A wheat ideotype for the high rainfall zone of south-west Victoria

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Abstract

With increasing interest in cropping in areas receiving >500mm rainfall, a wheat ideotype (ideal crop type) was developed to better understand the potential of these regions, identify desirable traits for plant breeding and provide guidelines for management. Long-term climate (radiation, temperature, rainfall) and soils data were used to quantify resource availability, define the growing season and assess the risks of crop damage from temperature and moisture stresses. These data, together with conventional wheat physiology, were used to determine optimum phenology, potential dry matter (DM) growth and partitioning into grain. Potential wheat yield for average conditions at Hamilton in south-west Victoria was calculated to be about 10.7 t/ha at 12% moisture or 9.9 t/ha accounting for abiotic stress at anthesis, more than 3 times greater than current average yields. Traits associated with these higher yields were identified.

Key Words

Phenology, climatic risks, frost, heat, drought

Introduction

The high rainfall zone (HRZ) can be defined as areas in southern Australia where average rainfall exceeds 500 mm at a shire level (Tim Reeves *pers. comm*.). This definition comprises 366 shires in New South Wales, Victoria, South Australia, Western Australia and Tasmania. In the past, water-logging has been a major constraint to cropping in the HRZ. Since the introduction of drainage technologies and the increased occurrence of drier seasons, cropping is now profitable for growers in this region. Grain production and area of cropping have more than doubled over the past 20 years to 3.4 M ha in 2005 (Neil Clarke and Associates *pers comm*.), with increases predicted to continue as climate change makes cropping more marginal in the traditional wheat belt. A further 11.5 M hectares are sown to pasture (Australian Bureau of Statistics survey and census data) much of which would be suitable for broad-acre cropping.

Average wheat yields in the zone are approximately 2.6 t/ha, well below calculated potential (Gardner *et?al.* 1983). Most cultivars grown in the region have been introduced from other high rainfall regions of the world or from the drier wheat belt of Australia and are not well adapted to the HRZ. To close the gap between actual and potential yields in the HRZ, crop ideotypes for sub-regions in southern Australia are being developed to identify traits for breeding, set priorities for research and provide guidelines for management. Ideotype development for south-west Victoria is discussed in this paper.

Design assumptions underlying this work are that wheat germplasm shows a range of responses to vernalisation, photoperiod and temperature (Snape *et?al.* 2001), such that breeders have available wide heritable variability in phenology, and also in dry matter (DM) partitioning. Conversely, because variability in wheat germplasm is small, it is assumed that conversion coefficients for light, water and nutrients to DM are at the norms of current commercial varieties.

Methods

Location

The environment considered was Hamilton in south-west Victoria (37?49'S, 142?04'E). The average annual rainfall for the location is 692 mm with the average growing season rainfall (April to November) 494 mm. Soils in the region are typically sodosols, chromosols or vertisols (Isbell 1996). It is assumed that artificial drainage prevents any water-logging.

The design process

A two step design process was employed using patch point historical daily meteorological data from 1950 to 2003 (from the SILO database, www.bom.gov.au/silo). The first step was to set crop development by defining and subdividing the growing season: the start of stem extension was set to allow just sufficient vegetative development for optimum tillering, and anthesis date was set to minimise abiotic risk (combined risk from frost, drought and heat) during late ear formation and anthesis. The second design step determined the delay in anthesis that would maximize DM partitioning to the grain, taking into account (a) increasing requirements for DM to support the grain (leaves, chaff and stem for photosynthetic and physical support) and (b) increasing grain losses due to abiotic damage at anthesis. Grain losses were assumed to be 50% when each abiotic stress occurred.

Defining the growing season

The growing season was defined as the period between the autumn break and terminal drought as they occurred in a majority of seasons. Plant available water (PAW) was estimated from rainfall and evaporation data using a simple bucket model with a capacity of 120 mm plant available water. The autumn break was deemed to have occurred if, after March 1, PAW was >0 mm through a 10 day period. The date of the autumn break was taken as the date on which this had occurred in 80% of years, the result being validated by experiences of farmers and scientists. Crop growth continued until simulated PAW was <0 mm; it resumed with subsequent rains until physiological maturity (GS87) which occurred 700?Cd after anthesis (GS61).

Phenological development

Plant development was considered in three phases; 'foundation' (germination to stem extension, GS31), 'construction' (GS31 to GS61) and 'production' (GS61 to GS87; Sylvester-Bradley *et?al.* 2008). Unlike other high rainfall regions in the UK and NZ, temperatures less than -5?C do not occur during winter, so extending the foundation phase to avoid such risks is of no benefit in south-west Victoria. DM accumulated in the foundation phase was not considered to contribute to final yield so the duration of this phase was set to a minimum for tillering: a period of 650?C days (allowing for 150 ?Cd for germination and emergence; Jame and Cutforth 2004) was deemed sufficient to provide 1,600 shoots m^{-2} (200 plants m^{-2} with 8 shoots each after 4.5 phyllochrons of 110?Cd; Baker *et al* 1986). This was considered ample for production of 500 fertile ears m^{-2}.

