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Foreword

Drivers of trends in Australian canola productivity and future prospects

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Introduction

Canola (*Brassica napus* L.) or edible oilseed rape, is the third most important oilseed produced globally, and production has expanded remarkably in most of the major producing nations in recent years (FAOSTAT 2015). Since 1993, annual production has increased 2-, 3- and 4-fold in China (to 14.5 Mt), Canada (to 17.9 Mt) and the EU (to 20.9 Mt) respectively. In the same period, production in Australia has increased 10-fold from 0.3 to 4.0 Mt and canola is now Australia's third most important food crop after wheat and barley, worth around AUS $2.7 Bill in 2012–13 (AOF 2015). The rising world population has increased the demand for vegetable oils, and along with renewable energy policies in some countries, has driven the global surge in oilseed demand which is predicted to continue. It has been estimated that global production of vegetable oils must nearly double by 2050 to meet FAO projections for food, fuel and industrial demands (FAO 2003; Lu *et al*. 2011).

Brassica napus was first trialled in Australia in the early 1960s and commercial production commenced in 1969 using imported Canadian varieties. However, it was the release of regionally-adapted varieties with improved tolerance to blackleg (*Leptosphaeria maculans*) and triazine herbicide tolerance (allowing control of Cruciferous weeds) that underpinned the rapid expansion of the crop in the 1990s. The first 30 years of canola production in Australia was reviewed in 1999, when the 10th International Rapeseed Congress was hosted in Australia, signalling Australia's rise as an important global producer and exporter of canola (Colton and Potter 1999). At that time, Australia produced 2.2 Mt from 1.85 M ha, a remarkable achievement from a recently introduced crop, and it was an appropriate time to review industry progress, and the science, technology, farming systems and marketing that had led to its success. Aside from biennial meetings of industry specialists at the Australian Research Assembly on Brassicas (published by Australian Oilseed Federation, AOF 2015), there has been no comprehensive review of industry progress over the last 15 years despite significant recent shifts in crop breeding and agronomy, and a doubling of production to 3.7 Mt from 2.6 M ha in 2013–14 (ABARES 2014). In this Special Issue of ***Crop & Pasture Science*** we present an up-to-date summary of the recent and future trends in genetics, plant breeding, crop physiology and modelling, pathology, and farming systems agronomy in Australian canola production systems, at a time when the area and production are at an all-time high. We also present recent reviews of production trends in other established canola-producing nations including Canada (Morrison *et al*. 2016*a*) and Germany (Hegewald *et al*. 2016) along with the challenges of the fledgling industry in the Pacific North-west of USA (Pan *et al*. 2016) where farmers and scientists face many of the same biophysical, socioeconomic and marketing challenges that faced the pioneering Australian farmers and technologists in the 1970s and 1980s. In this paper we introduce some of the key changes and drivers of recent trends in canola productivity in Australia, highlight aspects of some of the research presented herein, and discuss the impact of these results on future Australian canola production.

Background and production trends

In Australia, canola was initially grown in more reliable rainfall areas (>400 mm annual rainfall) due to its greater sensitivity than cereals to heat and drought, and the higher production costs which made it risky in more marginal environments (Colton and Potter 1999). Improved varieties and agronomy along with the overall farming systems benefits of weed and disease control in cereals have expanded the area cultivated to canola, and it is now grown in all but the driest margins of the wheat-belt (Fig. 1). The previous review of Australian canola productivity in 1999 ironically marked the start of a rapid decline in canola area to around 0.5 Mha in 2006, which resulted from a combination of poor seasonal conditions and the changing terms of trade (Fig. 2). During its rapid expansion in the late 1990s canola had extended away from the traditional, more reliable rainfall areas (annual rainfall > 450 mm) and into lower rainfall areas (<325 mm) especially in Western Australia, and in some cases onto less suitable soils. The period from 1998 to 2010, now known in Australia as the millennium drought (Verdon-Kidd *et al*. 2014) was characterised by dry autumns, late planting rains and limited soil water storage, together with hot, dry springs which favoured cereals such as wheat and barley over canola. As the area of canola declined and the crop retreated to the more reliable rainfall areas, the overall yield levels were maintained, except for the notable drought years of 2002 and 2006 (Fig. 2). Although some inter-annual variability in area and yield is likely to continue in response to seasonal conditions and relative prices, the current area is at an all-time high (Fig. 2).

