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Forage brassicas have potential for wider use in drier, mixed crop–livestock farming systems across Australia

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Abstract. Forage brassicas are currently widely used in temperate–humid livestock systems; however, they offer potential to diversify crop rotation and forage options in the drier, mixed crop–livestock zone of Australia. A literature review highlighted that in these hotter and more arid environments, forage brassicas are more likely to fit as autumn-sown forage crop where they offer an energy-rich, highly digestible feed source that could be used during periods of low production and nutritive value of other forage sources. However, brassicas can also accumulate several anti-nutritional compounds that require gradual introduction to livestock diets, thereby reducing potential health risks and optimising animal performance. Preliminary experimental and commercial evaluations in subtropical Australia found high production of some forage brassica genotypes (>5 t DM/ha with growth rates of 50–60 kg DM/ha.day), comparable or superior to widely used forage cereal or forage legume options. Several forage brassicas showed moderate to high resistance to the root-lesion nematode, *Pratylenchus thornei*, and hence are likely to provide break-crop benefits compared with susceptible species (e.g. wheat). Together, this evidence suggests that forage brassicas have significant potential for wider use in crop–livestock farming systems in Australia. However, research is needed to identify genotypic adaptation and to match different forage brassica genotypes to production environments or system niches, especially some of the new genotypes that are now available. There is also a need to develop regionally-relevant recommendations of agronomic and grazing management that optimise forage and animal production, and mitigate potential animal health risks.

Keywords: break crop, feed gap, grazing, nematodes, quality, rotation.

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Introduction

Forage brassicas (members of the Brassicaceae family) offer potential as alternative forage break-crop options for use across Australia's mixed crop–livestock farming zone. Although the benefits of break crops for reducing disease and weed pressures in subsequent cereal crops are well understood (Angus *et al*. 2015), in many regions, few profitable break-crop options exist. Canola (*Brassica napus* var. *annua* L.) has been widely adopted in areas with reliable annual rainfall >450 mm (Kirkegaard *et al*. 2016); however, in regions with less reliable winter rainfall and shorter growing seasons, canola is considered a risky crop because potential terminal drought and high temperatures during grain filling can reduce canola yield, quality and profitability (Robertson and Holland 2004). Forage brassicas could play a role similar to canola in crop rotations in these drier regions with much lower risk. In the past in many of these regions, ley pasture systems based on self-regenerating annual legume pastures were employed, but intensification of crop rotations has seen these systems decline (Howieson *et al*. 2000). Instead, there has been increasing use of annual forage crops (e.g. oats, *Avena sativa* L.; dual-purpose crops) or short-term pastures sown for 1–3-year phases (e.g. serradella, *Ornithopus* spp.; bladder clover, *Trifolium spumosum* L.; biserrula, *Biserrula pelecinus* L.), particularly in response to managing weed problems (Latif *et al*. 2019). In many regions, few annual forage-crop options are available apart from forage cereals such as oats, meaning that crop rotation is often limited. Hence, farmers are looking for annual forage-crop options that provide rotation benefits to both the crop and livestock enterprises with reasonably low management inputs or upfront costs.

Climatic variability across Australia's mixed crop–livestock zone also induces a high regularity of feed gaps (where livestock feed demands exceed on-farm forage supply). These feed gaps impose a large cost to livestock production, through the need either for expensive supplementary feeding, or to reduce or maintain lower stocking rates (Bell *et al*. 2018). Feed gaps occur either during autumn–winter when pasture growth is limited by low temperatures or moisture (e.g. subtropics), or during summer–autumn when much of southern Australia experiences a period of 'summer drought' of limited to no pasture growth (Moore *et al*. 2009). Hence, strategic use of forage brassicas that could be sown in late summer or early autumn to provide high-quality forage during these periods have a fit in many livestock systems across a broad range of environments (Bell *et al*. 2018). A major benefit of forage brassicas is their capacity to produce high biomass of high nutritive value over an extended period for use as a 'feed wedge', typically in summer–autumn when availability of other on-farm forage options is declining in quantity and nutritive value. Forage brassicas have long been used in this way in higher rainfall livestock systems, particularly in dairy or intensive beef or sheep systems, where they supplement other forages during periods of low pasture supply (Barry 2013; Ward and Jacobs 2013). For example, in New Zealand they are grown to provide a high-quality forage supply that can be used from early summer to late winter (de Ruiter *et al*. 2009*b*). A broad range of forage brassicas has been developed to fit different niches in these systems. Many of these forage brassicas are also available in Australia but have received little evaluation outside dairy and lamb-fattening systems in high-rainfall regions similar to those in New Zealand.

Research on the potential of forage brassicas outside the temperate–humid zone (i.e. with annual rainfall/potential evapotranspiration (aridity index) >0.5) is limited and is mostly focused on dual-purpose use of canola (e.g. McCormick *et al*. 2012). A major constraint to their wider use in the drier farming regions of Australia is lack of knowledge of production potential, use and management options, and potential systems benefits. In particular, forage brassicas in these regions may require a different use pattern, shifting from a summer-grazing crop sown in spring in temperate, humid environments (e.g. New Zealand) to a late-summer- or autumn-sown crop for winter grazing. Given the opportunities for alternative forage break crops outlined above, the purpose of this paper is to explore the wider application of forage brassicas in the drier Australian mixed crop–livestock zone (i.e. with aridity index 0.2–0.5). This is done by first reviewing the available literature through the lens of their application in these mixed-farming regions, including their likely environmental fit and use pattern, productivity potential, agronomic and management attributes, forage nutritional attributes, and potential impacts on animal production. We focus on literature available in similar environments in Australia, and relevant information from other geographies where appropriate. Then, in order to provide some experimental evidence of the potential of forage brassicas in drier and warmer environments than those where they are currently used, we report on a series of preliminary experimental studies conducted in environments with a short winter-growing season in southern Queensland (Qld) and northern New South Wales (NSW). These provide some preliminary evidence of the production of a range of commercial forage brassicas relative to other common or alternative winter-grown forage-crop options. At two of these sites we also assess the relative impacts of forage brassicas on root-lesion nematode (*Pratylenchus thornei*) populations. Finally, we propose areas of important knowledge gaps and research and development needs, in order to provide more robust advice and information to support the wider application of forage brassicas in Australia's mixed crop–livestock zone.

