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A cultivar phenology classification scheme for wheat and barley

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ABSTRACT

The relative time to maturity of grain crops is an important consideration for producers, yet there are no universally accepted classification schemes for cultivar phenology to guide decisions on variety selection and time of sowing. A first edition of an industry guide for wheat variety maturity was recently developed for use across Australia, representing a significant step forward for the grains industry. The aim of this paper was to revise and extend this industry guide to make it more robust, agronomically functional and meaningful to industry. The Australian Cereal Phenology Classification (ACPC) presented herein was developed using an unprecedented phenological data set with a diverse array of genotypes, environments and management. Field experiments were carried out with 70 wheat and 30 barley cultivars at 15 sites across Australia between 2017 and 2020. Thermal time to anthesis data were used to rank cultivars according to their relative phenology and divide them into classes, and then boundary cultivars of both species were selected to separate these classes. The resulting classification scheme divides wheat and barley into phenology classes ranging from 'quick' to 'mid' to 'slow'. New cultivars to market can be assigned a phenology classification based on their thermal time to anthesis relative to the boundary cultivars. The ACPC will help growers, agronomists, breeders and researchers make informed decisions regarding cultivar comparison and selection while reducing misclassification and confusion across regions. The same methodology used to derive and validate the ACPC can be applied internationally to standardise descriptions of crop phenology.

1. Introduction

Grain production in Australia occurs in environments characterised by highly variable season length and resource availability. To maximise yield, growers select suitable combinations of cultivar lifecycle duration and time of sowing to ensure crops flower in the optimal period for their environment (Flohr et al., 2017). Wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) in Australia will typically be sown in autumn (April to June), flower in late winter or spring (August to October) and then ripen for harvest in late spring to early summer (October to February) (Flohr

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et al., 2018; Hunt et al., 2019), but the exact timing and duration of these phases is dependent on the interaction between genotype, environment and management. Cultivar phenology, or 'maturity' as it is colloquially known, is therefore an important consideration for a grower. A cultivar's 'maturity' is determined by classifying it as having a relatively short, medium or long lifecycle when sown at the optimal time in a region to which it is adapted. The term 'maturity' as it is used in this context for wheat and barley is a misnomer, since it describes the duration of a cultivar's life cycle from sowing to anthesis and does not refer to either physiological maturity (*i.e.* hard dough 87; Zadoks et al., 1974) or harvest maturity (*i.e.* seed hard 92; Zadoks et al., 1974).

In Australia, there are around 200 wheat and 75 barley cultivars available to growers (Grain Trade Australia, 2019; Grains Australia, 2022). The majority of these cultivars are quick-developing spring cereals bred to be sown in early- to late-May (Hunt et al., 2019), but genetic diversity in commercial cultivars affords growers sowing opportunities from March through to July. A nationally consistent classification scheme for cultivar phenology in Australia has not been described in the literature, although many examples exist in industry. Crop sowing guides produced annually by state agriculture departments and the Grains Research and Development Corporation (GRDC) vary in the terminology used to describe phenology, with a confusing blend of poorly-defined qualitative descriptors for relative season length (Brown, 2020; GRDC, 2020a, 2020b; Matthews et al., 2021; Shackley et al., 2020). Cultivars range from those with a relatively short lifecycle (described as 'early maturing', 'fast' or 'quick', or suitable for 'late season' planting) such as Axe wheat or Keel barley, to those in the middle of the range (described as 'mid' or 'medium', or suitable for 'main season' planting), to those with a relatively long lifecycle (described as 'late maturing' or 'slow', or suitable for 'early' or 'long' season' planting) such as Sunbri wheat or Navigator barley. The 'maturity' of a cultivar is usually published by breeders at the point of its release to the market, along with other attributes like disease resistance, end-use quality classification and yield performance. Protocols for the Australian National Variety Trials include anthesis date in the list of measurements, but the methodology is poorly defined and not applied to all trials (GRDC, 2022). The absence of a universally accepted industry standard for describing cereal cultivar phenology has frequently led to misclassification, confusion and difficulties with making informed decisions regarding cultivar comparison and selection.

Internationally, phenology classification schemes vary in terms of their methodology, robustness and acceptance by industry. In the UK, recommended lists of cereal varieties drawn from national variety trials are published annually (AHDB, 2022) with the maturity of cereal crops determined from their ripening date (*i.e.* seed hard 91; Zadoks et al., 1974) relative to a benchmark variety. However, the recommended lists are not in widespread use across the UK. The United States also lacks a national industry standard for cultivar phenology classification. Across different states and growing regions, wheat and barley are classified as having early, mid-season/medium or late maturity based on their relative lifecycle duration. Varieties might be compared based on time to heading or time to maturity, days earlier or later than a standard variety, or days relative to the trial average heading date. The world's largest wheat producer, China, also describes cultivars from its breeding programs in terms of early, medium and late maturity, but 'maturity' here refers to the number of days from sowing to harvest (He et al., 2001). Thus, there is strong need for the development of a standard methodology for cultivar phenology classification for use in Australia and internationally.

The Australian Crop Breeders' "Industry Guide for Wheat Variety Maturity Description" (ACB, 2020) was recently developed to provide a consistent method of describing wheat variety phenology. The ACB Guide describes nine spring and three winter phenology groupings, with commercial cultivars used to define the upper and lower boundaries of each group. These phenology classifications have been defined by a consortium of Australian wheat breeders using data from field experiments conducted across Australia. The classifications are based on relative heading dates of locally adapted cultivars planted at their target sowing dates. The states of Victoria (Brown, 2020), South Australia (GRDC, 2020b) and Queensland (GRDC, 2020a) incorporated the ACB Guide into their crop sowing guides from 2021 onwards, using the quick/mid/slow maturity descriptors for wheat and barley. Victoria and South Australia have also extended the ACB Guide to durum wheat (*Triticum durum*) and oats (*Avena sativa*) (Brown, 2020; GRDC, 2020b). New South Wales (Matthews et al., 2021) and Western Australia (Shackley et al., 2020) have not yet adopted the ACB Guide or its terminology.

In developing the first edition of an industry guide to wheat maturity description, Australian Crop Breeders took a significant positive step forward for the grains industry. We believe that further revisions can be made to the ACB Guide (ACB, 2020) to make it more robust, agronomically functional and meaningful to industry. In short, these revisions are:

- Change the title of the classification system from a description of 'maturity' to phenology;
- Use thermal time data to compare relative phenology and revise the classification groupings;
- Combine wheat and barley to standardise phenology descriptions between the two crops;
- Increase the number of winter classes to accommodate existing and future diversity; and
- Ensure classes correspond to agronomically meaningful changes in times of sowing.

In this paper we describe the Australian Cereal Phenology Classification (ACPC), a revised scheme based on the ACB Guide (ACB, 2020) that implements the revisions listed above. The ACPC is based on empirical data obtained from field experiments carried out across the western, southern and northern grain-growing regions of Australia. The aim of the ACPC is to provide a nationally consistent approach to describing the development of wheat and barley that is recognised as the industry standard and used across Australia by growers, agronomists, plant breeders and research and extension organisations.

2. Methods

2.1. *Field experiments*

Twenty-three field experiments were established across 15 locations between 2017 and 2020 (Fig. 1) as part of the GRDC 'National Phenology Initiative' (NPI) project and the GRDC–NSW DPI 'Optimising grain yield potential of winter cereals in the northern grains region' (BLG104) project. Sites were established in the western, southern and northern grain producing regions of Australia between latitudes 37°33′S and 23°32′S. The NPI field experiments were used to derive the classification groupings and then field experiments from both the NPI and the BLG104 experiments were used to define the boundary cultivars and validate the classification scheme.

2.1.1. *National Phenology Initiative (NPI)*

NPI field sites were located across the western and southern grain producing regions of Australia (Fig. 1). These were Wagga Wagga in NSW (2019–2020; 35°03′S, 147°21′E), Yan Yean in VIC (2019–2020; 37°33′S, 145°06′E), Callington in SA (2019; 35.08°S, 139.05°E), Urrbrae in SA (2020; 34°58'S 138°38′E), and Dale in WA (2019–2020; 32°13'S 116°46'E). At each field site an Australian Phenology Panel of 96 cultivars was sown at eight times of sowing. Sowing dates earlier than 10 April and later than 18 June were excluded as these dates were outside the commercially relevant optimal sowing window for the environments studied; defined as the week beginning 18 April to the week ending 11 June ± 7 days (Flohr et al., 2018). The panel comprised 48

