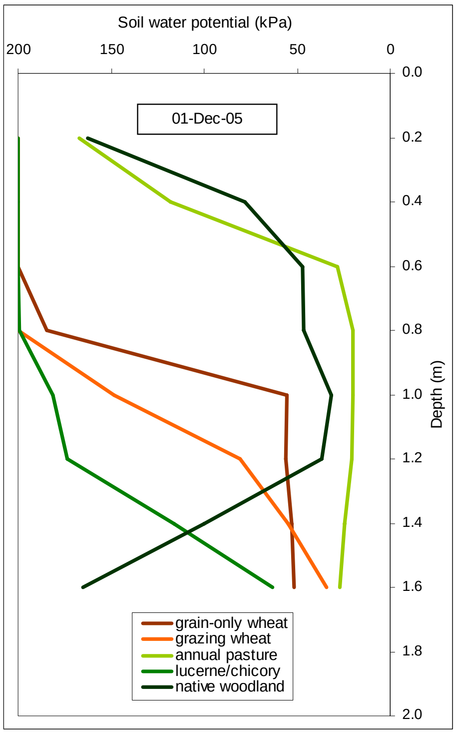


Fig. 9. End of season comparison of soil water status in each of the five paddocks.

The *wheat* and *perennial pasture* paddocks were the driest, having dried the soil to (or close to) the lower limit of the soil water sensor down to 0.8 m. Although not obvious from the figures here (but as has been discussed in section 4), some drying occurred down to 1.2 m in both *wheat* paddocks and to 1.4 m in the *perennial pasture*.

The *native woodland* and *annual pasture* were both much wetter than the other paddocks, with the woodland being slightly drier overall than the *annual pasture*. The *native woodland* was a less vigorous user of water during the winter and early spring months, and didn't start seriously drying down the soil until mid-December, as can be seen from the graph of the full data in Appendix C. The *annual pasture* produced much less growth than the *wheat* (see Fig. 3) so that it used less water, and it also has a shallow rooting depth as noted above, which precluded it from drying the soil much below 0.4 to 0.6 m.

6. Soil Moisture Conditions in Summer and Autumn

Just prior to harvest there was significant rainfall of about 30 mm on 2nd December. This caused immediate rewetting of the soil down to 0.2 m in all paddocks (see figures in Appendix C). In the *annual pasture* wetting extended to 0.6 m, with the result that the soil was almost as wet as in September at all depths. Under the *perennial pasture* some wetting was observed down to 1.2 m, which is difficult to explain unless drying of the soil during the preceding months had caused a preferential pathway for water to move to depth.

Further wetting occurred following another > 30 mm rainfall event on 17th January. Again this caused the soil at 0.2 m to wet straight away, and the effect was also evident, to different extents, deeper in the soil in most paddocks.

In response to the > 60 mm summer rainfall, wetting occurred to someextent down to at least 1 m under the *wheat* paddocks. It is difficult to be absolutely certain about wetting in summer because of the soil moisture sensors' response to temperature, which causes an apparent wetting trend (as described in Appendix B). Under the *annual pasture*, because the soil was so wet to start with at most depths, it is difficult to discern whether the rain entered the soil or ran off the surface. It is possible that more of the rain ran off the surface of this paddock in the intense summer storms than from, say, the *wheat* paddocks. The latter had a rougher surface and more scope for temporary surface detention of rainfall, allowing it to infiltrate over a longer period. Under *perennial pasture*, there was again evidence of wetting down to 1.2 m, while wetting down to 1 m was observed under the *native woodland*.

Since February there has been less than 30 mm of rain, all of which occurred in small events and did not cause the soil to wet at 0.2 m except in the *grazed wheat* and *annual pasture* paddocks in mid-April. The scattered natured of the showers may have resulted in more rainfall on those paddocks.