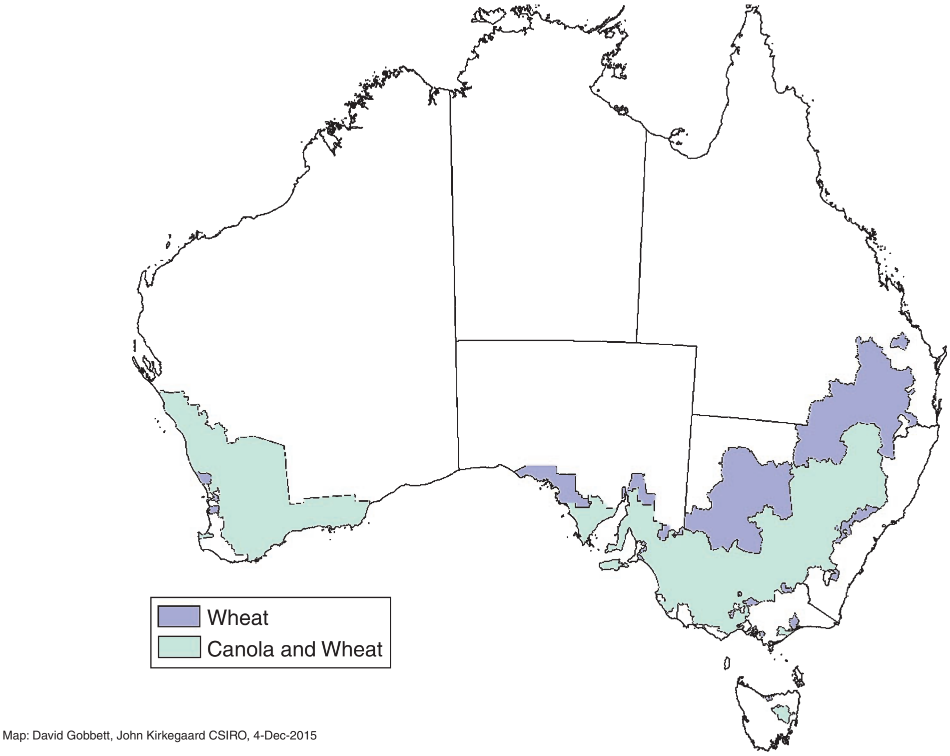

Fig. 1. Areas of significant wheat and canola production in Australia during the period 1998 to 2014. The areas are derived from ABARES production data compiled at Statistical Local Area level and include those SLAs that are at least 2000 ha in size, and in which the wheat area was >0.2% of SLA area, and canola was >0.1% of SLA area. Map courtesy Dave Gobbett CSIRO, Yield Gap Australia (www.yieldgapaustralia.com.au).

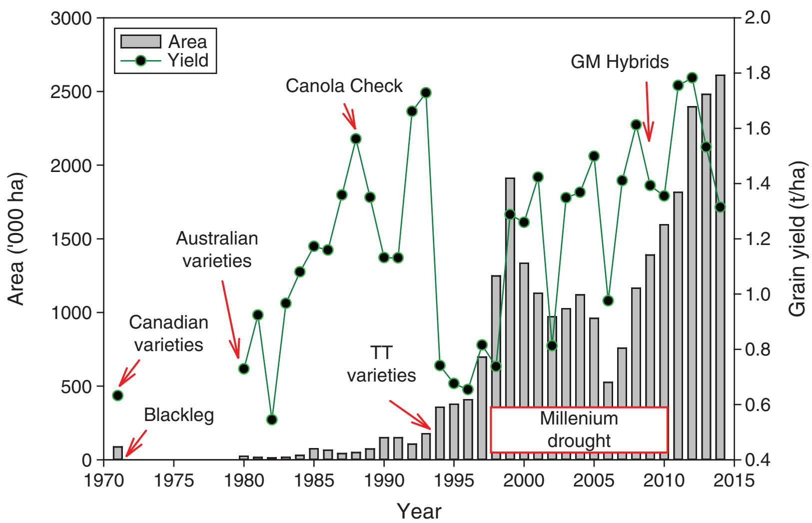

Fig. 2. Area and average national grain yield for canola in Australia highlighting some of the significant events influencing the observed trends. The linear trends (not shown) in grain yield fitted for the years 1980 to 1993 and 1998 to 2014 were 67 kg/ha.year (3.8% pa of 1993 yields) and 34 kg/ha.year (2% pa of 2014 yields) respectively. These periods represented periods of relatively stable production areas of <0.3 Mha before release of triazine-tolerant varieties, and 1 to 2 Mha after the release of triazine-tolerant varieties. Data compiled from ABARES estimates (ABARES 2014) and Australian Oilseed Federation estimates (AOF 2015).

