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Prologue: Amending agricultural water use to maintain production while affording environmental protection through control of outflow

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Abstract. The long-standing debate about the problem of dryland salinity in Australia has been increasingly well informed. We chart here the deepening understanding of the processes involved in how plants use water and what this means for flows in the regolith, from the introduction of the idea of the soil–plant–atmosphere continuum 50 years ago, through the comparative patterns of water use by annual and perennial vegetation and the variety of their hydrological effects in different landscapes, to the realisation, as demonstrated by many of the papers in this special issue of AJAR, that the era of unviable simplistic solutions to dryland salinity is behind us. The mood now is one of cautious optimism that we will be able to develop a wide range of options for maintaining economically viable farming systems that protect the environment by controlling outflow well enough to arrest the spread of dryland salinity.

Australia has seen a vigorous debate, over many decades, on the problem of dryland salinity and what to do about the underlying cause, excessive drainage and thence recharge in agricultural landscapes. The debate has been increasingly well informed through deepening understanding of the interacting processes involved in the use of water by plants, both agricultural and native, and the flow of water, both saline and fresh, in the regolith.

Notable advances have included: (*a*) the development by Philip (1957, 1966) of the notion of the soil–plant–atmosphere continuum (SPAC) and the way that water moves through it (Slatyer and Denmead 1964); (*b*) Downes' (1959) articulation of the need for the targetted introduction of perennials into agricultural landscapes; (*c*) Eagleson's (1982) insights into how natural ecosystems perform in relation to water supply, and his notion of hydrological equilibrium, in which these systems evolve canopies that are sufficiently conservative for a given hydrological environment that persistence of the ecosystem is assured by avoiding problems associated with boom and bust behaviour; and (*d*) the realisation, elaborated by de Wit (1958), Tanner and Sinclair (1983), and many others, that there is a strong nexus in crop plants between dry matter production and water transpired. This latter reached practical fruition in the analysis of farmers' wheat yields by French and Schultz (1984), who showed that yields had a clear upper bound when plotted as a function of seasonal water supply, an observation to which we will return. Their analysis alerted agronomists and farmers to the fact that most crops were yielding well below their water-limited potential, and that by implication most crops were being limited by factors other than water supply, such as inadequate nitrogen nutrition or root diseases; the latter especially could have hydrological implications in that inadequate root systems can increase deep drainage.

The debate remains vigorous because, at least in part, many interactions among crop yield, comparative water use by crops and native vegetation, and agricultural hydrology, are, as follows, seemingly paradoxical.

- Productivity of cropping farms has been rising for decades, and continues to rise, yet the growing of annual crops is usually held responsible for the spread of dryland salinity across many agricultural landscapes, an affliction that we would expect to reduce productivity.
- The sustained rise in productivity has been accompanied by rising average yields, rapidly rising during the 15 years before the recent prolonged drought. Yet the rising yields have not involved markedly greater water use by the crops and thence markedly less drainage. Further, the rises in yield are at least as great in Western Australia as in the rest of the country despite the reduced rainfall that much of the WA wheatbelt has suffered over the last 30 years.
- Although increasing productivity of crops does not result in markedly more water use and concomitantly reduced drainage, highly productive improved pastures can result in *increased* deep drainage, for the lush foliage reduces runoff (as demonstrated by less water in farm dams), leads to greater infiltration, and is often associated with shallower root systems (compared with native grasses), which can lead to substantially more deep drainage.

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- Pristine native vegetation, of the sort that once occupied the now arable landscapes before they were cleared for crops, uses almost all of the rain that falls on it, allowing on average only a tiny leaching fraction to pass beyond the root zone. The escaping flow is often as salty as sea water, for the roots remove almost all of the water, but almost none of the salt, as the soil solution flows downwards through the root zone. Yet despite this vegetation's ability to capture so effectively a limiting water supply, its net primary productivity is but a tenth of that of the agricultural plants that have largely replaced it. It uses a little more water but grows very much less.

This special edition of AJAR contains several papers that deal with the issues surrounding these apparent paradoxes. The most important of these is that of water use by crops, which needs to be examined at a range of timescales—not only seasonally, but also hourly and daily—to elucidate these seeming paradoxes, because shifts in the daily course of transpiration can explain some of the integral behaviour. Given the expected dependence of yield on water supply in a water-limited environment, it is a little dispiriting to see that large increases in yield do not lead to large increases in seasonal water use. If they did, it might lead to less drainage of water under such crops.

