CBCS
http://agrobiol.sggw.waw.pl/cbcs

Communications in Biometry and Crop Science
Vol. 6, No. 2, 2011, pp. 64–79

International Journal of the Faculty of Agriculture and Biology,
Warsaw University of Life Sciences, Poland

REGULAR ARTICLE

Agronomic practices for durum wheat in an area new to the crop

Mohammed S. Miyan[1*] , Alfredo Impiglia[2], Wal K. Anderson[3]

[1] Department of Agriculture, PO Box 483, Northam, WA 6401, Australia
[2] Food and Agriculture Organization of the United Nations, Viale delle Terme di Caracalla 00100 Rome, Italy
[3] Department of Agriculture, 444 Albany Highway, Albany, WA 6330, Australia and School of Plant Biology, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009 Australia.
Corresponding author: Mohammed S. Miyan; E-mail: shahajahan.miyan@agric.wa.gov.au

CITATION: Miyan, M.S., Impiglia, A., Anderson, W.K. (2011). Agronomic practices for durum wheat in an area new to the crop. *Communications in Biometry and Crop Science* 6 (2), 64–79.

Received: 15 August 2011, Accepted: 19 January 2012, Published online: 1 February 2012

ABSTRACT

Despite apparent climatic and edaphic similarities with traditional growing areas in the Mediterranean basin, durum wheat has not been grown extensively as a commercial crop in Western Australia. The principal objective of this study was to develop some effective agronomic management practices as one of the first steps in introducing durum wheat cultivation into Western Australia and to compare the responses to those found in more traditional areas in the world where durum is successfully grown. Twenty-seven experiments were conducted in 1998, 1999, 2000 and 2001 in the northern, central, and southern wheat belt of Western Australia using treatments which included: two durum wheat cultivars (*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.) and two bread wheat cultivars (*T. aestivum* L.); 3 sowing times; 5 nitrogen (N) rates and; 5 seeding rates. The experiments were conducted on a range of soil types and the seasonal rainfall ranged from 70 to 347 mm. The average yield advantage for bread wheat cultivars over durum wheat cultivars was 13 – 19% depending on site and season. The average grain protein percentage for durum cultivars was between 0.8 and 1.5% greater than for the bread wheat cultivars. Overall, it was concluded that durum wheat could be grown successfully in Western Australia using the practices resulting from the experiments described in this paper but that the long term success of the crop will depend on reducing the yield gap between bread wheat and durum wheat and on the continued quality and price advantage for durum wheat.

Key Words: *wheat; plant population; sowing time; soil type; crop rotation; protein content.*

INTRODUCTION

The introduction of any crop that is new to an area requires, in addition to economic considerations, an understanding of the basic agronomy required to grow the crop. Among factors known to influence the adaptation of crops are rainfall amount and seasonal distribution, temperature during the growing season and the extremes of temperature, the inherent soil characteristics and the nature of the existing farming system into which the new crop is to be introduced.

The climatic conditions in the wheat belt of Western Australia are very similar to those in the Mediterranean basin, the traditional home of durum wheat (*Triticum turgidum* L. subsp. durum (Desf.) Husn.) production (Kassam, 1981). The rainfall pattern shows winter dominance (>70% of annual rainfall, on average, falls during the growing season) and winter minimum average temperatures are mild (typically 4 – 8 C in the coolest month). Extremes of maximum temperature of greater than 30 C during grain filling or less than 2 C during flowering do occur in some parts and can have a major impact on grain yields and quality in some seasons. Despite the apparent similarity of the conditions compared to traditional durum wheat production areas the crop was not grown commercially in Western Australia until the late 1990s. Interest in producing durum wheat in Western Australia arose because of its high value relative to bread wheat (www.awb.com.au; verified 27. Dec., 2011) and its potential suitability for the local climate. The long-term prognosis for durum wheat in international markets is favorable (Impiglia, 2000).

The main crop in Western Australia is bread wheat (*T. aestivum* L.) so it can be assumed that much of what is already known for that crop can be compared to its close relative durum wheat. Bread wheat is grown in Western Australia in crop/pasture systems that often contain legume pastures such as subterranean clover (*Trifolium subterraneum* L.) or medics (*Medicago* spp.), grain legumes such as lupin (*Lupinus angustifolius* L.) and field pea (*Pisum sativum* L.), canola (*Brassica napus* L.), barley (*Hordeum vulgare* L.), and oats (*Avena sativa* L.). One of the major concerns for potential durum growers in Western Australia is producing grain at a protein level that will qualify for a premium. The inherent fertility of many soils is too low to produce high grain protein in most seasons unless the crop is rotated with legumes and/or high rates of N fertilizer are used to improve the grain protein percentage (Mason, 1975). This contrasts with soil conditions in more traditional areas such as the Mediterranean basin where the soil pH is often alkaline and clays or clay loams predominate (Kassam, 1981). Under these conditions rotations with legumes or the application of high rates of N fertilizer are less common.

It has been well recognized however, that adoption of grain legumes in farming systems can significantly increase cereal yields and grain quality in the following year in both the traditional areas, where durum is grown (Lopez-Bellido et al., 1998), and in Western Australia (Edward and Haagensen, 2000). The value of broadleaf crops, especially legumes, in rotation with durum wheat has been described in other semi-arid situations (Gan et al., 2003, Kirkegaard et al., 2004). The specific benefits of growing legume crops in a rotation include weed and disease management, soil structural benefits, erosion control and N nutrition for the following crops (Chatel and Rowland, 1982).

The agronomic practices previously found suitable on alkaline, red clay loam soils in Western Australia for producing high protein in bread wheat (Anderson et al., 1995) can be tested for durum wheat on less favorable soils, so that the potential area suitable for durum production can be expanded and more farmers given the opportunity to grow the crop. Durum wheat is often produced in countries with Mediterranean-type climates in rainfall zones, which are drier than for bread wheat but wetter than for barley (Impiglia and Ryan, 1997). An equivalent zonation of crops according to rainfall zones does not exist in Western Australia. This possibly reflects a different combination of economic and biological conditions. There is 3 x 106 ha of land that is estimated to be suitable for durum wheat production in Western Australia on the basis of soil type, soil depth and pH (Impiglia, 2000).