As a result of the large fluctuations in the areas sown to canola in Australia, it is difficult to establish meaningful overall yield trends, but the impressive early improvements were clear; rising from around 0.6 t/ha in the 1970s to 1.8 t/ha in 1993 (Fig. 2). This was largely due to the development of adapted, blackleg resistant varieties (Salisbury and Wratten 1999; Buzza 2007; Cowling 2007), along with highly successful agronomy packages such as CanolaCheck (Colton and Potter 1999). The yield progress during this early period on the small (<0.3 Mha) but relatively stable higher rainfall areas was a remarkable 67 kg/ha.year or 3.8% pa (based on 1993 yields). The introduction of triazine-tolerant (TT) varieties in 1993 led to an expansion of canola into more marginal areas of Western Australia, which combined with their inherently lower yield potential (Robertson *et al*. 2002*b*), and significant drought in 1994 saw average national yields collapse for several years as the area grown increased (Fig. 2). During the subsequent millennium drought period from 1998 to 2010 (Verdon-Kidd *et al*. 2014), the area stabilised at around 1 M ha, and in the period 1998 to 2014 average yields steadily returned to the levels achieved in 1999. The linear yield trend during the 16-year period 1998–2014 was 34 kg/ha.year or 2.0% pa based on 2014 yields, but in this case coincided with an increase in the area grown (Fig. 2). This basic estimate of recent national farm yield progress compares well with those established for the period 1991 to 2010 by Fischer *et al*. (2014) for China (37 kg/ha.year, 2%) and Canada (33 kg/ha.year, 1.7%), exceeds that of India (15 kg/ha.year, 1.4%) and France (21 kg/ha.year, 0.6%) but is lower than that achieved in Germany (68 kg/ha.year, 1.7%). A more recent estimate for yield gain in the Canadian Prairies for the period 2000 to 2013 is 54 kg/ha.year or 2.6% pa relative to 2013 yields, and factors behind this increase are discussed in detail by Morrison *et al*. (2016*a*).

National trends of farm yield are of interest, but in order to drive productivity gains, it is important to compare current performance against a defensible yield potential to assess the exploitable yield gap between potential yield and that achieved in farmer's fields (Kirkegaard *et al*. 2006; Fischer *et al*. 2014). Yield potential can be estimated with simple crop comparisons (e.g. canola yield = 50–60% of wheat yield; Holland *et al*. 1999), can be based on expected seasonal water-use efficiency (e.g. 15 kg/ha.mm of seasonal ET; Robertson and Kirkegaard 2005), or can use crop simulation models sensitive to crop, soil, climate and management factors to estimate yield potential (Kirkegaard *et al*. 2006, Lilley *et al*. 2015). The latter approach has recently been used to estimate potential canola yields and yield gaps at Statistical Local Area scale for the entire nation for the period 1998 and 2015, and has been made available in a web-based format (www.yieldgapaustralia.com.au/maps/). The analysis suggests that the overall, average farm yields across 162 SLAs in the period 1998 to 2012 (range 0.9 to 1.4 t/ha) were 42 to 68% of the water-limited potential yield (range 1.3 to 3.2 t/ha) assessed using the simulation analysis. A further estimate of yield potential can also be assessed from field experiments evaluating the latest varieties under optimum agronomy, such as those conducted as part of the National Variety Testing (NVT) series across Australia for canola since 2005 (www.nvtonline.com.au). A summary of the site mean yields achieved across a range of NVT sites in the period 2005 to 2014 confirms that for elite varieties under experimental conditions, average yields of 2.5 to 3.0 t/ha and

Table 1. Average site mean yields (and s.e.m.) at selected sites for specific canola classes in the National Variety Testing (NVT) series for canola (2005–14)

Sites representing a range of canola-growing regions in Australia for which at least 4 years of data were available in the period 2005 to 2014 have been included (6 to 8 years at most sites), and data are average and SE of site mean yields for most widely grown canola types indicated in those years. Full datasets are available online at: www.nvtonline.com.au. Imi = imidazolinone