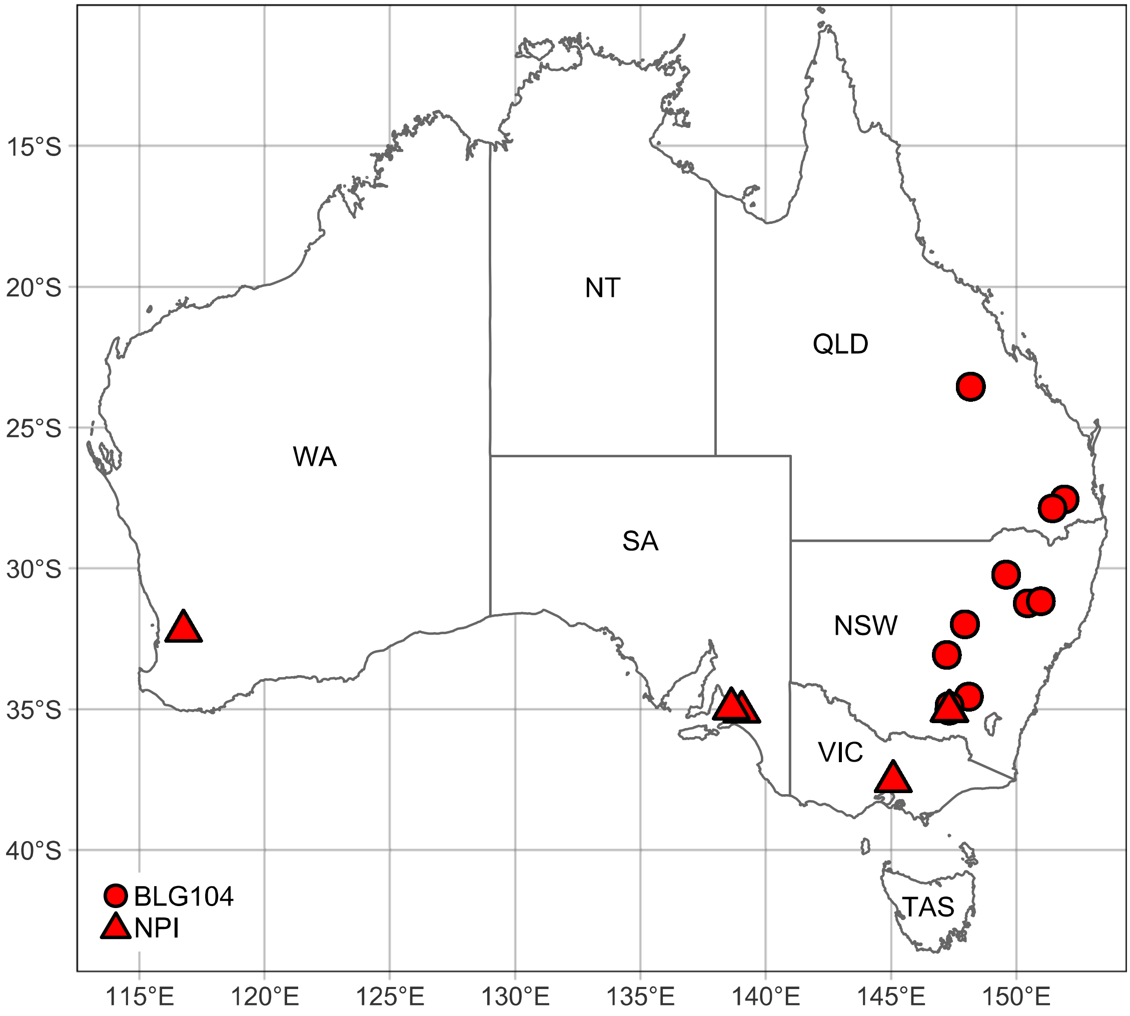

Fig. 1. Locations of field sites in NPI and BLG104 cultivar × time-of-sowing experiments.

commercial wheat cultivars and 30 commercial barley cultivars, plus an additional 16 near-isogenic lines of wheat and two experimental lines of barley that were excluded from the present study. The commercial cultivars included spring and winter types and were selected based on diversity of allele variation at the *Photoperiod1* (*PPD1*) and *Vernalisation1* (*VRN1*) loci, variation in phenology under field conditions and popularity among Australian growers. For a full list of cultivars from the Australian Phenology Panel included in the NPI field experiments refer to Table 1 and Table 2.

To ensure seed purity and a consistent maternal environment, all seed for the NPI field experiments was bulked up by Kalyx Australia at the GRDC National Variety Trial seed supply site near Young, NSW (34°21’S 148°18’E) in 2018. A sub-sample of all lines was received by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Canberra for genotyping to determine the alleles of major development genes regulating photoperiod and vernalisation responses (wheat: *PPD1* and *VRN1*; barley: *PPD1*, *VRN1* and *VRN2*) as reported by Bloomfield et al. (2018), Trevaskis et al. (2006) and Hemming et al. (2008).

Field experiments used a partially replicated (*p*-rep) design (Cullis et al., 2006) with the eight times of sowing blocked separately. Partial replication was imposed on 90 cultivars with the remaining six cultivars used as controls with a higher degree of replication. For each site-year there was a total of 960 plots. Plot size was three rows wide by 1.2–5.0 m long with a target plant density of 50 seeds per linear metre. Plots were sown in a north-south direction at row spacings of 0.250 m in NSW, 0.220 m in WA, 0.228 m in SA and 0.200 m in VIC. Pesticides and fertilizer were applied as needed throughout the season. Earlier times of sowing were irrigated after sowing to establish the crop, and then irrigated where necessary to avoid excessive moisture stress that would affect crop development.

2.1.2. *Optimising yield potential of winter cereals (BLG104)*

BLG104 field sites were located across the southern and northern grain producing regions of Australia (Fig. 1). These were Wagga Wagga (2018; 35°02’S, 147°19’3E), Marrar (2019; 34°52’S, 147°20’E), Wallendbeen (2018–2019; 34°32’S, 148°06’E), Condobolin (2018–2019; 33°03’S,147°14’E), Trangie (2018; 31°58’S, 147°57’E), Breeza (2019; 31°13’S, 150°28’E), Tamworth (2018; 31°09’S, 150°59’E), Narrabri (2019; 30°12’S, 149°35’E) and Edgeroi in NSW (2017; 30°09’S, 149°41’E), and Tosari (2019; 27°51’S, 151°26’E), Wellcamp (2017; 27°32’S, 151°56’E) and Emerald in QLD (2018–2019; 23°32’S 148°11’E). At each field site a selection of commercial spring and winter wheat cultivars with diverse phenology was sown at three or four times of sowing. As with the NPI field experiments, sowing dates earlier than 10 April were excluded as these were outside the commercially relevant sowing period. Eighteen wheat cultivars were common to both NPI and BLG104 field experiments: Beckom, Cutlass, EGA Eaglehawk, EGA Gregory, EGA Wedgetail, H45, Janz, LRPB Kittyhawk, LRPB Lancer, LRPB Spitfire, LRPB Trojan, Longsword, Mace, Manning, Mitch, Scepter, Sunlamb and Suntop. For a full list of cultivars included in the BLG104 field experiments, including indicative genotyping results, refer to Table 1.

A split-plot design was used in all experiments such that sowing time

Table 1
Commercial wheat cultivars used in the NPI and BLG104 cultivar × time-of-sowing field experiments. The year of release and pedigree of each cultivar is given along with its growth habit and alleles of major development genes governing responses to photoperiod and vernalisation.

Cultivar	Year of release[a]	Pedigree	Habit	Photoperiod or vernalisation gene allele[b]					Field experiment	
				Ppd-B1	*Ppd-D1*	*Vrn-A1*	*Vrn-B1*	*Vrn-D1*	NPI	BLG104
AGT Scythe	2005	CO4080–109/CO3749–009	Spring	a	d	v	a	v	✓	
Axe	2007	RAC-875//Excalibur/Kukri/3/RAC-875//Excalibur/Kukri	Spring	a	a	a	a	v	✓	
Beckom	2015	Annuello/Stylet//Young	Spring	b	a	a	v	v	✓	✓
Bolac	2006	Nesser/VI252//VI252	Spring	b	a	a	v	v	✓	
Braewood	2001	Cook*2/VPM 1//3*Cook	Spring	a	d	a	v	v	✓	
Calingiri	1997	Chino/Kulin//Reeves	Spring	d	a	v	a	v	✓	
Catapult	2019	Mace/Corack	Spring	b	a	v	a	v		✓
Condo	2014	Young/VR0525	Spring	NA	a	v	a	a		✓
Coolah	2015	Gregory/VQ2791//Gregory	Spring	b	a	v	v	a		✓
Corack	2011	Wyalkatchem/Silverstar	Spring	b	a	v	a	v		✓
Cutlass	2015	RAC1316/2*Fang	Spring	b	d	a	a	v	✓	✓
Derrimut	2006	VN0150/VN715	Spring	d	a	a	v	v	✓	
DS Pascal	2015	FAWWON10/CFR00–687–55	Spring	NA	c	v	a	a		✓
EGA Eaglehawk	2007	VPM/4*Sunbrook	Spring	b	b	b	v	a	✓	✓
EGA Gregory	2004	Pelsart/2*Batavia	Spring	b	a	v	v	a	✓	✓
EGA Hume	2001	Batavia//Batavia/Pelsart	Spring	b	a	a	v	a	✓	
EGA Wills	2006	4ASN29/4*Sunco//Batavia	Spring	a	a	v	v	a	✓	
Ellison	2002	Vicam-71/3*Suneca//SUN231A	Spring	mixed	mixed a/b/d	v	a	mixed a/v	✓	
Emu Rock	2011	96W657–37/Kukri	Spring	b	a	a	a	v	✓	
Forrest	2010	96WFHB5568/2*Kohika	Spring	not a/b/c	not a/d	a	a	v	✓	
Grenade CL Plus	2012	Gladius/4/RAC1268*2/3/Janz*2//Wilg4/11 A	Spring	a	d	a	a	v	✓	
H45	1998	WW15/QT7605	Spring	d	a	a	v	a	✓	✓
Janz	1989	3AG3/4*Condor//Cook	Spring	c	a	a	v	v	✓	✓
Kelalac	1988	TM56///Summit/AUS11577//WW15	Spring	not a/b	d	a	a	a	✓	
Kiora	2014	VQ4227/VP1081//VP1081	Spring	not a/c	a	a	v	v		✓
LRPB Beaufort	2008	H-93–179/H-95–322	Spring	b	a	b	v	v	✓	
LRPB Catalina	2006	VIL84/Silverstar	Spring	b	a	a	a	a	✓	
LRPB Crusader	2007	Sunbrook/H45	Spring	d	a	v	a	a	✓	
LRPB Dart	2012	Sunbrook/Janz//Kukri	Spring	b	a	a	a	v		✓
LRPB Gauntlet	2011	Kukri/Sunvale	Spring	a	a	a	v	v	✓	
LRPB Hellfire	2019	Gregory/Spitfire	Spring	b	a	v	a	a		✓
LRPB Lancer	2013	VIL84/Chara//Chara///Lang	Spring	a	a	a	v	v	✓	✓
LRPB Mustang	2017	Gregory/LPB1117	Spring	b	a	a	v	a		✓
LRPB Nighthawk	2019	LPB09–2209/ Gregory	Spring	a	c	w	v	a		✓
LRPB Reliant	2016	Crusader/Gregory	Spring	b	a	mixed	v	a		✓
LRPB Scout	2009	Sunstate/QH71–6//Yitpi	Spring	b	a	v	a	a	✓	
LRPB Spitfire	2010	Drysdale/Kukri	Spring	a	a	v	a	a	✓	✓
LRPB Trojan	2013	LPB 00LR000041/Sentinel3R	Spring	a	c	v	a	a	✓	✓
Mace	2008	Wyalkatchem/Stylet//Wyalkatchem	Spring	a	a	v	a	v	✓	✓
Magenta	2008	Carnamah/Tammin-18	Spring	b	a	v	a	v	✓	
Merinda	2007	Janz/SUN129A	Spring	b	a	a	v	v	✓	
Mitch	2014	QT-10422/Giles	Spring	not b	a	w	a	a	✓	✓
Ouyen	1993	Takari/TM56//Cocamba	Spring	d	a	a	a	v	✓	
Peake	2007	VN0150/VN715	Spring	d	a	a	v	v	✓	
RGT Zanzibar	2017	Frelon/61601//Capnor/Parador	Spring	b	a	w	v	a		✓
Scepter	2015	RAC1480/2*Mace	Spring	not c/d	a	v	a	v	✓	✓
Strzelecki	2000	Vicam S 71/Batavia	Spring	b	mixed a/d	mixed b/v	mixed a/v	mixed a/v	✓	
Sunbri	1987	Cook*2/VPM1//*Cook	Spring	a	c	a	v	v	✓	
Sunlamb	2014	2*Baconora/Sunlin	Spring	b	b	v	v	a	✓	✓
Sunmax	2016	CRW142.16/2*Sunzell	Spring	b	b	v	v	a		✓
Sunprime	2018	SUN445C/Gregory	Spring	d	a	a	v	a		✓
Sunstate	1992	Hartog//Cook*5/VPM 1	Spring	a	a	v	a	a	✓	
Suntime	2014	SUN457A/SUN405B	Spring	NA	b	b	a/v	a		✓
Suntop	2011	Sunco/2*Pastor//SUN129A*2/Sunvale	Spring	d	a	a	a	a	✓	✓
Sunvale	1996	Cook*2/VPM1/3*Cook	Spring	a	a	a	v	v		✓
Tenfour	2018	Rinconada/Fidel//Farak/Recital//Arturnik	Spring	b	a	a	a	a/v		✓
Vixen	2018	Mace/IGW3119	Spring	b	a	v	a	a		✓
Wyalkatchem	2001	Machete/W84.129–504	Spring	b	a	v	a	v	✓	
Yitpi	1999	C8MMC8HMM/Frame	Spring	b	d	v	a	v	✓	
Young	2005	VPM1/3*Beulah//Silverstar	Spring	a	a	a	a	a	✓	
DS Bennett	2019	Drysdale//K89.67/TC14.2	Winter	d	a	v	v	v		✓
EGA Wedgetail	2002	M3508/Dollarbird	Winter	b	a	v	v	v	✓	✓
Illabo	2018	Wedgetail/Beaufort//Wedgetail	Winter	b	a	v	v	v		✓
Longsword	2017	Mace/Sun435G	Winter	b	a	v	v	v	✓	✓