The yield of durum in the North African and West Asian regions can sometimes equal or exceed that of bread wheat in well-managed crops in zones where the average rainfall is greater than 350 mm, or with the use of supplementary irrigation (Srivastava et al., 1982). The yield advantage of bread wheat in lower rainfall situations (annual rainfall < 450 mm) in

South Australia was attributed to a greater number of smaller kernels per unit area compared to durum wheat (Zubaidi et al., 1999). Ketata (1987) reported a similar yield advantage for bread wheat over durum wheat from an experiment in Syria and for Tunisian national averages.

The reduction in grain yield of durum wheat, with later sowing, can be less than for bread wheat in Mediterranean countries (Ketata, 1987) but the importance of early sowing relative to the break of the season has been emphasized in Syria (Cooper et al., 1987) and America (Bolton 1981). Response to fertilizers is less pronounced in drier compared to more humid areas (Ohlsen and Kurtz, (1982), in America; Matar et al. (1992), in Mediterranean countries). There are few references to optimum seeding rates, or plant populations for durum wheat in the literature, but a population of about 250 plants/m^2 is common in experiments in traditional durum wheat growing areas (e.g. Harris et al., 1987).

The main objective of this study was to develop effective agronomic management practices for durum wheat so that farmers new to the crop would have a sound basis for managing its production in Western Australia. A second objective was to compare responses in an environment which was new to durum wheat to those found in more traditional areas for the crop thus providing a wider understanding of the requirements of durum wheat and the principles for transferring an old crop into a new area.

We recognize that there would be cultivar specific difference in agronomic responses to the environment and management factors, as reported in bread wheat (Anderson et al., 2004, 2011; Sharma et al., 2008). However, this paper uses the comparison of the two most promising cultivars of each of the durum and bread wheat to meet these objectives. The effects of sowing time, plant population (seeding rate) and N rate on the yield and grain quality of durum wheat, in comparison to bread wheat, were investigated in a range of potential environments in Western Australia over a period of four years.

MATERIALS AND METHODS

Four series of field experiments were conducted from 1998 to 2001 at either research stations or farmers' properties in the low (300 - 350 mm) and medium (350 – 450 mm) rainfall environments as follows: (1) Cultivar x N rate = C x N; (2) Cultivar x seeding rate = C x S; (3) Cultivar x seeding rate x N rate x sowing time = C x S x N x T; (4) Cultivar x sowing time = C x T; and (5) Split N applications on grain yield and protein = split N in 2001 only. Rainfall was recorded at or near each experimental site. Site details are shown in Table 1 and site locations in Figure 1.

BASAL TREATMENTS

The crop was sown each year and in all series as close as practical to the opening rains. Where sowing time was a variable the second and third sowings were at about 14 - 21 day intervals after the opening rains. Plots were 8 rows wide and 20 m long. To obtain the dual benefits of a disease 'break' and possible residual N effects the experiments were sown following a legume crop in the previous year (field peas, lentil, chickpeas or medic) or fallow at one site. All N was applied as urea at seeding and was separated from the seed. Basal phosphate was applied at sowing according to soil test at each site. Weeds were controlled using appropriate pre-and post emergent herbicides.

Table 1. Locations, experimental series, factorial treatment combinations (C=cultivar, N=nitrogen rate, S= seeding rate, T=time of sowing), sowing dates, rainfall and water supply, 1998 to 2001. Pre-season rainfall (PSRF) refers to the amount of rain from 1. January to sowing date, growing season rainfall (GSRF) to the amount of rainfall from sowing to maturity. Seasonal water supply was calculated based on the formula (PSRF*0.2) +GSRF.

Year/Site		Experimental Series			Rainfall/water supply		
No.	Name	No.	Treatment	Sowing date	Pre-season	Growing season	Seasonal supply
					--------------	mm	--------------
1998							
1	Binnu	1	C x N	May 27	84	272	289
		2	C x S				
2	Kalannie	1	C x N	June 5	74	179	194
		2	C x S				
3	Merredin	1	C x N	June16	49	199	209
		2	C x S				
4	York	1	C x N	June 5	58	299	311
		2	C x S				
1999							
5	Merredin	3	C x S x N x T	June 8/22	186	155	192
6	Balla	2	C x S	May 20	166	94	127
7	York	3	C x S x N x T	June 4/18	158	347	379
		2	C x S				
8	Salmon Gums	2	C x S	May 22	88	160	178
2000							
9	Cunderdin	3	C x S x N x T	June 17/19	180	193	229
10	Merredin	3	C x S x N x T	June 17/ July 6	219	119	163
11	Mullewa	3	C x S x N x T	May 25/ June 26	177	82	117
		2	C x S				
		1	C x N				
12	Salmon Gums	3	C x S x N x T	May 11/ June 20	332	70	136
2001							
13	York	1	C x N	May 21	41	221	229
		5	split N				
14	Mullewa	3	C x S x N x T	May 14/ June 4/ June 22	33	192	199
		4	C x T				
15	Salmon Gums	3	C x S x N x T	May 15/ May 31/ June13	133	148	175
		4	C x T				
16	Merredin	3	C x S x N x T	May 18/ June 5/ July 10	197	174	213
		4	C x T				

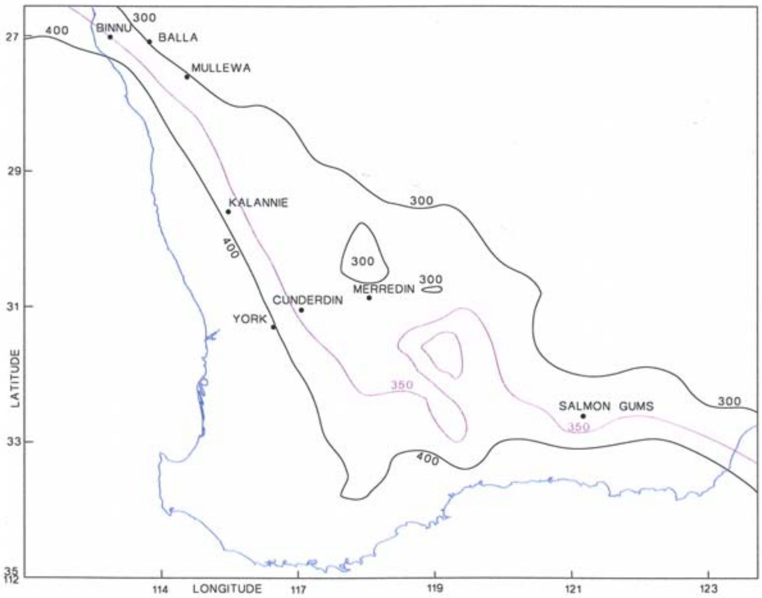


Figure 1. Map of Western Australia showing average annual rainfall isohyets and locations of the experimental sites.

