STRATEGIES FOR IMPROVING WATER-USE EFFICIENCY IN WESTERN REGIONS THROUGH INCREASING HARVEST INDEX

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Water-use efficiency, harvest index, sowing time, plant density, row spacing

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Take home message

Management for high water-use efficiency in low-rainfall environments aims to strike a balance between water-use, and thus crop growth, before and after anthesis. This ensures that high harvest index is achieved, but that there is sufficient early crop growth to compete with weeds, reduce evaporation and set yield potential.

Improving WUE in western NSW

In environments such as western NSW where yield is limited by water availability, there are four ways of increasing yield (Passioura and Angus 2010);

1. Increase the amount of water available to a crop (e.g. good summer weed control, stubble retention, long fallow, sowing early to increase rooting depth)
2. Increase the proportion of water that is transpired by crops rather than lost to evaporation or weeds (e.g. early sowing, early nitrogen, vigorous crops & varieties, narrow row spacing, high plant densities, stubble retention, good weed management)
3. Increase the efficiency with which crops exchange water for carbon dioxide to grow dry matter – transpiration efficiency or TE (e.g. early sowing, good nutrition, high TE varieties such as Spitfire$^{\phi}$, Scout$^{\phi}$, Drysdale$^{\phi}$, Gregory$^{\phi}$)
4. Increase the total proportion of dry matter that is grain i.e. improve harvest index (e.g. early flowering varieties, delayed nitrogen, wider row spacing, low plant densities, minimising losses to disease, high HI varieties such as H45$^{\phi}$, Hindmarsh$^{\phi}$, Wyalkatchem$^{\phi}$, Espada$^{\phi}$)

The last three of these all improve water-use efficiency (WUE), but in this paper we will focus on the fourth point – improving harvest index (HI).

Harvest Index

Harvest index is calculated as the ratio of grain to total dry matter (and is sometimes expressed as a percentage);

HI = grain yield/total dry matter

It is essentially the proportion of total crop dry matter made up of grain. In Australia, wheat HI is typically 0.30-0.45. In environments with long, cool finishes (e.g. Europe, NZ) it can be over 0.50, and the theoretical maximum value for wheat is 0.62 (Fischer 2011)

Whilst low harvest index can be the result of agronomic problems such as frost, heat shock or disease, in healthy cereal crops it is very strongly related to the split between the amount of water used before and after anthesis (Figure 1). Maximum HI is achieved when there is a 2-to-1 ratio between pre- and post-anthesis water use i.e. ⅔ of the total water-use is used before anthesis to build yield potential, and ⅓ used after anthesis to fill the potential. Management strategies which give the best chance of achieving this balance no matter what seasonal conditions bring will generally maximise yield and WUE.

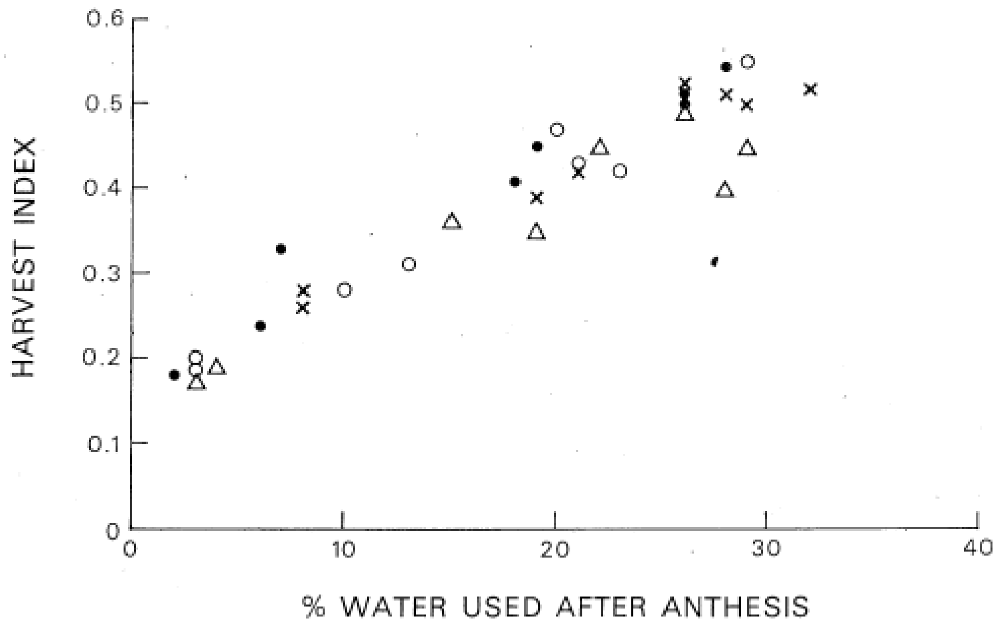

Figure 1. In healthy crops, harvest index is strongly related to the proportion of total water used before and after anthesis. The different symbols represent different varieties – Gabo (X), Pitic (), Emblem (), Heron (Δ). Figure taken from Passioura 1977.