(*continued on next page*)

Table 1 (*continued*)

Cultivar	Year of release[a]	Pedigree	Habit	Photoperiod or vernalisation gene allele[b]					Field experiment	
				Ppd-B1	*Ppd-D1*	*Vrn-A1*	*Vrn-B1*	*Vrn-D1*	NPI	BLG104
LRPB Kittyhawk	2016	WW11327/QT7208//WW3194	Winter	a	d	v	v	v	✓	✓
Manning	2013	H205.1/LH50M16/Savannah	Winter	b	a	w	v	v	✓	✓
RGT Accroc	2017	–	Winter	b	a	w	v	v		✓
Rosella	1985	Farro-Lungo/Heron//2*Condor/3/Quarrion (sib)	Winter	a	d	v	v	v	✓	
SQP Revenue	2009	Madsen/Brennan	Winter	b	a	v	v	v	✓	
Whistler	1998	Osprey/Hartog//Osprey*2/Darf	Winter	d	a	v	v	v	✓	

AGT, Australian Grain Technologies; CL, Clearfield; DS, Dow Seeds; EGA, Enterprise Grains Australia; LRPB, LongReach Plant Breeders; RGT, Rouergue Auvergne Gévaudan Tarnais (RAGT) Semences; SQP, Southern Quality Produce.

[a] Year of release in Australia.

[b] *PHOTOPERIOD1* (*Ppd-B1*: a, c, d, insensitive; b, sensitive; *Ppd-D1*: a and d, insensitive; b and c, sensitive) and *VERNALISATION1* (*Vrn-A1*: a, b, insensitive; v, w, sensitive; *Vrn-B1* and *-D1*: a, insensitive; v, sensitive) genes (Bloomfield et al., 2018; Cane et al., 2013).

Table 2

Commercial barley cultivars used in the NPI cultivar × time-of-sowing field experiments. The year of release and pedigree of each cultivar is given along with its growth habit and alleles of major development genes governing responses to photoperiod and vernalisation.

Cultivar	Year of release[a]	Pedigree	Habit	Photoperiod or vernalisation gene allele[b]		
				Ppd-H1	*Vrn-H1*	*Vrn-H2*
Banks	2017	WABAR2312/WABAR2332	Spring	Insensitive	Vrn1–2	DEL
Bass	2009	WABAR2023/Alexis	Spring	Insensitive	Vrn1–4	DEL
Baudin	2001	Stirling/Franklin	Spring	Sensitive	Vrn1–3/Vrn1–4	DEL
Biere	2016	2850–2–1/Quench	Spring	Insensitive	Vrn1-WT/Vrn1–2	DEL
Capstan	2004	Waveney/WI2875//Chariot/Chebec	Spring	Sensitive	Vrn1–1/Vrn1–4	DEL
Commander	2008	Keel/Sloop//Galaxy	Spring	Sensitive	Vrn1–4	DEL
Compass	2013	County/Commander//Commander	Spring	Insensitive	Vrn1–4	DEL
Dash	1995	Chad/Joline//Cask	Spring	Insensitive	Vrn1–3	WT
Fathom	2011	JE013D-020/WI3806–1	Spring	Sensitive	Vrn1–4	WT
Fleet Australia	2006	Mundah/Keel//Barque	Spring	Sensitive	Vrn1–1	WT
Flinders	2012	Baudin/Cooper	Spring	Insensitive	Vrn1–3/Vrn1–4	DEL
Franklin	1989	Shannon/Triumph	Spring	Insensitive	Vrn1–3	DEL
Gairdner	1997	Onslow/Tas 83–587	Spring	Insensitive	Vrn1–3/Vrn1–4	DEL
Granger	2013	Braemar/Adonis	Spring	Insensitive	Vrn1–2	WT
Grout	2005	Cameo/Arupo 31–04	Spring	Sensitive	Vrn1–4	DEL
Keel	1999	CPI18197/Clipper//WI2645	Spring	Sensitive	Vrn1–4	DEL
LG Alestar	2015	Henley/NSL02–4136A	Spring	Insensitive	Vrn1–2/Vrn1–3	DEL
Lockyer	2007	Tantangara/VB9104	Spring	Sensitive	Vrn1–4	WT/DEL
Navigator	2011	WI3788/WI3847	Spring	Sensitive	Vrn1–1	DEL
Oxford (Oxbridge)	2009	Tavern/Chime	Spring	Insensitive	Vrn1–1	DEL
RGT Planet	2016	Tamtan/Concerto	Spring	Insensitive	Vrn1–2	DEL
Rosalind	2015	Lockyer/Dash	Spring	Sensitive/Insensitive	Vrn1–3	WT
Schooner	1983	Proctor/Prior A//Proctor/CI3576	Spring	Sensitive	Vrn1–1	DEL
Scope CL	2009	Franklin/VB9104//VB9104	Spring	Sensitive	Vrn1–4	WT/DEL
Shepherd	2008	Baronesse/Cheri	Spring	Insensitive	Vrn1–2	DEL
Spartacus CL	2015	Scope/4*Hindmarsh//HMVB0325–106	Spring	Sensitive	Vrn1–4	DEL
Stirling	1981	Dampier/Prior/Ymer/3/Piroline	Spring	Sensitive	Vrn1–4	DEL
Westminster	2009	NSL 97–5547/Barke	Spring	Insensitive	Vrn1–3	DEL
Cassiopee	2012	Nadine/Mascara	Winter	Insensitive	Vrn1-WT	WT
Urambie	2005	Yagan/Ulandra//Ulandra	Winter	Insensitive	Vrn1-WT	WT

CL, Clearfield; LG, Limagrain Europe; RGT, Rouergue Auvergne Gévaudan Tarnais (RAGT) Semences.

[a] Year of release in Australia.

[b] *PHOTOPERIOD1 (Ppd-H1*: insensitive; sensitive), *VERNALISATION* (*Vrn-H1*: 1–4 insensitive; WT, sensitive; *Vrn-H2*: DEL, insensitive; WT, sensitive) genes (Fernández-Calleja et al., 2021; Trevaskis et al., 2006).

was randomly allocated to main-plots. Cultivars were then randomly allocated to individual plots within a main-plot, with three replicate blocks. If the seedbed was too dry to allow emergence at targeted sowing time, plots were irrigated to germinate seed and allow emergence. Target plant densities, fertiliser and all other crop management were implemented according to local district practice.