A combination of evaporation directly from the soil surface and some water use by weeds caused a steady drying down to 0.8 m in the *grain-only wheat* paddock (see figures in Appendix C). Again it is difficult to distinguish between drying of the soil and the fall off in the sensor reading caused by the declining soil temperature since February. The decline at depths of 1.2 m and below, however, is almost certainly temperature related. At all depths down to and including 1.2 m the soil was drier than at the same time in 2005. This reflects the better water extraction ability of wheat in comparison with the canola grown in 2004. The 1.4 and 1.6 m depths display the typical seasonal temperature effect, with no evidence of real wetting or drying during the 12 month period.

Drying appears to have occurred to about 1 m in the *grazed wheat* paddock, but it is very difficult at that depth to distinguish real drying from the temperature effect. At all depths down to and including 1.4 m the soil is drier than at the same time in 2005. This again reflects the better water extraction ability of wheat in comparison with the canola grown in 2004.

Drying has occurred to perhaps 0.6 m under the *annual pasture*, though the soil remains very wet. At all depths it is much wetter than at the same time in 2005. The shallow rooted, low leaf area nature of this pasture has not exploited the 2005 rainfall very well at all.

The *perennial pasture* has been actively extracting soil water down to at least 1.6 m. All depths are at least as dry as at the same time in 2005. In particular it can be seen that there has been strong water use at 1.4 and 1.6 m in 2006 compared with 2005.

The *native woodland* has also been actively extracting soil water down to at least 1.6 m. All depths at 1 m and above are at least as dry as at the same time in 2005, but below that the soil remains wetter, although not by that much.

7. Summary and Conclusions

The soil water measurements made at the Coolamon Focus Farm during the 12 month period from April 2005 to April 2006 clearly show the different patterns and extent of water use by the contrasting land uses.

Wheat was the most effective user of water in winter and spring. Grazing had little if any effect on water use of the wheat crops. Lucerne and native vegetation used less water in this period because they tend to grow less vigorously, while water use by *annual pasture* was probably limited by its shallow rooting depth and lower leaf area.

Over summer and autumn, water accumulated in the soil under *wheat* and *annual pasture* when rainfall occurred in amounts greater than 20 to 30 mm per day, while *perennial pasture* and *native woodland* continued to dry the soil.

Of the five contrasting land uses, *annual pasture* was the least effective at using soil water. This resulted in lower production of dry matter and a greater risk of groundwater recharge.

Appendix A. How the measurements were made

Overview

Measurements were made at one location in each paddock, adjacent to the transect along which soil and pasture sampling was carried out. A schematic representation of the measurement methodology is shown in Figure A1.

At each measurement location Watermark® gypsum blocks were installed at 8 depths (0.2 m intervals from 0.2 to 1.6 m) in a single 50 mm diameter borehole. Each sensor was packed in moist diatomaceous earth to ensure good contact with the soil, and the sensors were separated from each other by layers of bentonite.

Each set of 8 sensors was connected to a buried CSIRO Wireless micrologger located 1.5 m downslope from the sensors, the connecting cables being buried in a trench 0.4 m deep.