Harvest index and evaporation – managing trade-offs

Improving harvest index often comes at a cost, usually in the proportion of water that is lost to evaporation. You can see in the four ways of improving WUE above that there is a clear trade-off between achieving high HI (point 4 above) and reducing evaporation (point 2). Row-spacing provides a good example of this. Widening row spacing increases harvest index at the cost of evaporation (Table 1). You can see in Table 1 that there is no difference in yield between 229 mm and 305 mm row spacing, the wider row spacing loses more water to evaporation and doesn't grow as much dry matter, but compensates with higher HI. At 381 mm, evaporation is so much higher and dry matter production so much lower that the crop is not able to compensate with high HI and yield is reduced. Good in-crop agronomy is about optimising this trade-off to maximise grain yield and water-use efficiency.

Table 1. Dry matter production, grain yield, harvest index, transpiration and evaporation for Gladius⁽ᵇ⁾ wheat grown under different row spacing at Bungeet in 2009. Data courtesy of Nick Poole,

FAR and Adam Inchbold, Riverine Plains collected as part of Riverine Plain's GRDC funded WUE project.

Row spacing (mm)	Dry matter (kg/ha)	Grain yield (kg/ha)	Harvest index	Transpiration (mm)	Evaporation (mm)
229 (9")	10476	3031	0.29	191	96
305 (12")	9141	2988	0.33	166	120
381 (15")	7333	2542	0.35	133	153

Management strategies to improve HI

Rapid flowering: Variety selection or management that causes a crop to reach anthesis faster will reduce the amount of growth and thus water-use pre-anthesis. This allows more water to be available post-anthesis, resulting in higher harvest index. This is evident in Figures 2 and 3 from Trangie in 2009, where there was little rain received after early winter and crops were reliant on stored soil water. Varieties sown on the same date (27 April 2009) that were able to flower early had higher harvest index (Figure 2), with the higher harvest index resulting in higher yields (Figure 3).

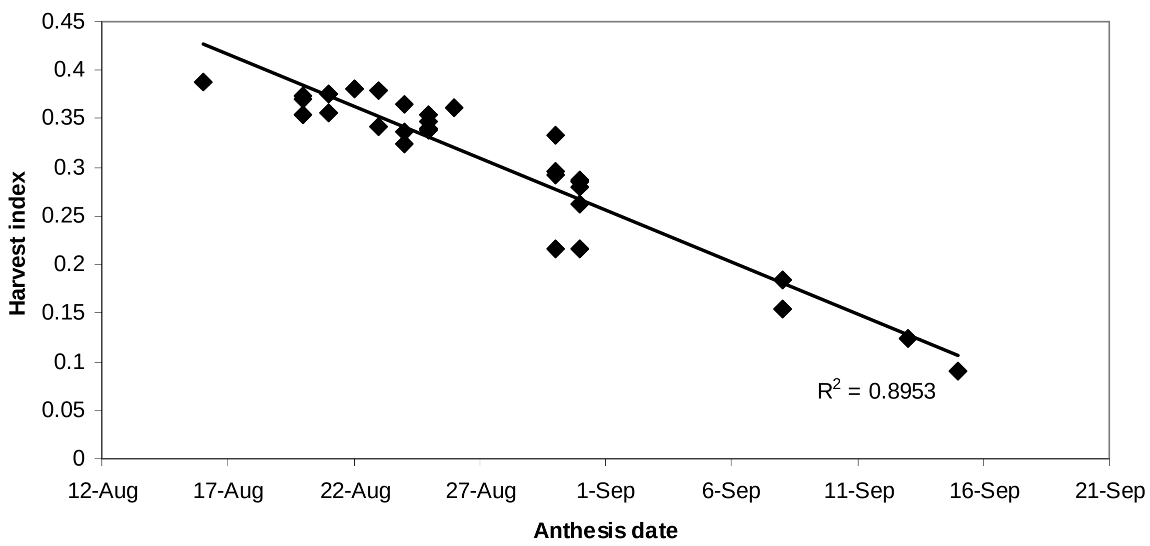

Figure 2. Anthesis date and harvest index of 30 bread wheat varieties sown at Trangie on 27 April 2009. Harvest index was greatest for varieties that were quickest to flower as they grew less dry matter and thus used less water prior to anthesis.