Review of literature

A diverse range of forage brassica genotypes is commercially available in Australia (Table 1), including forage rape (*B. napus* var. *biennis* L.), kale (*B. oleracea* var. *acephala* L.), hybrid brassicas (e.g. leafy turnips, *B. rapa* var. *rapifera* L. and *B. campestris* × *napus*; and raphanobrassica, *B. oleracea* var. *acephala* × *Raphanus sativus* L.), bulb turnips (*B. rapa* var. *rapa* L.), swedes (*B. napus* var. *napobrassica* L.), and forage radish (*Raphanus sativus*). The type of forage brassica selected is often dependent on the feed gap being filled, the livestock system being supported (Table 1), and environmental adaptation of the crop. Leafy forage brassica species including forage rape and leafy turnip can be strategically used as multi-graze crops that may be advantageous for finishing young livestock over summer–autumn (Lindsay *et al*. 2007; Barry 2013). Bulb turnips, swedes and kale, which are typically grazed only once, are often used as a feed stockpile where bulbs, taproots (turnips and swedes) or stems (kale) contribute a large portion of the grazable biomass.

In the past, forage brassicas (particularly bulb turnips) were utilised on ~70% of Australian dryland dairy farms (Moate *et al*. 1996), which predominate in the temperate high-rainfall zone of southern Victoria and Tasmania with some access to supplementary irrigation (Ward *et al*. 1998). However, the decline in total dry matter (DM) yields in common brassica crops, resulting from several factors including insect damage (Jacobs *et al*. 2001), has seen some replacement with other summer-active forage crops (e.g. warm-season grasses, chicory and plantain) (Jacobs and Ward 2011). In New Zealand, both bulb and predominately leaf-producing species are readily integrated into dairy and meat-livestock grazing systems (mostly lamb-finishing systems), with ~500 000 ha grown annually (Dairy NZ 2016).

Environmental fit for forage brassicas in the mixed farming zone

In temperate, humid environments, forage brassicas are most commonly used as a spring-sown crop to provide grazing during summer or early autumn (de Ruiter *et al*. 2009*b*). Kale, swedes and sometimes forage rape are sown in late summer to provide stand-over forage for winter grazing. However, the differences in climatic conditions between these environments and Australia's mixed-farming zone are likely to require different uses and growth periods for forage brassicas. We demonstrate this by comparing the seasonal aridity and temperatures of two temperate, humid environments in Australia and New Zealand where forage brassicas are commonly used with three example locations in Australia selected to represent the diversity of climatic conditions across the mixed crop–livestock zone (Table 2). These comparisons clearly demonstrate the hotter and more arid environments in Australia's mixed-farming regions where rainfall deficits occur for most of the year.

Table 1. Broad range of forage brassica genotypes commercially available in Australia, including their application and role in livestock systems

Species	Common cultivars	Application and roles
Forage rape (*Brassica napus* var. *biennis*)	Winfred, Ace, Goliath, Interval, Leafmore, Mainstar, Titan, Pillar, Rangi, SF Greenland, Stego	• Multi-graze crops (varies between cultivars) • Summer–autumn and autumn–winter grazing (region-specific) • Used in dairy, sheep and beef finishing systems
Bulb turnip (*Brassica campestris* var. *rapa*)	Green Globe, Rival, Barkant, York Globe, Dynamo, Australian Purple Top, Marco, New York, Manga, SF G2	• Single-graze crops • Both leaf and bulb portions better utilised via 'strip' grazing in summer–autumn and winter grazing • Typically used in dairy systems • Less prone to insect attack • Generally, less drought-resistant than forage rape
Kale (*Brassica oleracea* subsp. *acephala*)	Regal, Sovereign, Kestral	• Single-graze crop, but light grazing at the right time may allow regrowth • Best utilised via 'strip' grazing • Winter grazing • Intermediate types used in dairy and beef cattle and short types in sheep systems • More tolerant of cold conditions than other brassicas
Leafy turnip (*Brassica* spp.)	Hunter, Pasja II, Appin, SF Pacer	• Multi-graze crops
Raphanobrassica (*B. oleracea* var. *acephala* × *Raphanus sativus*)	Pallaton	• Spring, summer–autumn and winter grazing • Typically used in dairy and lamb finishing systems • Ready to graze earlier than forage rape • Single graze crops
Swede (*Brassica napus* subsp. *napobrassica*)	Domain	• Both leaf and bulb portions better utilised via 'strip' grazing • Winter grazing in areas with cold winters and wet summers; better bulb quality than turnips • Utilised in dairy, sheep and cattle systems
Forage radish (*Raphanus sativus* var. *oleiformis*)	Tillage radish, Graza	• Multi-graze crop, high grazing tolerance • Typically used in sheep and cattle finishing systems

Table 2. Comparison of climatic conditions of temperate, humid regions where forage brassicas are currently used (Lincoln, NZ and Hamilton, Victoria) with three example environments in the subtropical (Goondiwindi, southern Qld), temperate-subhumid (Temora, southern NSW) and Mediterranean (Katanning, south-west WA) regions of Australia's mixed-farming zone

Aridity index: ratio of rainfall to potential evapotranspiration. Shading indicates the relative aridity and temperatures between production environments and seasons

Climatic conditions	Temperate humid locations		Australia mixed farming zone		
	Lincoln, NZ	Hamilton, Vic.	Goondiwindi, Qld	Temora, NSW	Katanning, WA
Annual rainfall (mm)	631	681	609	527	478
Annual potential evapotranspiration (mm)	919	1308	2050	1640	1526
Aridity index					
Annual	0.69	0.52	0.30	0.32	0.31
Summer (Dec.–Feb.)	0.34	0.19	0.30	0.17	0.08
Autumn (Mar.–May)	1.04	0.54	0.30	0.36	0.33
Winter (June–Aug.)	2.74	1.70	0.40	1.02	1.37
Spring (Sept–Nov.)	0.49	0.60	0.25	0.34	0.28
Winter crop period (March–Aug.)	1.55	0.91	0.35	0.55	0.66
Summer crop period (Oct.–May)	0.41	0.27	0.28	0.20	0.12
Average temperature (°C)					
Summer (Dec.–Feb.)	16.2		26.3	23.2	21.5
Autumn (Mar.–May)	12.1	13.7	20.2	16.2	16.8
Winter (June–Aug.)	6.7	8.7	12.5	8.6	10.6
Spring (Sept.–Nov.)	11.3	12.0	20.3	15.0	14.6

