Water use efficiency of non-irrigated field crops

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Water use efficiency (WUE) is a measure of plant productivity per unit of water used and must be defined relative to the level of biological organisation - leaf, plant, crop or ecosystem - under consideration. Biochemists and plant physiologists have considered WUE primarily in terms of the function of the leaf where net CO2 uptake and water loss

per unit leaf area define a WUE. Reviews of WUE at this level include (1,2), the role of stomata and their interaction with the environment around the leaf have been accorded particular significance (3,4,5). Isolated plants grown in sealed containers have also contributed to the study of WUE (6), particularly the effects of how water is distributed throughout the plant life cycle and here the appropriate measure is usually the plant dry matter produced per unit of water transpired.

At the other end of the scale, farmers and field agronomists are most interested in WUE of individual crops or of farming systems and the most appropriate definitions of WUE may be in terms of total dry matter or grain yield and the net change in water status over the life of a crop. Reviews at this level are less frequent, but three of note are (7,8,9). Here water is lost through surface runoff, drainage and evaporation from the soil in addition to the water actually transpired by the crop. This may be far removed from the assimilation and transpiration of a single leaf, but there is a unifying theme in the linkage of dry matter production and water use.

Over much of Australia, water is considered the limiting environmental resource for crop prodiction and where this is true, an appropriate measure of WUE indicates the efficiency with which an organ or crop or farming system is using the limiting resource. For farmers, WUE may provide a benchmark against which to measure performance whilst for agronomists WUE provides a means of comparison between environments and farming systems.

In this review, I will consider the field measurements of WUE and attempt to show that studies of WUE at the leaf and plant level can be used to validate and extend the results of field measurements of WUE

Field measurement of WUE

Measurements of WUE on crops have invariably used the water balance equation [1] where SW1 and SW2 are initial and final soil moisture profiles, P the rainfall, RO any surface runoff, D deep drainage, SE soil surface evaporation and T the crop transpiration

$$SW1 + P = RO + D + (SE + T) + SW2 \qquad [1]$$

Making the assumption that RO and D are zero, measurements of soil water content at the start and the end of the crop cycle and of precipitation allow estimation of total evapotranspiration (ET = SE + T) as the residual term in the equation.

Since [I] has been widely used to measure WUE in the field, its limitation warrant consideration. Major problems are -

- Because ET is measured by difference, RO and D are generally assumed to be zero. This may be valid, but should not be assumed for all soils and all circumstance. Drainage may be important on coarse textured soils and RO may occur on soils such as red-brown earths where surface sealing may inhibit infiltration. Any errors of measurement are automatically lumped into the ET term.

- Measurement errors may be significant
- The method does not allow easy separation of the two components of the total evapotranspiration, namely the soil evaporation and crop transpiration.

Table 1 presents WUE measurements of field crops in Australia and selected measurements in similar environments overseas. In each case, water use was measured at least at sowing and crop harvest and in many cases at regular intervals through the lifecycle of the crop.

The measurements in Table 1 are of individual experimental crops. A second measure of WUE may be obtained by plotting a series of individual yields versus water use. Such data may come from irrigation experiments where water supply to the crop is an experimental treatment or where other experimental treatments lead to variation in crop growth and water use. Fig. 1 is an example from Griffiths, N.S.W. (22).

Analysed in this way, the slope of the regression line represents the WUE for biomass or for grain, after subtraction of a proportion of the water use represented by the intercept on the x axis. The positive intercept on the water use axis - at which grain yield is zero - has often been taken as a measure of the soil evaporation component of total ET. Other experimental data obtained over years in a single environment (Fig. 2) or even farm yields (Fig. 3) show a remarkable consistency in WUE as the total water use varies although the actual slope and the intercept value appear to vary between the data sets.

Table 1. Water use efficiency for cereal crops in Australia and overseas.

Location	Biomass kg/ha	WUE	Grain kg/ha	WUE	Comment	Reference
Queensland						
Narayan	8200	42.7	3030	15.8	Brigalow grey-brown and red clays, fallowed	10
Biloela			1950	13.4	4 years. Uncertainty about extraction below 120	11
New South Wales						
Wagga	12000	33.8	3330	9.4	Red-brown earth	12
Victoria						
Horsham	3610		3610	14.1		13
Rutherglen	13650	34.5	4624	11.7	Red-brown earth. 1971 trial	14
Rutherglen	14652	49.5	2994	10.1	red-brown earth. 1972 trial	14
South Australia						
Northfield			1808	4.5	Black earth Ug 5.11, fallow	15
Parafield			1709	4.9	Red-brown earth Dr 2.13, fallow	15
Pinery			949	4.5	Deep sand Uc 1.12, fallowed	15
Adelaide			3200	10.7		16
Kimba	12060	37.1	4120	12.7		17
Western Australia						
Wongan Hills	7590	29	3020	12.5	Deep loamy sand Uc 1.12	18
Merredin	6950	42	1955	11.8	Red-brown earth Dr 2.13	18
Merredin	7600	42	2485	13.8	Red-brown earth Dr 2.13	18
Merredin	8290	37	2775	12.4		18
Merredin	8020	39	3085	14.9		18
Syria						
Tel Hadya	10830	29.1	3560	9.6		19
Breda	4940	22.9	2130	9.9		19
United Kingdom						
Rothamsted		33		15.3	Spring wheat	20
Cambridge		36.4		14.8	Spring barley	21

French & Schultz (17) have used the same method to analyse an extensive set of water use and wheat yield data collected from experiments in South Australia between 1964 and 1975. This data, collected from many locations is much more variable than the more restricted sets presented in Figs 2 & 3. French & Schultz interpret their results by stating '----we have drawn an arbitrary line which encloses almost all the highest yielding crops at different levels of water use and thereby defines a linear relationship between potential yield and water use. The spread of data below this line indicates sites where yield was limited by factors such as extremes of temperature, agronomic deficiencies, the effect of pests and diseases and possibly soil erosion'.

The slope of the potential WUE line is 20 kg/ grain.mm of water use above an intercept value of about 110 mm. Both of these are greater than values in Figs 1-3 and although the authors extend and qualify their analysis, the figures of 20 kg/mm and 110 mm have been widely used in extension material as a means of defining potential yield for cereal crops.

The data presented in Table 1 and Figs 1-4 are all field measurements of WUE. Can theory now help to understand and interpret those measurements and particularly to understand the underlying causes of variation in WUE between environments?

Pathways of vapour and CO2 movement.

The linkage of dry matter production and water use arises from the shared pathways of water vapour and CO2 movement between the bulk atmosphere and the sites of CO2 assimilation in the leaf.

Movement along the pathway occurs in response to differences in vapour of CO2 concentration and the pathway can be segmented into steps with a concentration difference and associated resistance. Modern theory (4) favours the use of molar fluxes and conductances to analyse vapour and CO2 movement, however the resistance model is intuitively easier to follow and is adequate in this analysis. For vapour, the major resistances are those at the leaf boundary layer (rb) and the stomatal pore (rs). Movement of CO2 faces these resistances (r'b and r's) plus a resistance (r'm) associated with its movement in the mesophyll cells to the sites of CO2 assimilation. The stomatal and boundary layer resistances for vapour and CO2 are not identical, because of differing molecular size but are related by r'= 1.6r (4).

More complex analyses of the diffusion pathways can be developed including aerodynamic and intercellular space resistance and the segmentation of the mesophyll resistance into components representing the biochemical steps in CO2 assimilation.

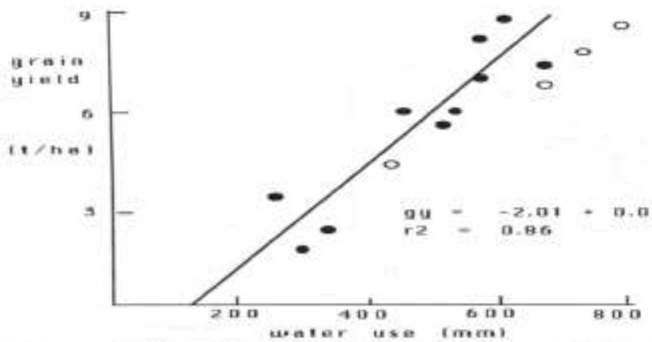


Fig. 1. Grain yield and water use for irrigated wheat
● Griffiths, ○ Leeton. Redrawn from (22).

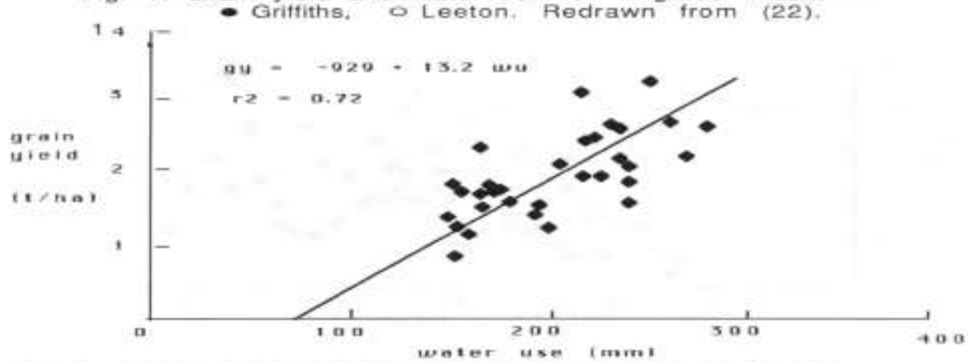
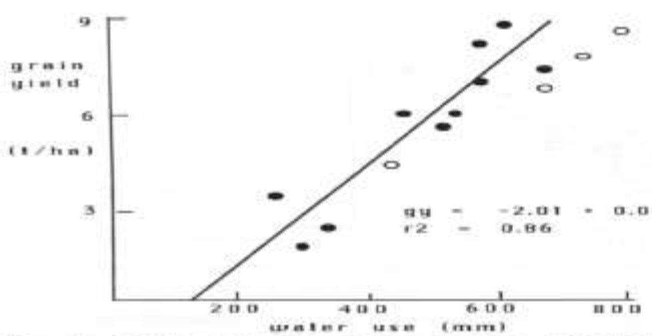


Fig. 2. Grain yield and water use from experiments in the wheatbelt of Western Australia., 1979 - 1985 .