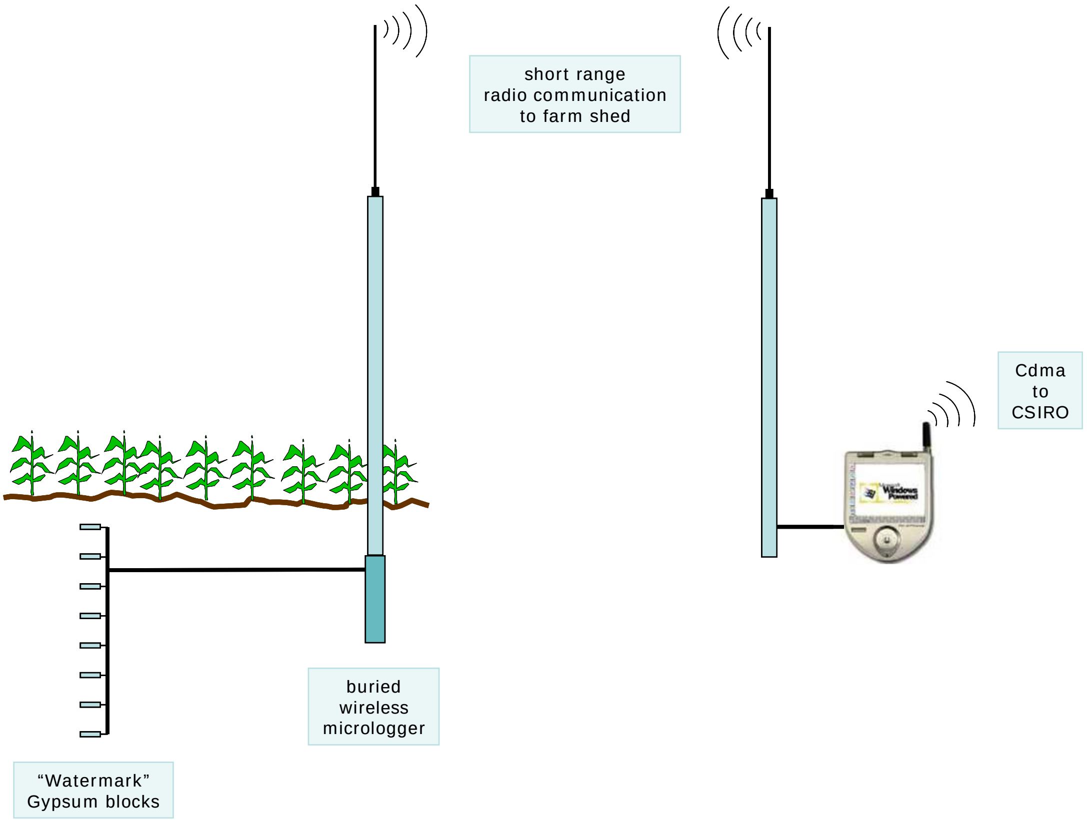


Figure A1   Overview of the measurement methodology.

At pre-programmed intervals (every 6 hours in this case), the microloggers read each sensor and radioed the results to a receiver at a central base station up to 3 km away. The receiver was connected to a small computer with a built-in cdma telephone. The computer stored the sensor results. Once each day it connected to the internet via the cdma telephone and sent the day's data file to a CSIRO computer. Before 3 am each day, the previous day's data was automatically added to an excel spreadsheet and graphs of the data were updated. These graphs were copied to the web server and displayed on the project website. All going well, the previous day's data were available for viewing after 3 am each day.

Occasional glitches occurred when the radio link failed because of excessive interference, or the cdma signal was not strong enough for the call to be made. Built-in fail-safe procedures keep these to a minimum and prevent data loss when it does happen. Provided the microloggers kept functioning, the data could also be recovered directly from their memories and patched into the dataset at a later date, as was done in several instances.

Watermark® gypsum blocks

The Watermark sensor was used for this project because it provides an inexpensive way to measure soil water status. It measures soil water potential rather than soil water content, which has advantages and disadvantages. Advantages include: inexpensive; easy to install; and provides an absolute measure of soil wetness or dryness. Disadvantages include: measurements cannot be directly related to soil water content or storage in mm; and the limit of accurate calibration is 200 kPa, whereas the theoretical lower limit for water extraction by crops is 1500 kPa.

The Watermark sensor is a type of gypsum block. These are porous blocks that wet and dry as the soil they are in contact with wets and dries. The water content of the block is measured by measuring its electrical resistance. The gypsum in the block provides a buffer against background soil salinity so that it does not affect the resistance measurement.

The water content of the block does not equal the water content of the soil, but is related to the 'soil water potential' of the soil with which the block is in contact. Soil water potential provides an absolute measure of how wet or dry the soil is; a value of zero indicates that the soil is 'saturated', a value of ~10 to 20 kPa indicates that the soil is at 'field capacity' or 'drained upper limit', while a value of 1500 kPa indicates that the soil is at 'wilting point' – i.e. so dry that plants cannot extract more water from it. [In contrast for a measurement of water content to be interpreted relative to the soil's upper and lower limits, the actual water contents at these limits needs to have been determined previously for the specific soil.]