The significantly more arid conditions, higher average temperatures, and high frequency of extreme heat events (e.g. on average, >30 days with maximum temperatures >35°C) from October to May in the Australian locations also demonstrates the challenge of using rainfed forage brassica as a late-spring- or summer-sown crop to graze in summer–autumn (October–May). Temperatures and climate aridity during summer and autumn in the Canterbury Plains of New Zealand are more like those experienced during autumn and winter (March–August) in Australia's mixed-farming regions. This clearly suggests that most forage brassicas are likely to fit these new environments as an autumn-sown crop that provides grazing in winter and early spring. However, there may be potential to examine options that could be sown in winter or early spring when soil moisture is often high, to be grown as a stand-over feed source to be grazed in summer.

Forage productivity potential

Research on forage brassicas in Australia has focused mostly on their use in the high-rainfall regions of the mixed crop–livestock zone, with limited information on the potential productivity of forage brassicas in low–medium-rainfall and subtropical regions. In the high-rainfall zone of southern-eastern Australian and New Zealand dairy regions, the average biomass production range is 5.0–25.8 t DM/ha for kale (de Ruiter *et al*. 2009*b*; Chakwizira *et al*. 2015*a*, 2015*b*), 3.0–14.0 t DM/ha for forage rape (Jacobs *et al*. 2006; Garcia *et al*. 2008; de Ruiter *et al*. 2009*b*), 2.0–14.3 t DM/ha for leafy turnip (Eckard *et al*. 2001; Jacobs *et al*. 2006; de Ruiter *et al*. 2009*b*), and 2.0–15.3 t DM/ha for bulb turnip (de Ruiter *et al*. 2009*b*; Rowe and Neilsen 2010, 2016). The relative productivity of forage brassica types appears to be heavily influenced by local environmental and soil conditions and potentially genotype (i.e. cultivar differences within species). Production levels recorded in the medium-rainfall zone are much lower than in these more humid environments, but relatively little research has been conducted recently in these regions; most was conducted >30 years ago with superseded genotypes (Table 3). A recent study demonstrated very high production potential in spring of 14 t DM/ha from a new cultivar sown in early April in the medium-rainfall zone near Wagga Wagga with supplementary irrigation to approximate average season conditions (140 mm rain plus 100 mm irrigation) (McGrath *et al*. 2020). The current data on biomass production of forage brassicas in Australia's mixed crop–livestock region are promising but limited (Table 3), and further validation of a wider range of modern genotypes is needed.

For forage brassicas to be successful and viable as a forage break crop in Australia's mixed crop–livestock zone, they would need the capacity to augment other forage sources by providing feed at critical times and/or provide higher forage quality. Research concentrating on the use of dual-purpose canola for both forage and grain purposes has reported forage production of 1.1–6.8 t DM/ha (typically 2.0–4.5 t DM/ha) in diverse rainfall environments (Kirkegaard *et al*. 2008*a*, 2012; McCormick *et al*. 2012; Sprague *et al*. 2014, 2015). However, in order to reduce grain-yield penalties, grazing of dual-

Table 3. Forage brassica biomass potential across varying production environments in the Australian medium (300–450 mm mean annual rainfall) and high (>450 mm mean annual rainfall) rainfall zones of the mixed-farming region

Species	Cultivar	Location	Coordinates	In-crop rainfall + irrigation (mm)	Max. biomass (t DM/ha)	Season	Reference
			Southern NSW and ACT				
Forage rape	Stego	Wagga Wagga, NSW	35°03′S, 147°18′E	357[A]	14.0	Spring–summer	McGrath *et al*. 2020
Forage rape	Winfred			119	2.1	Winter	Kirkegaard *et al*. 2008*b*
Leafy turnip	Hunter	Canberra, ACT	35°12′S, 149°04′E	~270	4.7	Early summer	Kelman and Dove 2007
			Central NSW				
Forage rape	Dwarf Essex	Euchareena, NSW	33°20′S, 149°10′E	280–368[B]	1.2–2.0	Winter	Gramshaw and Crofts 1969
					2.0–2.6	Early spring	
			South-west Victoria				
Forage rape	Titan	Ballarat, Vic.	37°56′S, 143°95′E	~125	4.5–5.6	Summer	Thomas *et al*. 2015
	Greenland				5.2–5.5		
	Winfred	Gnarwarre, Vic.	37°04′S, 148°94′E	~105	2.8	Summer	Paridaen and Kirkegaard 2015
			Northern NSW and Qld				
Forage rape	Rangi	Armidale, NSW	30°61′S, 151°55′E	~115–260	2.3–2.8	Winter	Spurway *et al*. 1974
					0.8	Early spring	
	Dwarf Essex	Theodore, Qld	24°50′S, 149°48′E	250 180	1.5	Autumn	French *et al*. 1988
					1.4	Winter	
	Giant kangaroo	Armidale, NSW	30°61′S, 151°55′E	168–310[C]	2.1–2.7	Winter	Wheeler 1963
					4.1–4.4	Early spring	
Kale	Thousand head				0.4–2.5	Winter	
					1.5–4.5	Early spring	
	Hungry gap				1.9–2.4	Winter	
					2.9–3.1	Early spring	

[A] Irrigated at two points in late September and October.

[B] Rainfall in the growing seasons of 1965 (280 mm) and 1966 (368 mm).