The main reason for this behaviour is schematically illustrated in Fig. 1, a variant of French and Schultz's (1984) portrayal of crop yield as a function of seasonal water supply. In this figure we have shown above-ground dry matter rather than yield, to avoid complications due to variations in harvest index, which may be unrelated to seasonal water use, e.g. frost damage at flowering. The solid line is essentially the upper bound of all possible points. It has a slope, often called transpiration efficiency, or TE, of 55 kg/ha.mm, a reasonably robust value for winter cereal crops in Australia.

Not so robust is water-use efficiency (WUE) defined as the ratio of dry matter produced to total seasonal water supply, e.g. the 3 points illustrated in the figure have the same seasonal water supply, 400 mm, but the dry matters produced, in ascending order, are 5.5, 11.0 and 16.5 tonnes, corresponding to overall water-use efficiencies of 16, 38, and 41 kg/ha.mm, respectively. To a good approximation, the variation in WUE arises not by variation in TE, but in the amount of water removed from the soil by means other than uptake by roots, described as 'lost water' in the figure. The predominant loss in southern Australia is by direct evaporation from the soil surface, although water can also be lost by runoff and by drainage beyond the reach of roots.

The main point of Fig. 1 is that crops that are not well managed, say, with a small leaf area owing to nitrogen deficiency or poor establishment, will leave a large proportion of the soil exposed to evaporation. Coupling this with the observation that during much of the vegetative life of a crop in the Mediterranean environment of southern Australia, the

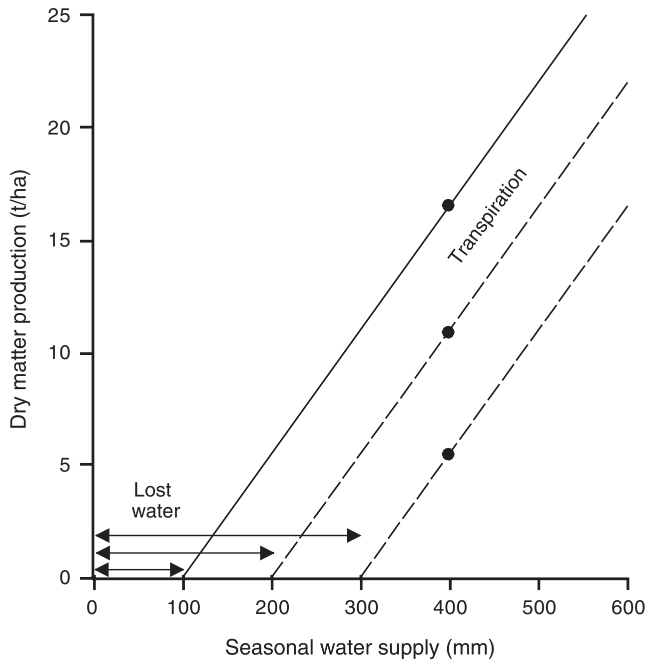

Fig. 1. Dry matter production in relation to seasonal water supply. The solid line represents well-managed winter cereal crops. The dashed lines and the points associated with them represent not so well-managed crops. The slopes of all these lines, transpiration efficiency, are 55 kg/ha.mm of water transpired, a reasonably robust value for winter cereal crops in Australia. The intercepts on the *x*-axis denote the water lost to the crops, by evaporation from the soil surface, by drainage, and by runoff.

topsoil is often wet, we find that the sum of transpiration and evaporative loss tends to be constant whether the crop is growing well or not. Norton and Waschmann (2006, this issue) drew this conclusion for N treatments on crop water use. This point is also central to paddock scale modelling by Ward (2006, this issue) to define how the herbaceous perennial, lucerne, can control drainage by taking up water from the deep subsoil in summer. In the autumn to spring growing season, topsoil water extraction is similar across species, both crop and pastures, both annual and perennial, over much of this period. The attainment of potential water use to values as high as 5 mm/day is common across a range of leaf areas while soil water reserves are high. The distinctive role of direct evaporation from soil in summer warrants detailed consideration in fallow periods to link soil water dynamics between successive crops. The level of soil water conservation from rainfall over the fallow period strongly influences crop growth if there is low rainfall in the following growing season, whereas in a growing season of above-average rainfall it can lead to greater drainage. Dolling *et al*. (2006, this issue) address this topic in crop rotations. They weigh the benefits of fallow for growth against the risk of drainage, and also provide a reference soil water loss over summer for gauging how effectively the inclusion of deep-rooted perennial pasture in a crop rotation can create a buffer in the deep subsoil for holding water that has escaped the roots of annual crops.