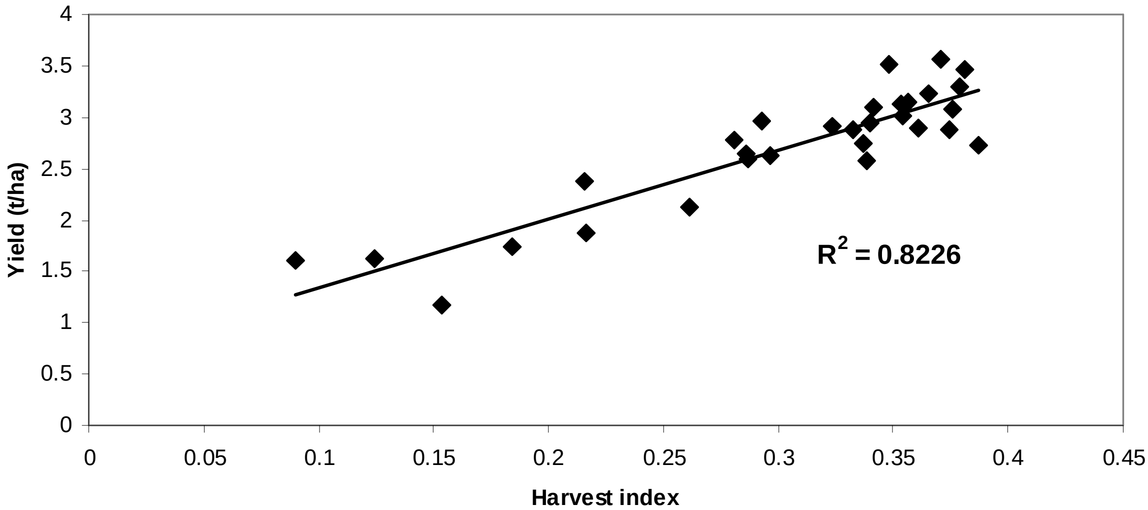

Figure 3: Yield and harvest index of 30 bread wheat varieties sown on the 27th April at Trangie in 2009.

However, in some environments early flowering incurs unacceptable frost risk and may reduce crop yield potential in good seasons. Early flowering reduces the yield potential by reducing the amount of growth during stem elongation and thus potential grain number per unit area. Ear weight at anthesis is related to potential grain number, and in a season with reasonable yield potential such as 2011, lower ear weights at anthesis and yield penalties can result from early sowing as Table 2 from Trangie in 2011 demonstrates.

Table 2: Early sowing resulted in lower anthesis ear weights of 6 early flowering varieties at Trangie in 2011. This resulted in an average yield penalty across these varieties of 0.3 t/ha.

	Ear weight at anthesis (t/ha)		
Variety	**30 April 2011**	**16 May 2011**	**Yield penalty from early sowing (t/ha)**
Axe	1.3	1.8	0.4
Crusader	1.5	1.6	0.4
Lincoln	1.7	2.2	0.3
Livingston	1.7	1.9	0.3
Merinda	1.9	2.4	0.3
Spitfire	2.1	2.1	0.4

Rules-of-thumb

The best way of managing flowering date is to identify the optimal flowering window for your environment (e.g. Figure 4 and Table 3 for Nyngan) and adjust your sowing date and cultivar maturity to make sure as much of your sown area is flowering within this window as possible. Across a sowing program this means starting ‘too early’ so not too much crop will be sown ‘too late’. For example if a wheat sowing program takes 30 days, from Table 3 below it would be optimal to start sowing on 22 April in order to have finished by 20 May and have the majority of crop flowering at a time likely to produce the highest yields.