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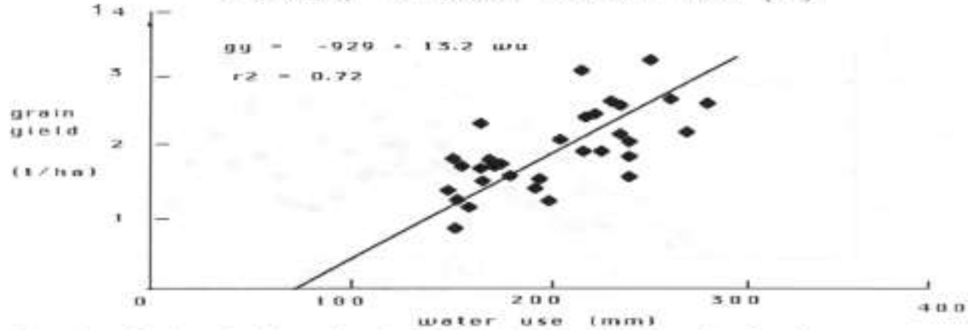

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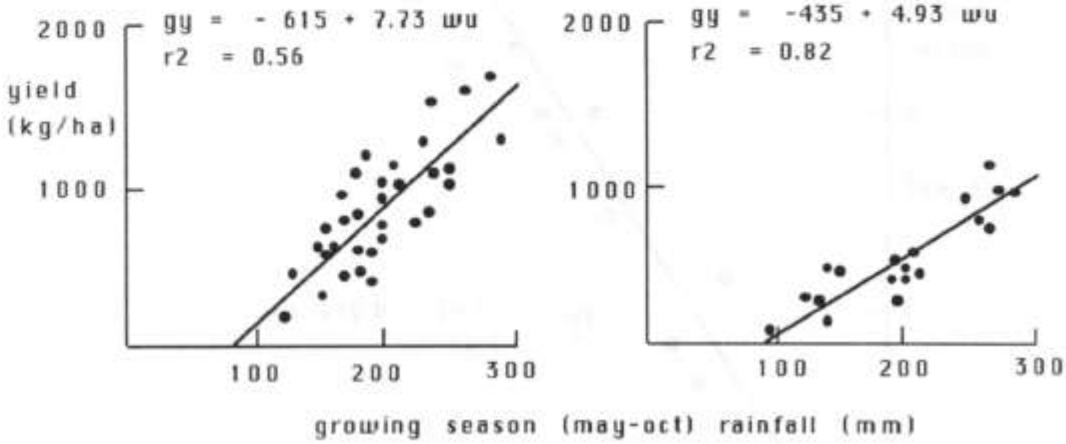

Fig 3. Grain yield and growing season rainfall relationships for (a) Merredin Research Station, W.A. and (b) Kummel property Morawa, W.A. (Data kindly supplied by Mr. N. Fallon).

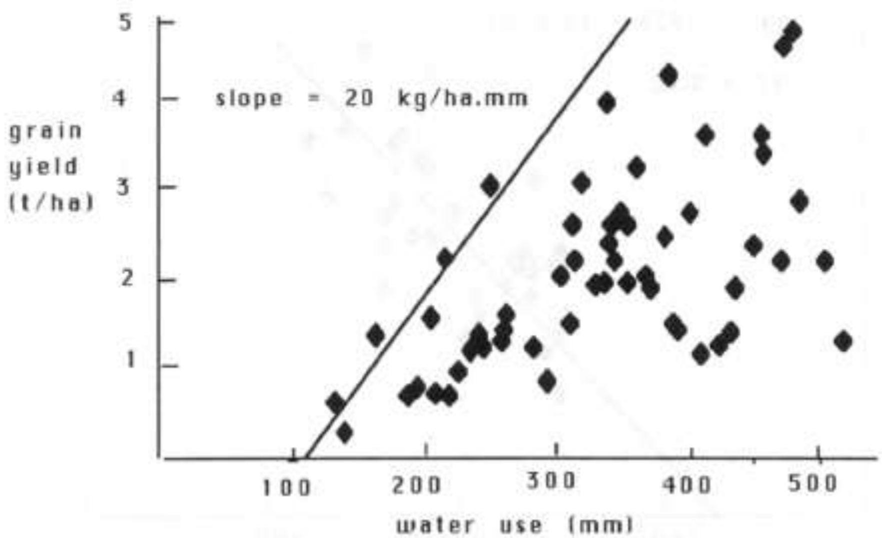

Fig. 4. Grain yield and water use in South Australia. Redrawn from French & Schultz (17).

Bierhuizen & Slatyer (24) formalized the description of the vapour and CO_2 transfer using the equations :

$$N_L = dC / (r'b + r's + r'm) \qquad [2]$$

and

$$T_L = (p\varepsilon/P)\ (e^*L - e)/rb + rs) \qquad [3]$$

where NL and TL are the CO_2 assimilation and transpiration per unit leaf area, dC is the CO_2 concentration difference between bulk air and the compensation point, e*L the saturation vapour pressure (at leaf temperature) and e the vapour pressure of the atmosphere, p the air density, e the ratio of the mole weight of water vapour to air and P the atmospheric pressure. The resistances are as defined previously.

Combining [2] and [3] and taking constant values for P, dC, p and E and by assuming that leaf and air temperature are the same, (i.e. e*L =e*) gives equation [4].

$$N_L/T_L = [\ k' / (e^*\text{-}e)\ ]\ [\ (rb + rs)/(r'b + r's + r'm)\ ] \qquad [4]$$

Bierhuizen and Slatyer argued that the ratio of the resistance (rb + rs) to (r'b + r's + r'm) would remain relatively constant during the day and that the WUE of the leaf was relatively constant when adjusted for the vapour pressure deficit (VPD) of the atmosphere.

Tanner and Sinclair (25) have shown that [4] can be modified and extended, using simplifying assumptions, to a whole canopy, Their expression for the transpiration efficiency (TE) of a closed canopy is -

$$TE = k/(e^*\text{-}e) \qquad [5]$$

where k is a species specific constant and (e*-e) the vapour pressure deficit of the atmosphere for the daylight period during which gas exchange occurs. The limitations and simplifying assumptions of [5] have been discussed (25), but despite these, the equation represents a theoretically based approach to the water use efficiency of field crops. Its major features are -

- k represents a species specific coefficient which may be calculated from theory and which depends primarily on the photosynthetic pathway (C3 or C4 species) and the chemical composition of the crop biomass. The latter is significant because 1 g of primary photosynthate is equivalent to about 0.83 g of carbohydrate, 0.40 g of protein and 0.33 g of lipid (26). Conversion coefficients for seed range from 0.42 for sesame to 0.75 for the grain of temperate cereals (27) depending on the proportions of lipid, protein and carbohydrate in the seed and this is one of the main reasons for

$$TE = m/E_0 \qquad [6]$$

Crop	C_3/C_4	Experimental k (mbar)	Calculated k (mbar)
Zea mays	C4	0.082-0.12	0.118
Sorghum bicolor	C4	0.138	0.118
Medicago sativa	C3	0.043	0.050
Glycine max	C3	0.040	0.035
Triticum aestivum	C3	-	0.051

$$Y/ET = [k/(e^*\text{-}e)]\ [1 - SE/ET] \qquad [7]$$

lower seed yield (and WUE) in protein and oilseed crops compared to the temperate cereals.

- (e*-e), the vapour pressure deficit (VPD) represents the influence of environment on WUE. Variations in VPD occur on a daily and on a seasonal basis and will vary between environments.

Equation [5] is similar in form to the empirical relationship deduced from the analysis of data on water use of plants grown in sealed containers (28).

where m is an empirical constant and E0 pan evaporation. The similarity of [5] and [6] is not unexpected, however the later analysis (7) shows that vapour pressure deficit rather than pan evaporation is the sounder normalizing factor and that k has a theoretical basis compared to the empirical 'm'. Reasonable agreement has been found between calculated and measured values of k (Table 2).

Table 2. Measured and calculated values of k in equation [5] for various field crops (25).

Analysing water use of a field crop

Direct application of [5] in the field is difficult because water balance measurements estimate ET not T. Equation [5] may be rewritten for ET as Equation [7] would be useful to us if SE/ET were constant, for example under a perennial crop with good groundcover, however for an annual field crop the ratio SE/ET will clearly vary from close to 0 to close to 1 through the life of the crop. We might also speculate that SE/ET may vary with other factors such as soil type and rainfall pattern. Separation of SE and T thus appears to be a key step in the further understanding of crop water use and WUE.

One approach is to analyse in more detail the patterns of crop growth and water use through the life cycle of a crop. Many of the measurements of WUE (Table 1) come from experiments where dry matter and soil water were measured at intervals from sowing to harvest. One such set of data was collected at Merredin W.A. in 1984 (18). The soil was a red-brown earth and crop dry matter, leaf area and soil profile water were collected fortnightly (Fig. 5). Soil water profiles were also measured on an ajacent unsown, weed free, fallow plot. Moisture profiles confirmed that water did not move below 120 cm and as sowing to harvest rainfall was only 102 mm there was no runoff and all water use was as ET.

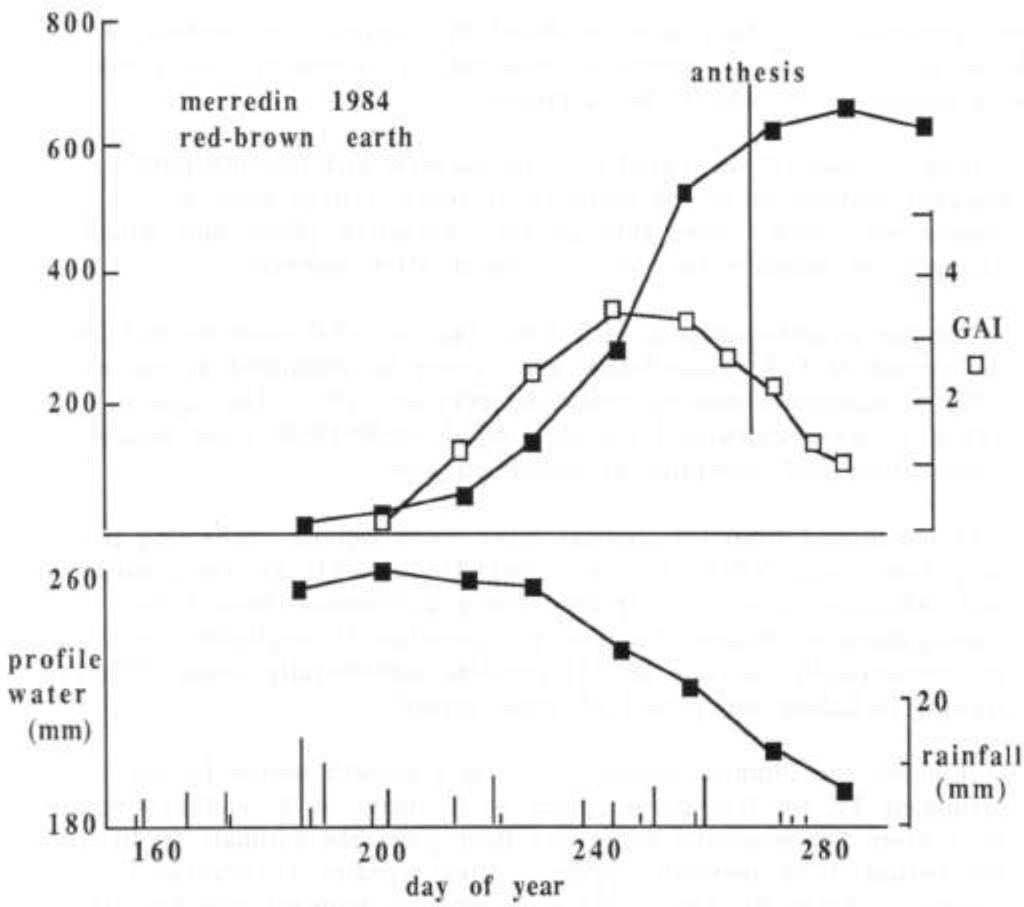

Fig. 5. Crop dry weight, green area index and soil profile water content for a red-brown earth at Merredin, W.A. The crop was sown on 11 June 1984 (day 163) and flowered on 23 September (day 267).

Separating ET into its components requires either direct measurement or estimation of SE or T. Fischer (7) used a relationship between transpiration efficiency and pan evaporation derived from pot experiments at Wagga, N.S.W.

$$TE = 10.2 - 1.3E_{pan} + 0.053\ E_{pan}^2 \qquad [8]$$

By dividing a measured biomass increment over a growth period by the TE for the same period, it is possible to estimate T and, by subtraction from total ET, the SE for the period. Equation [5] can be used in exactly the same way.