Sites	Mid-maturity		Sites	Early-maturity
(High rainfall)	Imi-tolerant	Triazine-tolerant	(Low rainfall)	Triazine-tolerant
		NSW		
SE (Gerogery)	2.81 (0.39)	2.75 (0.34)	NW (Coonamble)	1.67 (0.23)
SE (Grenfell)	2.45 (0.19)	2.28 (0.27)	NW (Trangie)	1.72 (0.20)
NE (Wellington)	2.49 (0.25)	2.21 (0.29)	CW (Condobolin)	1.44 (0.25)
NW (Gilgandra)	2.10 (0.06)	1.92 (0.11)		
		Victoria		
NE (Yarrawonga)	2.25 (0.38)	1.96 (0.33)	Mallee (Hopetoun)	1.18 (0.23)
NC (Diggora)	2.49 (0.22)	2.01 (0.28)		
SW (Hamilton)	2.51 (0.18)	2.54 (0.18)		
Wimmera (Minyip)	1.58 (0.29)	1.40 (0.25)		
		South Australia		
Mid-N (Riverton)	2.47 (0.38)	2.41 (0.22)	Yorke P (Minlaton)	1.99 (0.22)
Yorke P (Arthurton)	2.90 (0.28)	2.44 (0.29)	Upper EP (Tooligie)	1.26 (0.17)
Lower EP (Mt Hope)	1.99 (0.16)	1.69 (0.12)	SE (Keith)	1.58 (0.15)
SE (Bordertown)	1.89 (0.15)	1.73 (0.16)		
		Western Australia		
AZ 3 (Williams)	2.50 (0.22)	2.12 (0.14)	AZ 1 (Mingenew)	2.03 (0.41)
AZ 2 (Katanning)	1.88 (0.18)	1.73 (0.20)	AZ 2 (Nyabing)	1.69 (0.17)
AZ 2 (Cunderdin)	–	1.34 (0.12)	AZ 5 (Hyden)	1.10 (0.23)
AZ 6 (Munglinup)	1.51 (0.07)	1.78 (0.20)	AZ 5 (Scadden)	1.36 (0.14)

1.0 to 2.0 t/ha can be achieved in high and low rainfall sites respectively (Table 1). Together these measured and modelled estimates of current yield gaps in canola suggest there is significant scope to increase canola productivity on Australian farms with ongoing research, development and adoption of new technologies. In the following sections, we briefly review some of the key strategies targeted to improve canola productivity which are discussed in more detail in the manuscripts compiled within this Special Issue.