2.2. Data collection and analysis

Data collection was carried out using the FieldPrime software developed by CSIRO (https://compbio-pi.csiro.au/info/). Experimental plots were excluded if crops failed to establish or if development was affected by waterlogging, drought, frost or pests.

Anthesis was measured as per Celestina et al., (under review), whereby a subset of plants in each experimental plot was tagged after flag leaf emergence and monitored every 3–4 days on an ongoing basis to record the number of fertile culms that had reached anthesis. Observations of development were carried out twice a week until all fertile culms in the tagged subset (*i.e.* all main stems and tillers) had reached this development stage. According to this development scale, a spike is recorded as having reached anthesis when at least one floret in a central spikelet had flowered, when measuring anthesis directly; or, when the spike was fully emerged with the peduncle visible above the flag leaf ligule (for wheat) or when the awns were first visible above the flag leaf ligule (for barley), when measuring heading as a proxy for anthesis. The anthesis date for each experimental plot was then determined retrospectively by linear interpolation as the date on which 50 % of the total population of viable culms had reached anthesis. Anthesis date therefore denotes the median anthesis phase timing for a population of culms in an experimental plot.

In the BLG104 field experiments, anthesis was directly measured in all 3662 plots. In the NPI field experiments, observations of heading were used as proxy for anthesis in all 3860 plots and anthesis was also directly measured on a subset of cultivars (Axe, LRPB Beaufort, Beckom, Cutlass, EGA Gregory, LRPB Kittyhawk, LRPB Lancer, Mace, Manning, Scepter, LRPB Trojan, Suntop, Commander, Compass, Fathom, RGT Planet, Spartacus CL, Urambie) in 325 plots to validate the use of heading observations as a proxy for anthesis observations. Type II linear regression analysis using the standard major axis method (Legendre, 2018) confirmed a very strong positive linear correlation ($R^2 = 0.95$) between the thermal time from sowing to heading and thermal time from sowing to anthesis for wheat and barley (Supplementary Figure 1), with the anthesis date predicted to occur 38 °Cd after heading in wheat and 4.1 °Cd after heading in barley in a population of culms.

Air temperature data were collected at every site using temperature sensors shielded by Stevenson screens at 1.2 m above ground level. Thermal time from sowing date to anthesis date (TT_{AN}, °Cd) was calculated as the cumulative average daily air temperature using R package 'WeaAna'(Zheng, 2021). The base, optimum and maximum temperature were assumed to be 0, 26, and 37 °C, respectively (Bell et al., 2016; Porter and Gawith, 1999; Zheng et al., 2013), and the three-hourly method was used where possible whereby 8 × 3-hour estimates were averaged to obtain the daily thermal time (Gilmore and Rogers, 1958). The TT_{AN} (°Cd) was calculated for all 7522 plots, and then median values for TT_{AN} (°C d) for each cultivar at each site-year were determined.

Type II linear regression analysis using the standard major axis method (Legendre, 2018) was used to assess the strength of the correlation between TT_{AN} for cultivars common to both NPI and BLG104 field experiments. Linear regression was used to explore relationships between TT_{AN} and geographic and climatic variables.

2.3. Derivation of classification groupings and selection of boundary cultivars

The class groupings for the Australian Cereal Phenology Classification (ACPC) scheme were derived from wheat and barley TT_{AN} values obtained from the NPI field experiments. Cultivars of both species were divided into either winter or spring habit based on the presence of vernalisation sensitive winter alleles at the *VRN1* and *VRN2* loci (Bloomfield et al., 2018; Trevaskis et al., 2006). Cultivars within each habit were then sorted from quickest (shorter TT_{AN}) to slowest (longer TT_{AN}) development based on their median TT_{AN}. Spring cultivars were divided into nine equal groupings: Very Quick (VQ), Very Quick-Quick (VQ-Q), Quick (Q), Quick-Mid (Q-M), Mid (M), Mid-Slow (M-S), Slow (S), Slow-Very Slow (S-VS), Very Slow (VS). The quickest spring class (VQ) was centred around the median TT_{AN} of the quickest spring cultivar (Biere barley, 1048 °Cd) and the slowest class (VS) was centred around the median of the slowest cultivar (Sunlamb wheat, 1654 °Cd), with the seven remaining classes equally spaced in 76 °Cd intervals between these limits. Winter cultivars were divided into five equal groupings: VQ, Q, M, S and VS. The quickest class was centred around the median of the quickest winter cultivar (Urambie barley, 1269 °Cd) and the slowest class was centred around the median of the slowest winter (Manning wheat, 1865 °Cd). The remaining winter classes were equally spaced in 149 °Cd intervals between these limits.

Once the class groupings were derived for winter and spring cultivars, appropriate boundary cultivars were selected from both the NPI and BLG104 field experiments. Separately for each dataset, all cultivars were sorted from quickest to slowest development based on their median TT_{AN}. The relative ranking of cultivars in each dataset and the TT_{AN} interval between each class was used to select appropriate contemporary cultivars that corresponded to the boundary between neighbouring classes. Irrespective of the actual value of median TT_{AN}, the selected boundary cultivars were consistently separated by intervals of approximately 76 °Cd or 149 °Cd for spring and winter classes, respectively, in both the NPI and BLG104 datasets. After boundary cultivars were identified, all remaining cultivars from both NPI and BLG104 experiments were classified into the nine spring and five winter classes.

2.4. Validation of classification scheme and comparison with ACB Guide

The complete set of NPI and BLG104 field experiments was used to validate the new ACPC scheme. For each of the 23 site-years, cultivars were sorted from quickest to slowest by median TT_{AN} and the classification error was calculated as the percentage of site-years that cultivars fell outside their defined class (*i.e.* on the wrong side of the boundary cultivar).

For comparison between the new ACPC scheme and the previously published ACB Guide (ACB, 2020), wheat cultivars from the NPI experiments were matched to the boundary cultivars defined in the ACB Guide. The median TT_{AN} of these boundary cultivars was then used to model the classification groupings according to the ACB Guide (ACB, 2020). To account for boundary cultivars in the ACB Guide (ACB, 2020) that were not included in the NPI and BLG104 field experiments, substitutions were made based on days to heading data provided by Australian Grain Technologies and NSW Department of Primary Industries. The equivalent boundary cultivars were spring wheats Axe (VQ-Q), LRPB Spitfire (substitute for Vixen, Q), Young (substitute for Corack/LRPB Mustang, Q-M), Mace (M), LRPB Trojan (M-S), Yitpi (S), Sunbri (substituted for Sunzell, S-VS), EGA Eaglehawk (substituted for Sunmax, VS), and winter wheats EGA Wedgetail (substituted for Illabo, M) and Manning (substituted for RGT Accroc, S).

3. Results

3.1. Diversity in cultivar phenology across Australia

In total there were 7522 observations of thermal time from sowing to anthesis (TT_{AN}), of which 1497 were from barley and 6025 were from wheat. Two-thirds of the observations were from the BLG104 field experiments, and the remaining one-third were from the NPI field experiments. The date of anthesis for all cultivars at all sites and times of sowing is shown in Fig. 2a. Sowing dates across all site-years ranged from 10 April to 18 June, corresponding to anthesis dates from 21 June to 14 November. The duration of the period from sowing to anthesis in NPI ranged from 72 to 191 days, and from sowing to anthesis in BLG104 ranged from 66 to 198 days. Anthesis dates for spring cultivars tended to increase towards a maximum at the later times of sowing, and variation in anthesis dates decreased towards later times of sowing as differences between and within spring cultivars stabilised. Winter cultivars were more stable than spring cultivars in terms of the range of anthesis dates observed and the duration of time to anthesis.

The TT_{AN} ranged from as quick as 855 °Cd to as slow as 2860 °Cd across all site-years and times of sowing (Fig. 2b). All cultivars tended to have longer TT_{AN} at earlier times of sowing and shorter TT_{AN} at later times of sowing. Spring cultivars generally followed a slight curvilinear pattern, with a peak in TT_{AN} at sowing dates from late April to early May, whereas TT_{AN} of winter cultivars steadily decreased as sowing date was delayed. As with anthesis dates, variation in TT_{AN} was larger at the earlier times of sowing and reduced towards later times of sowing, with spring cultivars more variable than winter cultivars.

The TT_{AN} of each cultivar varied between and within field sites and times of sowing (Fig. 3, Supplementary Figure 2 and 3). As a result, the order of cultivars from quickest to slowest at each site-year varied, but

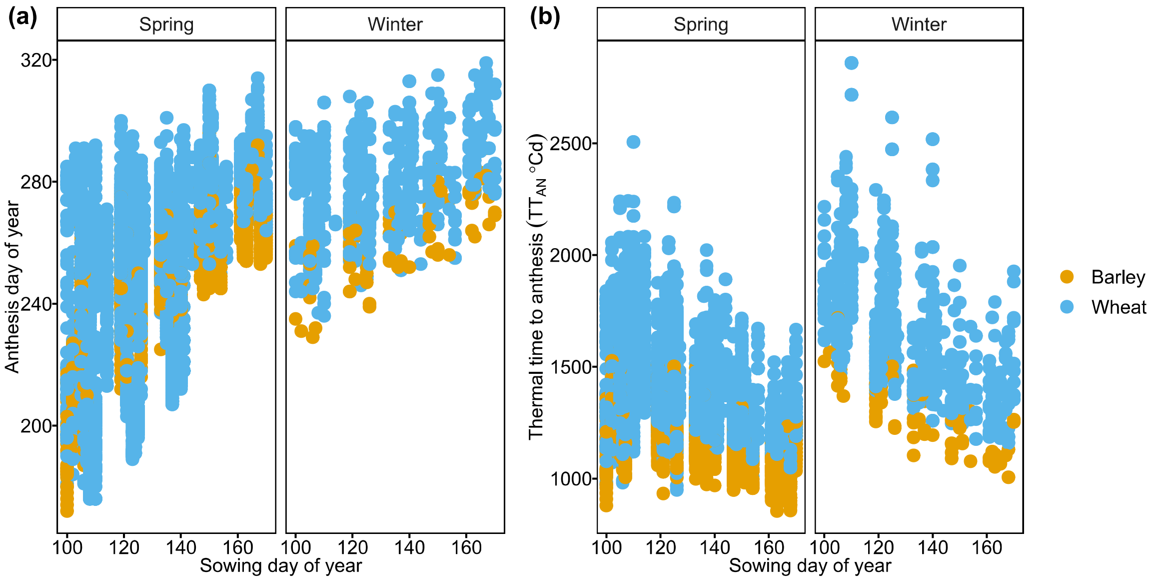

Fig. 2. (a) Anthesis date as day of year and (b) thermal time from sowing to anthesis (TT_{AN}) for all cultivars at all site-years. Day of year 100 corresponds to 10 April and day of year 170 corresponds to 18 June.