Sensors such as the Watermark, which measure soil water potential, require less care to be taken during installation. They do not need to be in intimate contact with the soil, as is required for most sensors that measure water content. Instead, the sensor can be bedded in a contact material (usually diatomaceous earth) that ensures good contact between the sensor and the soil and allow it to equilibrate with the soil's water potential. In contrast, if a soil water content sensor is bedded in a contact material instead of being perfectly in contact with the soil, it measures the water content of the contact material instead of the water content of the soil.

For more information, see Appendix B: Interpreting the measurements.

Wireless microloggers

The Wireless micrologger has been custom-designed by CSIRO Land and Water. Each logger can measure up to 8 sensors. At a pre-programmed time (or times) each day, the logger automatically turns on, measures the sensors and stores the data. Every time measurements are made, the logger has the capability to radio the results to the receiver, as described below. Alternatively, to save power, results from several measurement times can be radioed together.

The micrologger has been designed to be buried and left unattended for long periods of time. It has a low power requirement, and its high capacity batteries will last several years at daily or sub-daily measurement intervals. The data are stored in memory (up to 5,000 individual measurements can be stored), so that if radio transmissions are interrupted, the data can be recovered by manually interrogating the logger with a PC.

Each logger is sealed in a watertight PVC housing and lowered down a PVC casing. While the casing extends to the soil surface, the top of the logger is at least 0.3 m below the soil surface. Thus, although the top of the casing may occasionally be damaged by, for example, tillage operations, the logger remains protected. However, to transmit the radio signal, an antenna needs to protrude above the soil surface. This is designed to be easily laid down on the soil surface to permit spraying operations and easily disconnected and re-connected at sowing and harvest.

Radio communication

The radio signal from the logger is transmitted through the antenna protruding 2 to 3 m above the soil surface, to a similar antenna connected to a receiver located at some distance away (up to 10 km under ideal conditions).

Telephone link

The radio receiver is connected to a pc-EPhone®, a combined cdma telephone and personal digital assistance running the Microsoft Windows CE operating system. Custom software running on the pc-EPhone receives and stores the measurements sent by the microloggers. At a pre-programmed time each day, the pc-EPhone connects to the internet and uploads the data to a CSIRO ftp site. Should a cdma connection not be able to be established, the data is kept in protected storage to be sent the next day. If the cdma link fails completely, the stored data can be downloaded to a PC or to a compact flash card.

Loading the data to the web page

Each morning, software running on a CSIRO server automatically copies any incoming data files from the ftp site, processes them, and adds them to an excel spreadsheet. This spreadsheet updates charts of the data and saves them as "gif" images, which are uploaded to the web page and are immediately available for viewing. While the quality of the charts is not extremely high, they are small files (< 15 kB) that can be downloaded quickly even on slow dial-up lines.

Appendix B. Interpreting the measurements

The measurements reported were made with Watermark® gypsum blocks, as described in Appendix A. Gypsum blocks measure soil water potential, not soil water content. The two are related, but not uniquely; the relationship is not linear (it is in fact close to logarithmic) and varies with soil type and from place to place within a given soil type as individual soil properties vary.

Unlike soil water content measurement, water potential measurements cannot, by themselves, indicate how much water is stored in the soil and available for crops. Soil water potential measurements are, however, much easier and cheaper to make that soil water content measurements and still provide much useful information.

Soil water potential provides an absolute measure of how wet or dry the soil is:

- a value of zero indicates that the soil is saturated - ie. water will ooze from the soil;
- a value of ~10 to 20 kPa indicates that the soil is at field capacity or drained upper limit - this is the practical upper limit of wetness; a well-drained soil, would rarely spend more than a day or two wetter than this
- a value of 1,500 kPa indicates that the soil is at wilting point - ie. so dry that plants cannot extract more water from it.