Genetics and breeding

The early strategies and success of Australian canola breeders in developing adapted, disease-resistant varieties producing high oil yields of good quality has been previously reviewed (Salisbury and Wratten 1999; Buzza 2007; Cowling 2007). Potter *et al*. (2016) report a study of historic non-herbicide tolerant canola varieties that suggests genetic improvements may have contributed around 21.8 kg/ha.year (or 1.25% pa) to overall yield improvement in the period 1978 to 2012. However, the remarkable success of our major global competitors such as Canada, in achieving ongoing improvements in yield and quality (Morrison *et al*. 2016*a*) highlight the need for ongoing innovation in the Australian industry if we are to remain competitive. The initial targets for Australian breeders – blackleg resistance, high yield and quality – remain the key targets for breeders today. Salisbury *et al*. (2016) chart the ongoing innovation in Australian canola breeding in these important areas and highlight some of the changes during the last 15 years. These include the switch from public to private breeding and the associated diversification in the genetic background of Australian canola, a concern previously discussed by Cowling (2007). This has increased the development and release of hybrid varieties, new herbicide tolerance types including genetically modified Round-up-resistant (RR) varieties in 2008, new speciality oil types, as well as new sources of blackleg resistance. In 2013, open-pollinated TT varieties still comprised 81% and 70% of canola grown in Western Australia and south-eastern Australia respectively, but the focus of breeding companies has switched to hybrid varieties with a declining number of new open-pollinated releases in recent years (Zhang *et al*. 2016). The increasing use of new technologies such as doubled haploidy, molecular markers and genomic selection and a range of other 'omics' technologies are likely to speed up the identification of promising alleles for a range of traits and their breeding into elite varieties (Raman *et al*. 2016). In the area of blackleg resistance, Van de Wouw *et al*. (2016) outline the significance of the increased recent understanding of the genetics controlling the interaction between *L. maculans* isolates and *Brassica* varieties which has underpinned new breeding and management strategies to manage this devastating disease. As canola production intensifies, managing the durability of polygenetic resistance is the major challenge for the future, and will require integrated approaches of new genetic resistance, new fungicide chemistry and better cultural practices. Nelson *et al*. (2016) describe the potential application of genomics to improve the phenological adaptation of canola which is a key driver for higher productivity in different and changing environments. Understanding the genetics controlling responses to vernalisation and photoperiod in wheat, and using them as markers in breeding programs and in predictive models (Zheng *et al*. 2013), can unlock tremendous potential to tailor new varieties to specific environments with significant increases in yield potential. This vision is now targeted for canola (Nelson *et al*. 2016). In addition to improved phenological adaptation, breeders and geneticists are also seeking other specific traits to improve the adaptation of canola to drought (Norton 2007). Numerous traits such as carbon isotope discrimination, water soluble carbohydrate remobilisation, osmotic adjustment, deeper roots, early vigour and canopy architecture have been investigated in cereals with ideotypes proposed (e.g. Reynolds and Tuberosa, 2008), but these are yet to be confirmed as beneficial in canola. As a result there is currently little trait-based breeding in Australian canola, although the National Brassica Germplasm Improvement Program (NBGIP) has initiated investigations of drought tolerance as a breeding target. The ongoing empirical selection for early vigour, reduced height, flowering date and the move to hybrid varieties is likely to see ongoing improvements in yield under drier environments (Salisbury *et al*. 2016). The release in 2015 of a variety with a pod-shatter resistance trait (IH51-RR) may increase harvested yield under direct-heading and in situations where harvest is delayed by rainfall or contractor availability.

In terms of canola quality, Potter *et al*. (2016) report that simultaneous improvements in both oil content (0.09% pa) and protein (0.05% pa) have been achieved over the period 1978 to 2012 while glucosinolate content had decreased to 7–16 umole/g of meal by the mid-1990s. Innovative selection protocols show continuing improvements in the most recent releases (Salisbury *et al*. 2016). Further innovations in the Australian Industry have been high stability oils high in oleic acid and low in linolenic acid (Maher *et al*. 2007) and other speciality types including recent development of canola varieties high in 'fish oil' Omega 3 fatty acids herald a new age of speciality 'designer' oils (Lu *et al*. 2011). At the time of writing, 44 varieties of canola were available to growers in NSW including open pollinated and hybrid varieties, five herbicide-resistance categories (conventional, triazine, imidazolinone (Clearfield), glyphosate (Round-up), and RT (Roundup + Triazine), four different maturity classes, speciality oil types, winter grazing types and a pod-shatter resistance type (Matthews *et al.* 2015). This range of choice explains the wide adaptation and farming systems fit that canola has achieved across such a wide area of the Australian cropping zone (Fig. 1).