there were consistent trends in terms of cultivar ranking. In the NPI field experiments the quickest spring barley cultivar across all site-years was Biere, Keel or Stirling and the slowest was Capstan, Franklin, Navigator or Westminster. The quickest spring wheat cultivar across all NPI site-years was Axe, Emu Rock or H45 and the slowest was Sunlamb. In the BLG104 field experiments, LRPB Dart, H45 and LRPB Mustang were the quickest spring wheats and EGA Eaglehawk and Sunlamb were the slowest. Longsword was consistently the quickest winter wheat and Manning the slowest. In general, spring cultivars were represented across the entire range of thermal time from ~850 to 2600 °Cd, whereas winter cultivars were concentrated towards the slow end between ~1000 and 2900 °Cd. Wheat cultivars were poorly represented at the very quick end of the scale (<1000 °Cd) and barley cultivars were poorly represented at the slower end of the scale (>1900 °Cd).

There was a large amount of variation in TT_{AN} between and within sites, but some geographic trends were observed across latitude (Supplementary Figure 4) that suggested a possible relationship with temperature and/or photoperiod. TT_{AN} tended to be slower for all cultivars grown at the northernmost latitudes, and for winter cultivars in particular there was a tendency for TT_{AN} to decrease as field sites moved south. Linear regression of TT_{AN} against geographic and climatic variables (*e.g.* latitude, average winter minimum temperature, agroecological zone) did not identify any variables that were strongly correlated with TT_{AN}, and thus did not support shifting the slope or intersect of the classification groupings to account for this.

Comparison of the 18 cultivars common to both the NPI and BLG104 field experiments showed a systematic difference between TT_{AN} measured in the NPI field experiments (heading measured as proxy for anthesis) and TT_{AN} measured in the BLG104 experiments. On average, observations of TT_{AN} in BLG104 were ~130–280 °Cd slower than observations of TT_{AN} in NPI, which equated to around 6–12 calendar days. The biggest discrepancies tended to occur with winter cultivars (*e.g.* Longsword, LRPB Kittyhawk, EGA Wedgetail) and photoperiod sensitive spring cultivars (*e.g.* Cutlass, EGA Gregory and LRPB Spitfire).

3.2. Australian Cereal Phenology Classification (ACPC)

The ACPC classes and boundary cultivars are shown in Fig. 4b and Table 3. Wheat and barley were pooled and then spring cultivars were divided into nine classes and winter cultivars into five classes from quickest to slowest development based on relative TT_{AN}. Spring cultivars were separated into nine equidistant classes with 76 °Cd intervals and then LRPB Dart (Q), Mace (Q-M), LRPB Trojan (M), Coolah (M-S), RGT Zanzibar (S), EGA Eaglehawk (S-VS) and Sunlamb (VS) were selected as the spring wheat boundary cultivars. Rosalind (VQ-Q), RGT Planet (Q), Westminster (Q-M) and Navigator (M) were identified as spring barley boundary cultivars. Winter cultivars were separated into five equidistant classes with 149 °Cd intervals. The selected winter boundary cultivars were Longsword (Q), Whistler (M), DS Bennett (S) and SQP Revenue (VS) for wheat and Cassiopee (Q) for barley. Due to the limited diversity in winter habit cereals, the selected boundary cultivars did not perfectly align with numerical class divisions There were no appropriate boundary cultivars for VQ to VQ-Q spring wheat, M-S to VS spring barley, VQ winter wheat, or any winter barley other than the Q class.

All cultivars in the NPI and BLG104 field experiments were then ranked by median TT_{AN} and classified into phenology classes according to the ACPC (Fig. 5, Table 4). Spring wheat cultivars ranged from LRPB Dart (Q) to Sunlamb (VS) and winter wheats ranged from Longsword (Q) to Manning (VS). There were no spring wheats classified as VQ or VQ-Q and no winter wheats classified as VQ. Barley cultivars ranged from spring habit Biere (VQ) to Navigator (M) and winter habit Urambie (VQ) to Cassiopee (Q). There were no barley cultivars at the slower end of the scale. When ranked by median TT_{AN}, the classification of the 18 cultivars common to both the NPI and BLG104 field experiments was consistent apart from two exceptions: LRPB Spitfire and LRPB Lancer (Fig. 5). LRPB Spitfire was on average 56 °Cd quicker than boundary cultivar Mace (Q-M) in the NPI field experiments, but 6 °Cd slower than Mace in the BLG104 field experiments. On balance LRPB Spitfire was classified as Q relative to Mace (Q-M). Similarly, LRPB Lancer was on average 3 °Cd faster than Trojan (M) in the NPI field experiments but 44 °Cd slower in the BLG104 field experiments and was therefore classified as M, marginally slower than the M boundary Trojan.

The ACPC was then validated by assessing the frequency that cultivars common to both NPI and BLG104 field experiments were classified incorrectly at each of the 23 site-years (Table 5). All cultivars were classified correctly most of the time, except for Beckom which was classified incorrectly 59 % of the time. Beckom was correctly classified as Q-M, marginally slower than Mace (Q-M) but faster than LRPB Trojan (M), at seven site-years. Beckom was incorrectly classified as Q at six site-years and M at four site-years. LRPB Spitfire and Suntop also had high error rates of 48 %. Suntop was correctly classified as Q-M at 11 site-years and incorrectly classified as Q at four site-years and M at six

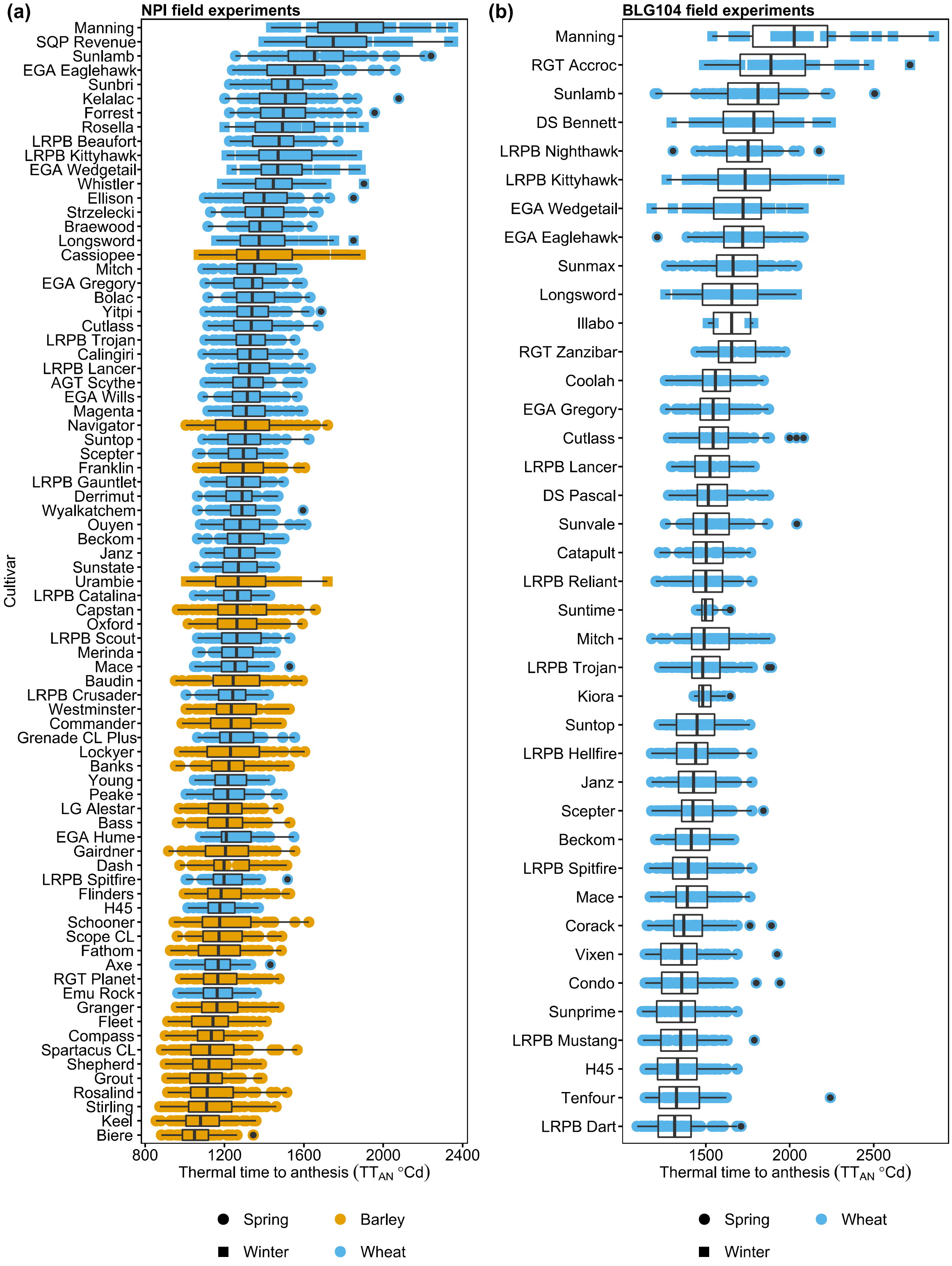

Fig. 3. Boxplots of thermal time from sowing to anthesis (TT_{AN}) for all cultivars in the (a) NPI and (b) BLG104 field experiments. Cultivars are ranked from quickest to slowest according to median TT_{AN}. The vertical line within the box indicates cultivar median, the lower and upper hinges of the boxplot correspond to the first and third quartiles, the lower and upper whiskers extend to the largest value no further than 1.5-times the interquartile range from the hinge, and the black dots indicate outliers.

site-years. LRPB Spitfire was correctly classified as Q at 11 site-years and incorrectly classified as Q-M at 10 site-years. The classification of winter cultivars had a much lower error when compared to the classification of spring cultivars. The degree of classification error was always limited to plus or minus one class grouping.