EXPERIMENTAL TREATMENTS AND DESIGN

In Series 1 in 1998 and 2001, five experiments were conducted with two durum wheat cultivars (Tamaroi and Wollaroi) and two bread wheat cultivars (Amery and Spear) and five N rates (0, 20, 40, 60 and 80 kg/ha of N). Series 2, (9 experiments) from 1998 – 2000, included the same durum and bread wheat cultivars and five seeding rates (50, 100, 150, 200 and 250 viable seeds/m^2). Seeding rates were calculated using percentage germination and mean 1,000-grain weight to achieve the target plant population per m^2. Series 3 experiments were sown at 9 sites during 1999-2001 comparing Spear and Westonia bread wheat with Wollaroi and Tamaroi durum wheat cultivars at 0 and 50 kg/ha of N, 100 and 200 viable seeds/m2 and 2 sowing times. A complete factorial design was used. Series 4 (3 sites) in 2001, included 2 bread wheat cultivars (Westonia and Carnamah) and 2 durum cultivars (Tamaroi and Wollaroi) and 3 times of sowing in a complete factorial combination replicated three times.

The durum wheat cultivar Wollaroi, used in these experiments, was selected for eastern Australian conditions where rain falls mainly in the summer and the soils are deeper. They thus have a greater plant available water capacity, and are more fertile. The cultivar Tamaroi was selected in South Australia but was derived from the same breeding program as Wollaroi. No locally bred durum wheat cultivars were available. The bread wheat cultivars Amery, Westonia and Carnamah in contrast were bred and selected for Western Australian conditions, where the rainfall has a winter dominance, the soils are shallower, less fertile and with a lower water storage capacity. The cultivar Spear was bred in South Australia but is well adapted to Western Australian growing conditions.

Split N applications were applied in one experiment using Westonia bread wheat and Wollaroi durum wheat at the York site in 2001. The treatments were; (1) 0 N; (2) 25 kg/ha of N at sowing; (3) 50 kg/ha of N at sowing; (4) 75 kg/ha of N at sowing; (5) 25 kg/ha at sowing plus 25 kg/ha at tillering; and (6) 25 kg/ha of N each at sowing, tillering and anthesis.

MEASUREMENTS

Soil samples were collected from all trial sites in all years prior to seeding. The samples were taken at 0 - 10 cm depth from 10 - 20 positions at each site. The samples were bulked to provide one representative sample per site and were analyzed for pH (in 0.01M $CaCl_2$). Soil texture was assessed manually at each site over the full soil profile.

Plant numbers were counted at two locations of 1m x two rows in each plot. Grain yield, and grain protein (by near infrared reflectance calibrated against the standard Kjeldahl test) were measured for all plots.

STATISTICAL ANALYSES

The experiments were laid out as randomized complete blocks for Series 1, 2 and 4 and split plot designs were used for Series 3. Statistical analyses of variance were carried out using Genstat® for Windows 5th edition. All differences discussed in the paper were significant at $P < 0.05$ unless otherwise stated.

The optimum plant population was estimated for each cultivar x plant population data set by the methods of Anderson et al., (2004). In short, an inverse polynomial curve of plant population versus grain yield, forced through the origin, was fitted using actual counted plant numbers by the method described by Del Cima et al, (2004). The optimum population was defined as the point when the slope of the curve was 2.5 kg/ha of grain for each extra plant/m^2. In cases where the initial slope of the fitted curve was negative, the smallest plant population was used as the best estimate of the optimum. Where the estimated optimum was larger than the highest experimental data point, the highest counted plant population was used as the best estimate of the optimum.

Rather than using a "global" response curve to model the effect of plant population on yield we divided the total number of records into groups of optimum population densities using a regression tree analysis (S-PLUS 2000) similar to Del Cima et al. (2004). For the purpose of grouping the sites annual rainfall was divided into pre-sowing rainfall (PSRF, January to sowing date) and growing season rainfall (GSRF, sowing to harvest). Stored soil water (SW) was estimated as (PSRF x 0.2).

The idea of regression tree analysis is similar to the multivariate technique of linear discriminant function analysis where the within group variation is minimized and the between group variation is maximized. The groups or nodes formed in regression tree analysis follow a binary pattern. All records were initially placed in a single group (Group 1). We then divided records in Group 1 into Groups 2 and 3 based on soil type, water supply, and species. Group 2 was then divided into 4 and 5 and Group 3 into 5 and 6 until homogeneous groups were achieved. In this manuscript Group 8 (Table 4) comes from the partitioning of Group 1 => Group 2 => Group 4 => Group 8, which is a grouping of records dominated by species 'durum', water supply 'Water < 143mm', and of soil type 'loam'. In the ideal case group means would be significantly different. Thus the t-test statistic for the difference in optimum population density between Group 8 (durum) and Group 9 (bread) equals (95-113)/SQRT(25^2/21 + 23^2/22) = -2.45, suggesting that there is a real difference in the optimum population density between durum and bread wheat, i.e. bread wheat requires a higher population density for maximum yield than durum wheat under these soil and water conditions.

The optimum sowing time for each experiment of Series 4, where three sowing times were used, was estimated by fitting splines to the yield data and estimating the time when the maximum grain yield was achieved (Sharma et al., 2008). Where there were only two sowing times, in the experiments of Series 3, the optimum sowing time was taken to be the sowing time that gave the highest grain yield for each cultivar. The mean optimum sowing period was then calculated for each experiment. The optimum sowing periods for the northern (Mullewa, 3 experiments), central (Merredin, Cunderdin and York, 6 experiments) and southern (Salmon Gums, 3 experiments) parts of the state were then calculated by combining sites and years in each area.

RESULTS AND DISCUSSION

The rainfall in the growing season varied from 70 mm to 347 mm and the water supply for crop growth (including an estimate of stored soil water) varied from 117 to 379 mm (Table 1). The soil tests (Table 2) showed that only one site (Binnu 1998) had soil with a surface pH ($CaCl_2$) of less than 5.5. The soil at all sites was a loam or loamy earth except the site at Balla, in 1999, which was a sand and the site at York in 2001, which was a heavy clay.