Table 3 illustrates the calculation of T and SE from the data presented in Fig. 5 and for a similar trial conducted at Wongan Hills, W.A. in 1983 (18).

I have presented this data in some detail to illustrate the method of analysis and some of the problems inherent in estimating rather than directly measuring SE and T. Some points are -

- Both [5] and [7] are based on total biomass and this invariably requires estimation of the quantity of roots. I have used a conversion which varies through the vegetative phase and which assumes no increase in root dry matter after anthesis.
- The pan evaporation is a daily total, but the VPD must be that for the period of CO_2 assimilation and cannot be estimated as the mean VPD at maximum and minimum temperature (29) . The data in Table 3 were calculated for the period 08.30-18.30 from hourly temperature and humidity recorded on site.
- TE calculated from [5] changes much more rapidly reflecting the very low winter VPD's and the rapid rise of VPD as temperature and radiation increase in spring. These differences have little consequence in winter, because transpiration is negligible, however the theoretically derived TE [5] predicts substantially lower TE's in spring, including the period of grain growth.
- dividing the biomass produced during a growth period by the estimated TE for that period gives an estimate of T, and subtraction of T from the measured water use then gives the estimate of SE for the period. Both methods appear to over predict T (bracketed figures in Table 3). This could arise because biomass was too high or because TE was too low. The latter would arise if the measured daytime integral of VPD were higher than the effective VPD when the crop was assimilating carbon. Midday stomatal closure due to lowered leaf water potential (2) or a direct effect of low atmospheric humidity (30) is a possible cause.

Table 3. Calculation of transpiration efficiency (TE), transpiration (T) and soil evaporation (SE).

Date (MERREDIN)	Tops g/m2	Biomass g/m2	Change in Biomass	Epan mm/day	TE (1) g/m2.mm	(e*-e) mbar	TE (2) g/m2.mm	Water Use (mm)	Equation [8] T	Equation [8] SE	Equation [5] T	Equation [5] SE	SE algorithm T	SE algorithm SE
11 Jun-21 Jun				1.92	7.9			8.9		8.9		8.9		8.9
22 Jun-5 Jul	2.8	3.6	3.6	2.28	7.5	3.00	17.0	14.2	0.5	13.7	0.2	14.0	(-1.1)	15.3
6 Jul-19 Jul	9.0	12.6	9.0	2.86	6.9	2.78	18.3	12.6	1.3	11.3	0.5	12.1	(-2.8)	15.4
20 Jul-2 Aug	47.2	70.8	58.2	1.89	7.9	4.28	11.9	8.4	7.3	1.1	4.9	3.5	1.2	7.2
3Aug-16 Aug	138.5	193.9	123.1	1.70	8.1	3.58	14.2	19.4	15.1	4.3	8.6	10.8	13.7	5.7
17 Aug-30 Aug	297.0	386.1	192.1	2.14	7.7	5.03	10.1	31.8	25.1	6.7	18.9	12.9	29.1	2.7
31 Aug-13 Sept	516.0	619.2	233.1	3.10	6.7	7.07	7.2	25.6	34.9	(-9.3)	32.3	(-6.7	21.3	4.3
14 Sep-27 Sep	703.0	773.3	154.1	4.20	5.7	9.43	5.4	26.0	27.2	(-1.2)	28.5	(-2.5	20.7	5.3
28 Sep-11 Oct	764.0	834.3	61.0	4.95	5.1	13.52	3.8	16.6	12.1	4.5	16.2	0.4	12.3	4.3
12 Oct-23 Oct	730.0			8.05	3.2	19.31	2.6	0.6	0.0	0.6	0.0	0.6	(-2.2)	2.8
								164.1	113.0	51.1	100.9	63.2	92.2	71.9

Day of Year	Tops g/m2	Biomass g/m2	Change in Biomass	Epan mm/day	TE (1) g/m2.mm	(e*-e) mbar	TE (2) g/m2.mm	Water Use (mm)	Equation [8] T	Equation [8] SE	Equation [5] T	Equation [5] SE	SE algorithm T	SE algorithm SE
15 Jun- 5 Jul								27.2		27.7		27.7		27.7
6 Jul-19 Jul	4.5	5.8	5.8	2.35	7.4	5.86	8.7	16.2	0.8	15.4	0.7	15.5	(-7.6)	(-8.6)
20 Jul- 3 Aug	14.0	18.2	12.4	2.98	6.8	6.35	8.0	14.7	1.8	12.9	1.5	13.2	(-2.2)	(-16.9)
4 Aug-17 Aug	43.3	64.5	46.3	3.06	6.7	5.89	8.7	21.8	6.9	14.9	5.3	16.5	6.5	15.3
18 Aug-31 Aug	99.5	139.3	93.0	2.52	7.3	3.93	13.0	25.5	12.8	12.7	7.2	18.3	11.1	14.4
1 Sep-14 Sep	228.2	296.7	157.4	3.52	6.3	4.07	7.3	50.2	25.1	25.1	21.7	28.5	36.0	14.2
15 Sep-29 Sep	407.7	489.2	192.5	4.28	5.6	9.51	5.4	50.7	34.3	16.4	35.9	14.8	46.9	3.8
30 Sep-12 Oct	619.0	700.5	211.3	5.56	4.6	13.71	3.7	49.4	45.8	3.6	56.8	(-7.4)	47.1	2.3
13 Oct-26 Oct	737.0	818.5	118.0	7.63	3.4	23.24	2.9	38.8	35.0	3.8	40.5	(-1.7)	32.1	6.7
27 Oct- 9 Nov	767.5	849.0	30.5	8.47	3.0	20.27	2.5	7.7	10.2	(-2.5)	12.1	(-4.4)	3.7	4.0
								302.7	170.2	132.5	168.2	134.5	183.4	119.3

Independent measurement of SE would also allow separation of SE and T. Direct measurement of SE is possible (31) however there remains the problem of integrating instantaneous measurements over a 3-6 month crop life cycle. Two phases of moisture loss are recognised for a bare soil surface (32) . An initial phase after the soil is thoroughly wetted allows evaporation to be determined by the daily energy input and daily SE approximates pan evaporation. A second phase begins when the moisture supply to the surface determines water loss and during this phase the cumulative evaporation increases in proportion to the square root of time.

Crop simulation models have used algorithms to simulate this two phase evaporation and these can be used to estimate soil evaporation under a crop canopy by assuming that 'under canopy' SE is proportional to the radiant energy reaching the soil surface.

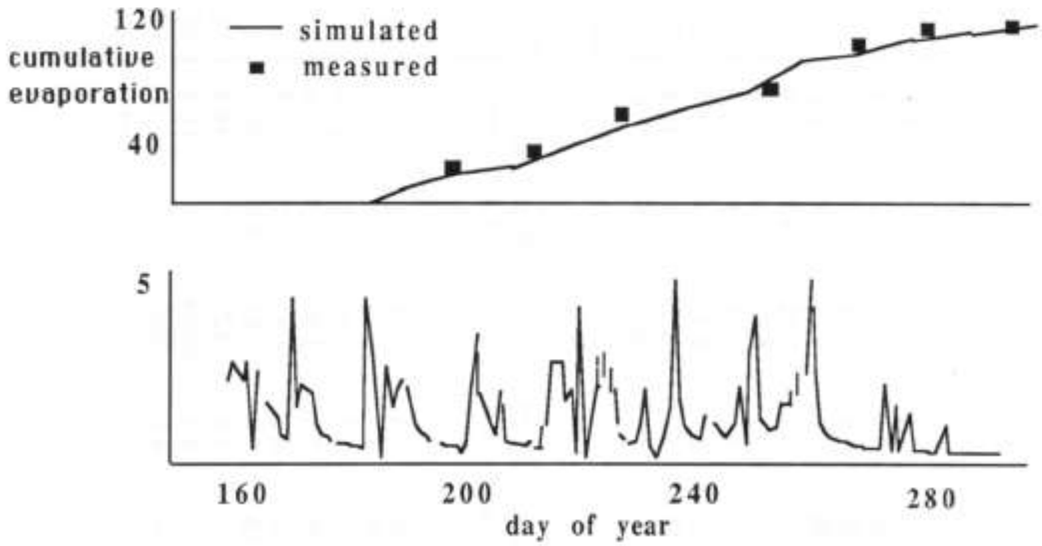

Fig. 6. Simulated daily bare soil evaporation. Simulated cumulative evaporation ,and measured bare plot water use n . simulated daily bare soil evaporation.

I have used one of these algorithms to simulate SE for a bare soil surface (Fig. 6). the algorithm was calibrated by adjusting the coefficients which govern the length of phase 1 and the rate of mositure loss in phase 2 of bare soil evaporation and Fig. 6 shows the simulated daily SE and the cumulative SE with the measured water use from the bare plot. An estimate of SE under the crop was then obatained by reducing bare soil SE by the proportion of radiant energy reaching the ground surface. The latter was calculated as exp(-0.45*GAI) where GAI is the green area index of the crop. Estimates of SE and T (obtained by subtraction of SE from measured water use) are given in the final two columns of Table 3.

Clearly in this case I could have used the measured SE (as was done by (19)),but the simulation procedure has the advantage of generality and can be used to extend the analysis by changing the rainfall patterns or soil properties.

Table 4 summarises the results of the three methods of separating SE and T. Given the uncertainties in each of the methods, there is reasonable agreement that SE was about 60 mm or 40% of water use at Merredin and about 130 mm or 44% at Wongan Hills. Other estimates of SE in Australia include those of Doyle and Fischer (33) who estimated SE values of 73 to 162 mm under a range of experimental treatments at Tamworth. The average SE was 112 mm or 30% of ET. Other estimates are of 27 mm or 14% of ET at Narayan and 162 mm or 35% of ET at Rutherglen (10); and of 60-150 mm (17) depending upon soil type

Table 4. Estimates of transpiration, and soil evaporation (SE) for trials at Merredin and Wongan Hills, W.A.

Method	Merredin		Wongan Hills	
	T	SE	T	SE
Equation [7]	113.0	51.1 (31%)	170.2	132.5 (44%)
Equation [5]	100.9	63.2 (38%)	168.2	134.5 (44%)
SE algorithm	92.2	71.9 (44%)	183.4	119.3 (39%)
Total Water Use	164.1		302.7	

Partition of water use through the life cycle

Because grain dry matter is mainly formed in the post-anthesis period with only a small contribution from pre-anthesis material, grain yield and thus the WUE (for grain) are largly determined by the post-anthesis water use and the WUE in that period. This, we have seen, is determined by the ambient VPD. Table 5 re-analyses the data of Table 3 to allow calculation of 'potential' grain yield by partitioning the pre-and post-anthesis water use and estimating post-anthesis biomass production from equation [5].

For these trials, post-anthesis water use was 15% and 28% respectively of ET. A ratio of pre- to post-anthesis water use of 2:1 has been suggested where water limits grain yield (34) and a figure of 28% post-anthesis water use is given for both high and low yielding crops in South Australia (17).

Table 5. Calculation of grain yield from post-anthesis water use

Location	Pre-anthesis T (mm)	Post-anthesis T (mm)	Post-anthesis TE (g/m2.mm)	Biomass (g/m2)
Merredin	141	7.4	5.4	40.1
	85%	16.2	3.8	61.6
		675 g/m2 10% =		65.6
				169.2
				(Measured = 195.5)
Wongan Hills	217.3	38.9	3.72	144.7
	72%	38.8	2.19	85.0
		7.7	2.96	22.8
		514 g/m2 10 % =		51.1
				303.6
				(Measured = 300.6)

Calculation of grain yield using [5] and adding 10% of anthesis biomass gave yield estimates quite close to those measured in the field. French and Schultz (17) were unable to relate grain yield to any combination of post-anthesis water use and pan evaporation, but this may have been because they were using evaporation rather that VPD and because they were integrating over the whole period from anthesis to maturity.

