Field Crops Research 209 (2017) 108–119

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Water and temperature stress define the optimal flowering period for wheat in south-eastern Australia

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ARTICLE INFO

Keywords:
APSIM
Drought
Frost
Heat
Optimal flowering period
Simulated yield

ABSTRACT

Across the Australian wheat belt, the time at which wheat flowers is a critical determinant of yield. In all environments an optimal flowering period (OFP) exists which is defined by decreasing frost risk, and increasing water and heat stress. Despite their critical importance, OFPs have not been comprehensively defined across south eastern Australia's (SEA) cropping zone using yield estimates incorporating temperature, radiation and water-stress. In this study, the widely validated cropping systems model APSIM was used to simulate wheat yield and flowering date, with reductions in yield applied for frost and heat damage based on air temperatures during sensitive periods. Simulated crops were sown at weekly intervals from April 1 to July 15 of each year. The relationship between flowering date and grain yield was established for 28 locations using 51-years (1963–2013) of climate records. We defined OFPs as the flowering period which was associated with a mean yield of ≥ 95% of maximum yield from the combination of 51 seasons and 16 sowing dates. OFPs for wheat in SEA varied with site and season and the relative importance of seasonal water supply and demand and extremes of temperature in defining the window also varied. Quantifying OFPs will be a vital first step to identify suitable genotype x sowing date combinations to maximise yield in different locations, particularly given recent and predicted regional climate shifts including the decline in autumn rainfall.

1. Introduction

In all environments there exists a period during which wheat (*Triticum aestivum* L.) must flower in order for grain yield to be maximised, herein referred to as the optimal flowering period (OFP). Flowering during the optimal period is critical to grain yield as grain number is determined just prior to and at flowering (Fischer, 1985) and grain yield is most sensitive to stresses during this period, including drought (del Moral et al., 2003; Giunta et al., 1993) and extreme high (Ferris et al., 1998; Shpiler and Blum, 1990; Tashiro and Wardlaw, 1990) and low temperatures (Boer et al., 1993; Fuller et al., 2007). In temperate climates such as northern Europe, flowering date has a broad optimum. However, in environments with a distinct dry season, flowering outside narrow OFPs can result in drastic yield reductions (Bodner et al., 2015). The wheat belt of south eastern Australia (SEA) is one such environment, which has a predominantly Mediterranean climate with a cool wet season during which rain-fed wheat and other grain crops are grown, and a hot, dry season where land is left fallow. Whilst rainfall in the north-east of the region is equi-seasonal in distribution, cropping is still confined to the cool season by high summer temperatures and insufficient precipitation to sustain summer crops (Chenu et al., 2013; Potgieter et al., 2002). In the 2012/2013 season the south eastern states of Australia (New South Wales, Victoria and South Australia) produced over 14 Mt of wheat, 63% of Australia's total wheat production (Commonwealth of Australia, 2013). The majority of annual production is exported, making the region important for global food security.

In SEA, spring wheat cultivars are established following rainfall in April-May (austral autumn) and grow during winter to mature at the end of spring. Significant yield progress has been made by breeders selecting cultivars with development patterns such that once established in autumn they will flower during the optimal period (Richards, 1991; Richards et al., 2014). However, since 1996, rains that could once be relied upon by farmers to establish crops in April-May have declined significantly (Cai et al., 2012; Pook et al., 2009). This decline was particularly severe during the millennium drought (Verdon-Kidd et al., 2014) at which time wheat crops established and flowered too late and yield was reduced by terminal drought and heat (Commonwealth of Australia, 2013). Reduced autumn rainfall has been attributed to anthropogenic climate change (Cai et al., 2012; Murphy and Timbal,

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http://dx.doi.org/10.1016/j.fcr.2017.04.012
Received 11 September 2016; Received in revised form 11 April 2017; Accepted 20 April 2017
Available online 08 May 2017
0378-4290/

