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Review

Closing the gap between actual and potential yield of rainfed wheat. The impacts of environment, management and cultivar

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ABSTRACT

Studies that compare the genotypic improvement of historical cultivars with yield progress in commercial crops provide evidence of the impact of past and current research in crops. The analysis of experiments designed to examine combinations of environment (E), management practices (M) and cultivars (G) also provides evidence of the relative importance of each of these factors for yield improvement. The evidence shows that variation due to E far outweighs the variation of grain yield that can be attributed to M or G, or the interactions between these factors, and between these factors and E.

The major 'gap' between yields achieved on farms and the theoretical potential as estimated by seasonal rainfall or water use, is found where seasonal water supply is greater than about 250 mm and when management, not rainfall or cultivar is limiting productivity. This suggests that tactical (in season) management, including the choice of crop and cultivar, fertilizer amount and timing, weed, insect and disease control when combined with management of strategic factors (that have an effect for more than one season) such as soil acidity, compaction, low organic matter, non-wetting and water-logging will provide additive benefits that can address the variability imposed by the environment.

In the semi-arid cropping regions of the world where inter-seasonal variability of rainfall is high, it is particularly important for farmers to maximize grain yields in seasons when the rainfall is adequate to produce profitable crops. Current technologies are already relatively efficient in the drier seasons so that the relative impact on farm productivity of research to improve yields in dry years is likely to be small.

Field studies in Western Australia that have included a range of environments (sites $\times$ seasons) cultivars, and levels of management (sowing times, fertilizer treatments, seed rates) show that the main effect of E has accounted for about 80% of the variability in grain yield, M has accounted for about 6%, and G for about 3%. The G $\times$ M and G $\times$ E interactions were generally unimportant. This is confirmed by studies in similar rainfed environments elsewhere. Some studies that include M as part of the E term show apparently large G $\times$ E interactions, possibly due to either the selection of very different cultivars or environments, or both. The usefulness of such results at the farm level is doubtful due to the variable management inputs in the experiments and a lack of validity for farmers who may not be concerned with variability across widely separated locations. In studies that examine genetic responses to individual management practices differences are often very specific to the environmental conditions experienced in the experiments. The aim of the review is to discuss how management factors can contribute to closing the yield 'gap' between actual and potential grain yields in the variable environment experienced by rainfed crops.

The impacts of tactical and strategic management practices appear to be independent and additive rather than co-dependent, allowing for adoption one at a time as resources permit. The use of strategic practices that ameliorate acidity or compaction for example, will lift the grain yield at all levels of tactical inputs such as fertilizer, thus reducing the seasonal variability of yield even though the response to fertilizer does not change. It is concluded that in principle, the best way to maintain productivity under conditions of seasonal variability is to use both tactical and strategic management to close the gap between actual and potential grain yields in the average and better seasons.

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1. Introduction

The average yield of rainfed wheat in Western Australia passed from a period of very slow growth until the early 1990s, followed by a period of relatively rapid improvement for about a decade until about 2000. Since that time average grain yields of wheat have undergone a period of extreme year-to-year variability (Fig. 1). It is possible that the improved levels of management used by farmers in the current decade (Anderson et al., 2005) have added to the seasonal variability in grain yield in addition to the variability in seasonal rainfall. Since the lowest yields in the post-2000 period are not less than the average yields in the pre-1990 period it can be assumed that the changes in cropping technology have continued to be effective in the less favourable seasons. However, variability of grain yield is not a problem of itself provided that water use efficiency of grain yield is maximised over a range of seasonal conditions through profitable means (Passioura, 2002). It is thus important to explore the factors that have contributed to yield improvement in the past and the possible means to continue improvement in future. The aims of this review and discussion are

1. To discuss the relevance for yield improvement of management practices (M) and cultivars (G) and their interaction with the environment (E).
2. To discuss ways that tactical (in season) and strategic (longer term) crop management methods can be used to address the yield 'gap' between actual and potential yield and reduce the impact of variable seasonal conditions on grain yield.

This review mainly concerns rainfed wheat (*Triticum aestivum*) in the cropping zone of Western Australia (approx. 27–34°S latitude, 115–124°E longitude average annual rainfall 300–600 mm with ~80% in the growing season). However, limited information from other crops and other regions, both rainfed and irrigated, that has possible relevance is also considered.

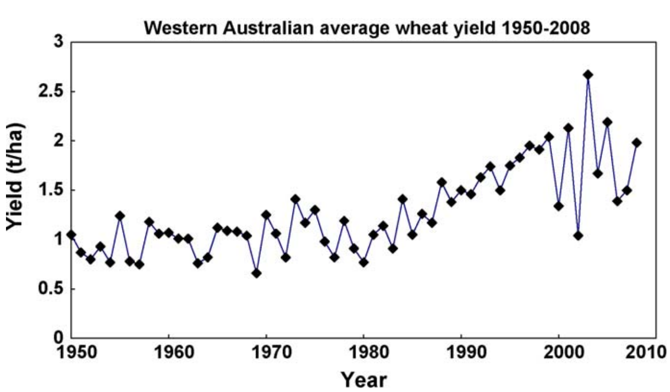

Fig. 1. Average yield of wheat in Western Australia 1950–2007. Data from Co-operative Bulk Handling Ltd.

1.1. The size of the 'gap' and the potential for improvement

The evidence from rainfed environments in Australia indicates that when rainfall, or water supply (rainfall plus stored water), is less than about 250 mm in the growing season rainfall (GSRF) itself limits grain yield and transpiration use efficiency (TUE in kg grain per unit of rainfall) is close to the theoretical maximum (French and Schultz, 1984; Cornish and Murray, 1989; Anderson, 1992). A review by Sadras and Angus (2006) of rainfed wheat crops worldwide confirms that this syndrome is experienced in many environments. Some examples for three shires in Western Australia are shown in Fig. 2 using data from the period 1997–2006 indicating how the commercial yield of wheat has deviated from the potential as calculated using the French and Schultz (1984) model.

The evidence reviewed applies to commercial yields and experimental treatments that are broadly similar to average commercial practice. The point of departure of commercial yields from the potential line is approximate, and varies from perhaps 200 mm to over 300 mm (see Fig. 2). However, experimental studies show that when water supply is larger it is mostly management that limits productivity and examples are given from experiments in the references listed above of how management can be used to lift yields closer to the potential at seasonal rainfall amounts up to about 350–400 mm. This suggests that the main scope for improving grain yield across seasons resides in improving management to fully utilise all the rain that falls in higher rainfall years.

There is evidence that the cultivars currently available for use in rainfed situations can produce yields of over 7 t/ha (summarised by Zhang et al., 2006). This suggests that average farm yields of about 2 t/ha in rainfed environments, are not limited by low genetic yield potential and thus selection of cultivars by the farmer could place more emphasis on management factors such as disease resistance and grain quality that might stabilise yield, reduce costs for control of biotic factors, or improve the price obtained.

Using the average yield of wheat in selected shires across the rainfall zones of Western Australia over the period 1997–2006 and the daily rainfall for the major township in each shire over the same period, the average yield 'gap' can be calculated. The losses of water have been estimated as a fixed percentage (30%) of seasonal rainfall (calculated from sowing to maturity) rather than as a fixed average of 110 mm as found by French and Schultz (1984) in their crops in South Australia. This gives numbers similar to those found locally of ~50 mm in the low and medium rainfall areas of Western Australia (Anderson, 1992) and ~150 mm as found in the high rainfall areas (Zhang et al., 2005). The estimates of potential yield