In contrast, a measurement of soil water content can only be interpreted in this way if the values of water content at these three limits (saturation, drained upper limit, and wilting point) are known in advance, which is usually not the case.

Temperature effects

A complication in interpreting measurements from gypsum blocks, and most other soil water sensors (including the very expensive ones), is that they are temperature dependent. Their output is affected not only by water content, but also by the soil temperature at the time of the measurement. Soil temperature changes in response to air temperature, although the magnitude of the change in soil temperature decreases with depth.

At shallow depths (less than about 200 mm), soil temperature reaches a peak in early afternoon and a low around dawn. Because of the time it takes for the soil to heat up and cool down, these daily variations are not seen below 200 mm, and so aren't a concern for the measurements reported here, the shallowest of which is at 200 mm. However, the seasonal oscillation in air temperature shows up at much greater depths, because in 6 months heat can travel down as far as 2 meters into the soil and cause a temperature rise. The seasonal oscillation of the Watermark gypsum block output caused by temperature is illustrated in Fig. B1.

The consequence of the temperature effect on gypsum block measurements is that some extra care is required when interpreting their output:

- in spring and summer, a gradual wetting in gypsum block output is more likely to be a result of increasing soil temperature than an increase in soil wetness
- in autumn and winter, a gradual drying in the gypsum block output is more likely to be a result of decreasing soil temperature than a decrease in soil wetness