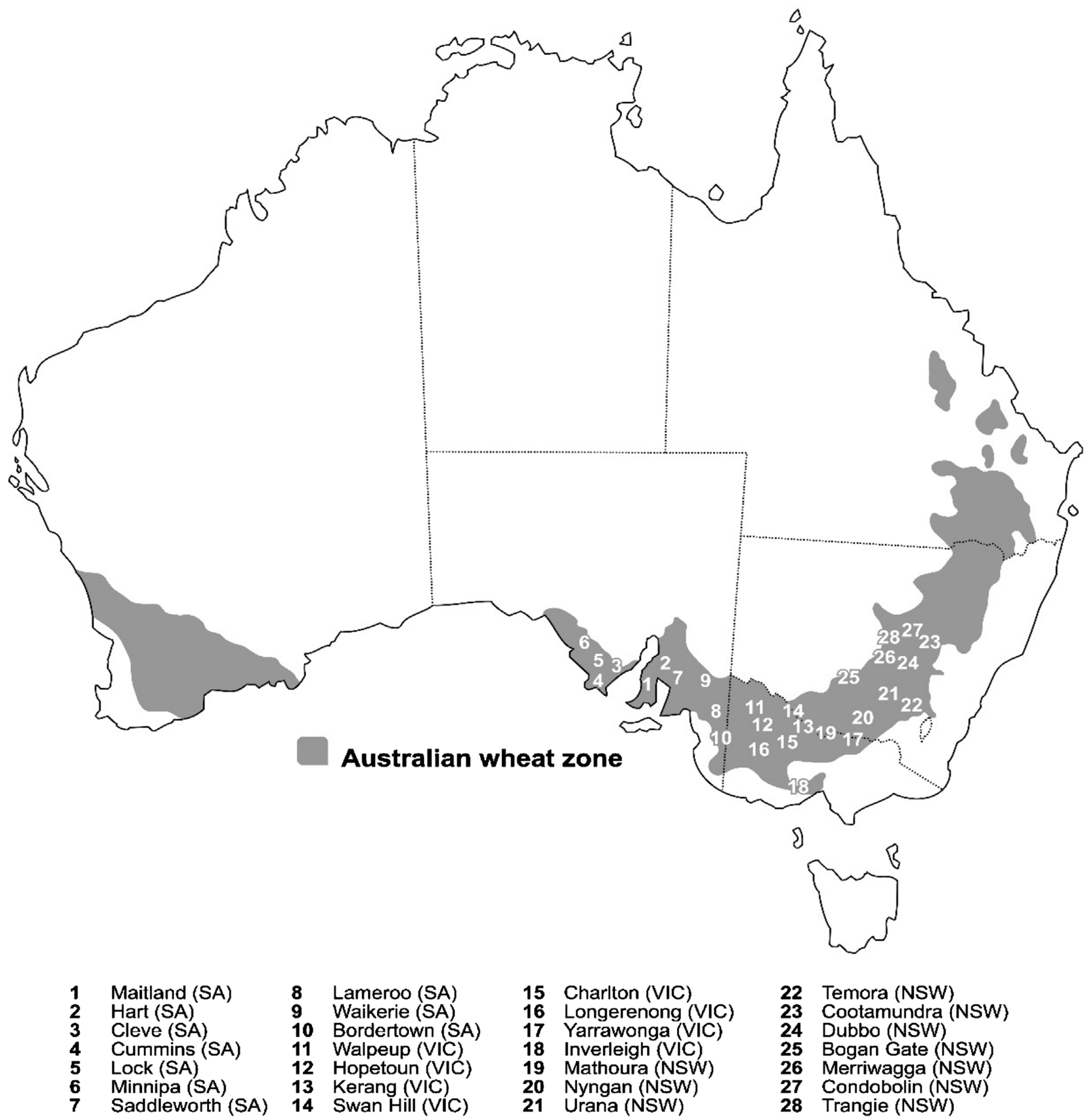

Fig. 1. Dryland cereal-cropping areas in Australia (shaded) and the locations used for this study.

2008) and is likely to persist. New combinations of management and genetics will be required to stabilise flowering date in order to overcome the observed yield decline (Kirkegaard and Hunt, 2010), and maintain the viability of SEA wheat farms and their contribution to global food security. A clear first step in this process is to identify the current OFP for environments in the SEA wheat belt.

A combination of environmental factors (precipitation, soil type, temperature) influence the opening, closing and duration of the OFP. Previous authors have stated that OFPs in SEA occur after the last spring frost and before the onset of heat and water stress (Anderson and Smith, 1990; Richards, 1991; Zheng et al., 2012). Untimely spring frosts (September to October) are common in the Australian wheat belt (Boer et al., 1993; Fuller et al., 2007; Zheng et al., 2012). A yield penalty of 10% as a direct result of frost is common (Fuller et al., 2007), and more catastrophic events are frequent (Crimp et al., 2015). Zheng et al. (2015) analysed the frost and heat patterns of the Australian wheat belt, and found that the only regions that could be classified as almost "frost free" were some areas of the coastline in South Australia and north-east of central Queensland, while frosts occurred in other regions in 80% of years. Wheat is most sensitive to frost during reproductive growth stages. When wheat ears are exposed to freezing temperature after heading, frost damage will reduce the number of grain and sometimes cause death of entire ears (Fuller et al., 2007).

High temperatures during sensitive reproductive growth stages can also result in a yield penalty (Ferris et al., 1998). Gomez-Macpherson and Richards (1995) found that grain yield declined by 1.3% per day that sowing was delayed after late-May due to high temperatures around the time of anthesis and grain-fill. High temperature events ($>$ 35 °C) during the period between head emergence to 10 days after anthesis can significantly reduce grain number and quality (Tashiro and Wardlaw, 1990). Similarly, heat shock during the grain filling period can also cause grain abortion and degrade grain quality (Randall and Moss, 1990; Stone and Nicolas, 1995).

Perhaps the most important determinant of the OFP is the pattern of water supply and demand experienced in a given environment (Bodner et al., 2015). Whilst drought patterns in SEA are well described (Chenu et al., 2013), the effect of seasonal water supply and demand in determining OFPs has been overlooked in previous analyses of OFPs e.g. Zheng et al. (2012), Zheng et al. (2013), Bell et al. (2015). In all of these studies OFPs were defined only by temperature extremes, which