Generalization to field measurements of WUE

This analysis, although restricted to only two trials, illustrates how the theoretical basis of WUE can be used to dissect and add meaning to individual experiments. Can we now extend this to a more general analysis of WUE in the field?

Some important conclusions we have drawn are -

- Soil evaporation is a major component of ET and appears to vary greatly both as an absolute amount and as a proportion of Et. This variation is due to differences in soil properties, rainfall distribution and canopy cover.
- The value of the vapour pressure deficit (e*-e) determines WUE on a daily basis.
- The amount of water used post-anthesis is of equal significance because grain yield is largly determined by post-anthesis water use and the ambient VPD.

A first approach can be to model yield based on some simple assumptions.

Model I	Model II
ET variable 160-320 mm	ET variable 160-320mm
SE = 80 mm	SE = 40,42.5,45,47.5 and 50% of ET
Post-anthesis T = 30% of T	Post-anthesis T = 30% of T
(e*-e) = 10,15 or 20 mbar	(e*-e) = 10,15 or 20 mbar

Fig. 7a shows the results for Model I. Here SE is a constant 80 mm and post-anthesis transpiration is assumed to be 30% of total T. The slopes of the three lines represent the WUE's in the different VPD environments, the lines cross the water use axis at 80 mm.

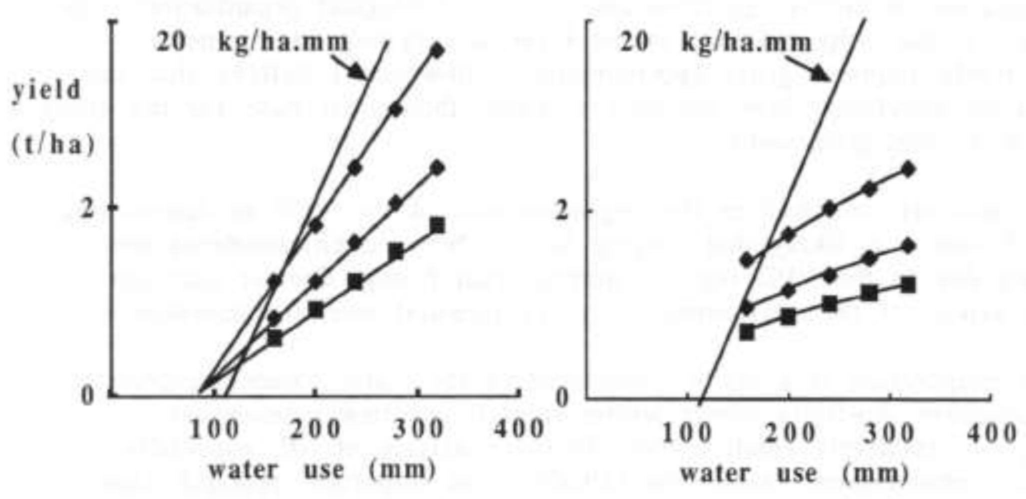

Fig. 7. Predicted yield-water use relationships for Model I and Model II.

An equally naive assumption is that SE increases as a proportion of ET as ET itself increases (Model II). In this case (Fig. 7b) the WUE decreases with increasing water supply. Neither model represents true reality, however the resemblance of Fig. 7a to Figs 1-4 is striking. The different slopes (WUE's) are generated by the differing VPD environments during grain filling. Comparing Figs. 4 and 7, I see the 20 kg/ha.mm 'potential' WUE line as only one of many 'potential' yield lines, albeit one appropriate to an environment with very low VPD and high TE. Where a crop WUE falls below this line it may be because sub-optimal management or detrimental biotic influences (weeds, diseases nutrition etc) reduce yield, or it may be that the best possible yield in that season and at that location was less than 20 kg/ha.mm due to the seasonally determined pattern of water use and TE.

The term 'potential' thus needs careful qualification. I believe that the most appropriate measure against which to judge field crops is not some absolute potential, but the WUE achievable in that environment and that season, and this may be substantially less than 20 kg/ha.mm. The consistent WUE seen in a given environment (Figs 1-3) arises from the consistency of seasonal trends in VPD at a given location whilst grain yield itself varies because of year to year variation in rainfall and therefore in total water supply.

Conclusions

I have attempted to show that water use measurements on field crops in Australia can be interpreted and understood by developing the theory of vapour transfer and CO2 assimilation of a leaf. The upward integration of knowledge from one level of biological organisation - the leaf - to the crop and then to the level of cropping environments inevitably requires gross approximations, however I believe that the analysis developed here provides a useful theoretical base for the study of WUE and grain yield.

The analysis emphasises the important role of the VPD in determining WUE and it is likely that varying WUE's between environments are largely due to the VPD regimes during grain filling. Greater attention to this aspect of the environment in experimental work is desirable.

Soil evaporation is a major component of the water balance, especially in southern Australia where winter rainfall is often received as frequent, relatively small events. Further analysis of SE, especially direct measurement, would be valuable, as important research topics such as conservation tillage and trash retention modify the soil surface and have the potential to change SE with flow on effects on other components of the water balance.

For grain growers and agricultural scientists, the comparative WUE's in Table 1 are evidence that Australian cereal crops are as efficient in using water as cereal crops in other countries with a technically advanced agriculture. For grain growers, WUE calculations based on growing season rainfall can provide an important benchmark and focus for analysis of their crop enterprise. However, for this to be useful, the analysis of the benchmark 'potential' must be appropriate to that environment taking into account the likely SE given soil type and rainfall pattern, and the VPD regime during grain filling.

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New directions for irrigated pastures

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Background

Since the turn of the century, irrigation in Australia has undergone a spectacular development, and now totals some 1.5m ha. Victoria and Southern NSW account tor over 1.0m ha, including 800,000 ha of irrigated pastures. Cropping and horticulture are the main enterprises in most of the worlds major irrigation developments, so that the dominance of pastures in irrigated S.E. Australia is unique.

It may be this -uniqueness" which has led to an interesting paradox: pastures dominate our irrigation areas but have been largely ignored by our research groups. Eight research centres have been established in the Murray Valley to work on irrigated horticulture and cropping (Griffith (2), Dareton, Irymple, Merbein, Tatura, Loxton and Yanco). Only Kyabram Research Institute has concentrated on animal production in the irrigation areas with inputs from Deniliquin and Leeton, especially in the 1960's. This lack of research effort is reflected in the low productivity of the pasture based industries (1).

Before we examine the performance of irrigated pastures it is important to understand that every irrigated farm has a limited water supply. Distribution of irrigation water is based on a system of farm water rights and sales allocations too complex to explain here. The key point is that because water is already fully committed on most farms, any new pasture initiative requires that water be diverted from existing uses to keep the farm within its water budget.

Table 1. Land use value of production from irrigation in Victoria.

Land Use	Irrigated Area (1000 ha)	Product	Annual Farm Gate Value ($m 1982-85)
Perennial Pasture	230	Dairying	230
Annual Pasture	220	Vegetables and other row crops	140
Cropping and lucerne	67	Tree fruit	110
Horticulture	53	Meat and Wool	90
		Grapes	60
Total	570		630

WHY DO WE NEED NEW DIRECTIONS?

The current crisis in Australian agriculture has combined with a number of longer term factors to suggest that we should seriously reassess both our irrigated pastures per se and our attitude to the pasture/animal industries in the irrigated areas. Irrigated agriculture began in S.E. Australia in the last two decades of the nineteenth century. The stimulus for this development was the idea that large scale irrigation development could protect the pastoral industries, upon which Australia was so dependent, from the devastations of recurring drought (2). No research was carried out to devise new production systems for these irrigated pastures, so irrigation was simply added to sub. clover/ryegrass or white clover/ryegrass pastures that had been developed for rainfed systems.

The irrigation capacity of the Murray-Darling system is almost completely utilised so that future emphasis must be on increasing the productivity of our existing irrigation resource (3). Cockroft et al. (1) point out that this situation represents a watershed for agricultural science in the irrigation areas, as expansion mentality is replaced by intensification. Against this background, a critical examination of the 'crop' which dominates our irrigated areas seems timely.

There has been massive investment by governments to develop water storage and distribution systems and by individuals to purchase, develop and irrigate land. These nigh costs make it essential that a real competitive advantage in agricultural or horticultural production be obtained - this advantage may be in the form of new products, greatly increased yields, special quality or some other key advantage such as out of season or year round production to ensure a premium price on local or export markets. Production systems which exploit these competitive advantages are, at present, the exception rather than the rule in the irrigated animal industries, as can be seen from the dairy industry.

Pastures for dairying dominate irrigated agriculture in Victoria (Table 1). There are three geographic regions in Victoria for dairying, one irrigated, the other two rainfed (Fig la). As would be expected, the patterns of milk production for the two rainfed areas peak in spring and then drop quickly as the pasture supplies decline over summer. It is interesting (surprising ?) to note that the pattern of milk supply from irrigated northern Victoria is identical, peaking in October and then declining rapidly. The three regional supply curves in Fig. la result in the price scheme shown in Fig lb, with high prices occurring when the milk supply is low. Potentially, the irrigated areas can manipulate animal production through feed supply to gain a competitive advantage in out of season or year round supply. Such production systems need to be developed.

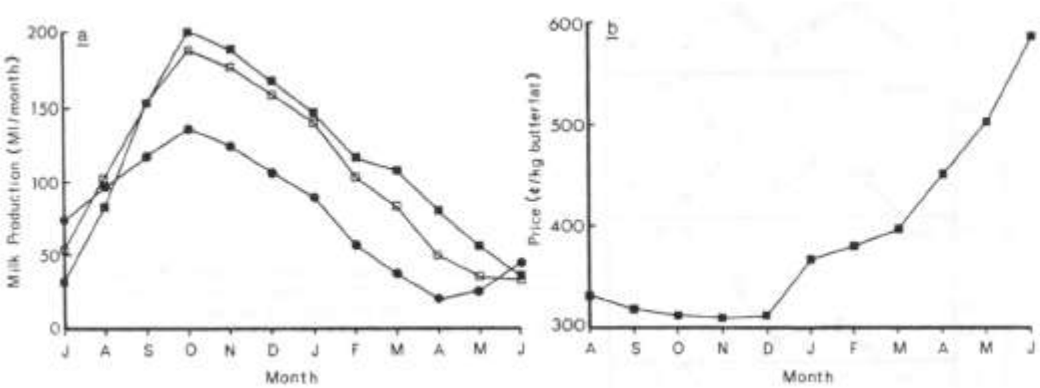


Figure 1. Monthly milk supply (1985/86) from the northern (n) irrigated area and the western (•) and eastern (D) rainfed regions of Victoria. (b) Approximate monthly butterfat prices.