The final date of anthesis was set as the latest of the dates when (i) total risk of abiotic damage to grain set was minimised, (ii) sufficient DM had been formed to support the grain and (iii) maximum accumulation of WSC had occurred without compromising yield due to abiotic stresses. The minimum risk date was determined from the occurrences of frost, heat and drought sufficient to damage grain set. Frost damage occurred with minimum air temperatures <0?C on any day during a 10 day period around anthesis. Similarly, heat damage occurred with maximum temperatures >30?C for any day during 10 days around anthesis, and drought damage affected grain set when PAW was <1 mm on any of the 10 days from 20 days before anthesis (around booting).

Radiation capture, DM accumulation and partitioning

Green area index (GAI) was expanded from nil at emergence to 1.2 at GS31, to 6.2 at 15 days before GS61, and then is maintained at 6.2 until GS87. DM accumulation was calculated from daily intercepted solar radiation using the de Lambert-Beer law assuming an extinction co-efficient (K) of 0.55 and conversion to DM at 1.2g/MJ and water use was adjusted according to canopy cover.

DM was partitioned to leaf laminae at 50 g/m green area (Stapper and Fischer 1990) with an equivalent weight for leaf sheaths. The stem DM required to resist lodging was estimated according to the method of Berry *et al.* (2007), assuming 500 surviving shoots m^{-2}, a crop height of 700 mm and a leverage developed in the greatest wind speed experienced in 90% of years (17 m/s). Chaff requirements were 9?mg DM/grain (Beed *et al* 2007) and individual grains were 45?mg DM. Final grain yield was calculated as the sum of the DM accumulated during the production phase plus any WSC accumulated during the construction phase (i.e. that not required for leaf, sheath, structural stem or chaff).

Results

At Hamilton, the autumn break occurred by April 18 in 80% of years, and stem extension started on 18 June. Anthesis on October 5 gave minimum risks for grain set; frost (4%), heat (2%) and drought (2%) (Figure 1).

In an average season at Hamilton, the grain DM formed in 700?C days after October 5 (unaffected by abiotic stress) was calculated to be 9.7 t/ha (11.0 t/ha at 12% moisture). Approximately 13.1 t/ha DM would be required to provide photosynthetic and physical support for this grain, 1.6 t/ha DM more than would have been formed during crop construction. The minimum postponement of anthesis necessary for formation of sufficient support DM for subsequent grain growth was 6 days to 11 October. On this date grain DM was calculated to be 8.9 t/ha with no WSC contributing to yield. A further delay in anthesis of 160?Cd (to 26 October) allowed formation of 2.5 t/ha WSC, 0.4 t/ha of associated support DM, and increased grain DM to 9.4 t/ha (10.7 t/ha at 12% moisture) with abiotic risks only increasing to 4% frost, 6% heat and 6% drought (combined risk of 15%). Mean yield loss per year due to these risks was calculated to be 0.79 t/ha giving an average expected yield for the location of 9.92 t/ha (at 12% moisture). Dates and durations for the different stages of crop development together with DM accumulation and partitioning are shown in Table 1. Harvest index was relatively low at 0.37 compared to other high rainfall regions of the world, largely because 6.7 t/ha structural stem DM was required to ensure lodging resistance. Optimum grain DM production and minimum risks were achieved with a shorter foundation phase and longer construction phase than occurs in current commercial cultivars (Jamieson *et?al.* 2007); thermal duration of the construction phase was nearly double the duration of the foundation phase.