Phenology, physiology and modelling

Brassica napus has wide phenological adaptation with a range of responses to temperature and photoperiod (Mendham and Salisbury 1995). The original adaptation of canola to the Australian environment, where spring-type canola grows for a 5–7 month period through the mild winter period, required a unique combination of phenological traits (Buzza 2007). Neither European winter types (grown for 12 months), nor Canadian spring types (grown for 4 months in summer) were suitable and an Australian canola type was derived from a combination of European, Canadian and Asian (in particular Japanese) ancestry (Cowling 2007). In Australia, canola is sown in autumn, when soil moisture levels are suitable, and requires a sufficient vegetative period to generate a canopy appropriate for the yield potential related to the resources available (mostly water and nitrogen), along with a flowering period that avoids the temperature extremes of frost and heat at sensitive periods. Aspects of the physiological understanding of phenological adaptation of canola up to the late 1990s was reviewed by Walton *et al.* (1999) and Robertson *et al.* (2002*a*) and a wide range of canola maturity types suited to the diverse range of canola-growing environments had been developed at that time. However, since then emerging changes in the areas, climatic conditions and farming systems in which canola is grown require ongoing adaptation to increase productivity. Emerging issues include the development of winter types and winter-spring intermediate types adapted to higher rainfall zones (Riffkin *et al.* 2012, 2016; Christy *et al.* 2013; Sprague *et al.* 2015), improved adaptation in the more marginal, drought/heat-prone low rainfall areas with earlier flowering and maturity (Cowling 2007; Zhang *et al.* 2013), along with changing climatic conditions in the traditional canola-growing areas during the millennium drought (Verdon-Kidd *et al.* 2014). This has seen sowing dates moved earlier, with often unexpected and unpredictable flowering responses in current varieties developed for later sowing, leading to significant yield penalties (Brill *et al.* 2015). The development of dual-purpose canola systems, where the crops are sown earlier than normal and grazed, and development is slowed by defoliation to maintain suitable flowering windows for seed production (Kirkegaard *et al.* 2008, 2012; Sprague *et al.* 2015; Lilley *et al.* 2015) has provided further novel options to adapt canola to new production environments. Further changes in climate are predicted for most of the Australian canola-growing regions including more frequent temperature extremes and generally drier conditions (CSIRO and BOM 2007) which amplifies the need for improved understanding of the factors controlling crop development and growth, and response to environmental stress. Frost during early pod-fill can kill newly formed seeds in the pods, but the lengthy flowering period usually provides adequate compensation for loss (Walton *et al*. 1999) provided reasonable conditions for compensation persist (Kirkegaard *et al.* 2016). Late frost that occurs after flowering has ceased but when the seed has around 60% moisture can be devastating and trigger decisions to cut the crop for hay. Though farming systems generally strive to manage canola to avoid exposure to damaging heat during sensitive reproductive stages, it is a common occurrence in low rainfall, marginal areas and the frequency of hot days is predicted to increase (CSIRO and BOM 2007). Lilley *et al.* (2015) recently incorporated frost and heat indices into simulation predictions based on limited published data on the impacts of temperature extremes on yield in the field, and although field validation is limited, yield predictions were improved in a recent study on sowing time effects in NSW (Kirkegaard *et al.* 2016). Improved understanding of the impacts of temperature extremes on yield and quality in canola and improving genetic tolerance remain key objectives for physiologists (Morrison and Stewart 2002; Robertson and Lilley 2016) and breeders in Australia (Salisbury *et al.* 2016) and elsewhere. Morrison *et al.* (2016*b*) present a novel screening technique to investigate the impacts of heat on pollen germination, which is often assumed to be the major cause of sterility and yield loss under heat stress. Heat stress temperatures (>29°C) generally led to raceme sterility, yet pollen germinated up to temperatures of 33°C suggesting other processes are involved in heat stress susceptibility.

In addition to appropriate adaptation of crop phenology to different growing environments, the trajectory of crop biomass through time must be tailored to, and make the most efficient use of, the resources available. Under Australian conditions, the growth and potential yield of canola is almost always limited by water, so that capturing and using water efficiently has been a strong focus for physiologists, breeders and agronomists alike (Zeleke *et al*. 2014). Canola is expected to yield around 8 to 15 kg/ha.mm of seasonal ET (Robertson and Kirkegaard 2005) although in higher rainfall environments other factors such as nitrogen (Norton 2016) or even light (Mendham and Salisbury 1995) may be more important yield-limiting factors. A generally close association between yield potential and biomass at flowering provides biomass targets that can assist in variety selection and management in different environments (Walton *et al*. 1999; McCormick *et al*. 2012, 2015). Zhang and Flottmann (2016) confirmed the higher yield of hybrid varieties in high rainfall environments was associated with increased biomass production at all growth stages, leading to more pods and seed per m^2. The radiation use efficiency (RUE) measured for hybrid varieties in those studies (1.74 g MJ/m^2 PAR) exceeded that of TT varieties (1.41), and both exceeded the 1.20 to 1.35 g MJ/m^2 PAR previously assumed for canola (Robertson *et al.* 2002*b*; Robertson and Lilley 2016), suggesting improvements through hybrid breeding and indirect selection. Riffkin *et al.* (2016) have also demonstrated a positive correlation between the length of the flowering to maturity phase and yield of longer-season, winter types although interactions with seasonal water supply make the genetic components of this difficult to dissect. The improved capture and partitioning of resources for a given biomass has been considered by researchers for some time, including limiting the height, number of branches, flowers (including apetalous types) and pod number, length and insertion angle to improve the radiation environment and seed retention (Walton *et al.* 1999; Norton 2007).