For the last ten years or more, there has been a research push to develop cropping systems for irrigated grain production suited to the soils of the Riverine Plain (4, 5, 6). However, the value of grains on the export market have declined as many third world countries have become self sufficient and developed countries have competed to maintain or increase export volumes. The irrigated areas appear to have few competitive advantages in grain production and it can be argued that at this point in history, the comparative advantage of Australia lies in animal products and that the allocation of research resources in irrigated agriculture needs to reflect this reality. Excellent returns should be available from investing in the development of the irrigated animal industries because (i) they already dominate irrigated agriculture in S.E. Australia, (ii) little research effort has so far been applied to realise their productive potential, (iii) the opportunity exists to develop value added products, for domestic and export markets and (iv) in contrast to grains for export, animal products tend to generate a large multiplier effect in the community because of processing requirements. New directions for the management and utilisation of irrigated pastures are a prerequisite for the development of the irrigated animal industries.

Because the research effort into irrigated pastures has been so limited, the scientific literature contains few clues on new directions. To identify these new directions, we need to take a critical look at our current annual and perennial pastures: their performance, strengths and weaknesses — and look for opportunities. New directions will only come about by seizing opportunities.

Irrigated annual pastures

Annual pastures occupy approximately 450,000 ha in Victoria and N.S.W. These pastures are mainly based on subterranean clover (Trifolium subterraneum L.) and annual ryegrass (Lolium rigidum Gaud) and regenerate from seed each autumn in contrast to perennial pastures.

The tact that irrigated farms have a limited water supply is the principal reason for using annual pastures. As well, early studies showed that for a traditional sheep operation, there was no advantage from including perennials in the system (7). Total water use is much lower than for perennial pastures because no irrigations are applied during summer when evaporative demand is greatest. Annual pastures are more productive during autumn/winter when the growth rate of perennial pastures is low (8) but overall production is lower than for perennials.

The average yield of rainfed annual pasture in northern Victoria is approximately 5 t DM/ha with the range being 2-6 t depending on rainfall (9). Irrigation is used to extend the growing season of these pastures in both autumn and spring, as well as to greatly reduce year-to-year variability. Yields range from 5-12 t DM/ha/yr depending on the timing of establishment and of the final irrigation in spring (10, 11, 12). Stockdale (8) measured an average yield (1976-1980) of 11 t DM/ha when the first irrigation was applied in mid March.

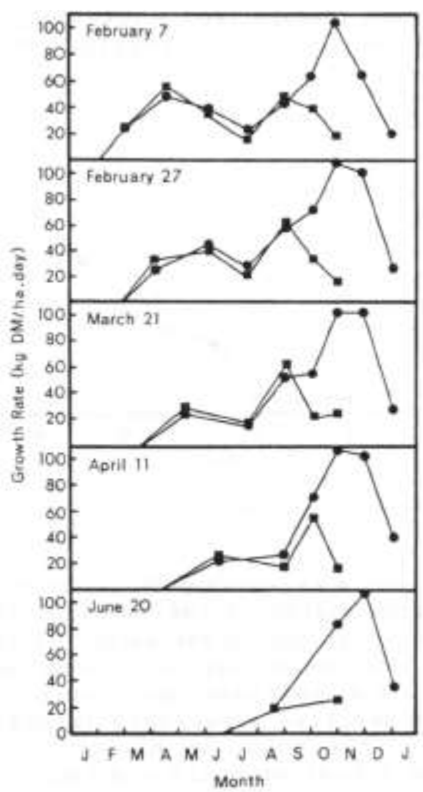


Figure 2. Growth rates of subterranean (■) and Persian clover (●) from a range of establishment times (From 11). The average timing of the autumn break in northern Victoria is late April.

Time of establishment in autumn has obvious effects on production (Fig. 2), with the density of established seedlings being another important factor (13, 14). Seedling density is controlled by seed production in the previous spring, survival of that seed over summer and the interactions of germination inhibitors, soil water supply and soil temperature at the time of germination. To achieve high seedling densities (>1000/m') from early irrigations, luxury quantities of seed must be produced, as hardseededness, high temperatures and slow rates of germination limit establishment in February to less than 1U% of available seed (15). This inhibition of germination means that annual pastures cannot be established any earlier than February.

Irrigated sub. clover and annual ryegrass pastures have only a few competitive advantages over rainfed pastures. Stocking rates can be higher than on neighbouring rainfed farms because of an increase in total pasture production, a dramatic reduction in year-to-year variation and an extension of the growing season in both autumn and spring. Unfortunately, extending the growing season simply brings irrigated farms into competition with high rainfall areas such as the Slopes and Tablelands which have more reliable rainfall and a longer growing season. Annual pastures face the added disadvantage that the capital costs of the irrigation infrastructure ie., channels, drains, laser grading etc., are the same per hectare as for more intensively irrigated crops or perennial pastures.

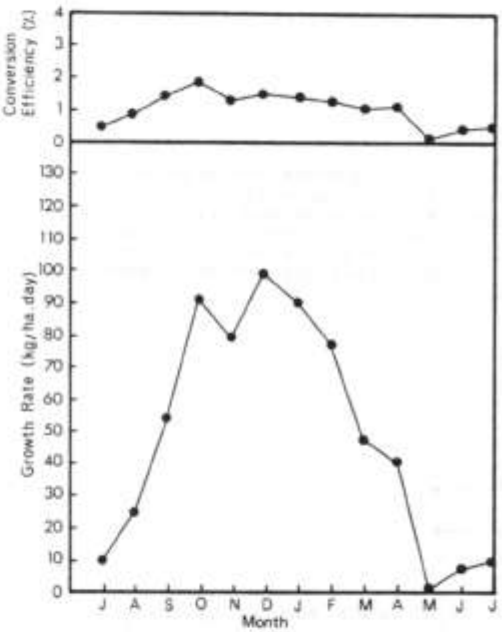


Figure 1. Growth rate and percent conversion of solar energy to plant DM of a paspalum dominant pasture in northern Victoria (From 8). The average yield of this pasture over five years was 18.3 t DM/ha - 50% greater than the regional average.

Irrigated perennial pastures

Irrigated perennial pastures are critical for the future of intensive animal production systems because they give the potential for year round production. It is these pastures which can provide a key competitive advantage for irrigated areas. Therefore, this review concentrates mostly on perennial pastures.

The current 350,000 ha of irrigated perennial pastures in S.E. Australia are mainly mixtures of the temperate (C3) species white clover (Trifolium repens) and perennial ryegrass (Lolium perenne) with the subtropical (C4) species paspalum (Paspalum dilatatum) which is sometimes sown but is more usually a volunteer.

Productivity of Perennial Pastures

The heavy soils of the irrigation areas in the Riverine Plain have a major influence on the productivity of the region. Several recent reviews (1, 3, 16) have dealt extensively with this subject.

One of the major reasons why pastures are criticised as an inefficient user of irrigation water is the low dry matter (DM) yield of perennial pastures. Annual yields as high as 18-20 t DM/ha have been recorded in northern Victoria (8, Fig. 3) but the average is only 12 t/ha (16). This represents less than 1% conversion of solar energy to DM, while Cooper (17) suggests that 4% conversion should be a realistic objective.

As well as DM yield, feed quality must be considered when discussing pasture productivity. Martin (18) measured in vitro DM digestibility of 77% for white clover and ryegrass, and 65% or less for paspalum during the period between October and April. Paspalum is the highest yielding component of our perennial pastures but has the lowest quality, while clover which is critical for pasture quality may make up as little as 10% of the annual pasture yield. Thus current techniques of management are not meeting the aim of providing a high yielding and high quality pasture for grazing livestock throughout the year. To develop our understanding of the productivity of these mixed pastures, it is worthwhile examining the performance of the individual species.

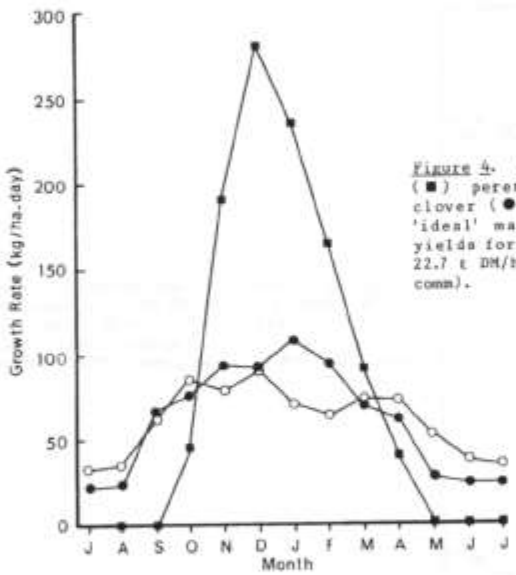


Figure 4. Monthly growth rates of paspalum (■) perennial ryegrass (○) and white clover (●) grown in pure swards with 'ideal' management. Four year average yields for these plots were 32.8, 23.7 and 22.7 t DM/ha respectively (F.M. Martin pers comm).

Martin (19) measured the field growth rates of pure swards of white clover, perennial ryegrass and paspalum under "ideal" management (Fig. 4). Production from the C4 species, paspalum, peaks during summer but ceases during the period from May to September. The production of DM by white clover and ryegrass is more uniform throughout the year, with ryegrass producing more in autumn—winter but white clover having higher growth rates during summer. On the basis of these data, we can conclude that while paspalum is well-suited to the summer irrigation environment, ryegrass in particular and white clover are not. Soil water supply and ambient temperature appear to be the two important factors involved.

The three species have distinct requirements with respect to irrigation frequency (Fig. 5). After irrigation, white clover maintains maximum levels of productivity for only 4-5 days, while paspalum is able to maintain maximum levels throughout the 10 days of a normal irrigation cycle.

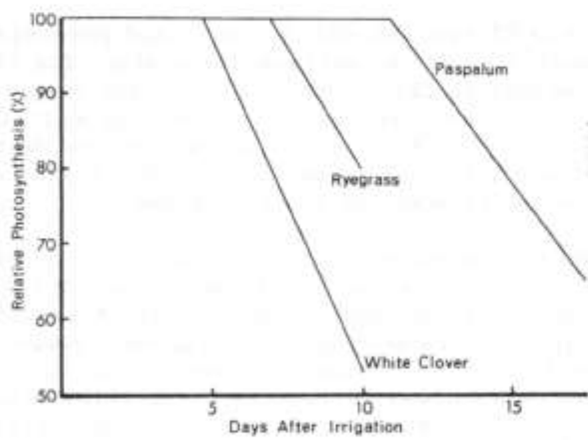


Figure 5. Photosynthethic rates (% of a well watered control) for pure swards of paspalum, perennial ryegrass and white clover during a drying cycle after irrigation (From 22).

In a recent review, Grieve et al. (20) concluded that waterlogging of irrigated pastures is a major cause of low productivity but again, paspalum appears to be the least affected species. Donohue et al. (21) measured a 25% reduction in the yield of perennial ryegrass ponded for 24 hours at each irrigation , compared to a non ponded control. In a similar experiment, Blaikie (unpublished results) found a 30% reduction in white clover yield, but paspalum was not affected.