[C] Rainfall in the growing seasons of 1959 (168 mm) and 1960 (310 mm).

purpose canola is ceased before bud elongation, which typically occurs in mid–late July (Sprague *et al*. 2014, 2015). Long-season winter cultivars of canola suited for dual-purpose application have been shown to provide 1200–2500 dry sheep equivalent (DSE) grazing days/ha reliably over a grazing window of 60–90 days across a range of environments (Lilley *et al*. 2015; Sprague *et al*. 2015). Forage brassicas would also need to compete with the low-cost option of sowing left-over canola seed for the purpose of winter grazing, a practice that is increasingly common in lower rainfall regions (A Fletcher, pers. comm.). Forage brassicas may also become a viable alternative by providing additional livestock-system benefits over the summer–autumn feed gap (e.g. late-season grazing for lamb finishing; McGrath *et al*. 2020) that are not possible with dual-purpose crops and some typical annual forages (e.g. *Trifolium* spp. and forage oats). However, the potential of spring-sown winter canola to fill a similar niche and allow flexibility to produce a grain crop the following year needs also to be considered (Paridaen and Kirkegaard 2015).

Agronomic management

Forage brassicas are suited to a range of soil types of varying fertility and have few specific adaptations to soil characteristics in New Zealand (de Ruiter *et al*. 2009*b*). However, their adaptation to Australian soils is not well understood, particularly their suitability where more hostile soil constraints occur (e.g. acidity, salinity, sodicity, boron or aluminium toxicity). The capacity of forage brassicas to access deep, stored soil moisture will be more critical in drier growing conditions where the soil profile is replenished less by in-crop rainfall. When they are grown as a winter crop in high-rainfall zones, several forage brassicas (e.g. kale and forage rape) have deep taproots and have been noted to utilise deep subsoil moisture if it is available. Fodder radish was shown to have roots to a depth of 2.4 m, much deeper than winter rye (*Secale cereale* L.) (1.1 m) and Italian ryegrass (*Lolium multiflorum* L.) (0.8 m) (Kristensen and Thorup-Kristensen 2004). Long-season dual-purpose canola sown in early autumn (e.g. March) has been found to extract water to 2 m in grazed and 3.2–4.0 m in ungrazed crops (McCormick *et al*. 2012; J Kirkegaard pers. comm.), and similar depths of extraction may be expected in forage types. This ability to explore subsoils suggests that these species have greatest application on deeper soils with higher water-holding capacities. However, other forage brassicas (e.g. turnips, swedes) are noted to have less extensive root systems (de Ruiter *et al*. 2009*b*) and, hence, would presumably be less able to utilise deeper soil moisture, making them more reliant on in-crop rainfall or irrigation.

For high productivity, forage brassica crops require high levels of nutrient supply, particularly nitrogen (N), potassium (K), sulfur (S) and phosphorus (P) (Wilson *et al*. 2006; Chakwizira *et al*. 2009; de Ruiter *et al*. 2009*b*). For example, high rates of fertiliser are recommended for forage brassicas in high production regions of New Zealand: 50 kg P/ha at the time of establishment and 250–500 kg N/ha applied in a 50 : 50 split at 30–40 days and 60–80 days after crop emergence (de Ruiter *et al*. 2009*b*). Soil fertility contributes to large variation in biomass production within and across different growing environments (Wilson *et al*. 2006; Table 3). Hence, it is important to determine the timing and rate of fertiliser application that maximise economic return and minimise losses or wastage (Chakwizira *et al*. 2011). Further, nitrate can accumulate in the foliage of many forage brassicas under high N availability, posing risks of nitrate toxicity in livestock, and thus, N management to match growth potential is essential (Jacobs and Ward 2008; Fletcher *et al*. 2010*b*; Fletcher and Chakwizira 2012*a*, 2016). In New Zealand, farm decision-support tools have been developed to assist with site- and season-specific N and P application rates and management for forage brassica crops that will optimise fertiliser efficiency and mitigate livestock risks and environment losses (Wilson *et al*. 2006), but it is unclear how applicable the underpinning calculations are in other production environments.

Until recently, few herbicides have been registered for use in forage-brassica crops in Australia; this may impose a major difficulty for weed management and limit use of forage brassicas in cropping systems. Several pre- and post-emergent options are now available in New Zealand. Recent developments of herbicide-tolerant genotypes and new herbicide registrations have improved this situation. Several forage-brassica genotypes (leafy turnip, forage rape, bulb turnip and swede) with tolerance to chlorsulfuron (750 g/kg; Telar) have been developed and commercially released in New Zealand with Cleancrop technology (Dumbleton *et al*. 2012). However, in Australia, chlorsulfuron is currently registered only for cereal crops and significant investment is required to fulfil regulatory requirements to bring these products to market. A new herbicide ForageMax (halauxifen + aminopyralid; Corteva AgriSciences Australia, Sydney) for in-crop broadleaf weed control has recently been registered for use in Australia for forage brassicas and dual-purpose canola (Wells 2014; Wells and Plater 2018), which will aid weed management in forage brassicas.

Sowing methods and recommendations are well established in high-rainfall production environments (de Ruiter *et al*. 2009*b*), but several of these aspects may require further attention to be relevant in more arid production regions. For example, most forage brassicas have small seeds (<4 mg), and recommended sowing depth for forage brassicas is 10–15 mm in New Zealand (Salmon and Dumbleton 2006; de Ruiter *et al*. 2009*b*). However, in environments with less reliable follow-up rainfall and higher evaporative demand, such shallow seeding would pose significant risk to establishment. Research has shown that sowing to 25 mm depth is equally effective for several forage brassicas (Salmon and Dumbleton 2006), but understanding is lacking about the potential for deeper sowing into soil moisture to protect germinating seeds from rapid dehydration. Similarly, seeding rates are often recommended to establish relatively high plant populations: 20–30 plants/m^2 for bulb turnips and swedes, and 80–100 plants/m^2 for leafy turnips, rape and kale (de Ruiter *et al*. 2009*b*). In more arid environments with less available water and nutrients, it is likely that lower sowing rates and plant populations may optimise the input costs of seed against production potential. Yet, higher densities may help with forming early canopy cover to compete with weeds and provide opportunities for earlier grazing. Finally, in temperate, higher rainfall environments, forage brassicas are reported to have wide sowing windows from spring through to late autumn, providing greater flexibility and enabling them to be used to target different periods of forage supply (Jacobs *et al*. 2001; Ayres and Clements 2002; Barry 2013; Brown *et al*. 2007; Rawnsley *et al*. 2013; Ward and Jacobs 2013). However, these sowing windows are likely to be more limited in the mixed-farming zone, probably to exclude summer periods when temperatures and evaporative demand are significantly higher than in temperate regions (Table 2).