The robustness of TE arises to a large extent due to the narrow range of 0.65–0.75 kPa, for the average atmospheric vapour pressure deficit (VPD) in this environment during the growing season from sowing to physiological maturity in about 80% of seasons. Other factors such as diffuse light and strong stomatal control can affect seasonal TE, but these tend to be minor at the seasonal time scale (except for some new varieties deliberately bred for larger TE through low stomatal density). This overriding influence of VPD on seasonal TE is evident in 2 papers that deal with lengthening the traditional cereal season by introducing annual species adapted to high temperature. In Western Australia (Fillery and Poulter 2006, this issue), long-lived annual pastures based on the legumes *Serradella* and *Casbah biserrula* operated well into summer, thereby taking up 20–30 mm more water from soil to the depth normally attained by cereal roots, although with no significant increase in overall pasture production relative to annual subterranean clover or to lucerne swards. Here, late-season activity under high VPD resulted in a little more growth from moderate additional water use. In the Victorian Wimmera region, on Vertosols, a safflower crop with a 40-day longer growing season than cereals performed as well as first-year lucerne in extracting 100 mm more soil water than wheat for a ~50% greater biomass (Norton and Waschmann 2006, this issue). The penalty of operating late season under high temperature and VPD did not appear to affect safflower physiology insofar as water-use efficiency was comparable between it and wheat, namely ~20 kg/ha.mm. Clearly there are niche conditions for annual crops to reduce deep drainage without major compromises to productivity.

By contrast with annual crops, the TE of the perennial native vegetation that they replaced is small. There are 2 main reasons for this. The first is that native vegetation does most of its growing during the summer when VPD is large, 1.5–2 kPa, twice that which the crops experience when growing during the cool period between mid-autumn and mid-spring. The second reason is that, being perennials, they invest heavily in deep permanent root systems and other structures that consume much of the annual net photosynthesis, so that what appears above ground is a much smaller proportion than that in annual crops. The behaviour of summer-active native perennial grasses is especially interesting in this respect; even more interesting is the way water flow is partitioned between transpiration, runoff, and drainage. Clean surface runoff is the characteristic form of outflow from native grassland, which gives reliable farm water supply as well as reducing the risk of insidious deep drainage (Dunin and Downes 1962). This diversion from groundwater recharge is critical for groundwater accounting in the Liverpool Plains (Sun and Cornish 2006, this issue). There, and in widespread areas of the cereal belt, dominant native grasses are tropical in origin and are C_4 plants with high TE during that functional period when canopy temperature exceeds 15°C. These species use almost no soil water in winter–spring, and this, combined with an effective mulch of senescent material, maintains surface soil at field capacity for long periods, the mulch being especially effective when ungrazed. On duplex soils with poorly permeable subsoils, these conditions lead to substantial runoff from the predominantly winter rains, and thence a limited advance into a subsoil root zone scavenged of soil water in the previous summer.

By contrast, improved pastures (e.g. clover/ryegrass) are winter active. Their transpiration during the growing season removes water from the topsoil thereby creating space to store much more of a fall of rain than under *Themeda*. This allows substantial infiltration, and hence much less runoff. Further, the shallow rooting depth and summer dormancy of the improved pastures result in the subsoil under them being substantially wetter at the autumn break than it is under *Themeda*. This in turn leads to larger deep drainage because the water that does infiltrate the subsoil has less space available for its storage and the wetting front soon advances beyond the reach of the roots. Another important native grass, *Danthonia*, a C_3 species, is predominantly winter active, but can also respond to summer rain and has deeper roots than those of the introduced pastures (Sandral *et al*. 2006, this issue). It is thus intermediate in hydrological behaviour between *Themeda* and the introduced pastures.

Our challenge is to help farmers manage agricultural landscapes in such a way that they can control deep drainage while continuing to make a living. Alert economists have pointed out that trying to reduce drainage in these landscapes to pre-clearing levels, which hydrologists estimate could involve retiring as much as 80% of arable land, is not a sensible way of managing resources: why forgo the use of such a large percentage of arable land, and in so doing incur very large costs, to save a much smaller percentage of it from salinity?

The question arises of what is acceptable deep drainage? This question has become much richer in the last few years with the increasing realisation, mostly resulting from aerial electromagnetic surveys coupled with good ground-truthing, that there is great variation below ground in the occurrence of saline and fresh aquifers, both laterally and vertically (e.g. Cresswell *et al*. 2004). Thus any introductions of perennial vegetation that aim to reduce deep drainage must be well targetted. Trees planted in the wrong place will make matters worse if they reduce accessions of water to fresh aquifers. Even without considering this spatial variability, wholesale planting of trees can be hydrologically damaging, at least for several decades. Young trees tend to be profligate in their water use as they develop the structures needed to assure their survival in a highly variable environment. The result is that fresh water flows can be reduced (Jackson *et al*. 2005). A good example is that of the regenerating forests in

Melbourne's water catchments, which substantially reduced stream flows below those prevailing before the disastrous fires on *Black Friday* in January 1939. Indeed, there is evidence that such flows were still reduced nearly 50 years later (Kuczera 1987).