A model ACB Guide (ACB, 2020) was constructed using TT_{AN} data and matched boundary cultivars from the NPI field experiments (Fig. 4a). Compared to the ACB Guide, the new ACPC (Fig. 4b) is designed with equally spaced classification groupings and two additional classes to describe winter habit cultivars. Wheat and barley were

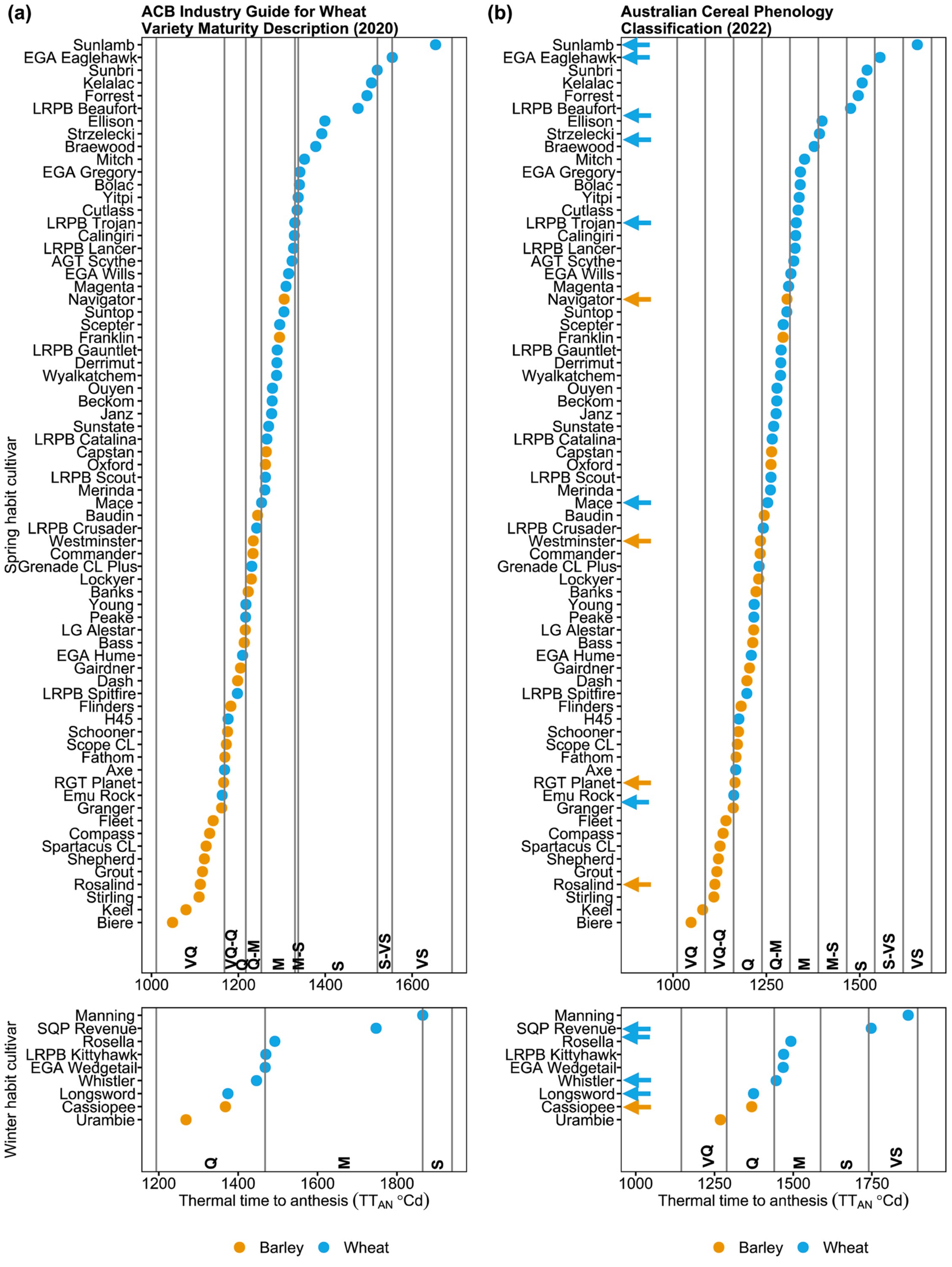

Fig. 4. (a) Model of the Australian Crop Breeders Industry Guide for Wheat Variety Maturity Description (ACB, 2020), compared to (b) the Australian Cereal Phenology Classification (ACPC). Cultivars are ranked from quickest to slowest according to median TT_{AN}. Vertical grey lines indicate the division of spring and winter habit cultivars into classification groupings and blue or orange arrows indicate the location of wheat and barley boundary cultivars separating each class. VQ, Very Quick; VQ-Q, Very Quick-Quick; Q, Quick; Q-M, Quick-Mid; M, Mid; M-S, Mid-Slow; S, Slow; S-VS, Slow-Very Slow; VS, Very Slow.

pooled together in the ACPC which had the effect of expanding the range of possible TT_{AN} for spring and winter habit cultivars and resulted in many cultivars being classified differently than they had been before (Table 4). The ACPC shares two key mid-range spring wheat boundary cultivars, Mace (Q-M) and LRPB Trojan (M), with the ACB Guide, but these cultivars shifted to the quick side of their respective class boundary. All other boundary cultivars in the ACPC were new selections that better separated the classes. For example, LRPB Beaufort is classified as S and clearly separates from quicker cultivars in the ACPC (Fig. 4b, Fig. 5a), but in the ACB Guide (Fig. 4a) it would likely be pooled with cultivars such as Ellison, Mitch and Bolac. Similarly, winter wheat SQP Revenue is 255 °Cd slower than Rosella on average, but both would

Table 3
Classes and boundary cultivars that define the Australian Cereal Phenology Classification (ACPC).

		Wheat		Barley	
Spring		Quick boundary	Slow boundary	Quick boundary	Slow boundary
Very Quick	VQ				< Rosalind
Very Quick-Quick	VQ-Q		< LRPB Dart	≥ Rosalind	< RGT Planet
Quick	Q	≥ LRPB Dart	< Mace	≥ RGT Planet	< Westminster
Quick-Mid	Q-M	≥ Mace	< LRPB Trojan	≥ Westminster	< Navigator
Mid	M	≥ LRPB Trojan	< Coolah	≥ Navigator	
Mid-Slow	M-S	≥ Coolah	< RGT Zanzibar		
Slow	S	≥ RGT Zanzibar	< EGA Eaglehawk		
Slow-Very Slow	S-VS	≥ EGA Eaglehawk	< Sunlamb		
Very Slow	VS	≥ Sunlamb			
Winter		Quick boundary	Slow boundary	Quick boundary	Slow boundary
Very Quick	VQ		< Longsword		< Cassiopee
Quick	Q	≥ Longsword	< Whistler	≥ Cassiopee	
Mid	M	≥ Whistler	< DS Bennett		
Slow	S	≥ DS Bennett	< SQP Revenue		
Very Slow	VS	≥ SQP Revenue			

be classified as M using the ACB Guide (Fig. 5b) compared to Rosella as M and Revenue as VS according to the ACPC (Fig. 4b).

4. Discussion

The study presented here has the most diverse array of genotypes (full sampling of Australian cultivar genotypic and phenotypic diversity), environments (from southern VIC to the central wheat belt of WA to northern QLD in Australia) and management (sowing dates from April to June) ever published in a phenology study. Using specially developed protocols common to all field sites, it has yielded an unprecedented phenological data set that makes for a robust resource to derive and validate the Australian Cereal Phenology Classification (ACPC). The ACPC enables wheat and barley cultivars to be organised into phenology classes based on their relative time to anthesis when sown at the optimal time in a region to which they are adapted.

The ACPC is a revised version of the previously published ‘Industry Guide for Wheat Variety Maturity Description’ (ACB, 2020) and uses the same nomenclature to describe relative lifecycle duration (*i.e.* quick, mid and slow phenology). The use of the term ‘phenology’ instead of ‘maturity’ in the name of the classification scheme makes it clear that it is the relative time from sowing to anthesis that is being described in the ACPC, not the time to physiological maturity or harvest maturity (Celestina et al., 2021). The critical period that determines yield in most crops is around anthesis, hence flowering date is more agronomically important than ripening date (Slafer et al., 2014). In another key point of difference from the ACB Guide (ACB, 2020), the ACPC has been developed using thermal time data from national field experiments. The accumulated thermal time from sowing to anthesis – also known as growing degree days or heat units – is a more useful metric to compare crop phenology than calendar days, because the duration of phenophases in a crop’s life cycle is determined by the accumulation of thermal time and a cultivar’s genetically programmed response to photoperiod and vernalisation (Hemming et al., 2008; Slafer and Rawson, 1994). Thermal time allows for the comparison of phenology between cultivars and controls for confounding effects arising from sowing in different environments and at different times (Gilmore and Rogers, 1958; Hyles et al., 2020).