Forage brassicas are susceptible to a range of invertebrate pests and crop diseases, but the incidence and severity of these is largely driven by environmental conditions and on-farm management practices (e.g. trash removal, seed treatment and chemical usage, including timing of application and methods; de Ruiter *et al*. 2009*b*). Extensive guidelines that have been developed to manage these issues in high-rainfall environments (e.g. Berry 2000; Harvey 2007; Rimmer *et al*. 2007; de Ruiter *et al*. 2009*b*) will still be relevant in lower rainfall situations; however, damage or infestation thresholds for treatment are likely to be lower in line with the lower production expectations. Diamondback moth (*Plutella xylostella*) is likely to be an important issue during establishment periods, particularly where canola is also widely grown (Furlong *et al*. 2008). However, later infestations may be managed by increasing grazing pressure to avoid large losses and expensive insecticide applications, and to minimise applications that would increase problems with insecticide resistance in diamondback moth. The fungal disease blackleg (also known as dry rot; caused by *Leptosphaeria maculans* L.) is a major disease in most forage brassicas (Yu *et al*. 2005; de Ruiter *et al*. 2009*b*) as it is in canola (Van De Wouw *et al*. 2016) and hence is likely to require management to avoid transmission of the disease to canola crops in the mixed crop–livestock zone. Blackleg severity increases in grazed dual-purpose canola compared with ungrazed crops, so this may be the case in forage brassicas (Sprague *et al*. 2010).

Nutritional value and grazing management for livestock production

Forage brassicas provide forage with high nutritive value for livestock and generally outperform other grass-based forages at the same point in the growing season in terms of digestibility and metabolisable energy (ME) concentration, while providing comparable levels of crude protein (CP) (Fig. 1; Barry *et al*. 1984; Lindsay *et al*. 2007; Sun *et al*. 2012). Differences in plant allocation to leaf and petiole, stem and bulb fractions among forage brassica species influence their total nutritive value. The biomass of leafy turnips comprises almost entirely leaf and petiole, whereas bulb turnips offer a ~60 : 40 leaf : bulb ratio. Forage rape typically has a higher leaf to stem ratio of 70 : 30 compared to kale with 35 : 65 (Rowe and Neilsen 2010; Westwood and Mulcock 2012).

The high ratio of readily fermentable to structural carbohydrates in brassica plants facilitates their rapid and extensive degradation in the rumen (Sun *et al*. 2012; Daza

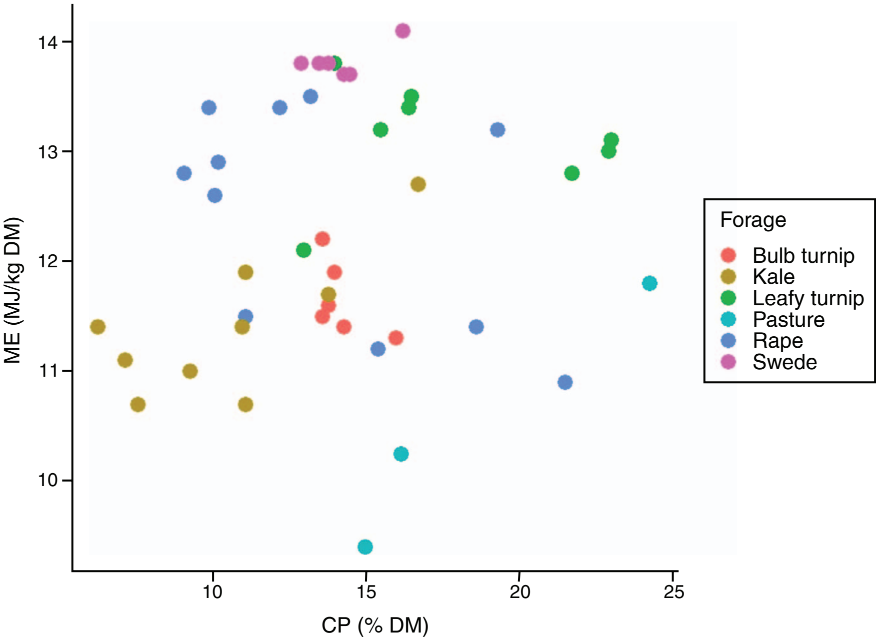

Fig. 1. Nutritive characteristics of forage brassicas and pasture (ryegrass–clover) as measured in field trials in Australia (Ward and Jacobs 2013; Thomas *et al*. 2015) and New Zealand (Lindsay *et al*. 2007; Sun *et al*. 2015; Westwood and Mulcock 2012). ME, Metabolisable energy; CP, crude protein; DM, dry matter.

et al. 2019). High ME concentrations are correlated with reduced methane emissions by sheep. Feeding rape and swedes (with >13 MJ/kg DM) to sheep in New Zealand reduced methane production by >20% per unit DM intake compared with ryegrass (with 9.4 MJ/kg DM) at the same time of year (Sun *et al*. 2012); further experiments confirmed consistent reductions in methane yield from livestock fed brassicas compared with pasture (Sun *et al*. 2016). However, forage brassicas often have neutral detergent fibre (NDF) concentrations <30% DM, which is considered suboptimal for rumen function, particularly when content of highly digestible carbohydrates (e.g. soluble sugars) is also high. Predictions of liveweight gain (LWG) are typically higher in livestock grazing brassicas than temperate grass pastures in the same environment, but animal performance varies widely and is often lower than would be expected for the ME concentrations. Reported growth rates for livestock grazing forage brassicas range from 19 to 320 g/day for sheep (Barry *et al*. 1981*a*; Reid *et al*. 1994; Campbell *et al*. 2011) and from 393 to 1120 g/day for cattle (Woods *et al*. 1995; Atkins *et al*. 2020). Some studies have shown an initial period of weight loss or low growth rate when livestock are moved from pastures onto a brassica crop (Barry *et al*. 1981*b*; Woods *et al*. 1995), which may be responsible for variable growth rates over different grazing periods.