Nevertheless, in agricultural landscapes, is there an overall average rate of deep drainage that we should aim for? In general, landscapes most at risk are those that had deep drainage of less than about 5 mm per year when they were pristine; drainage rates larger than this kept the aquifers largely flushed of salt. Deep drainage in arable landscapes can be many times greater than that in the pristine. The challenge is to decrease this drainage substantially while, if watertables are close enough to the surface to be accessible by roots, increasing the discharge through appropriate perennial plants whose roots can tap such watertables (Barrett-Lennard *et al*. 2005). The model study of groundwater hydrographs in the Liverpool Plains places great weight on uptake from the capillary fringe to explain why groundwater fluctuations appear damped (Sun and Cornish 2006, this issue).

There is no single solution to dealing with this challenge. Appropriate techniques depend on the circumstances and must maintain economic viability of farmers. For example, in some landscapes, contour planting of trees may be able to increase uptake from the watertable without greatly affecting the performance of nearby crops (White *et al*. 2002), and in flat landscapes at risk of becoming saline, productive salt-tolerant shrubs such as saltbush may be able to delay the expected onset of salinity by many decades (Barrett-Lennard *et al*. 2005).

Extensive integration of herbaceous perennials into cropping rotations, particularly lucerne, has been canvassed as a solution to restore the natural water balance across recharge areas. This strategy appeals, where profitable, for it removes accrued subsoil water thereby enabling greater control of ensuing deep drainage (Latta and Lyons 2006, this issue). A national survey of hydrological performance by lucerne in arable soils (Ward *et al*. 2006, this issue) shows a 5-fold variation, from 50 mm to 250 mm, in the ability to create a buffer in which water and nutrients that leak below the crops can be held for a few seasons, remaining largely accessible to the roots of the next phase of perennials.

Variability in subsoil extraction due to lucerne is linked to the level of constraint imposed on uptake that is experienced by annual crops during seasonal growth (Rodriguez *et al*. 2006, this issue). Thus, a soil afflicted with major subsoil constraints may only permit a net extraction of 50 mm over the course of a growing season. Lucerne in such a soil will induce a soil water deficit of only about 60 mm in the equivalent soil depth to the crop before its roots advance deeper into the subsoil in summer to withdraw an additional 35 mm by the end of its first year. By the third year the deep subsoil deficit might approach 70 mm. The corresponding values in a more hospitable soil, with net extraction by crops of 100 mm, may be 70 mm and 120 mm, respectively, for cumulative deep extraction by lucerne after the 1st and 3rd years. These latter values point to a good prospect for reinstating the natural water balance while lucerne remains functional in recharge areas. In dealing with soils limited in extraction due to subsoil constraints, amelioration involves using a mix of introduced perennials, both woody and herbaceous, to deliver a catchment water balance that curtails the spread of salinity.

The expansion of knowledge during the last few years of the interacting processes involved in the use of water by plants and the flow of water in the regolith has been remarkable. This, coupled with many new management options, has changed the atmosphere in the salinity debate from one of gloom to one of optimism (Passioura 2005). Although there are still many who think that the best we can do is buy time, the mood now is that extra time will allow us to develop an even greater range of options for maintaining economically viable farming systems while markedly reducing the risk of dryland salinity.

References

Barrett-Lennard EG, George RJ, Hamilton G, Norman HC, Masters DG (2005) Multi-disciplinary approaches suggest profitable and sustainable farming systems for valley floors at risk of salinity. *Australian Journal of Experimental Agriculture* **45**, 1415–1424. doi: 10.1071/EA04157

Cresswell RG, Dent DL, Jones GL, Galloway DS (2004) Three-dimensional mapping of salt stores in the southeast Murray-Darling Basin, Australia. 1. Steps in calibration of airborne electromagnetic surveys. *Soil Use and Management* **20**, 133–143. doi: 10.1079/SUM2004260

Dolling PJ, Fillery IRP, Ward PR, Asseng S, Robertson MJ (2006) Consequences of rainfall during summer–autumn fallow on available soil water and subsequent drainage in annual-based cropping systems. *Australian Journal of Agricultural Research* **57**, 281–296. doi: 10.1016/S0378-3774(01)00161-5

Downes RG (1959) The ecology and prevention of soil erosion. In 'Biogeography and Ecology in Australia.' (Eds A Keast, RL Crocker, CS Christian) pp. 472–486. (Junk: den Haag, The Netherlands)

Dunin FX, Downes RG (1962) The effect of subterranean clover and Wimmera ryegrass in controlling surface runoff from four-acre catchments near Bacchus Marsh, Victoria. *Australian Journal of Experimental Agriculture and Animal Husbandry* **2**, 148–152. doi: 10.1071/EA9620148

Eagleson PA (1982) Ecological optimality in water-limited natural vegetation soil-vegetation systems. 1. Theory and hypothesis. *Water Resources Research* **18**, 325–340.