In lower and medium rainfall environments more prone to drought and heat, physiological studies have focused more on improved capture and efficient use of water, with a focus on ensuring adequate, but not excessive biomass to match the yield potential of the environment. Norton (2007) described a range of potentially useful features for water-limited environments including more determinate flowering, semi-dwarf types, storage carbohydrates, and improved root vigour and adaptation to soil constraints. Current canola pre-breeding efforts in Australia include aspects of heat and drought tolerance through the National Brassica Germplasm Improvement Program (NBGIP) to make novel traits available to breeding programs.

Much of the phenological understanding of canola responses in Australia up to 2000 were encapsulated in the canola simulation model APSIM-Canola (Walton *et al.* 1999; Robertson and Kirkegaard 2003). The canola module was developed in the late 1990s and since then has been used to investigate a wide range of agronomic, physiological, plant breeding and farming systems issues (Robertson *et al.* 2015). However despite its widespread use, it has not always provided suitable predictions of crop yield for all users (Christy *et al.* 2013), and there had been no comprehensive peer-reviewed account of the scientific underpinnings of the canola module in APSIM until now. In this Special Issue, Robertson and Lilley (2016) present a summary of the physiological evidence justifying the parameters, review the model performance and reflect on several areas in which the model could be improved. These include improved definition of phenology parameters especially in high-yielding environments, improved oil content prediction, physiological characterisation of new hybrid types and physiological responses to high and low temperature extremes. Increasingly, efforts to compare simulation models and approaches globally under the Agricultural Modelling Improvement Program (AGMIP) initiative already underway in wheat have also recently commenced in canola, and aim to incorporate the best features of different simulation approaches into improved models. A different approach to simulate phenology for winter canola in Germany is reported here by Böttcher *et al.* (2016). A well validated simulation model sensitive to both genetic and management factors provides an excellent tool with which to explore the potential Genotype × Environment × Management scenarios likely to improve productivity in different systems. Improvements to crop simulation of growth, development and yield might also assist in future breeding programs, as discussed by Nelson *et al.* (2016), if genotypic information on aspects of crop response such as vernalisation and daylength can be included.

Farming systems evolution and tactical agronomy

The farming systems benefits of canola as a break crop for weed and disease control in cereal cropping systems has always been a major driver for adoption (Norton *et al.* 1999; Kirkegaard *et al.* 2008; Angus *et al.* 2015). Originally canola was grown as the first crop after grass-clover pastures to control weeds and diseases before a sequence of cereals and to capitalise on the high N availability in relatively short (2–4 years) crop phases (Norton *et al.* 1999). But as cropping intensity in Australia has increased at the expense of pasture area, canola is now grown more intensively in longer or even continuous crop sequences, often further down the rotation (Norton 2016). This change in the farming system, together with recent changes in climate, adoption of modern no-till seeding technologies and the availability of new herbicide tolerant and vigorous hybrid varieties (Zhang *et al.* 2016), has stimulated a re-examination of several aspects of canola agronomy in recent years. Increasing the intensity of canola production and its frequency in the crop sequence generates a significantly increased risk of Blackleg, which requires increased attention to in-paddock stubble management, separation from nearby infected residues and the rotation of canola varieties according to major resistance genes (Van de Wouw *et al.* 2016). In Germany, where canola area doubled to 1.5 Mt from 1990 to 2013 at a time when total agricultural area declined, Hegewald *et al.* (2016) have demonstrated associated reduction in seed yield (12%) and oil yield (14.6%) associated with increasing the intensity of canola production, despite full fungicide programs applied to the crops. Although the cause of the yield decline in that study was not identified, similar studies in Canada using spring canola have demonstrated increased Blackleg incidence and root-maggot (Della spp.) damage were both implicated in yield decline as canola frequency increased (Harker *et al.* 2015). Sowing times, seeding technologies and plant density targets have also been re-evaluated in different regions in the face of climate, equipment and varietal changes in recent years (Brill *et al.* 2015). The traditional optimum sowing window of late-April to early May in eastern Australia has been re-evaluated by Kirkegaard *et al.* (2016) who reviewed 9 field studies (2002 to 2012) and conducted simulation analysis to investigate the benefits of earlier April sowing. The study demonstrated declines in seed yield (–6.0 to –6.5%), oil content (–0.5 to –1.5%) and water-use efficiency (–3.8 to –5.5%) for each week delay in sowing after early April, suggesting opportunities to develop new earlier sowing strategies with appropriate varieties to increase productivity. Brill *et al.* (2016) has shown that the risks of poor establishment in early-sown crops that are often sown deeply (>30 mm) into stored moisture, can be reduced by increasing the seed size, either using hybrid varieties with inherently larger seed or screening open-pollinated seed to >2 mm diameter. The higher cost and increased vigour of hybrid seed (Zhang *et al.* 2016) has also stimulated a re-evaluation of the optimum plant density required in different environments. Recommended plant density for canola was originally 50 to 70 plants/m^2 (Walton *et al.* 1999) but has gradually been revised down to 30 to 50 plant/m^2 (GRDC 2009) although the recommended rates vary with region and row configuration. In a study comprising 24 experiments in the low and medium rainfall areas in Western Australia, French *et al.* (2016) found a median economic optimum density of 32 plants/m^2 but this differed for hybrid Round-up resistant varieties (25 plants/m^2), hybrid-TT varieties (30 plants/m^2) and farmer-saved open-pollinated TT varieties (75 plants/m^2). Clearly there appears to be scope to adjust seeding rates according to variety choice and yield potential in different environments, but plant densities <20 plants/m^2 were less able to suppress annual ryegrass weeds, so maintaining adequate plant population is an important consideration in contemporary farming systems.