Table 2. Soil pH and texture assessed by hand texturing samples from 0-10 cm depth. Typical mechanical analyses: heavy clay >50% clay, 40% sand; clay loam 10-30% clay, 40-60% sand; loams and loamy soils 10-20% clay, 80-90% sand; deep sand ~90% sand, <10% clay. Previous crops at the trial sites where lupin (*Lupinus angustifolius* L.), Faba bean (*Vicia faba* L.), Medic (*Medicago* spp.), Chickpea (*Cicer arietinum* L.), Field pea (*Pisum sativum* L.).

Year/ Site	pH ($CaCl_2$)	Soil texture	Previous crop
1998			
Binnu	4.5	Loamy earth	Lupins
Kalannie	5.0	Red clay loam	Long fallow
Merredin	8.0	Red clay loam	Faba bean
York	7.8	Brown clay loam	Faba bean
1999			
Merredin	6.5	Loamy earth	Faba bean
Balla	5.0	Deep sand	Lupins
York	7.0	Loam	Faba bean
Salmon Gums	6.5	Loam	Medic
2000			
Cunderdin	7.5	Loamy earth	Medic
Merredin	7.8	Calcareous loamy earth	Chick pea
Mullewa	7.5	Loamy earth	Field pea
Salmon Gums	7.7	Loamy earth	Field pea
2001			
York	5.9	Heavy clay	Faba bean
Mullewa	5.5	Loamy earth	Chick pea
Salmon Gums	6.0	Loamy earth	Field pea
Merredin	6.5	Red clay loam	Medic

NITROGEN RATE

The only significant increase in yield due to applied N was at the York site in 1999 ($P < 0.05$). There was no significant cultivar by N rate interaction at any site (Series 1 and 3).

In the N rate experiments of Series 1 (5 sites), the average amount of applied N required to reach 13% grain protein in the durum cultivars was 23% (or 15 kg/ha) less than for bread wheat (estimated from the relationships between grain protein and N applied at each site). Durum wheat cultivars had higher protein content than the bread wheat cultivars even where no N was applied (Table 3). On average, in the N rate experiments, the grain protein of the durum cultivars was about 1% higher than in the bread wheat cultivars at any yield level (Figure 2). The initial response of grain protein to added N fertilizer (data from both Series 1 and Series 3) was about the same for both bread and durum wheat (~ 0.5% for 40 - 50 kg/ha of N). However, the profitability of applying N fertilizers to simply increase grain protein is doubtful at current premium levels and fertilizer prices so it is more important to emphasize selection of soil type and crop rotation. At the York site in 1999, the only site where yield was increased by the addition of N, the grain protein level was almost certainly diluted by the increased yield.

Table 3. Average grain protein percentage at zero applied N and average amount of applied N required to reach 13% grain protein (Estimated from experiments in Series 1, cultivar x N-rate). Standard errors are in parenthesis.

Wheat species	Avg.protein content at 0 N	Avg. N required for 13% protein
	--%--	--kg ha^{-1}--
Bread	11.7 (0.62)	65 (13.5)
Durum	12.1 (0.60)	50 (13.4)

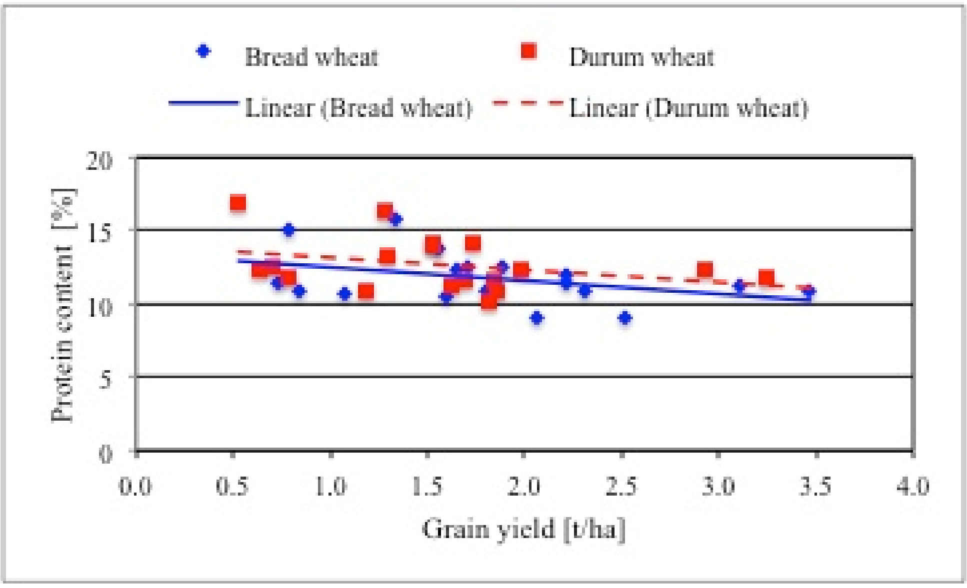


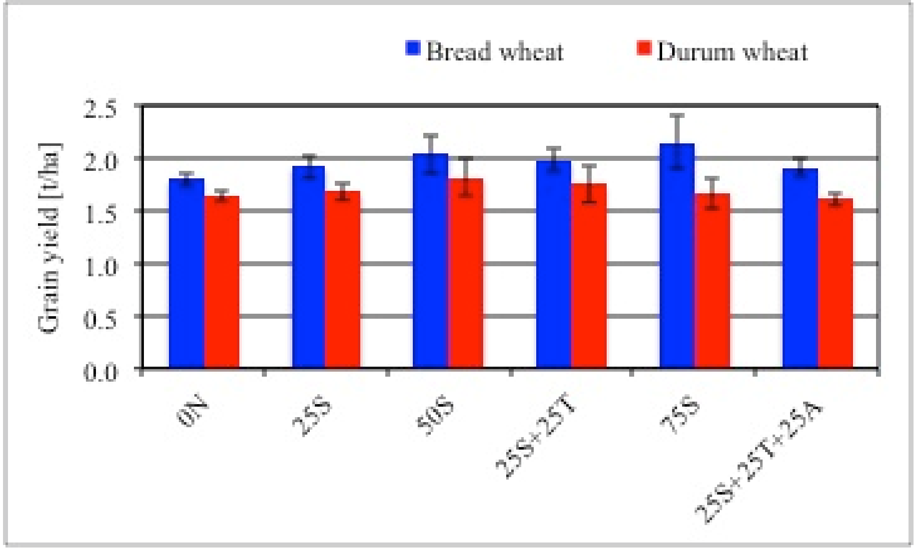
Figure 2. Relationship between grain yield and grain protein of bread and durum wheat cultivars at 0N in the N rate experiments (Series 1).