Fillery IRP, Poulter RE (2006) Use of long-season annual legumes and herbaceous perennials in pastures to manage deep drainage in acidic sandy soils in Western Australia. *Australian Journal of Agricultural Research* **57**, 297–308. doi: 10.1016/S0378-3774(01)00161-5

French RJ, Schultz JE (1984) Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. *Australian Journal of Agricultural Research* **35**, 743–764. doi: 10.1071/AR9840743

Jackson RB, Jobbagy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, le Maitre DC, McCarl BA, Murray BC (2005) Trading water for carbon with biological carbon sequestration. *Science* **310**, 1944–1947. doi: 10.1126/science.1119282

Kuczera G (1987) Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. *Journal of Hydrology* **94**, 215–236. doi: 10.1016/0022-1694(87)90054-0

Latta RA, Lyons A (2006) The performance of lucerne–wheat rotations on Western Australian duplex soils. *Australian Journal of Agricultural Research* **57**, 335–346. doi: 10.1016/S0378-3774(01)00161-5

Norton RM, Wachsmann NG (2006) Nitrogen use and crop type affect the water use of annual crops in south-eastern Australia. *Australian Journal of Agricultural Research* **57**, 257–267. doi: 10.1016/S0378-3774(01)00161-5

Passioura JB (2005) Epilogue: from propaganda to practicalities — the progressive evolution of the salinity debate. *Australian Journal of Experimental Agriculture* **45**, 1503–1506. doi: 10.1071/EA04181

Philip JR (1957) Evaporation, moisture and heat fields in the soil. *Journal of Meteorology* **14**, 354–366.

Philip JR (1966) Plant water relations: some physical aspects. *Annual Review of Plant Physiology* **17**, 245–268. doi: 10.1146/annurev.pp.17.060166.001333

Rodriguez D, Nuttall J, Sadras VO, van Rees H, Armstrong R (2006) Impact of subsoil constraints on wheat yield and gross margin on fine-textured soils of the southern Victorian Mallee. *Australian Journal of Agricultural Research* **57**, 355–365. doi: 10.1016/S0378-3774(01)00161-5

Sandral GA, Dear BS, Virgona JM, Swan AD, Orchard BA (2006) Changes in soil water content under annual- and perennial-based pasture systems in the wheatbelt of southern New South Wales. *Australian Journal of Agricultural Research* **57**, 321–333. doi: 10.1016/S0378-3774(01)00161-5

Slatyer RO, Denmead OT (1964) Water movement through the soil–plant–atmosphere system. In 'National Symposium on Water Resources, Use and Management'. 9–13 September 1963, Canberra. Chapter 2. pp. 264–289. (Melbourne University Press: Melbourne, Vic.)

Sun H, Cornish PS (2006) A catchment-based approach to recharge estimation in the Liverpool Plains, NSW, Australia. *Australian Journal of Agricultural Research* **57**, 309–320. doi: 10.1016/S0378-3774(01)00161-5

Tanner CB, Sinclair TR (1983) Efficient water use in crop production: research or re-search? In 'Limitations to efficient water use in crop production'. (Eds HM Taylor, WR Jordan, TR Sinclair) pp. 1–27. (American Society of Agronomy: Madison, WI)

Ward PR (2006) Predicting the impact of perennial phases on average leakage from farming systems in south-western Australia. *Australian Journal of Agricultural Research* **57**, 269–280. doi: 10.1016/S0378-3774(01)00161-5

Ward PR, Micin SF, Dunin FX (2006) Using soil, climate, and agronomy to predict soil water use by lucerne compared with soil water use by annual crops or pastures. *Australian Journal of Agricultural Research* **57**, 347–354. doi: 10.1016/S0378-3774(01)00161-5

White DA, Dunin FX, Turner NC, Ward BH, Galbraith JH (2002) Water use by contour-planted belts of trees comprised of four eucalyptus species. *Agricultural Water Management* **53**, 133–152. doi: 10.1016/S0378-3774(01)00161-5

de Wit CT (1958) Transpiration and crop yields. Verslagen Landbouwkundige Onderzoekingen No. 64, Wageningen, The Netherlands.