The changing position of canola in the rotation has increased the reliance of canola on nitrogen fertiliser which is often the most limiting nutrient in canola production, and the highest single input cost for many growers. In this issue, Norton (2016) provides a comprehensive review of the evolution of current N management in Australian canola. Overall there are few reported interactions between variety and N rates and most growers use a budgeted N-rate requirement of 80 kg N/t expected seed yield less indigenous N supply. Split applications provide options to delay decisions until there is more certainty about seasonal conditions with little loss in agronomic efficiency. The recognised reduction in seed oil content associated with N application (–0.03 to –0.13%/kg N) is generally offset economically by the yield response, but this was not the case in a recent study conducted in the low rainfall areas of Western Australia (Seymour *et al.* 2016). In that study, while seed yield reached 90% of maximum at 46 kg N/ha, gross margin was maximised at 17 kg/ha N due to the relatively small yield increase compared to oil content decrease in response to N in that environment, and the uncapped premium price paid for oil content >42%. Given that the relative yield and profit of hybrid compared to open-pollinated varieties declines in these lower rainfall environments, there will be ongoing efforts to reduce input costs in hybrid systems, and the continued availability of open-pollinated varieties will be advocated for those areas (Zhang *et al.* 2016). As for the recent innovations that have led to increased productivity in Canadian Prairie canola production systems (Morrison *et al.* 2016*a*), there is clearly an ongoing need to re-examine best management practices in the canola production systems in different regions of Australia, as farming systems evolve with new varieties and management practices.

Future directions – G × E × M approaches to canola productivity research

The workshop funded by the Grains Research and Development Corporation from which this Special Issue has been developed, signalled a desire for the industry to embrace a national Genotype × Environment × Management approach to improved canola productivity in Australia. This approach is in keeping with the original vision established at the first ARAB meeting in 1977, an acronym which then stood for 'Australian Research Agronomists and Breeders' (Buzza 2007), and was rooted firmly in the philosophy of shared knowledge and the importance of understanding genotype and management interactions to underpin productivity increases. New research projects targeting a range of diverse Australian environments, systems and end products aim to provide physiological understanding to underpin the different tactical agronomy decisions to optimise the productivity and profitability of modern canola varieties. As a consequence, the focus on understanding the phase durations, biomass production, partitioning, N and disease management of vigorous winter hybrid canola in the high rainfall zones of southern Australia, contrasts with the studies of low plant population, earlier and deeper sowing and reduced and delayed N management strategies developed for open-pollinated TT varieties in the low rainfall regions of western Australia. Yet the improved understanding of the genetic, phenological and physiological drivers of crop response described in this Special Issue can be shared across the country and the globe to keep pace with the predicted increase in global demand for canola. As the tools and techniques of modern molecular breeding and phenotyping increase the rate of development and diversity of traits available in new varieties, so too will modern precision management techniques and the suite of nutritional and crop protection products evolve. Envisaging and capturing the synergies offered by these innovations in the canola farming systems of the future will be the challenge for the next generation of canola researchers, if we are to maintain the impressive achievements of the past.

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