Previous studies on hard grain bread wheat in Western Australia (Anderson et al., 1995) have shown that grain protein commonly exceeded 13% from crops grown on friable red brown earth soils with medic or field peas as the previous crop. In the current study using a wider range of soil types, the success rate of achieving high protein was less even though all the sites were in a legume or fallow in the previous year. In all cases this series of experiments was grown following legumes since it was assumed that grain protein in the range suitable for high quality durum wheat was unlikely to be achieved economically in other rotations. The relative importance of soil type selection and legume rotation for durum wheat crops was greater in these experiments than shown in some other environments and cropping systems (Ketata, 1987, Syria and Tunisia; Matar et al., 1992, Mediterranean basin; Lopez-Bellido et al.,1998, Spain; Gan et al., 2003, America), but similar to that in others (Gashawbeza et al., 2003).

Recent changes in the premium payable for protein have reduced the price penalty in Australian durum wheat for protein of less than 13% (www.awb.com.au). Prices for durum wheat can be higher compared to bread wheat when farmers achieve a grain protein of over 11.5% (APDR2 grade) or 13% (APDR1 grade), but similar to bread wheat where the protein level is lower.

At the York site, in 2001, where various split N treatments were applied, grain protein was increased more in the durum cultivar using split N application at the same N rate when grain yield was not changed significantly (Figure 3). This compares to experiments with durum wheat in Syria where the grain yield response to added N was less when all the N was applied at sowing compared to when it was all applied at tillering, but the percentage of vitreous kernels (highly correlated with grain protein percentage) was greater (Anderson, 1985). The use of split N applications deserves further study as a means of meeting protein targets in durum wheat. The yield and protein responses can be compared for this experiment with the experiment at the same site in 1999 where the response of grain protein to added N (50 kg/ha) was much less than in 2001. This was related to the increased grain yield response in 1999 (7 kg of grain per kg of N compared to 4 kg grain of N in 2001). It is possible that a strategy of split N application in the wet year of 1999 may have increased protein more than applying all N at seeding.

Grain yield



Protein content

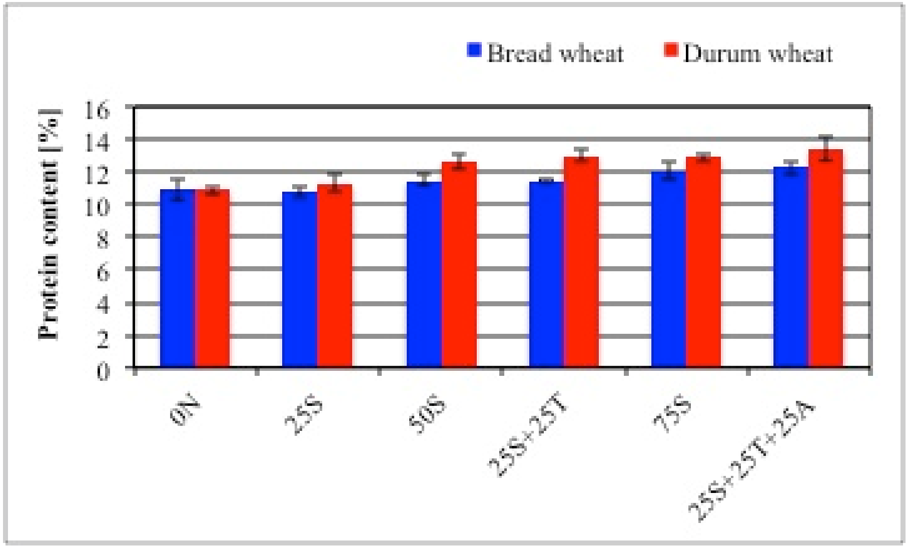


Figure 3. Grain yield and grain protein responses of bread wheat cv. Carnamah and durum wheat cv. Wollaroi to split N applications at York in 2001. S = applied at seeding, T = applied at tillering, A = applied at anthesis. Vertical bars are standard errors.

PLANT POPULATION

The range of optimum population (or crop density) in the experiments was between 93 and 160 plants/m². Farmers may use higher populations where competition with weeds is likely. Our estimates should thus be viewed as minimum populations applicable to weed-free situations.

The first grouping in the regression tree (Table 4) indicated that the only site with a very heavy clay soil required more plants to reach the maximum grain yield (Group 3) than on the loamy soils. Similar findings were reported by Del Cima et al. (2004) but are in contrast with those of Anderson et al. (2004). The difference is probably a reflection of the soil type, which can hold more water than the loamy soils to support a higher optimum plant population (Table 4).

In the loamy soils, when water supply (SW + GSRF) was less than 143 mm, optimum plant population to achieve maximum yield for the durum wheat cultivars was 95 plants/m² (Group 8) compared to bread wheat at 113 plants/m² (Group 9). This was the only grouping where the durum and bread wheat cultivars responded differently. This discrimination is based on regression tree approach which aims to maximize between inter-group variance and minimize intra-group variance. The sites contained in Group 8 and in Group 9 were the same (Cunderdin, Salmon Gums, Mullewa and Balla). These sites were located in the low and medium rainfall zones in the South, Center and North of the cropping area. The sites that fell into the remaining groups were also distributed across rainfall zones and latitudes.

Table 4. Optimum plant population as a function of soil type, water supply (0.2 PSRF + GSRF) cultivar and N application as determined by a regression tree technique. Soil types were Loam (Sandy loam to clay loam) and VHC (Very heavy clay). Durum wheat cultivars used were Tamaroi and Wollaroi and bread wheat cultivars were Amerey and Spear. Numbers in parentheses are standard deviations of the optimum populations.

Classification Criteria							
Soil type	Water supply	Species	N-rate	Optimum Plant Population	Group Number	Mean sowing date	Number of sites/records
	-- mm--		-kg ha^{-1}-	-plants m^{2}-			
Loam	< 143	Durum		95(25)	8	26-May	4/21
		Bread		113(23)	9	29-May	4/22
	181-206			93(27)	20	24-May	3/22
	> 206			126(39)	21	27-May	2/10
	< 181		0	129(42)	22	10-June	4/16
			50	150(28)	23	29-May	3/16
VHC				160(29)	3	21-May	1/9

When the rainfall was between 181 and 206 mm the optimum plant population was 93 plants/m² (Group 20). However, when rainfall was > 206 mm, the optimum plant population increased to 126 plants/m² (Group 21) and the mean grain yield was over 1 t/ha more. This is qualitatively similar to the response reported by Anderson et al. (2004) who found that the optimum population for bread wheat increased by about 40 - 50 plants/m² for each ton of grain yield.