Several mechanisms have been suggested for the apparent underperformance of ruminant livestock on brassica forage, but the primary driver it is thought to be depressed voluntary feed intake in response to plant secondary metabolites (Duncan and Milne 1990; Barry 2013). Brassicas contain significant levels of glucosinolates, S-methyl-cysteine sulfoxide (SMCO), inorganic sulfate and nitrates, which have anti-nutritional degradation products (Barry 2013). In the rumen, glucosinolates can produce nitriles and isothiocyanates (suspected depressants of voluntary feed intake), with the latter further degrading to goitrogenic compounds that reduce the uptake of iodine by the thyroid (Louda and Mole 1991; Tripathi and Mishra 2007). Glucosinolate-derived nitriles in turnip and forage rape have also been implicated in secondary photosensitisation of cattle (Collett *et al*. 2014). The breakdown of SMCO during ruminal fermentation results in dimethyl sulfide, which inactivates haemoglobin, leading to anaemia and reduced voluntary feed intake and animal growth (Barry *et al*. 1984; Duncan and Milne 1990). Together glucosinolates, SMCO and inorganic sulfate contribute to a high concentration of S in brassicas, reducing the bioavailability of copper (Cu) and selenium (Se), which are essential trace elements for ruminants (Barry 2013; Spears 2003). This could further exacerbate the effect of low Cu concentrations in brassica plants compared with pasture (Reid *et al*. 1994). The high water content of brassicas could also inhibit DM intake (Lambert *et al*. 1987), with DM concentrations in the range of only 7–10% for bulb types and 12–17% for leafy types (Sun *et al*. 2012; Westwood and Mulcock 2012; Daza *et al*. 2019; Keim *et al*. 2019).

Nitrates tend to accumulate at higher levels in forage brassicas than other forages, particularly when excess soil N is available (Fletcher *et al*. 2010*b*; Fletcher and Chakwizira 2012*b*). Forage brassicas with nitrate concentrations of 2000 mg NO_3/kg DM may impede animal performance, with concentrations of 20 000 mg NO_3/kg DM causing death in livestock (Nichol 2007). In addition to the rate and timing of nitrogenous fertiliser application, nitrate accumulation in brassicas appears to be subject to significant seasonal effects, with greater nitrate concentrations having been observed in crops of turnip, swede, rape and kale when grown in autumn than in spring (Guillard and Allinson 1989). This could be attributable to higher soil mineral N in association with cooler temperatures and reduced light availability in autumn, which may decrease photosynthetic activity and thus the rate of conversion of nitrates to amino acids; the same mechanism is believed to cause nitrate toxicity in animals grazing brassicas on overcast days (Nichol 2007). Other authors have also noted a longer growing period in their spring-grown crop, which may have reduced nitrate concentrations because this tends to happen as plants mature. Conversely, summer droughts can reduce growth rates and lead to nitrate accumulation (Chakwizira *et al*. 2015*b*). Although these various issues for animal health and productivity are known to occur in forage brassicas, their expression is not consistent, and the environmental or management stimuli leading to problems are not well understood. However, some animal-health risks may be reduced in newer brassica cultivars such as kales with lower glucosinolate concentrations (Barry 2013) and raphanobrassica which lacks a specific maturity requirement.

Efforts to improve animal performance on brassicas have routinely involved supplementing the diet with minerals, protein or additional feed of higher fibre and/or DM content (with an added benefit of diluting brassica toxins). Responses of animals to hay, Cu, Se and iodine supplementation have been recorded but effects are typically short-lived (i.e. the first few weeks on brassica crop) and not observed consistently among experiments or years in the same experiment (Barry *et al*. 1981*b*; Lambert *et al*. 1987; Cassida *et al*. 1994; Reid *et al*. 1994). For example, applying a ruminal bolus containing cobalt, Se, Cu and iodine to pregnant dairy heifers on kale improved their trace-mineral blood profiles and increased body condition, but did not affect liveweight (Atkins *et al*. 2020). Similarly, orally dosing lambs on forage rape with copper oxide influenced health indicators measured in the liver and blood but did not improve animal growth rate (Dove and Milne 2006). However, in the same study, lambs supplemented with protein showed significantly greater growth rates, warranting further investigation. Current recommendations for transitioning livestock onto brassicas are to provide restricted access (1–2 h/day increasing to full access over 7–10 days) and supplement with hay (Ayres and Clements 2002).

Grazing management to optimise animal performance and brassica DM yield differs among forage brassica species and cultivars. Bulb turnips and swedes are grown to accumulate biomass until they reach full maturity before being suitable for grazing and only provide a single grazing opportunity, because the bulbs are consumed by livestock. However, these plant types provide an advantage of being able to be used as stand-over forage without losing biomass and nutritive value for an extended period. Different genotypes of bulb turnips reach grazing maturity at different times: 60–90 days after sowing (DAS) for early-maturing, 80–100 DAS for mid-maturing, and 90–120 DAS for late-maturing species (de Ruiter *et al*. 2009*b*). Because of this once-off grazing of bulb brassicas, grazing management often focuses on allowing the plant to reach maximum biomass and nutritive value before grazing commences, to ensure optimal utilisation. Forage rape and brassica hybrids (e.g. leafy turnips and raphanobrassica) can be grazed several times, but some erect genotypes are known to have limited regrowth capacity after the initial grazing. In leafy brassicas, ME and CP concentrations decrease as the crop matures and the proportion of stem increases, and accordingly, lower rates of intake and animal growth are consistently reported for forage rape with lower leaf : stem ratios (Dove and Milne 2006; Judson *et al*. 2013; Thomas *et al*. 2015). For most forage rape crops, it is recommended that grazing commence at 70–100 DAS, often indicated by the change in leaf colour from green–blue to purple–bronze (Ayres and Clements 2002). Hybrid leafy turnips grow rapidly and can be grazed at 40–70 DAS (Ayres and Clements 2002); kale can be grazed at any time, but is generally only grazed once, with optimal grazing maturity at 125–180 DAS (de Ruiter *et al*. 2009*b*).