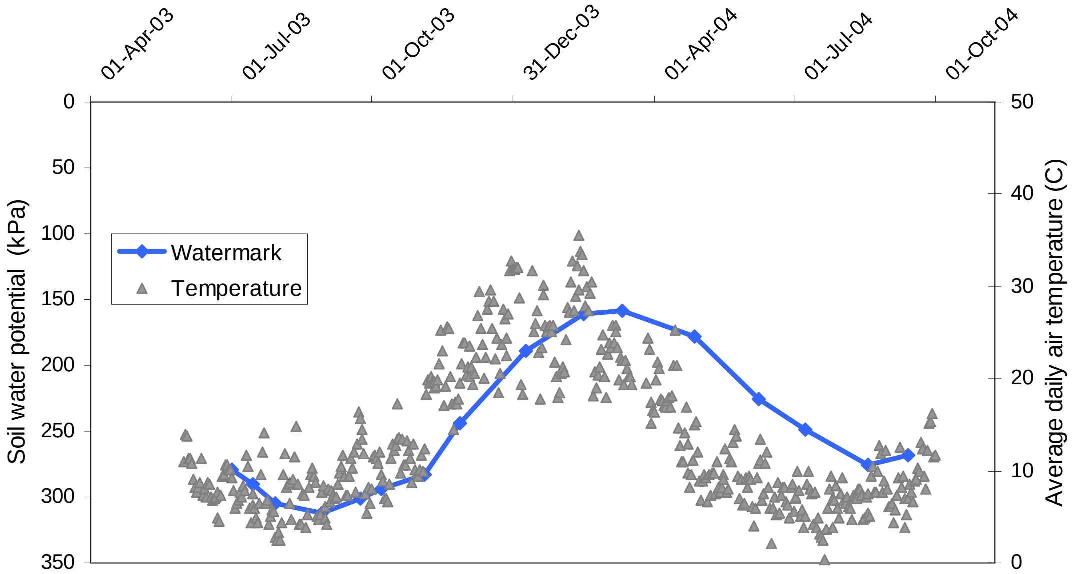
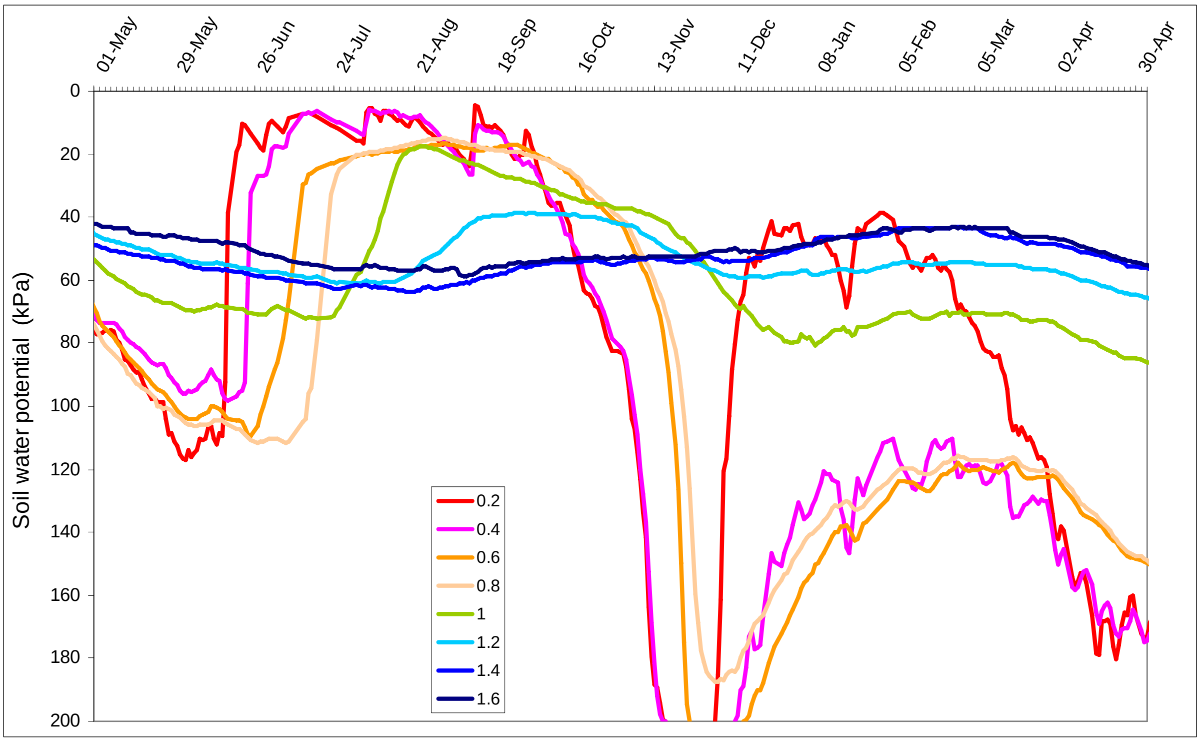