The ACPC divides spring cultivars into nine equal classes (VQ, VQ-Q, Q, Q-M, M, M-S, S, S-VS, VS) and winter cultivars into five equal classes (VQ, Q, M, S, VS). Compared to the ACB Guide (ACB, 2020), the ACPC increases the resolution at the slow end of the classification scale and has greater coverage across the full spectrum from VQ to VS. Winter and spring habit are separated, but wheat and barley are classified together. This has the effect of expanding the range of possible phenological diversity for the two species, as well as enabling phenology classifications to be standardised across wheat and barley, thus allowing growers to optimise sowing time across cereal species. When considering the full range of TT_{AN}, barley cultivars tend to occupy the quick to mid end of the scale, and wheat the mid to slow end of the scale. Therefore, barley cultivars that were previously classified as relatively slow have been scaled and reclassified into quicker groups, and wheat cultivars that were previously classified as having the quickest phenology have been reclassified into slower groups. The winter cultivars have been divided into five classes, increasing the number of groupings by two compared to the ACB Guide (ACB, 2020). By having a greater number of classes for winter habit wheat and barley, the ACPC accommodates existing and future diversity for winter cultivars since there are currently no VQ winter wheats and no winter barleys classed as M, S or VS.

To be agronomically functional, the classification groupings should relate to a substantial change in sowing date. A change in sowing date of at least one week is useful for Australian growers and aligns with information presented in state sowing guides (Brown, 2020). Spring classes in the ACPC are separated by 76 °Cd which equates to roughly 4–5 days at anthesis in the warmer months and 7–10 days difference in sowing time in the cooler autumn period. Winter cultivars are characterised by having a more stable flowering time over a range of sowing dates (Richards, 1991) owing to their obligate vernalisation requirement, so the larger interval between winter class groupings (149 °Cd) translates to a wider sowing period without a subsequent difference in flowering time. Although the winter phenology class groupings are twice as wide as the spring groupings (149 °Cd compared to 76 °Cd) there is little justification for expanding to nine classes for winter cultivars given the stability of the flowering period. Conversely, there is some value in recommending that the number of spring classes should also be reduced to five so that the class groupings are the same for winter and spring. The bulk of spring cultivars are classified in the Q to M range, and there is a high level of phenological redundancy in both spring wheat and spring barley cultivars.

The assigned phenology classification for a given cultivar according to the ACPC is only applicable to cultivars sown at the optimal time in a region to which they are adapted. When sown outside the commercially relevant sowing period their development speed and phenophase duration will vary, and cultivars are likely to change rank (and therefore class) with sowing time and environment. All wheat and barley cultivars will generally have a longer TT_{AN} when sown earlier than optimal and a shorter TT_{AN} when sown later than optimal due to the effects of temperature and daylength on development. However, this variation in TT_{AN} with sowing date is considerably more pronounced in winter cultivars and facultative spring cultivars that are strongly photoperiod

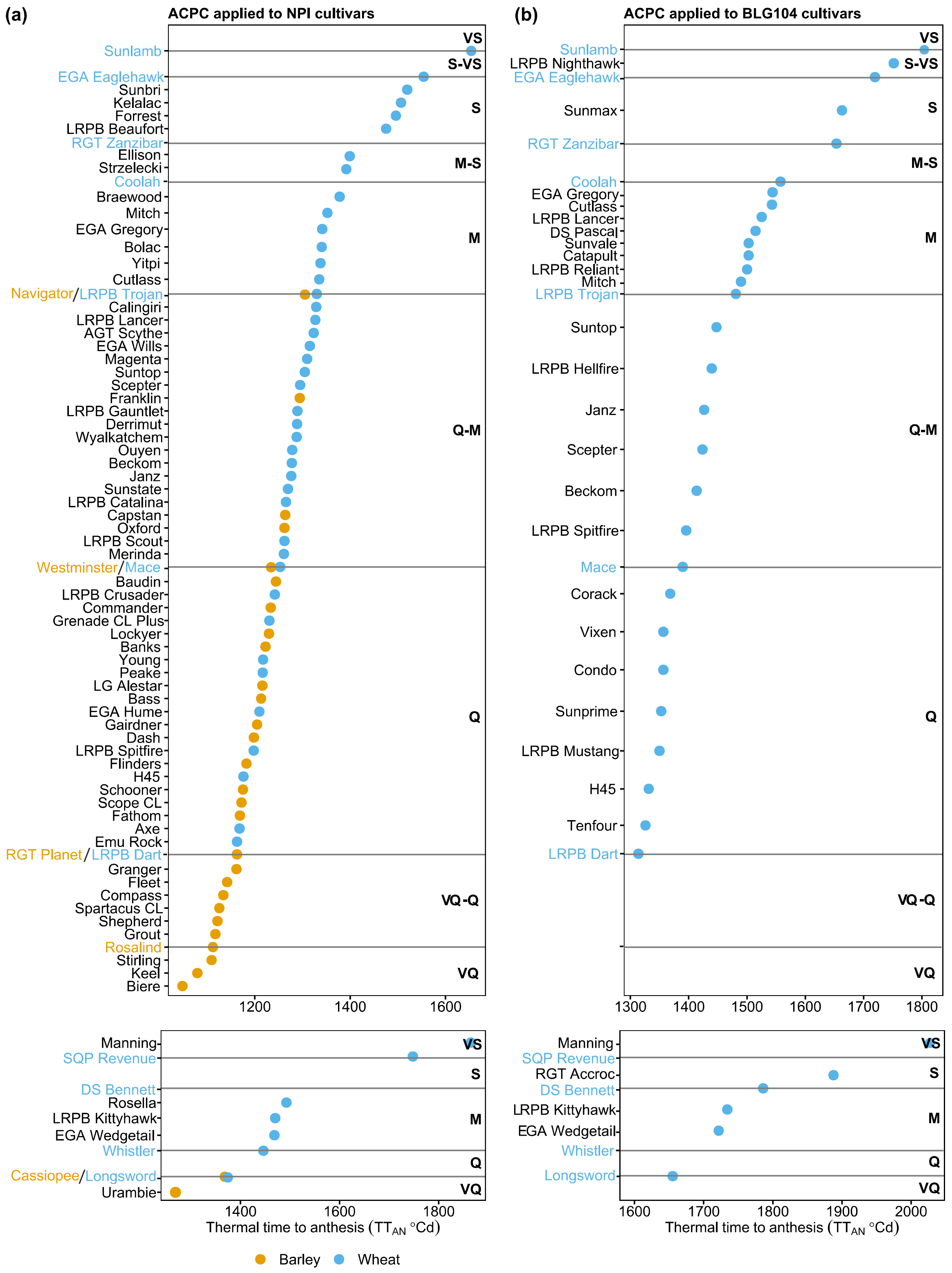

Fig. 5. Cultivars in the (a) NPI and (b) BLG104 field experiments classified according to the Australian Cereal Phenology Classification (ACPC). Cultivars are ranked from quickest to slowest according to median TT_{AN}. Horizontal grey lines indicate the division of spring and winter habit cultivars into classification groupings and blue or orange font indicates wheat and barley boundary cultivars. VQ, Very Quick; VQ-Q, Very Quick-Quick; Q, Quick; Q-M, Quick-Mid; M, Mid; M-S, Mid-Slow; S, Slow; S-VS, Slow-Very Slow; VS, Very Slow.

and/or vernalisation sensitive and thus have a strong response to daylength (Trevaskis et al., 2006; Beales et al., 2007). Users of the ACPC are advised that winter habit and facultative spring habit cultivars are not stable in ranking when sown outside the optimal period. Some barley cultivars (*e.g.* Commander and Scope CL) also exhibit a genotype × environment response of TT_{AN} but they are not as responsive as facultative spring wheats (*e.g.* LRPB Beaufort, Forrest, Kelalac, EGA Eaglehawk and Sunlamb).

Table 4
Classification of spring and winter habit cultivars in the NPI and BLG104 field experiments into phenology classes according to previously published varietal information and the new Australian Cereal Phenology Classification (ACPC). Boundary cultivars are indicated in bold with grey shading.