Crop rotation implications

Forage brassicas are likely to offer benefits like canola and mustards in terms of crop disease and grass-weed management when used as a rotation crop with cereals, although there is almost no direct evidence of this in the literature. Over many studies, break-crops of canola or mustard have been found to increase grain yields of subsequent wheat (*Triticum aestivum* L.) crops by 0.6–0.8 t/ha or ~20% on average (Angus *et al*. 2015). Glucosinolates occur in both roots and shoots, and some of their breakdown products have biocidal properties that can naturally biofumigate the soil against soil-borne fungal pathogens and nematodes, which are common issues in cereal–crop rotations (Sarwar *et al*. 1998; Gimsing and Kirkegaard 2009; Dutta *et al*. 2019). These benefits may be conferred by simply including brassicas in the crop rotation or by incorporating brassica plant material into the soil (Dutta *et al*. 2019). However, the extent to which forage brassicas provide biofumigation is unclear, especially as most grazing varieties have been bred for lower glucosinolate concentrations (Kirkegaard and Sarwar 1998). In addition to their potential as soil biofumigants, dense canopies of brassica crops and residues with low carbon (C) : N ratio are known to accelerate the breakdown of cereal residues left on the soil surface in no-till farming systems and, hence, to reduce the persistence of residue-borne diseases (e.g. *Fusarium* spp.). Rapid decomposition of canola residues is also known to increase N availability in subsequent grain crops compared with those following cereals (Kirkegaard *et al*. 1999). Broadleaf forage brassicas are highly competitive with weeds and provide opportunities for both chemical and non-chemical grass-weed control (e.g. grazing), making brassicas an ideal break crop in cereal-dominated cropping systems (Beckie *et al*. 2008). Large-rooted brassicas such as tillage radish and canola are also known to break down subsoil physical constraints in problem soils (Chen and Weil 2010), and similar benefits may be possible from several forage brassica species. However, there is a risk that forage brassicas may dry the soil profile more than other crops (especially short-season grain crops), which may pose additional risks for subsequent crops in lower rainfall environments (Kirkegaard *et al*. 1994).

Summary

There has been little research examining the application of forage brassicas outside their current regions or production systems. Despite this, there is strong evidence that forage brassicas have many favourable attributes that would suit wider application in the drier mixed-farming regions of Australia. They offer potential for high forage DM yields of high nutritive value for livestock, flexibility in their agronomic (e.g. sowing time) and grazing management, and potential rotation benefits akin to oilseed brassicas. A large range of genotypes is available but there is little information on their likely adaptation to more arid environments or when integrated into cropping systems. Despite opportunities to improve livestock growth rates during feed gaps, several potential animal-health risks require practical solutions. Sound management recommendations on most aspects of forage brassica use are available that will be mostly applicable, but some regionally relevant aspects of agronomic management and genotype suitability are lacking. Finally, there are several known aspects of forage brassicas that offer promising benefits for crop rotations and livestock feeding systems, but these currently lack validation and quantification in mixed farming systems.

Preliminary studies

Materials and methods

The potential of forage brassicas in mixed crop–livestock systems was further assessed in a series of preliminary experiments and on-farm evaluations conducted to provide evidence on the productivity of forage brassicas relative to other winter-grown forage options. All research activities were geographically focused in the subtropical summer-dominant rainfall zone in southern Qld and northern NSW but across different environments in this region, where little work has been done previously with modern forage brassica genotypes (Fig. 2). These subtropical, mixed-farming regions experience much warmer temperatures with low and variable rainfall over winter than the typical production environments for forage brassicas, and hence provide a good testbed to challenge their potential wider adaptation. Three experiments compared the DM production of a range of commercial forage brassica genotypes with other winter-growing forage benchmarks under current recommended management (Table 4). Root-lesion nematodes (*Pratylenchus thornei*) are an increasing threat to grain-production systems in this region where there is an over-reliance on cereals, and there are limited crop-rotation options to help with nematode management (Owen *et al*. 2013). Like canola, forage brassicas are thought to be resistant to root-lesion nematodes, so at two of these sites, the impacts of forage brassicas on existing

Fig. 2. Locations of experimental (○) and on-farm evaluation (●) sites in preliminary studies in subtropical mixed crop–livestock zone of Australia.

Table 4. Growing details and site characteristics for the three experimental sites (Expts 1–3) and five on-farm demonstration sites in southern Queensland and northern New South Wales between 2011 and 2014

PAWC, Approximate plant available water-holding capacity for wheat (obtained from APSoil database for nearest locations with common soil types, https://www.apsim.info/apsim-model/apsoil/). Locations are shown in Fig. 2

Site location	Year	Sowing date	In-crop rainfall (mm)	N applied (kg/ha)	Soil type	PAWC (mm) to 1.8 m	pH (0–0.1 m)	OC% (0–10 cm)	Colwell P (mg/kg)
Experimental sites									
Expt 1. Pilton, Qld	2011	21 May	132	0	Black Vertosol	216	5.8	1.86	45
Expt 2. Formartin, Qld	2012	21 June	171	100	Black Vertosol	288	8.7	0.96	15
Expt 3. Tulloona, NSW	2013	5 June	83	0	Grey Vertosol	238	8.2	0.92	7
Commercial participatory evaluations									
Meandarra, Qld	2012	~15 June	64	0	Grey Vertosol	217	8.6	0.79	17
Delungra, NSW	2013	12 April	103	25	Black Vertosol	139	6.7	1.65	16
Wallumbilla, Qld	2013	18 March	219	0	Grey Vertosol	181	8.7	0.76	9
Roma, Qld	2013	11 March	66	0	Grey Vertosol	125	7.6	1.05	13
Chinchilla, Qld	2014	~8 March	185	0	Black Vertosol	185	8.5	0.87	34

populations were assessed to gain information about the potential for break-crop benefits in crop rotations. In addition, five commercial participatory evaluations were conducted to test the relative productivity of forage brassicas compared with widely used forage cereals (oats and barley, *Hordeum vulgare* L.), with the aim of providing information on likely challenges and the robustness of forage brassicas under real-world management rather than in experimental plots (Table 4).