Application of N (50 kg/ha) increased the average grain yield and the optimum plant population from 129 to 150 plants/m² when water supply was less than 181 mm (compare Group 22 and 23). However, this was the only grouping where N application affected the optimum population and it was not associated with a yield response at any of the sites.

Under these circumstances it is unlikely that N fertilizer would be added in practice so the recorded difference in optimum population is of doubtful practical significance.

The implication of these findings (summarized in Figure 4) is that durum wheat cultivars required fewer plants than the bread wheat cultivars to reach their maximum yield in low rainfall areas (< 143 mm water). When the seasonal water supply exceeded 143 mm both durum and bread wheat required higher plant populations to reach their maximum yield. This relationship is again in general agreement with Anderson et al. (2004) but the optimum populations for a given yield level is somewhat higher. This was possibly due to the predominance of loam and clay loam soils chosen for our experiments.

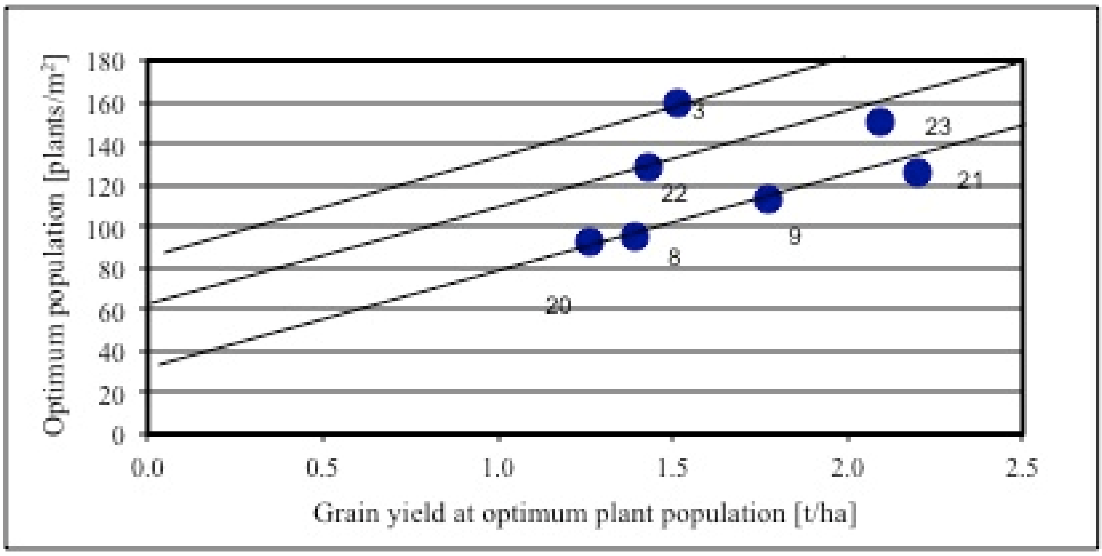


Figure 4. Relationship between population and grain yield at the optimum plant population. Numbers on the figure refer to the regression groups in Table 3, and the lines at a slope of 50 plants/m^2 for each 1 t/ha of yield, connect groups of sites described in the text.

Figure 5. Relationship between average grain yield ($LSD_{0.05}$ = 0.09 t/ha) and protein ($LSD_{0.05}$ = 0.31%) of bread and durum wheat cultivars. Data are from the seeding rate experiments of Series 2. Vertical bars are standard errors.

The effect of increased plant population on grain protein was not consistent across sites. There were only two sites where the grain protein was less than the delivery standard of 11.5% protein for the APDR2 Grade (Binnu 1998, 9.6 - 9.8% where soil pH was less than 5.5, and Balla 1999, 10.1 - 10.6%, on a sandy soil). However, the average grain protein percentage in the seed rate experiments (Series 2) was 11% higher in the durum wheat than in the bread wheat cultivars when the yield was 19% lower (Figure 5).

Given that the average seed size of the durum wheat cultivars was larger than in the bread wheat (40 - 45 mg for durum wheat vs. 35 - 40 mg for the bread wheat in our experiments) and assuming a 75% establishment, the minimum seeding rate for durum wheat for the range of optimum populations in Table 4 ranged from about 50 to 100 kg/ha. Since reduced plant establishment is likely at high target populations (Del Cima et al., 2004) it would be advisable to increase seed rates, above this range, when higher populations are required (e.g. >150 plants/m^2).

TIME OF SOWING

At eight of the twelve sites the earliest sowing gave the highest grain yields for all cultivars. There was a significant effect of sowing time ($P < 0.05$) or an interaction between cultivar and sowing time for grain yield in seven of the experiments (data from Series 3 and 4 used). The highest grain yields were obtained (Table 5) in the North (Mullewa) from sowing dates between 14 May and 26 June. This is similar to the estimate of Kerr et al. (1992) in that area for bread wheat. The length of the growing season in the North is about five months and the average minimum temperature in the coolest month is about 7 C.

Table 5. Periods when the average grain yields at each site were maximum in the sowing time experiments of Series 3 and 4.

Region/Location	Sowing date
North	
Mullewa 2000	May 25 – June 26
Mullewa 2001 (Series 3)	May 14 – June 6
Mullewa 2001 (Series 4)	May 14 – June 22
Optimum period	**May 14 – June 26**
Central	
Merredin 1999	8-June
York 1999	4-June
Cunderdin 2000	June 17 – June 29
Merredin 2000	June 17 – July 6
Merredin 2001 (Series 3)	May 18 – June 5
Merredin 2001 (Series 4)	May 18 – June 5
Optimum period	**May 18 – July 6**
South	
Salmon Gums 2000	10-May
Salmon Gums 2001 (Series 3)	May 15 – May 31
Salmon Gums 2001 (Series 4)	15-May
Optimum period	**May 10 – May 31**

In the center (Merredin, Cunderdin, York) the optimum period was 18 May to 6 July, somewhat later than the period estimated for bread wheat by Anderson and Smith (1990). The data were obtained from sites where the growing season is about six months and the average minimum temperature in the coolest month is about 5 C. In the South (Salmon Gums) the optimum period was from 10 May to 31 May. This is a more restricted period than estimated by previous authors (early May to early June, Shackley (2000) for a range of southern locations, but our data were obtained from one, low rainfall site only. At this location the average minimum temperature of the coolest month is 4.5 C and the growing season varies between 5 and 7 months.