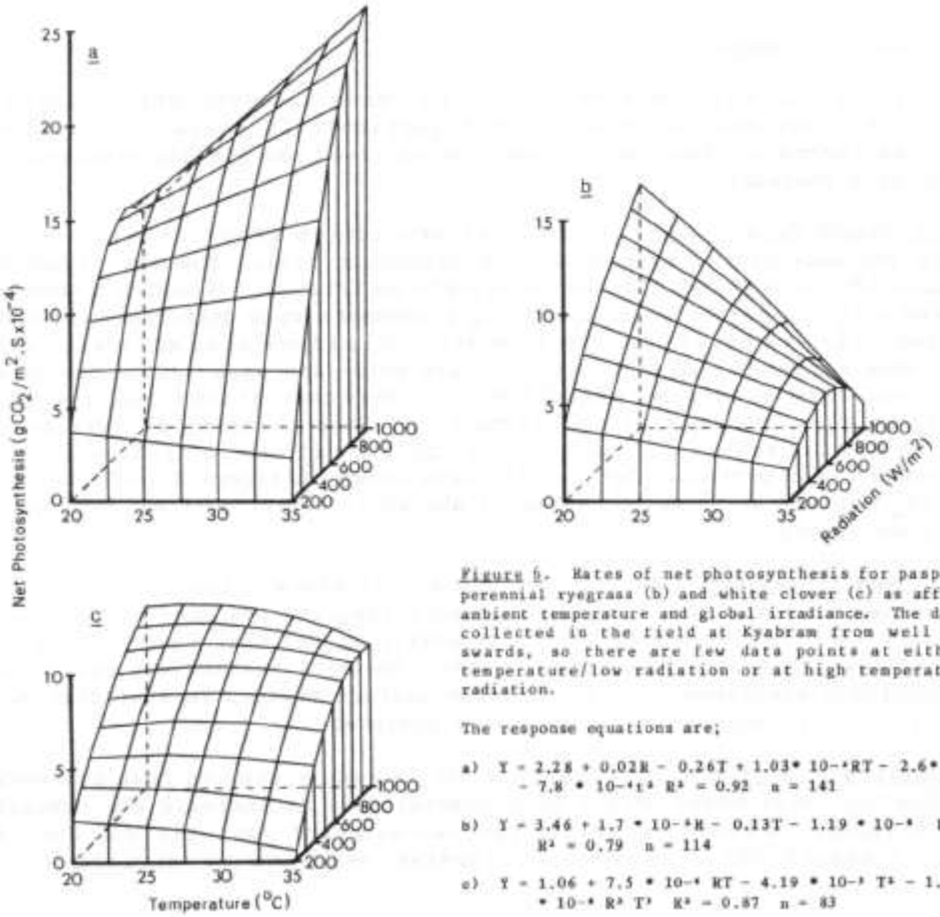


Figure 6. Rates of net photosynthesis for paspalum (a) perennial ryegrass (b) and white clover (c) as affected by ambient temperature and global irradiance. The data were collected in the field at Kyabram from well watered swards, so there are few data points at either high temperature/low radiation or at high temperature/low radiation.

The response equations are;

a) $Y = 2.28 + 0.02R - 0.26T + 1.03 * 10^{-4}RT - 2.6 * 10^{-4} R^2 - 7.8 * 10^{-4}t^2$ $R^2 = 0.92$ $n = 141$

b) $Y = 3.46 + 1.7 * 10^{-4}R - 0.13T - 1.19 * 10^{-4} R^2T^2$ $R^2 = 0.79$ $n = 114$

c) $Y = 1.06 + 7.5 * 10^{-4} RT - 4.19 * 10^{-3} T^2 - 1.19 * 10^{-4} R^2 T^2$ $R^2 = 0.87$ $n = 83$

As well as the problems of maintaining optimum water and oxygen conditions in the heavy soils in the region, the climate during summer is not suited to high levels of productivity by the C3 species white clover and perennial ryegrass. In controlled environment studies the optimum temperature for the growth of white clover has been defined as 22-24'C (23), 20-25'C for ryegrass and 30-35'C for paspalum (24). In northern Victoria, the average maximum temperature during January and February is 30'C, with one day in four being 33'C or more. While temperatures are likely to be optimal for the growth of paspalum, adverse effects could be anticipated for the C3 species.

Figure 6 shows the effect of ambient temperature and solar radiation on the net photosynthetic rate of pure swards of paspalum, perennial ryegrass and white clover. These data show quite clearly that paspalum reaches maximum rates of net photosynthesis at high temperatures and irradiances. However, in contrast, the net photosynthetic rate of ryegrass declines at all levels of irradiance as temperature increases above 20'C, with the decline being most rapid at high irradiance. The response of white clover to increasing irradiance was relatively independent of temperature over the 20-35'C range.

Taken together, these responses of the individual species to the soil and climatic conditions during the irrigation season strongly promote the dominance of paspalum in mixed pastures. This compounds the problem of feed quality and seasonality of production. To overcome these problems, systems of management need to be developed that favour white clover and ryegrass. By careful watering, we could expect to improve the productivity of white clover. However, since the performance of ryegrass is dictated so strongly by the prevailing temperature (Fig. 6) and stage of plant development (25) there is little possibility of making this species more productive through better management. Consequently, there is little chance of establishing a stable mixture of the three species except at high proportions of paspalum. This raises the question of why we grow our pastures as mixtures.

Why Have Mixed Pastures?

The preceding information shows that the three species, white clover, perennial ryegrass and paspalum are not particularly compatible in the irrigated environment. However, common reasons given for growing pastures in mixed cultures include:

(i) Year Round Production. Continuous production from the mixture of temperate and subtropical species is one important goal. However, Clanton and Nichols (26) summarised the USA experience as follows: "Complex mixtures formulated with the objective of combining components with different seasonal growth potential to obtain season–long production have been advocated but have not been successful in practice. If both cold– and warm–season pastures are desired, they should be established as separate stands and managed according to their respective requirements." This thinking is developed further in a later section of this review, because it can be applied to all the components of a mixture. The growth rates shown in Figure 3 confirm that a three way mixture of paspalum, ryegrass and white clover does not produce a uniform feed supply.

(ii) Nitrogen Efficiency. Fixation by legumes provides a low cost N supply to the grasses in a mixture. In the U.K., pure ryegrass pastures are normal, but Haycock (27) concluded that "It is generally agreed that white clover is of value to low input pasture systems." Such low input systems are essential in the uncertain environment of the rainfed pasture regions in Australia but the concept is less applicable to irrigated pastures.

(iii) Utilisation of the Environment. It is widely assumed that mixtures can utilise the environment better than monocultures to increase the overall yield. However, in their extensive reviews of plant competition, Donald (28) and Trenbath (29) found no conclusive evidence to support this hypothesis.

(iv) Stability. Mixed pastures can be very stable - there are examples in nothern Victoria of mixed pastures sown more than 50 years ago. New pastures tend to be unstable, being clover dominant at first until N fertility builds up, making grasses more competitive until the sward is mostly grass (30). Wolfe (31) points out that this transition to grass dominance can be accelerated by applying N fertiliser. The problem with this stability is that it only occurs at high grass contents.

After reviewing the current performance of irrigated pastures, particularly the perennials, it is clear that the search for new directions is very relevant. The remainder of this review is devoted to examining some of the possible new directions, with special emphasis on trying to identify, develop and exploit the competitive advantage irrigation offers.

New directions

We have identified several areas where we believe substantial advances could be made to improve the competitive advantage of irrigated pastures. These new directions are very diverse; they range from simply addressing some of the problems of current pastures we have identified in this review, through to more speculative ideas and examples of how new directions for pastures can be integrated with animal industries. However, they all have one thing in common - an increased reasearch effort will be needed if we are to make significant progress.

Increased Production and/or Utilisation of Pastures

Two things are very clear from the preceding discussion on current pasture performance. Firstly, current production is low and with conversion efficiencies of only 1% over summer, this represents a serious under-utilisation of resources. Secondly, because current production is so low, there is great potential for improvement if we can overcome the limitations.

Problems in the root zone are the primary cause of the low productivity of current irrigated crops and pastures in the Riverine Plain (3, lb, 20, 32). However, with some minor exceptions (32, 33) the root zone limitations of pastures have generally been neglected as an area for research. The degree to which the roots control the above ground performance of plants has been highlighted by studies of horticultural plants (34) and more recently by Meyer et al. (35) with soybeans.

Martin (19) showed that by radically ameliorating the profile of a red-brown earth, an annual yield of 38 t DM/ha from a white clover/perennial ryegrass/paspalum mixture was possible but this was not grazed. Research is needed to better define the factors in the root zone which limit pasture productivity and how the root zone might be most economically modified or ameliorated to better suit the requirements of pastures. While soil amelioration offers the potential to increase production, one serious constraint is that current methods such as deep ripping greatly reduce trafficability and lead to increased pasture damage by grazing animals (33) so that more practical soil amelioration techniques are needed (36, 37).

Annual pastures pose a major problem when considering management practices for increased production. Extending the autumn growth period (Fig. 2) certainly boosts production but there is a corresponding increase in irrigation water use. If irrigated from early February to mid-November a sub. clover based pasture will use 70% of the irrigation water needed for a perennial pasture (38) without the advantages of year round production. Perhaps we should replace the whole concept of annual pastures as we now know it with the concept of 'special purpose pastures' designed to produce feed exactly when it is needed for an animal production program, whether it be to supplement large areas of rainfed pasture or smaller areas of perennial pastures or pure legumes.

The other important aspect of pasture production is utilisation by grazing animals. In general, utilisation of our pastures is much lower than one would expect and there are a number of reasons for this. Lazenby (39) suggests that 75% utilisation is a high but realistic target to set, but it is likely that on many farms it is only 50% (40) and it is enlightening to speculate as to what might be happening with irrigated pastures. In a recent dairy farm management study (41), the average production in northern Victoria was 199 kg milk fat/ha. To produce a kilogram of milk fat, cows require 3U kg DM of feed (42). Therefore, we can calculate that on an average irrigated dairy farm, 6 t DM/ha of pasture was eaten by the grazing animals out of the 12 t grown. (This excludes requirements of young stock and assumes that no additional feed was brought into the system). There are two possible explanations; either we are greatly over-estimating the average productivity of irrigated pastures at the farm level, or more likely, the utilization rate is very low.

Improvements in % pasture utilisation by the grazing animals would appear to offer a great opportunity to increase the output of animal products without greatly increased costs because the feed is already being grown. As the potential is so great, attempts to increase utilisation should not be ignored by researchers but it is important to realise that two factors mitigate strongly against increased utilisation rates. Firstly irrigated pastures are poorly utilized because their seasonal pattern of production does not match animal demand, this is particularly so in spring when pasture production is very high relative to other seasons and greatly exceeds demand. To achieve increased rates of utilisation requires the use of higher stocking rates. But the second factor which makes high rates of utilisation difficult to achieve is the three way relationship between stocking rate, production per animal and production per hectare. The information in Figure 1 was collected over a two year period with dairy cows in northern Victoria. This type of relationship where production per hectare is only maximised by limiting individual animal performance is well documented (44). Therefore, to achieve high rates or production per hectare the amount of pasture offered to grazing animals must be limited. The effect on pasture utilisation can be seen in Figure 8, taken from the same experiment as Figure 7. High levels of efficiency were only achieved by severely limiting pasture supply per animal. Therefore, increasing pasture utilisation will be difficult unless we can at least partly break the link between individual animal performance and rates of pasture utilisation. Feeding supplements may provide the answer. A system of heavy grazing pressure to increase pasture utilisation plus supplementary feeding to increase individual animal performance could dramatically increase the productivity and profitability of the animal industries in the irrigation areas.