	Phenology classification			Phenology classification	
Cultivar Spring wheat	Old[a]	New (ACPC)	Cultivar Spring barley	Old[a]	New (ACPC)
		VQ	Biere	VQ	VQ
			Keel	Q	VQ
			Stirling	Q	VQ
		VQ-Q	**Rosalind**	VQ to Q-M	**VQ-Q**
			Grout	Q	VQ-Q
			Shepherd	M	VQ-Q
			Spartacus CL	VQ to Q	VQ-Q
			Compass	VQ to Q-M	VQ-Q
			Fleet		
			Australia	M	VQ-Q
			Granger	Q to M-S	VQ-Q
LRPB Dart	VQ	**Q**	**RGT Planet**	Q to M	**Q**
Emu_Rock	VQ-Q to Q	Q	Fathom	Q to M	Q
Axe	VQ	Q	Scope CL	Q to M	Q
Tenfour	Q	Q	Schooner	M	Q
H45	VQ	Q	Flinders	M to S	Q
LRPB Mustang	Q	Q	Dash	M	Q
Sunprime	Q	Q	Gairdner	Q-M to S	Q
Condo	Q	Q	Bass	M	Q
Vixen	Q-M	Q	LG Alestar	Q to M-S	Q
Hume	Q	Q	Banks	Q-M to M-S	Q
Peake	Q	Q	Lockyer	M-S	Q
Corack	Q-M	Q	Commander	Q-M to M-S	Q
Young	VQ	Q			
LRPB Crusader	Q	Q			
Grenade CL Plus	Q to Q-M	Q			
LRPB Spitfire	Q to Q-M	Q			
Mace	Q to Q-M	**Q-M**	**Westminster**	Q-M to S	**Q-M**
Merinda	Q-M	Q-M	Baudin	M	Q-M
LRPB Scout	Q to M	Q-M	Oxford	Q-M to S	Q-M
LRPB Catalina	Q	Q-M	Capstan	S	Q-M
Sunstate	Q	Q-M	Franklin	S	Q-M
Janz	Q	Q-M			
LRPB Hellfire	M	Q_M			
Beckom	M	Q-M			
Ouyen	Q-M	Q-M			
Wyalkatchem	Q	Q-M			
Derrimut	M-Q	Q-M			
LRPB Gauntlet	Q to M	Q-M			
Scepter	Q-M to M	Q-M			
Suntop	Q to M	Q-M			
Magenta	M to M-S	Q-M			
Wills	M	Q-M			
AGT Scythe	Q-M	Q-M			
Calingiri	M to M-S	Q-M			
LRPB Trojan	Q-M to M-S	**M**	**Navigator**	S	**M**
LRPB Lancer	M-S to S	M			
Kiora	M-S	M			
LRPB Reliant	M	M			
Catapult	M to S	M			
Sunvale	M	M			
DS Pascal	M to M-S	M			
Suntime	M-S	M			
Cutlass	M to M-S	M			
Yitpi	M to M-S	M			
Bolac	S	M			
EGA Gregory	M to S	M			
Mitch	M to M-S	M			
Braewood	S	M			
Coolah	M to S	**M-S**			**M-S**
Strzelecki	S	M-S			
Ellison	M	M-S			
RGT Zanzibar	M-S	**S**			**S**
LRPB Beaufort	S to S-VS	S			
Sunbri	VS	S			
Forrest	S-VS to VS	S			
Kelalac	VS	S			
Sunmax	S	S			
EGA Eaglehawk	VS	**S-VS**			**S-VS**
EGA Nighthawk	S	S-VS			
Sunlamb	S to VS	**VS**			VS
Winter wheat			Winter barley		
		VQ	Urambie	Q	VQ
Longsword	Q	**Q**	**Cassiopee**		**Q**
Whistler	Q	**M**			**M**
Illabo	M	M			
EGA Wedgetail	M	M			
LRPB Kittyhawk	M	M			
Rosella	M	M			
DS Bennett	S	**S**			**S**
RGT Accroc	M-S	S			
SQP Revenue	S	**VS**			**VS**
Manning	S	VS			

VQ, Very Quick; VQ-Q, Very Quick-Quick; Q, Quick; Q-M, Quick-Mid; M, Mid; M-S, Mid-Slow; S, Slow; S-VS, Slow-Very Slow; VS, Very Slow.

[a] The old phenology classifications are based on information gathered from state sowing guides, breeder factsheets and agronomic advice. Alternate classification terminology *(e.g.* short/long season, early/late maturity) have been converted to the equivalent quick/slow terminology for consistency.

Table 5
Validation of Australian Cereal Phenology Classification (ACPC) using wheat cultivars common to both NPI and BLG104 field experiments across all 23 site-years. The frequency of correct/incorrect classification of non-boundary wheat cultivars and percentage error is shown. Boundary cultivars are indicated with grey shading.

Spring wheat		Correct	Incorrect	Error
LRPB Dart	Q			
H45		19	0	0 %
LRPB Spitfire		11	10	48 %
Mace	Q-M			
Beckom		7	10	59 %
Scepter		18	4	18 %
Janz		14	7	33 %
Suntop		11	10	48 %
LRPB Trojan	M			
Mitch		13	8	38 %
LRPB Lancer		17	6	26 %
Cutlass		19	4	17 %
EGA Gregory		13	8	38 %
Coolah	M-S			
RGT Zanzibar	S			
EGA Eaglehawk	S-VS			
Sunlamb	VS			
Winter wheat				
Longsword	Q			
Whistler	M			
EGA Wedgetail		16	2	11 %
LRPB Kittyhawk		19	1	5 %
DS Bennett	S			
SQP Revenue	VS			
Manning		14	0	0 %

Setting any type of quantitative limit or boundary cultivar limit in a classification scheme is inevitably going to result in errors, with cultivars falling on the wrong side of the defined boundary. Classification error may arise from natural variation in cultivar phenology due to interactions between genotype, environment and management; particularly for those cultivars that are more sensitive to vernalisation and photoperiod. Errors in the measurement of plant development or collection of climatic data may also result in incorrect anthesis dates and/or thermal time values, and therefore incorrect phenology classifications. Validation of the ACPC against field data demonstrated that overall, cultivars are correctly classified 73 % of the time, although there can be more error associated with some cultivars. Nevertheless, when a given cultivar is classified incorrectly, this error only results in the cultivar moving up or down one class. The effect of this would be a potential error in sowing time of up to ± 7–10 days. Breeders need to ensure that new cultivars to the market are evaluated against the nominated boundary cultivars in a range of suitable environments to ensure their classification is accurate. In addition, designated boundary cultivars will inevitably become redundant in time as they are superseded by new cultivars that are released to market. The ACPC will need to be periodically reviewed to assign new boundary cultivars as needed.

The range of values obtained for thermal time to flowering – from approximately 800° to 3000 °Cd – defines the scope of possible values that could be observed for a cultivar in a given environment and time of sowing in Australia. However, defining phenology classes in terms of quantitative thermal time values rather than with boundary cultivars was not feasible because TT_{AN} was found to vary between and within field sites and between methods of scoring plant development (*i.e.* anthesis measured directly by observation of flowering on the spike, or anthesis measured using spike emergence as a proxy). Trends in TT_{AN} were also apparent across latitudes, most notably with winter cultivars and facultative spring cultivars that were vernalisation-sensitive or photoperiod-responsive. Once cultivars in an experiment are ranked from quickest to slowest based on median thermal time, the numerical value for TT_{AN} does not matter – only the ranking relative to the boundary cultivars does. In our experiments we found that even when the absolute value of TT_{AN} changed, the overall ranking of cultivars from quick to slow, and the position relative to the boundary cultivars, tended to stay the same.

The classification scheme described herein could be extended to all grain crops in Australia and internationally using the methodology described in this paper. That is, climatic and phenological data collected from cultivar × time of sowing field experiments distributed across key growing regions. It is our aim that the ACPC is extended first to all cereals in Australia including oats, sorghum, triticale and rye, and then to oilseeds and pulses. Having all major crop cultivars classified according to the same scheme would allow growers to make better decisions across whole-farm cropping programs. Critically, development of regionally consistent phenology classification schemes requires the cooperation of agronomists, breeders and research and extension officers, as well as the acceptance of consistent protocols to define what constitutes anthesis date in cereal, pulse and oilseed species and how to measure this in a population of plants. Robust phenology classifications depend on accurate measurement of crop development in a population of plants – something that is difficult to achieve with existing development scales like Zadoks' decimal code (Zadoks et al., 1974) and the BBCH scale (Meier, 2001), which tend to be subjective and qualitative and applicable only to representative individual plants and/or main stems. We recommend that stakeholders collaboratively develop and publish clear protocols for the measurement of anthesis in all major crop species, as has been done for wheat and barley (Celestina et al., , under review). In determinate cereal crop like wheat and barley, anthesis date in a population of culms can be determined as described either by observing spike emergence or flowering on the spike. For oilseeds and pulses with an indeterminate flowering habit, it is more appropriate to define anthesis date as the date of the appearance of the first flower on the main stem (Lilley et al., 2019; Whish et al., 2020), with cumulative degree days therefore calculated as the accumulated thermal time from sowing to the start of flowering.

5. Conclusion

The Australian Cereal Phenology Classification (ACPC) has been derived from a dataset of unprecedented breadth and quality, representing the full diversity of G ×E × M for wheat and barley in the grain producing regions of Australia. This scheme divides wheat and barley cultivars into nine spring phenology classes and five winter phenology classes according to their relative thermal time from sowing to anthesis, with boundary cultivars separating the classes. The ACPC makes a number of revisions to the ACB Guide (ACB, 2020), most important of which is the use of thermal time data to define and classify cultivar phenology. New cultivars to market can be ranked by their relative thermal time to anthesis and assigned into a class defined by contemporary boundary cultivars. Classes in the ACPC are designed to accommodate existing and future diversity and they correspond to agronomically meaningful changes in sowing dates. The ACPC will help growers better match crop life cycle to seasonal conditions in their environment and maximise yields achieved with new cultivar releases while reducing confusion across regions. The same methodology could also be applied internationally and to a range of crop species to standardise descriptions of crop phenology.

CRediT authorship contribution statement

Corinne Celestina: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing – original draft, Writing – review & editing, Visualization. **James Hunt:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Haydn Kuchel:** Conceptualization, Writing – original draft, Writing – review & editing. **Felicity Harris:** Methodology, Investigation, Data curation, Writing – review & editing, Project administration, Funding acquisition. **Kenton Porker Ben Biddulph:** Investigation, Writing – review & editing. **Maxwell Bloomfield:** Investigation, Writing – review & editing. **Melissa McCallum:** Investigation, Writing – review & editing. **Ghazwan Al Yaseri:** Investigation, Writing – review & editing. **Rick Graham:** Investigation, Writing – review & editing. **Peter Matthews:** Investigation, Writing – review & editing. **Darren Aisthorpe:** Investigation, Writing – review & editing. **Jessica Hyles:** Investigation, Resources, Writing – review & editing. **Ben Trevaskis:** Investigation, Resources, Writing – review & editing. **Enli Wang:** Writing – review & editing, Software. **Zhigan Zhao:** Writing – review & editing, Software. **Bangyou Zheng:** Writing – review & editing, Software. **Neil Huth:** Writing – review & editing, Software. **Hamish Brown:** Writing – review & editing, Software.

Data Availability

Data will be made available on request.

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Conflict of interest

The authors declare no conflicts of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2022.126732.

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