The significant interactions between variety and sowing time for grain yield (4 experiments) indicated that the short season durum cultivar Wollaroi lost less yield from late sowings than the other cultivars (13 kg/ha/day compared to 22 kg/ha/day for Spear). This is similar to the results of Ketata (1987) for countries in the Mediterranean basin. Generally, bread wheat cultivars Spear and Westonia out-yielded the durum cultivars Tamaroi and Wollaroi by about 16% at earlier sowings (1st week of June) and by 13% at later sowings (3rd week of June). The yield advantage of the bread wheat cultivars was possibly due to superior local adaptation.

GRAIN YIELD AND PROTEIN OF DURUM WHEAT RELATIVE TO BREAD WHEAT

Bread wheat cultivars out-yielded durum wheat cultivars in all cases of our experiments. Given that the highest seasonal rainfall recorded for our experiments was only 347 mm (Site 7 in 1999) this result is similar to that of Zubaidi et al. (1999) in South Australia, where durum wheat cultivars only equaled or out-yielded bread wheat in zones where the average rainfall exceeded 450 mm. However, Ketata (1987) reported that in Syria, under seasonal rainfall that ranged from about 150 to 450 mm, durum wheat out-yielded bread wheat and responded more to increased seasonal rainfall.

The interaction between time of sowing and cultivars for grain protein was significant at 4 sites. The interaction showed that the durum wheat cultivars had more than a 1% higher grain protein at both sowing times (Table 6). At these sites the average grain protein of the durum wheat exceeded the minimum of 13% required for the Australian Durum 1 (ADR1) grade.

Table 6. Average grain protein (%) for two bread and two durum wheat cultivars at two sowing times. Data are the mean of 4 sites where the cultivar x sowing date interaction was significant ($P < 0.05$). Standard errors are in parenthesis.

Wheat species	Sowing time Late May	Late June
	---------------------------------%	-----------------------------
Bread	12.2 (1.32)	12.5 (1.31)
Durum	13.6 (1.45)	13.7 (1.22)

COMBINED RESPONSES

In the factorial experiments (Series 3) where a durum and a bread wheat cultivar were compared for their responses to early sowing (May), N fertilizer (50 kg of N) and higher plant population (50 vs. 200 plants/m^2), in both cultivars early sowing gave the most frequent yield increase. There were no consistent higher order interactions. There were 4 sites at which there were no yield responses to management practices and it is assumed that either the rotation history and soil type at these sites were sufficient to achieve the rainfall limited yield potential without changing the management, or that some unidentified factor was limiting the response to plant population, sowing time or N rate.

CONCLUSIONS

The currently available durum wheat cultivars tested in our experiments yielded about 16% less on average than locally adapted bread wheat cultivars. It appears that unless this yield gap can be reduced or closed, as is the case in other areas, it will be difficult for farmers in Western Australia to produce the crop profitably. However, the protein content of durum was about 1% higher when compared at similar grain yields as bread wheat. The average price advantage for durum wheat compared to bread wheat at 13% protein has been about 9% over the period from 1996 (www.awb.com.au; verified 27. Dec., 2011). This advantage can be greater in some years. However, the reduced N requirement to achieve a high grain protein in durum wheat should be considered when evaluating the potential profitability of the crop compared to bread wheat.

The following agronomic practices appear to be suitable for the production of durum wheat in Western Australia:

- Loam or clay loam soils were satisfactory for durum wheat production, where the crop was grown after legumes. This combination of soil type selection and legume rotation is probably more advisable in Western Australia than in more traditional areas of durum wheat growing.
- When the crop was grown on clay or clay loam soils in a legume rotation there was no yield response to added N fertilizer. This implies that N fertilizer will not be required at the yield levels found in these experiments, provided that appropriate soil types and rotations are chosen.
- The optimum sowing period for the durum cultivars tested was late May to early June in the North of the state, in June in the Center and in May in the South. However, this may change when locally adapted durum wheat cultivars of different maturity become available. The growing season in the countries of the northern hemisphere is probably slightly longer at 5 – 7 months than that indicated by these experiments in Western Australia. This is possibly related to deeper soils that can hold more available water.
- The minimum plant population (crop density) to obtain the maximum grain yield of durum wheat, in weed-free situations, was similar to that required for bread wheat (40 – 50 plants/m^2 for each ton of expected yield), except in lower rainfall situations where lower populations were adequate.
- The grain weight of durum wheat cultivars is typically higher than in bread wheat cultivars, so the average, minimum seed rate to maximize grain yield is about 25-30% greater. Based on our experiments this gives seeding rates of about 50 – 100 kg/ha based. Our experience is that local farmers are unlikely to use seed rates at the lower end of this range since they rely on higher seed rates as part of their integrated weed management systems. This is probably similar to commercial practice in traditional areas.

The major requirements for further research that are indicated by this research fall into two areas. Firstly, there is a need to develop and test locally adapted durum wheat cultivars that will close the yield gap to bread wheat and possibly extend the length of the growing season through earlier sowing when rainfall allows. Secondly, it is desirable to test the adaptation and agronomic requirements of durum wheat when grown on other common soil types such as sandy or duplex soils, or even acid soils.

ACKNOWLEDGMENTS

We wish to acknowledge the technical assistance of Louise Evans, Mechelle Owen, Frank Boetel, Tony Dale and James Bee. The Research Support Unit staff from Mullewa, Avondale, Wongan Hills, Salmon Gums and Merredin provided technical support for crop management. Thanks to Mario D'Antuono for his statistical support, to the farmers who supplied experimental sites, and to the useful suggestions from Darshan Sharma on the development of the manuscript. The Grains Research and Development Corporation is gratefully acknowledged for financial support.

REFERENCES

Anderson, W.K. (1985). Grain yield responses of barley and durum wheat to split nitrogen applications under rainfed conditions in a Mediterranean environment. *Field Crops Research* 12, 191–202.

Anderson, W.K., Crosbie, G.B., Lemsom, K. (1995). Production practices for high protein, hard wheat in Western Australia. *Australian Journal of Experimental Agriculture* 35, 589–595.