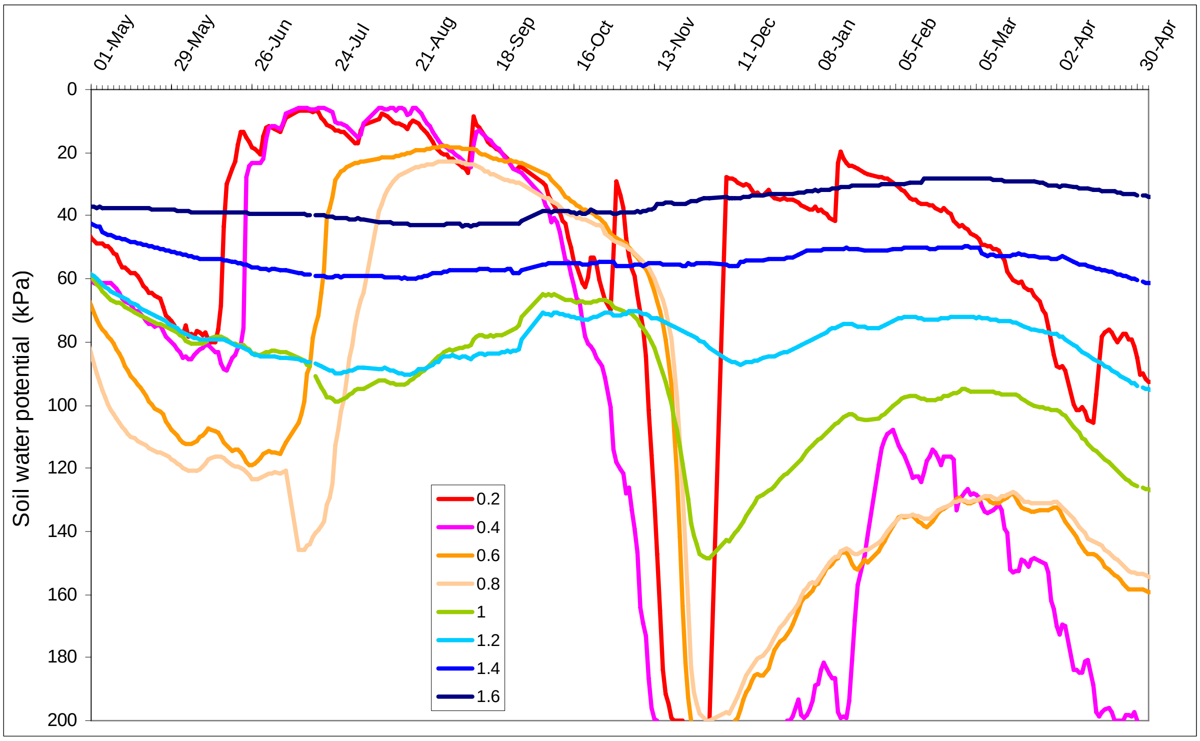
Figure B1 Soil water potential measured by a Watermark® gypsum block for a 12 month period at a depth of 1.7 m in a paddock at Charles Sturt University, Wagga Wagga. Independent measurements of soil water content with a neutron probe showed no variation during this period, because the soil had been previously dried by lucerne and there was insufficient rainfall to rewet it. The oscillation correlates with observed air temperature, subject to a lag of about 1 month.