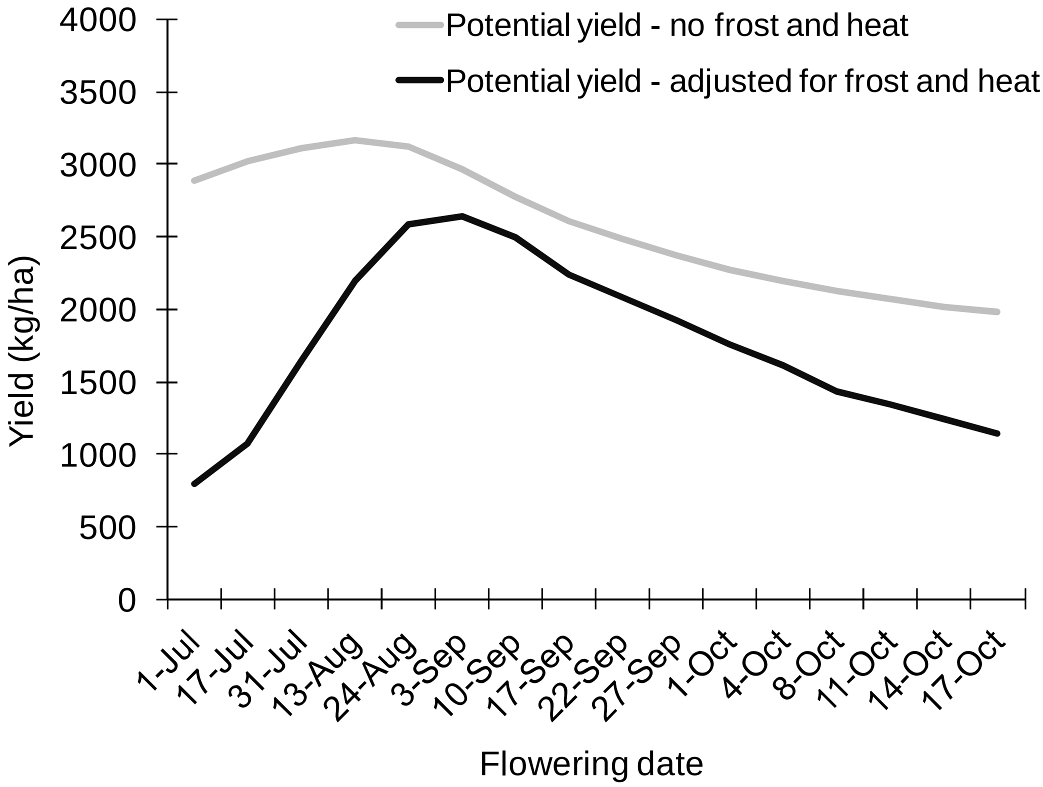

Figure 4. APSIM simulated mean wheat flowering date and yield at Nyngan 1890-2009. The optimal flowering date for yield (3 September) corresponds to a main season variety (e.g. Livingston⊕, Spitfire⊕, Crusader⊕) being sown on 6 May (see Table 3 below).

Table 3. APSIM simulated mean wheat sowing date, flowering date and yield for a main season variety (e.g. Livingston⊕, Spitfire⊕, Crusader⊕) at Nyngan 1890-2009.

Sowing date	Flowering date	Mean yield (adjusted for frost and heat) (t/ha)
1 April	1 July	0.8
8 April	17 July	1.1
15 April	31 Jul	1.6
22 April	13 Aug	2.2
29 April	24 Aug	2.6
6 May	3 Sep	2.6
13 May	10 Sep	2.5
20 May	17 Sep	2.2
27 May	22 Sep	2.1
3 June	27 Sep	1.9
10 June	1 Oct	1.8
17 June	4 Oct	1.6
24 June	8 Oct	1.4
1 July	11 Oct	1.3
8 July	14 Oct	1.2
15 July	17 Oct	1.1

Delayed nitrogen. Deferring nitrogen fertiliser application until after the end of tillering (Z30) reduces the number of tillers produced by a wheat plant, reducing the amount of growth and thus water-use prior to anthesis. It also provides an opportunity for growers to 'play the season' and only invest in nitrogen fertiliser when there is a good chance of it being profitable to do so. One disadvantage of this approach in western NSW is that rain doesn't necessarily fall at the right time to apply nitrogen, and the fast growing season means that crops don't have as much time to compensate for early N stress as in cooler environments with a longer growing season.