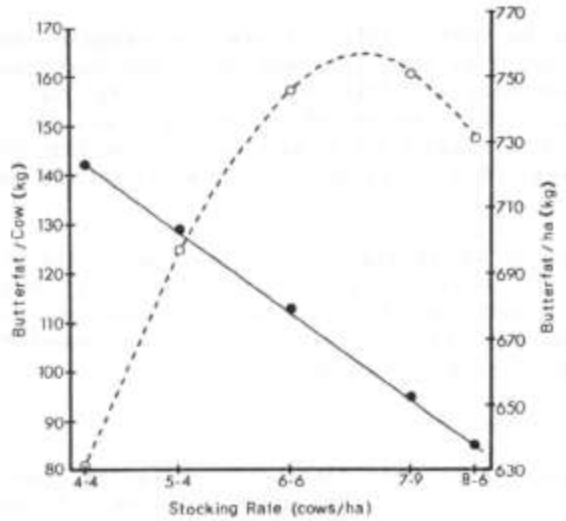
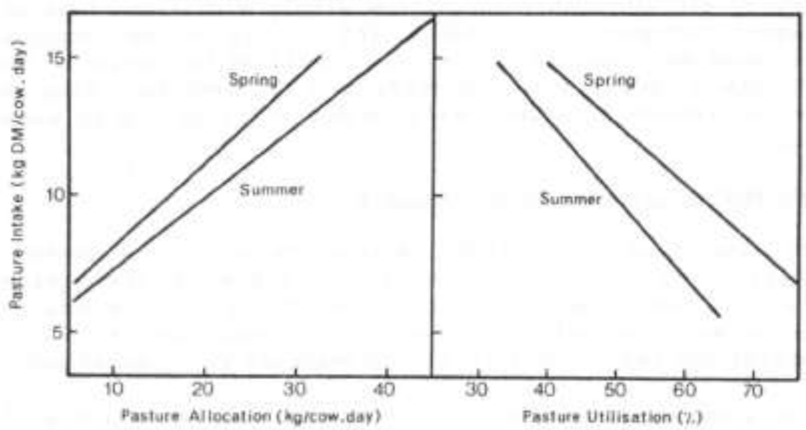


Figure 7. Effect of stocking rate on butterfat production per cow (●) and per hectare (○) (From 42).

Figure 8. Effect of pasture allocation per cow on pasture intake per cow, and the effect of pasture intake per cow on percent pasture utilisation for dairy cows grazing perennial pasture in northern Victoria (From 43).



Pure Legume Pastures

It has become increasingly clear that legumes hold the key to high levels of animal performance. In reviewing the literature, Reed (45) noted a positive relationship between liveweight gain of both sheep and cattle, and the legume content of the pasture. Extrapolating this relationship leads to the conclusion that pure legume pastures might be the best option. There is indeed some evidence to support this (46, 47) and also some preliminary indications that pasture utilisation rates can be increased with high legume content (G. Rogers - pers. com.).

Legumes are usually of higher quality than grasses but comparative research with grass and legume feeding to animals clearly shows that even when the in vitro quality of the two is similar, the voluntary intake of legumes is greater than that of grasses because of shorter retention times in the rumen (48). This results in greater yields of milk in dairy cows (49, 50). In addition, it has been suggested that responses to concentrate supplements may be greater when the basal ration is a legume rather than a grass; for example, Moate and Rogers (51) found that marginal responses were 0.3 and 0.8 kg milk/kg DM when oats were fed to supplement either ryegrass or clover, respectively. Reasons for this are as yet, unclear.

On quality grounds alone, there is a strong case to consider pure legume pastures for the irrigated areas. The case is even stronger when we consider the major shortcomings of both perennial ryegrass and paspalum discussed earlier. However, there are a range of other advantages or potential advantages of pure legumes plus some problems which must be considered.

Yield data on pure legumes vs. mixed pastures are rare. In a cutting experiment conducted for four years with high input levels at Kyabram, annual yields of 23.7 and 22.7 t DM/ha from pure swards of perennial ryegrass and white clover were measured (Fig. 4). These yields were slightly less than the mixture but demonstrate that pure legume pastures need not lead to large yield losses. Lucerne is the most common legume grown as a pure sward in S.E. Australia and yield levels confirm that very productive pure legume pastures should be possible.

Potentially, one of the most important advantages of pure legume pastures is that legumes retain their quality much better than grasses as they mature (46, 52). This means that timing of cutting or grazing is less critical for legumes but perhaps more importantly, it makes possible the conservation of high quality fodder. The seasonal variation in pasture growth is considerably greater than the variation in animal requirements so fodder conservation is likely to be an essential part of any intensive animal production system.

A range of pure legume pastures could be used to manipulate the timing of feed supply to suit a particular animal industry. Very drought sensitive legumes such as white clover would need regular irrigation throughout summer and could form the basis of a legume system. Special purpose pastures could then be incorporated to produce extra feed when required. Annuals such as sub. clover and Persian clover (Fig. 2) could be important, while perennial species which can tolerate drought (such as lucerne and red clover) could be used to effectively utilise winter/spring rainfall plus any spare irrigation water available over summer. Any feed shortages could be alleviated with strategic irrigations applied to these perennials, or with high quality, conserved legumes.

Nitrogen fixation by legumes to supply the grasses is a key advantage cited for growing mixed pastures. In cropping systems, legumes are also grown to fix N for supply to other species, but in rotation rather than mixtures. Holford (53) measured values of soil nitrogen accumulation under lucerne of 110 to 140 kg N/ha.yr over a range of soil types. Three and a half years of lucerne growth was sufficient to eliminate the need for N fertiliser on the following wheat crops for three to five years (54). Some system of rotation will be needed to utilise the N fixed by a pure legume pasture, not only because the N is a valuable resource, but because it is easier to keep legumes dominant in a pasture if N fertility is low. The relative efficiency of N fixation and reuse in a rotation system compared to a mixed pasture will need to be determined.

There could be many problems with pure legume pastures, but two are immediately apparent. Firstly, although pure legume pastures would avoid some of the management compromises inherent in mixtures, knowledge of the management of pasture legumes in pure swards is scant, and the suitability of current species and cultivars to pure swards is unknown. Secondly, nutritional disorders in livestock are seen as a major limitation of pure legume pastures. The long term answer to the problem of bloat may lie in plant breeding; the oestrogenic problems associated with sub. clover and red clover were solved in this way. In the short term there are two possible solutions - treatment with a bloat prophylactic or mixing the diet with other feeds to reduce or eliminate bloat. Bloat prophylactics are cheap and simple to administer in intensive systems, but very frequent (twice daily) dosing is necessary. This suits a dairy operation and is in fact routine on many dairies if high clover contents occur in pastures. With mixed pastures it is difficult to predict when or if bloat will occur - it would be more certain if pure legume pastures were in use, perhaps making long acting rumen implants an attractive option for dairy cows as well as for less intensively handled animals. The successful utilisation of pure legume pastures probably lies in supplementing them with other feed sources, unlike mixed pastures which tend to be the sole ration. This concept is explored more fully in a later section, but the possibility exists of controlling bloat with the non-pasture portion of the ration.

While nutritional disorders in livestock may be seen as a major stumbling block for pure legume pastures, it is interesting to note that a high legume diet can have advantages in this area. In reviewing the literature, Reed and Cocks (55) found that problems with intestinal worm burdens in sheep and cattle, hypomagnesemia, meat taint and reproductive inefficiency were all significantly reduced on legume dominant rather than grass dominant pastures.

In summary, pure legume pastures appear to offer exciting prospects for boosting the productivity of the irrigated animal industries. Some pure legume pastures are already beginning to be used for animal production in the Riverine Plain, as shown in some of the following examples.

Integration with animal industries

So far in this review we have considered pasture production per se, but pastures have little commercial value — their value derives from the animal production they generate. The degree to which they suit an animal production system should be at least as important as their total production. In fact we believe that the great untapped potential for irrigated pastures lies in better integration with the animal industries. Thinking on irrigated pastures has been far too limited, concentrating on annual sub. clover and ryegrass or perennial white clover/ryegrass/paspalum pastures and developing animal industries and patterns of production which suited or could be adapted to one or both of these pastures. The lack of a competitive advantage from this approach was well illustrated in Fig. 1. In this final section of the review we outline some examples of how thinking can be changed so that pasture systems are developed to suit the production of specific animal products and give irrigation a real competitive edge. The examples are all of innovative thinking applied to the main beef, sheep and dairy industries rather than ideas for new exotic animals etc.

1) Effective Use of Limited Water Rights

There are large areas in the western region of the Riverine Plain with very limited irrigation supplies. Water rights are typically 0.3 to 0.6 Ml/ha in the western irrigation districts and even lower for many properties with river pumping licences, compared to a minimum of 12 M1 needed to fully irrigated one nectare of perennial pasture. These very low water rights were issued to stabilise the wool industries on the large landholdings in these

areas (2). However, as Myers (2) points out, this concept of drought insurance was never successful and there has generally been a separation of irrigated and rainfed production systems within the same region. The problem has been that irrigated pastures grown as drought insurance tended to be neglected during good or average years, greatly reducing their potential in dry years. Returns from this type of scheme have generally failed to meet the costs associated with the irrigation development.

A group of farmers near Hay in NSW is attempting to develop a production system which will make small areas of irrigated pastures very profitable on large farms (56). This is only possible if the irrigated pasture can be used to increase the utilisation of the large areas of rainfed pasture in all years, not just during droughts. Using a linear program model the Hay group was able to show that with a 4000 ha property but no irrigation, the operator could run 2070 merino ewes and produce a gross margin of $49,700. If 1000 M1 of irrigation water was added and used to produce annual pasture, then stock numbers could rise by 50% but with the cost of irrigation development, total GM would rise by only $100. [This supports our earlier conclusion that irrigation of annual pastures provides little competitive advantage]. However, the model showed that using white clover pastures, the gross margin would increase by $36,000 even after paying 18% interest on the $120,000 needed for the irrigation development.

The system is now well beyond the stage of a computer model — over the last 4 years in the Hay district the area under irrigation has doubled as unused pumping licenses have been taken up in response to the improved profitability and the ratio of annual to perennial pasture has declined from 10:1 to 4:1.

Pure swards of white clover are the most favoured perennial pastures because of very high quality and suitability for set stocking. This has been the first attempt at large areas of pure legume pastures and is proving very successful. There are three key elements of the system that lead to such dramatic increases in productivity.

a) Wool quality is increased by reducing the effects on fibre strength of seasonal variations in quality and quantity of pasture. Quantity is also increased as improved nutrition adds about 20% to the fleece weights for weaners and hoggets.

More flexibility is introduced into the timing of weaner sales. Traditionally, weaners are sold at 7 months to minimise stock numbers over summer. This is still an option, but increasingly, weaners are being kept until 12 months and sold off shears, giving an average $3/lamb increase in gross margin. Also, the severe problem of grass-seed injury in weaners can be virtually eliminated.

The most important factor is the very large increase in stocking rate, much larger than would be predicted from the actual production of irrigated feed. This is via the original concept of irrigation for these regions ie., to stabilise the production from the rainfed pastures. Stocking rate is a function of risk and in a low and variable rainfall environment where the spring flush must provide sufficient feed for spring, summer and the following autumn, stocking rates must be set very low (about 1.3 dse/ha). With a small area (<10%) of pure legume pasture to provide some high quality feed in summer and autumn, the stocking rate can be raised to at least 6 dse/ha without any increase in risk. Despite this, the farmer may perceive an increase in risk and can offset this by allocating some of the increased profits to drought reserves of cash or fodder.

This developing system provides a good example of the sort of thinking needed to provide the new directions for irrigated pastures.