Appendix C. Data Summary

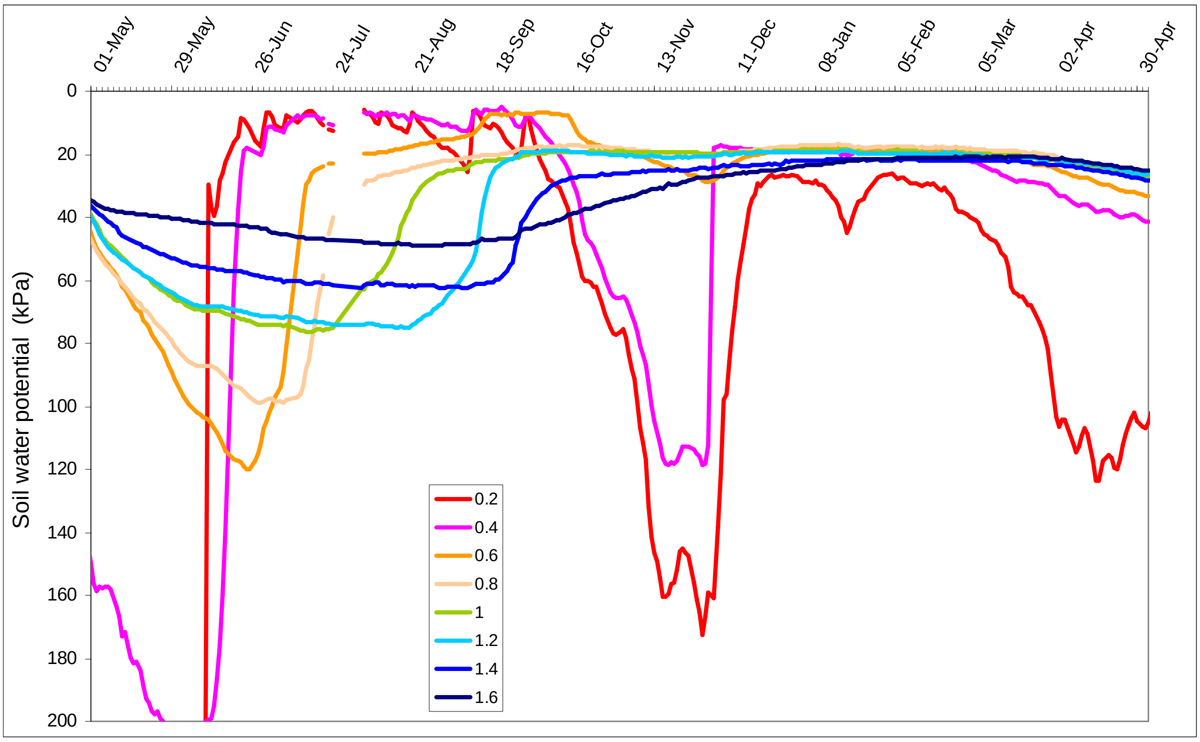
Grain-only wheat



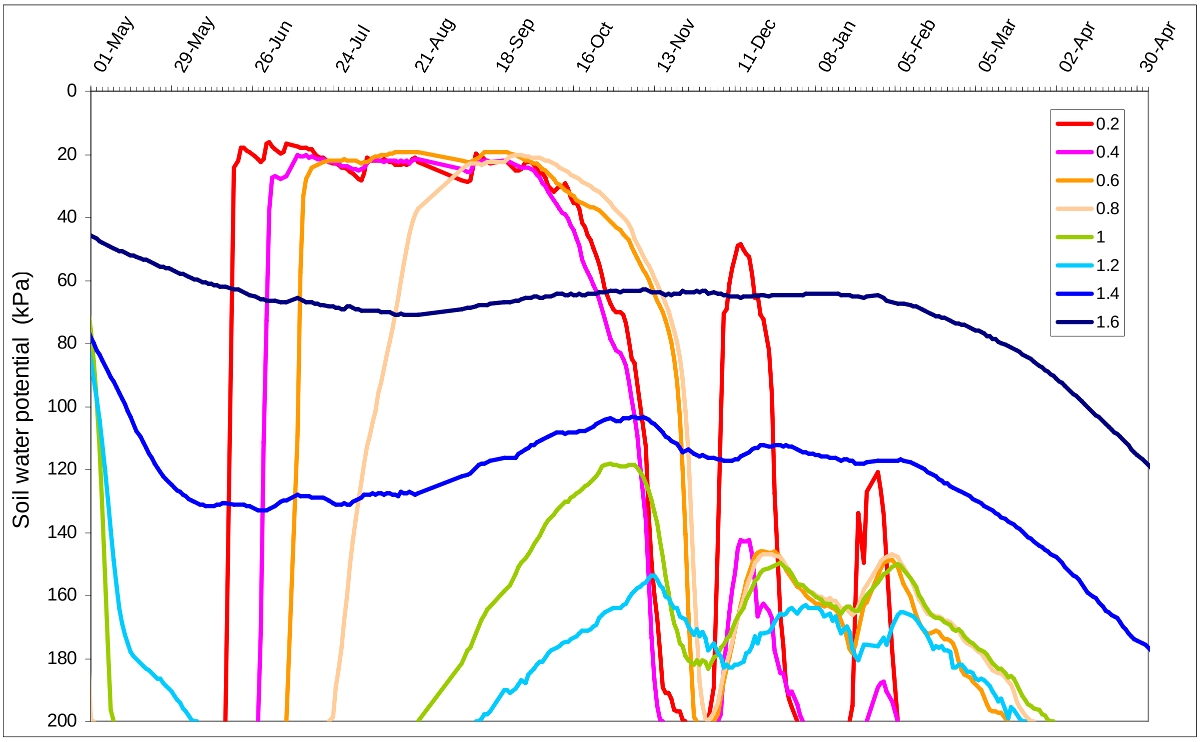
Grazed wheat



Annual pasture



Perennial pasture



Native woodland