Rules of thumb

Use soil test results to make a decision on upfront N. If there is more than 60 kg/ha N in a Deep N test, a wheat crop can make it to stem elongation before N is applied without suffering a yield penalty. Top-dress during stem elongation according to anticipated yield potential – 40 kg/ha total N (including soil N) per t/ha of grain yield potential is a good rule of thumb, or use a decision support tool such as Yield Prophet®. If there is less than 60 kg/ha N at sowing, particularly if you have stored soil water, it is worth applying some N upfront – ideally either deep banded, pre-drilled, or spread/streamed and incorporated by sowing. When placing urea with the seed, remember wheat establishment can be adversely affected above 20 kg/ha N (this figure is lower with wider row spacing and lower seed bed utilisation), and canola is even more sensitive.

Row spacing and plant density. As discussed above, adjusting row spacing and plant density for high HI can result in a yield penalty due to increased evaporation and reduced yield potential. This is especially the case in seasons with high yield potential such as shown in Figure 5 from Coonamble in 2010.

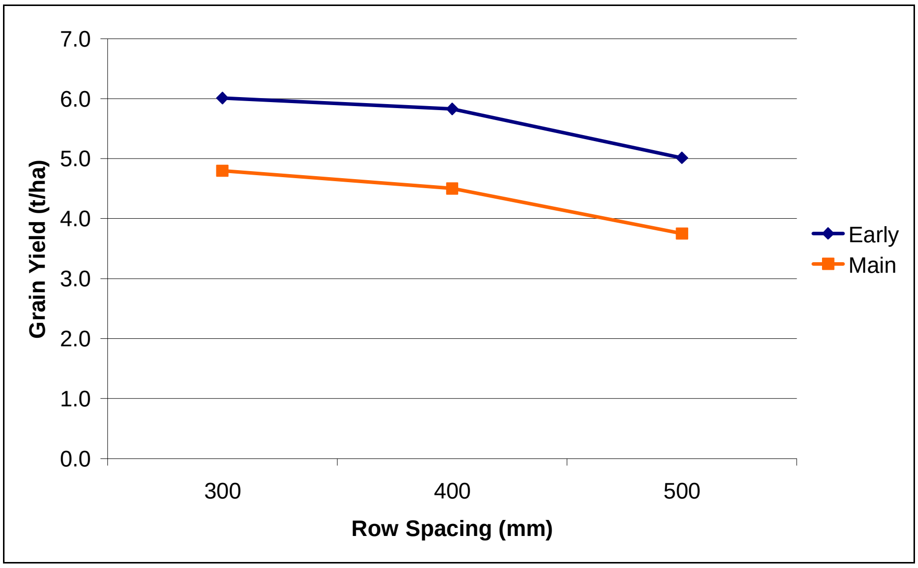

Figure 5. Increasing the row space from 300 to 500 mm reduced yield in a good season at Coonamble at 2010. The yield penalty from wide rows was similar for the early sow time as it was for the main sow time.

Rules of thumb

Row spacing: 250-300 mm is a good compromise between sowing speed, trash handling, herbicide safety, managing tiller number, weed competition and minimising evaporation. Above 300 mm there is often a yield penalty when yields exceed 3 t/ha, and the crop's competitive ability with weeds is compromised. These downsides need to be balanced against possible system benefits e.g. cheaper capital cost and faster sowing speeds.

Plant density: When sowing early, particularly into high N, plant numbers can be very low (<40 plants m^2) before there is a negative impact on yield (Figure 6). If plants are arranged in a perfect matrix, potential yield can be achieved under irrigation with as few as 24 plants/m^2 (Fischer et al. 2005). There are some significant operational benefits to sowing at low rates e.g. reduced seed cost and faster sowing due to less time spent loading the seed box. However, there is not much evidence of any yield benefit at very low sowing rates, even in dry seasons, and it comes at the cost of increased evaporation, reduced competition, and little margin of error if there are any problems with establishment (e.g. mice, locusts, herbicide damage, crusting etc.). On 300 mm row spacing, 50-80 plants/m^2 is plenty if sowing in April, but this should be adjusted upward to around 100 plants/m^2 as sowing moves into May and higher again in June (Figure 6). In dry environments, there is not much to be gained in exceeding 150 plants/m^2, and percent establishment will reduce on wider row spacing.