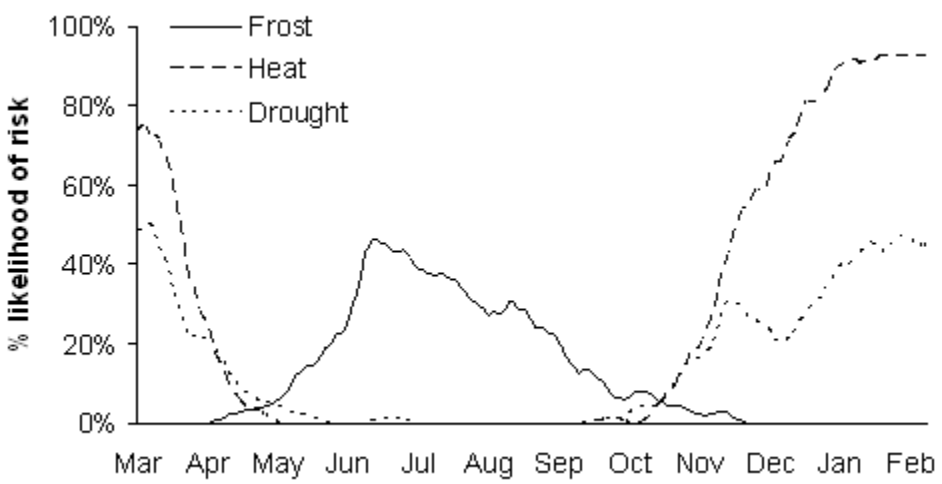

Figure 1. Percentage likelihood of the risk of frost (<0?C in any one day over a 10 day period), heat (>30?C in any one day over a 10 day period) and drought (PAW<1 mm) at Hamilton, Victoria. Risk calculations are based on 54 years of historical daily meteorological data (1954-2003).

Table 1. Dates, durations, DM accumulation and partitioning for the developmental stages for the wheat ideotype designed for Hamilton Victoria.

	Foundation	Construction	Production	Total
Optimum Dates	18 Apr – 17 Jun	18 Jun – 26 Oct	27 Oct – 13 Dec	
Duration (deg C days)	650	1,262	700	2,612
Duration (days)	61	131	48	240
DM accumulation (t/ha)	1.5	15.5	6.9	23.9
DM partitioning (t/ha)				
Leaf & Sheath		4.4		
Structural stem		6.7		
Chaff		1.9		
WSC		2.5		
Grain (no abiotic stress)				9.4 (10.7)[†]
[‡]Grain (with abiotic stress)				8.7 (9.9)[†]

[‡] Grain yield loss due to abiotic stresses at anthesis (frost, heat and drought) is estimated at 50% in 15% of years.
[†] Values in parentheses are grain yields at 12 % moisture

Discussion

Crop phenology is crucial in determining crop adaptation, not only for the avoidance of risks during critical stages of development, but also for the allocation of carbon to different plant organs (Richards 1992). The HRZ environment differs from other grain producing regions of Australia, not only in rainfall but also in having a longer period before terminal drought, and it also differs from other more temperate HR regions (New Zealand and the UK) in that it has winter-dominant rainfall and lacks severe winter frosts. This initial study appears to show that the HRZ requires a relatively rapid passage through vegetative development, and a more protracted reproductive phase in order to capture and allocate resources in a way that might maximise grain yields. The growing season in the traditional wheat belt of Australia is relatively short and necessitates rapid progression through all developmental stages; here crops sustain few tillers, have small canopies and a low yield potential. By contrast, the longer season in the HRZ provides time to establish more tillers, to develop a full canopy capable of intercepting most incoming solar radiation, enabling the production of large amounts of DM. The onset of stem extension is often delayed in current varieties by genes for vernalisation or photoperiod sensitivity, intended to avoid flowering during periods of high frost risk. This long foundation phase can result in excessive tiller and DM production in the HRZ which does not contribute to grain yield and can reduce PAW during grain fill.

By comparison, a longer foundation phase in other HRZ regions in the world, e.g. NZ and UK, is necessary to avoid frosts (<-5?C) around the terminal spikelet stage. Conditions from anthesis to physiological maturity in these regions are more favourable and so delaying anthesis through a longer foundation phase does not have the same negative impact on grain production. Although studies have shown some capacity to manipulate phase durations independently (Gonzalez *et al.* 2005; Miralles *et al.* 2000), the extent to which the construction phase can be lengthened relative to the foundation phase remains uncertain.

Our calculations indicate that relatively large amounts of DM are required to provide physical support for the crop and photosynthetic activity. Suboptimal development in current cultivars is the likely reason for inefficient partitioning and is reflected in lower harvest indices (Riffkin *et al.* 2003, Zhang and Evans 2004). Further gains in yield could also be made by reducing the requirement for non-grain DM. Such strategies may include increasing the specific leaf area to reduce the DM required for light capture, reducing weights of sheaths and chaff, and most importantly, improving the strength of structural stem material so that less DM is required to prevent lodging.

Conclusion

Wheat yields in the Hamilton area of the HRZ have the potential to increase more than 3 fold. For this to occur, wheat varieties need to be better tailored to the environment. The ideotype defined here was designed to exploit conditions unique to southern Victoria. It assumes that the construction phase of wheat's development can be long in relation to the foundation phase but, with this exception, all assumptions in the development of the ideotype were based on well established physiological principles. Germplasm must be investigated to determine whether photoperiod and temperature responses can be combined to create a phenology better suited to the HRZ. The design approach used in this study might also be applicable to other regions or to adaptation of crops to environments that are being significantly modified by climate change.

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