Anderson, W.K., Sharma, D.L., Shackley, B.J., D'Antuono, M.F. (2004). Rainfall, sowing time, soil type, and cultivar influence optimum plant population for wheat in Western Australia. *Australian Journal of Agricultural Research* 55, 921–930.

Anderson, W. K., Smith, W.R. (1990). Yield advantage of two semi-dwarf compared to two tall wheats depends on sowing time. *Australian Journal of Agricultural Research* 41, 811–726.

Anderson, W.K., Van Burgel, A.J., Sharma, D.L., Shackley, B.J., Zaicou-Kunesch, C.M., Miyan, M.S., Amjad, M. (2011). Assessing specific agronomic responses of wheat cultivars in a winter rainfall environment. *Crop and Pasture Science* 62, 115–124.

Bolton, F.E. (1981). Optimizing the use of water and nitrogen through soil crop management. In: Monteith, J., Webb, C., (Eds.) Soil water and nitrogen, Martinus Nijhoff/Dr. W. Junk, The Hague, 231–247.

Chatel, D., Rowland, I. (1982). Nitrogen fixation and inoculation by lupins. *Journal Agriculture., Western Australia* 23, 92–95.

Cooper, P.J.M., Gregory, P.J., Tully, D., Harris, H.C. (1987). Improving water use efficiency of annual crops in the rainfed farming systems of West Asia and North Africa. *Experimental Agriculture* 23, 113–58.

Del Cima, R., D'Antuono, M. F., Anderson, W. K. (2004). The effects of soil type and seasonal rainfall on the optimum sowing rate for wheat in Western Australia. *Australian Journal Experimental Agriculture* 44, 585–94.

Edward, A., Haagensen, A. (2000). Wheat in farming systems. In: Anderson, W. K., Garlinge, J. R., (Eds) *The Wheat Book – Principles and Practice* Bulletin 4443. Agriculture Western Australia, Perth, 9–130.

Gan, Y.T., Miller, P.R., McConkey, B.G., Zentner, R.P., Stevenson, F.C., McDonald, C.L. (2003). Influence of diverse cropping sequences on durum wheat yield and protein in the semiarid northern Great Plains. *Agronomy Journal.* 95, 245–252.

Gashawbeza, B., Yaekob, A., Zemede, A., Kiftew, J., Tadesse, T. (2003). Fertilizer N effects on yield and grain quality of durum wheat. *Tropical Agriculture* 80, 146–151.

Harris, H. C., Goebel, W., Cooper, P.J.M. (1987). Crop genotype-environment interaction. In: Srivastava, J. P., Porceddu, E., Acevedo, E., Varma, S., (Eds.) *Drought tolerance in winter cereals*. John Wiley and Sons, Chichester, 37–54.

Impiglia, A. (2000). Durum. In: Anderson, W. K., Garlinge, J. R., (Eds.) *The Wheat Book-Principles and Practice*. Bulletin 4443. Department of Agriculture Western Australia, Perth, 273–292.

Impiglia, A., Ryan, J. (1997). Cereal quality and mineral nutrition in the West Asia and North Africa environments. In: Johnston, A. E., (Ed.) *Food security in the WANA region, the essential need for balanced fertilization*. International Potash Institute, Basel, Switzerland, 177–190.

Kassam, A.H. (1981). Climate, soil and land resources in North Africa and West Asia. In: Monteith, J., Webb, C., (Eds.) *Soil water and nitrogen*, Martinus Nijhoff/Dr. W. Junk, The Hague, 1–29.

Kerr, N.J., Siddique, K.H.M., Delane, R.J. (1992). Early sowing with wheat cultivars of suitable maturity increases grain yield of spring wheat in a short season environment. *Australian Journal Experimental Agriculture* 32, 717–723.

Ketata, H. (1987). Actual and potential yields of cereal crops in moisture-limited environments. In: Srivastava, J. P., Porceddu, E., Acevedo, E., Varma, S., (Eds.) *Drought tolerance in winter cereals* John Wiley and Sons, Chichester, 55–62.

Kirkegaard, J.A., Simpfendorfer, S. Holland, J. Moore, K. J. Rebetzke, G.J. (2004). Effect of previous crops on crown rot and yield of durum and bread wheat in northern NSW. *Australian Journal of Agricultural Research* 55, 321–334.

Lopez-Bellido L., Fuentes, M., Castillo, J. E., Lopez-Garrido, F. J. (1998). Effects of tillage, crop rotation and nitrogen fertilization on wheat-grain quality grown under rainfed Mediterranean conditions. *Field Crops Research* 57, 265–276.

Mason, M.G. (1975). Nitrogenous fertilizers for cereal production. *Journal Agriculture W. A.* 16, 3–10.

Matar, A., Torrent, J., Ryan, J. (1992). Soil and fertilizer phosphorus and crop responses in the Dryland Mediterranean zone. In: Stewart, B. A., (Ed.) *Advances in soil science* 18. Springer Verlag, New York, NY, USA, 81–146.

Ohlsen, R.A., Kurtz, L.T. (1982). Crop nitrogen requirements, utilization, and fertilization. In: Stephenson, F. J., (Ed.) Nitrogen in agricultural soils. *Agronomy Monograph* No. 22 ASA, CSSA, SSSA. Madison, Wisconsin, USA, 567–604.

S-PLUS (2000). *S-PLUS 2000 Professional. Release 3.* (MathSoft Inc.: Seattle, WA, USA)

Shackley, B.J. (2000). Crop management. In: W. K. Anderson and J. R. Garlinge (Eds) *The Wheat Book – principles and practice,* 131–163 (Agriculture Western Australia Bulletin 4443).

Sharma, D.L., D'Antuono, M.F., Anderson, W.K., Shackley, B.J., Zaicou-Kunesch, C.M., Amjad, M. (2008). Variability of optimum sowing time for wheat yield in Western Australia. *Crop and Pasture Science* 59, 958–970.

Srivastava, J.P., Kamel, A.H., Anderson, W.K. (1982). Trends and perspectives in durum wheat production in the Mediterranean basin. In: Bianchi, A., (Ed.) *Proceedings of the International Symposium on Durum Wheat, Foggia.* 3-4 May, 1982, 109–127.

Zubaidi, A., McDonald, G.K., Hollamby, G.J. (1999). Shoot growth, root growth and grain yield of bread and durum wheat in South Australia. *Australian Journal of Experimental Agriculture* 39, 709–720.