The idea of adjusting seeding rate in response to sowing time, variety (some varieties have inherently high tiller numbers e.g. Bolac, Sunvale), initial soil N and row spacing is to achieve an ideal head density. A good rule of thumb for low rainfall environments is that WUE is maximised when a crop has 1 head/m^2 per mm of water-use (Zhang et al. 2010 - estimate water-use by growing season rain + stored soil water), so in low-rainfall environments around 250-350 heads is plenty. At this level, there is still a lot of flexibility if the season turns out better than expected. Australian wheat cultivars grown under favourable conditions can hold 2 g of grain per head, so 250 heads/m^2 is enough for 5 t/ha of yield (e.g. at Temora in 2011 Eaglehawk sown at 40 plants/m^2 on 15 April yielded 6.3 t/ha with only 300 heads/m^2, so each head held 2.1 g of grain).

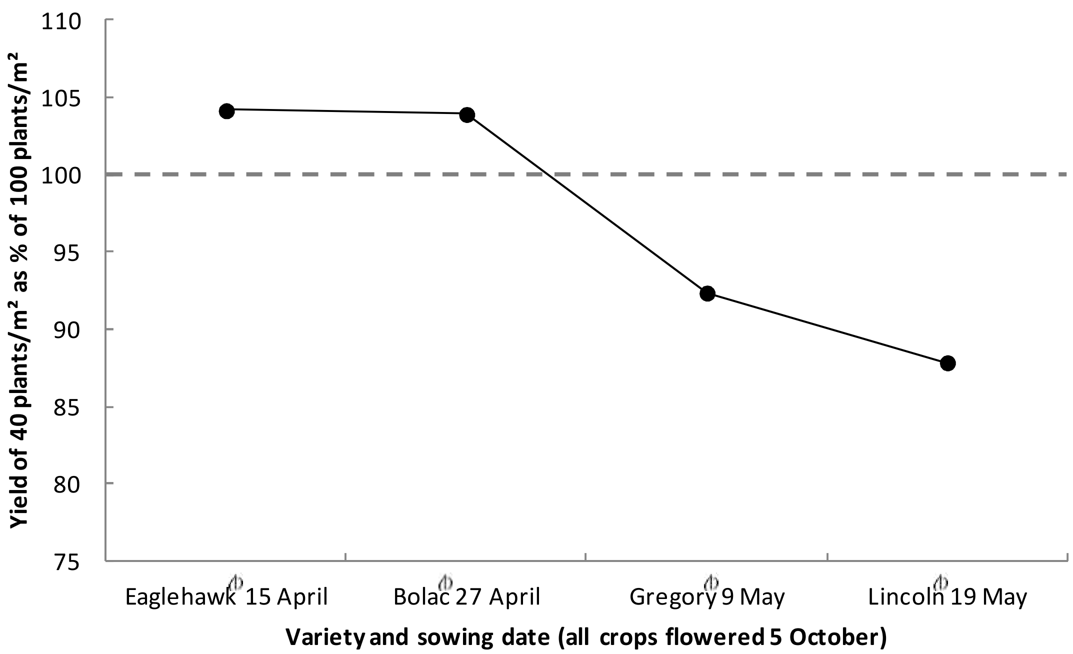

Figure 6. Grain yield of wheat grown at 40 plants/m² as a percentage of grain yield at 100 plants/m² for varieties with different maturities sown at different times at Temora in 2011 to flower on the same date (5 October).

High HI varieties. Some cereal varieties have inherently high harvest index, and it is probably no coincidence that this is the case for the most widely grown wheat (Wyalkatchem⟨PBR⟩) and barley (Hindmarsh⟨PBR⟩) varieties in Australia. However, remember that we are interested in HI as a means-to-an-end i.e. grain yield. Therefore, it is best to select the varieties with the best yield, disease and quality attributes for your environment. It would not make sense to grow Wyalkatchem⟨PBR⟩ at Nyngan just because it has a good HI, when its other agronomic and quality attributes are completely unsuitable!

Rules of thumb

Use NVT, DPI and grower group trials to select the varieties that have the best yield, disease and quality attributes for your region. The attribute of a variety that is most important for WUE is its maturity, and unfortunately maturity information about specific varieties from breeding and seed companies is often not very useful. Use local field days, which are generally run when crops are flowering, to get a good feel for comparative cultivar maturity (e.g. Table 4), and use this knowledge to make sure you are sowing the right variety at the right time to hit your optimal flowering window (see 'early flowering' above).