2) Suckling Lamb Production/Sheep Dairying

These two new industries are being developed around Leeton in southern NSW by Tavella Cheese Pty Ltd in association with the NSW Department of Agriculture and local ricegrowers who have been spurred into action by low grain prices.

a) Suckling Lambs

The suckling lamb industry aims to produce small (minimum of 11 kg live weight), whole lamb carcasses for export markets in the EEC, Middle East, USA and Japan. Tavella Cheese Pty Ltd and the Export Development Unit of the NSW Dept. of Agriculture agree that there is immediate demand for 6,000 to 8,000 suckling lambs/week if they can be supplied consistently throughout the year as only irrigated areas can. The potential market is estimated at 1 million lambs/year (57).

The necessary animal production techniques have mostly been developed. With hormone treatment ewes will lamb at any time of the year and 8 month lambing systems are a reality with 2 flocks giving a lambing every 4 months (58). A new sheep breed, Hyfer (for high fertility) is being developed by the NSW Dept. of Agriculture to greatly increase lambing percentages (59) and with the ability to lamb naturally at any time of the year. The weakest link is pasture technology to provide the constant feed supply needed to produce lambs year round. This situation may be tailor made to larger properties with limited water rights, using their irrigation water to produce pure legume pastures such as Haifa white clover and other special purpose legume pastures to supplement the feed supplied from rainfed pastures. Because the ewes have such a short lactation (4-6 weeks) they require a high quality feed for only 3 months per year to cover 1.5 late pregnancy and lactation periods. Their much lower feed quality requirements for the rest of the year could then be met from largely dry or conserved fodder. Traditional annual and perennial pastures could not provide the consistent supply or high quality of feed needed to maximise production from this system. If this industry is to develop to its potential, then it is essential that we develop a pasture system to provide the consistency of supply that the market is demanding.

b) Sheep Dairying

Sheep dairying needs a larger supply of high quality feed than a suckling lamb enterprise because of the much longer lactation period for the ewes. This means that sheep dairying would be better suited to properties with higher irrigation entitlements than needed for suckling lambs.

Gross margin estimates by the NSW Dept. of Agriculture (60, 61) suggest that three separate ewe flocks, one lambing every four months might be a better option than two flocks each on eight month lambing. The flock management involves mating the ewes to ensure a very compressed lambing pattern; leaving the lambs on the ewes for two weeks before they are sold or hand reared; then milking the ewes twice daily for 14 weeks. As with the suckling lamb enterprise previously described, the animal husbandry aspects are fairly well developed (62).

Pasture supply is critical if an efficient industry is to develop – current pastures would produce a milk supply curve similar to that shown in Fig. 1 for the dairy industry in northern Victoria. Such extreme variations in supply are not acceptable to the processing and marketing operations for sheep milk products. Each ewe requires a maintenance type ration for half the year while she is dry, so one–third of her total feed requirement could be met from dry feed or conserved fodder of moderate quality. This would be easy to supply or purchase. The major task for the irrigated pastures is to supply the constant amount of high quality feed needed by the ewes during

late pregnancy and lactation. Traditional annual and perennial pastures could partly meet this requirement but the spring surpluses from grass dominant pastures do not provide a high quality feed for later use by lactating animals (47). Both annual and perennial pure legume pasture could play an important role. Firstly, in reducing the extreme variation in the pasture supply curve and secondly in providing high quality conserved fodder as it is unlikely that any practical system could provide a constant supply of high quality grazing every day of the year. The quality of the pastures will become increasingly important as higher milk yields are obtained through selection of ewes and/or importation of new genetic material.

Both these new sheep industries are in their infancy but both offer very exciting prospects because a) there is large potential for them to expand into major export industries, perhaps $100m each b) both are being market driven, c) the animal science technology has already been developed, d) the requirement for year round supply of lambs and milk give irrigation a special advantage and e) both are demanding new thinking on irrigated pastures.

This new thinking on irrigated pastures ie., developing pasture systems to suit the production and marketing requirements of animal products, has the potential to be applied to all our irrigated animal industries and dramatically improve their competitive positions.

3) Kyabram Dairy System

Because of the seasonality of pasture production and low productivity, the concept of pasture as the sole diet for dairy cows in irrigated northern Victoria is being challenged. Our concept of a highly productive dairy farm for the future is pure legume pastures integrated with fodder crops.

The reasons for using pure legume pastures were outlined earlier. Fodder crops are a potential addition to the legumes because the environment in northern Victoria is ideal for their growth, particularly summer fodder crops (63). The best summer crops have exceeded yields of 30 t DM/ha while winter crops in a double cropping system have achieved 16 t DM/ha (64) or a total annual yield of 46 t. The main crop for a legume/fodder crop dairy system is maize because it is very productive (63) and it is considered throughout the world as the crop most suited to silage making.

Maize silage is a potential supplement to pasture (65) and is currently used on a number of farms in Victoria to alleviate shortages of pasture in autumn and early spring. It has been found that cows respond well to maize silage supplementation, but no extra milk is produced once maize silage exceeds 40% of the diet (Stockdale, unpublished results). Because protein deficiency is probably the major cause of this limitation, an experiment was done at Kyabram in 1986 to assess the use of a pure legume pasture instead of traditional perennial pasture in a pasture/maize silage ration.

Twenty-four cows in mid lactation were stall-fed each day for a period of five weeks with 7.5 kg DM/cow of forage harvested pasture [either ryegrass/white clover (67% DMD, 16% protein and 75% ryegrass) or Persian clover (76% DMD and 21% protein)] supplemented with maize silage (67% DMD and 8% protein) ranging from 0-11 kg DM/cow. The results of this experiment are summarized in Figure 9a. For cows fed perennial pasture, milk yields peaked at approx. 20 1/cow when maize silage constituted about 40% of the diet, confirming earlier results. When Persian clover was fed instead of perennial pasture, a milk yield of 24 1/cow was achieved at maximum silage intakes which constituted 60% of the diet, with no indication that a plateau milk yield had been reached. Furthermore, the marginal return to maize silage supplementation was greater where Persian clover was the basal feed, even at low levels of maize silage, eg., the return to the first five kg of maize silage was 0.9 1 milk/kg maize DM for perennial pasture, compared to 1.4 1 for Persian clover. The response to maize silage supplementing the legume can only be explained if associative effects on digestion occurred which improved the utilization of one or both of the feeds. Differences in partitioning of nutrients or the use of body reserves did not contribute to the better milk yield from maize silage with Persian clover because the basal ration had no influence on changes in cow condition (Fig. 9b).

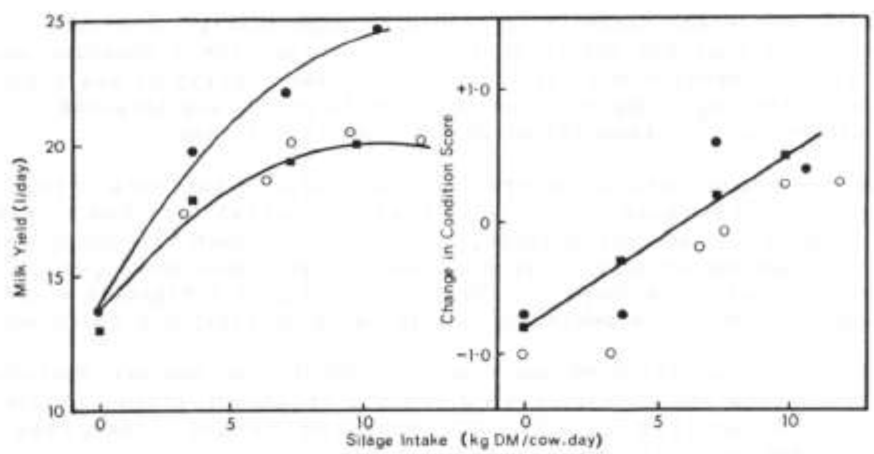


Figure 9. (a) Milk yield response from cows fed 7.5 kg/day of perennial pasture (•) or Persian clover (•) and supplemented with maize silage. Data from a previous experiment where perennial pasture was supplemented with maize silage are included (0), (b) Changes in body conditior. score of the dairy cows over the five weeks of the experiment.

This experiment has provided one example of the value of legumes in a dairy farming system where the use of a pure legume pasture resulted in a marked improvement in the value of maize silage for lactating cows. In an earlier section we raised the concept that hard grazing to achieve high rates of pasture utilisation might be combined with some form of supplementation to achieve high milk yields per cow and a great improvement in overall efficiency. This experiment with Persian clover and maize silage has shown that such a system is achievable.

Another result of interest from this experiment concerned bloat, which was not observed in any cows fed more than 4 kg DM/day of maize silage.

Therefore, while bloat is likely to be a problem if legumes alone are fed, supplements to the diet could provide a simple remedy.

Much research, particularly with regard to legume agronomy, needs to be undertaken before the commercial development of the Kyabram dairy system is complete. However, we can envisage irrigated dairy farms of the future based solely on pure legume pastures and fodder crops. The cows would graze legumes during the day and be fed maize silage on a feeding pad at night. It is conceivable that farmers would plant any or all of a number of legumes, including subterranean clover, Persian clover, red clover, white clover and lucerne, which would be grown as monocultures to meet the grazing requirements of the herd for the year. By having legumes and fodder crops as the basis of a dairy system, we are using one feed that is best for animal performance and the other feed that is highly suited to exploit the natural advantages that the Kyabram environment has for plant productivity, to supplement and complement the legume pastures and to operate in rotation with the legumes.

4) A Lean Beef Production System

In recent years, there has been a growing recognition of the relationship between human diet and health. Of particular concern has been the level of fat intake and its association with heart disease. Education by groups such as the National Heart Foundation is starting to convince consumers that they should be more discerning about the meat they buy. Beef and lamb producers must respond by reducing fat levels in meat if they are to compete effectively and retain or increase their proportion of the meat market.

An entrepreneur at Kyabram has developed a production system for lean beef. The carcass type which attracts a premium is one with low intra-muscular fat and an average fat covering over the 12th and 13th ribs of 4.7-4.9 mm. (This product has been endorsed by the National Heart Foundation as a low cholesterol meat and can be marketed with a NHF sticker). A premium price is paid for ideal carcass conformation and electrical stimulation of the lean carcasses helps ensure tender meat. But continuity of supply to the customers is essential and currently this is achieved to some extent by large inputs of grain to the pasture feed base.

We suggest that the natural advantages of irrigation could be used to further develop lean beef production in a similar fashion to the Kyabram dairy system. What is required for the production of year-round quality lean beef is a streamlined operation for which we know production costs. This cannot be achieved by relying on traditional pastures of rapidly changing quality and purchased grain of highly variable price and energy content. Fodder crop silage could provide the year round feed base with high quality legume pastures providing daily grazing. The pasture supply would need to be quite different to that proposed for the dairy industry. Cows need 16% protein in early lactation reducing to 13% in late lactation and 11% when dry (66). On the other hand, beef vealers need a constant 127 protein (67). The skill needed to assure success of this system will be to select the right combinations and proportions of legumes that will supply sufficient pasture for all periods of the year.

Conclusions

Existing annual and perennial pastures and the animal industries they support in the irrigation areas have not been developed to specifically exploit the competitive advantages of irrigation and have low productivity. This has led to severe criticism of the whole concept of using 'valuable' irrigation water on pastures. Radical changes are needed both in the productivity of the pasture systems themselves and in the integration of animal and pasture production to take better advantage of the irrigated environment.

We have presented some ideas and examples of how such systems might be developed. Considerable research and development is needed but there are exciting prospects for irrigated agriculture if new directions are adopted for irrigated pastures. It is to be hoped that the excitement associated with these new directions will stimulate interest in thinking, research and development for irrigated pastures.

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