Table 4. Anthesis dates of 12 wheat varieties sown on three different dates Trangie in 2011. Dates highlighted in grey fall during the optimal window for Trangie (11-24 September). Nyngan is warmer than Trangie, so anthesis dates from the corresponding sow times will be earlier in that environment. APSIM modelling indicates that optimal sowing dates are about a week earlier at Nyngan compared to Trangie e.g. if optimum sow date for Gregory⟨PBR⟩ at Trangie is 16 May, it will be ~9 May at Nyngan.

	Sowing date		
Variety	**30 April**	**16 May**	**9 June**
Livingston⟨PBR⟩	29-Aug	12-Sep	25-Sep
Crusader⟨PBR⟩	1-Sep	12-Sep	24-Sep
Merinda⟨PBR⟩	1-Sep	16-Sep	26-Sep
Lincoln⟨PBR⟩	2-Sep	13-Sep	26-Sep
Spitfire⟨PBR⟩	2-Sep	13-Sep	25-Sep
Gauntlet⟨PBR⟩	3-Sep	19-Sep	28-Sep
Sunguard⟨PBR⟩	4-Sep	18-Sep	28-Sep
Sunvale	6-Sep	23-Sep	1-Oct
Gregory⟨PBR⟩	7-Sep	20-Sep	1-Oct
Sunzell⟨PBR⟩	10-Sep	23-Sep	1-Oct
Eaglehawk⟨PBR⟩	19-Sep	28-Sep	5-Oct
Wedgetail⟨PBR⟩	19-Sep	28-Sep	6-Oct

You can't manage what you don't measure!

Measuring HI is one of the best ways of benchmarking your crops WUE and diagnosing potential problems, yet it is almost never done commercially. This is probably for a good reason – it needs to be done at harvest which is a busy and stressful time of year, and to do properly requires a lot of work and specialised equipment (hand cutting a known area of crop, drying at 70°C for 48 hours, weighing and then threshing the grain and weighing). However, there is a very quick method for estimating HI (Passioura and Angus 2010) that can be done in the field and involves cutting individual stems off at ground level, balancing them on a fulcrum, and measuring the total length of the stem to the tip of the ear (not including awns), and the distance from the base to the balance point (Figure 6). HI can then be calculated using the equation given below.

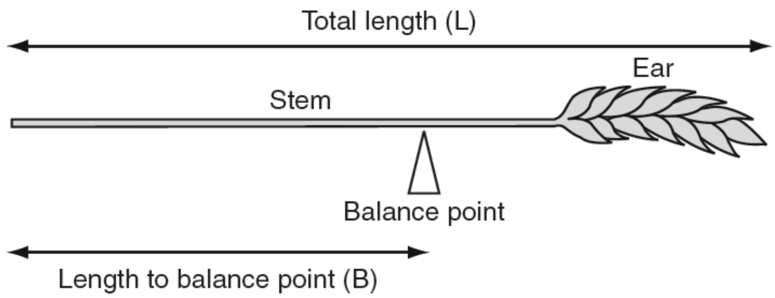

Figure 6. Technique for estimating harvest index of wheat by cutting a stem off at ground level, finding the balancing point, as shown, and measuring distance to balancing point (B) and total length (L) not including the awns. The function relating the ratio B/L to the harvest index, HI, measured by weighing and threshing, is HI = 2B/L - 0.96. Trial and error is needed to find out how many stems need to be measured to get a reasonable estimate of harvest index. Figure taken from Passioura and Angus 2010.

References

(Some of these are not publicly accessible, if you would like a copy please contact the authors)

Fischer RA (2011) Wheat physiology: a review of recent developments. *Crop & Pasture Science* **62** (2), 95-114.

Fischer RA, Sayre K, Oritz-Monasterio I (2005) The effect of raised bed planting on irrigated wheat yield as influenced by variety and row spacing. In 'Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico' (Eds CH Roth, RA Fischer and CA Meisner). ACIAR proceedings No. 121. http://aciar.gov.au/files/node/703/PR121%20Part%20A%20for%20Web.pdf,

Passioura JB (1977) Grain-yield, harvest index, and water-use of wheat. *Journal of the Australian Institute of Agricultural Science* **43** (3-4), 117-120

Passioura JB, Angus J (2010) Improving productivity of crops in water-limited environments. *Advances in Agronomy* **106**, 37-75.

Zhang HP, Turner NC, Simpson N, Poole ML (2010) Growing-season rainfall, ear number and the water-limited potential yield of wheat in south-western Australia. *Crop & Pasture Science* **61** (4), 296-303.

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