Site locations and conditions

All evaluation sites were in the subtropical mixed-farming region of Australia in farmer's fields on soils used for grain or forage cropping (Table 4). The Pilton experimental site (Expt 1) had been sown to forage oat the previous year and had been tilled before sowing. The Tulloona and Formartin experimental sites (Expts 2 and 3, respectively) had grown wheat the previous year and had been managed with full stubble retention with an 8-month fallow prior. Expt 3 had been managed to bring nematode numbers to above the economic threshold (>2000 *Pratylenchus thornei*/kg soil) by growing a susceptive wheat cultivar the previous year. The five commercial participatory evaluation sites had been previously managed in preparation for an autumn-sown cereal forage crop including a period of weed-free summer fallow to accumulate soil moisture and mineral N. All on-farm evaluation sites were sown in fields with a history of annual cereal forage crops (mainly forage oat and barley).

The experimental locations experience a climate with a summer-dominant rainfall, with a short winter growing season due to low or variable rainfall between May and October. Consistent with this expected climate, dry winter growing seasons were experienced across the three experimental and five on-farm evaluation site years, with 80–170 mm rain occurring in-crop (Table 4). Accumulating soil moisture and mineral N during fallow periods is a critical practice in farming systems in this region; all experiments were preceded by a 6–9-month fallow period, and plant-available soil-water at sowing was >100 mm in all cases.

Experimental evaluations

The three experimental evaluations included a selection of nine or ten entries of different forage options, including four or five forage brassicas that were compared with four or five other forage options (cereals and legumes). These forage entries were selected based on the local interests of farmers and advice from seed companies. The forage brassicas used were based on initial recommendations of seed companies and included six commercially available varieties (leafy turnip, kale and four forage rape varieties), although inconsistent representation of all genotypes occurred owing to lack of seed availability in some cases (Table 5). In Expts 1 and 2, forage cereal references of oats, barley or wheat were included for comparison with forage brassicas; however, in Expt 3, because of the prior application of a residual herbicides that would affect grasses, a cereal reference was removed. The forage cereal varieties in Expt 2 were chosen because of suspected differences in root-lesion nematode tolerance and resistance. A selection of commercial forage legumes was also included at all experimental sites as other forage alternatives, to provide a further comparison with forage brassicas (Table 5).

Experiment 1 was implemented as a stratified strip-plot design with plots 6 m wide by 100 m long with different entries sown down a slope, so that replicates ($n = 5$) were taken across the slope. The site had a high population of broad-leaf weeds (turnip weed, *Sisymbrium thellungii*; bell vine, *Ipomoea* spp.; and New Zealand spinach, *Tetragonia tetragonioides*) that germinated after sowing; these were difficult to control with herbicides owing to the diversity of different species being grown in proximity. Biomass was measured only once, just before grazing (11 September, 114 DAS). Expt 2 was sown in a randomised block design with four replicates per entry and plots 2 m wide by 10 m long. Biomass was measured at maturity of the wheat grain-crop reference (12 October, 111 DAS). Expt 3 was sown in a randomised block design with three replicates per entry and plots 2 m wide by 8 m long. Biomass was measured on two occasions; the maximum biomass corresponding with 99 DAS (12 September) was reported.

All species within all experiments were sown at ~25 mm depth and a row spacing of 330 mm, with a cone seeder fitted with knife-points and press-wheels. Seed was accompanied by a

Table 5. Genotypes of forage cereals, brassicas and legumes and their corresponding sowing rates used across three preliminary experimental evaluations conducted in southern Queensland and northern New South Wales

Genotypes evaluated	Sowing rate (kg/ha) Expt 1 Pilton	Expt 2 Formartin	Expt 3 Tulloona	Established density (no. of plants/m^2) in Expt 2
Forage cereals				
Oat cv. Genie	–	70	–	146
Barley cv. Urambie	50	–	–	–
Wheat cv. Wedgetail	50	–	–	–
Wheat cv. Mackellar	–	70	–	82
Wheat cv. Kennedy	–	70	–	70
Forage brassicas				
Rape cv. Winfred	3.0	2.0	3.5	27
Rape cv. Titan	5.0	–	–	–
Rape cv. Leafmore	–	4.0	3.5	84
Rape cv. Interval	–	4.0	3.5	50
Leafy turnip cv. Hunter	5.0	4.0	–	20
Kale cv. Sovereign	3.0	4.0	3.8	66
Forage legumes				
Field pea cv. Morgan	100	70	95	15
Field pea cv. Hayman	–	–	68	–
Field pea cv. Percy	–	–	101	–
Common vetch (*Vicia sativa* L.) cv. Blanchefleur	30	–	8.0	–
Purple vetch (*Vicia benghalensis* L.) cv. Popany	–	–	8.0	–
Sulla cv. Wilpena	5.0	–	8.0	–

starter fertiliser at 25 kg/ha (Granulock Z: 11% N; 21.8% P; 4% S; 1% Zn; Incitec Pivot, Melbourne), but only one experimental site was provided with additional N fertiliser (Table 4). Experimental sowing rates used were those recommended by seed providers, although adjustments were made according to seed size and germination-test results (Table 5). In some cases, the sowing rates were adjusted based on seed sizes to achieve equivalent seed rates for individual genotypes (e.g. field pea (*Pisum sativum* L.) in Expt 3). Expts 1 and 3 achieved adequate plant stands, in that all crops achieved rapid and effective groundcover; however, establishment densities were not quantified. In Expt 2, which had very dry conditions after sowing, variable and reduced populations were found in some genotypes (e.g. Hunter leafy turnip and Winfred forage rape) (see Table 5). Soil-water and nutrient availability was not determined before sowing but most sites had historical information on their soil fertility and water-holding capacity (Table 4).

At each of the experimental sites, measurements of DM production were taken at ~100 DAS, corresponding with peak biomass production. This may underestimate the productivity of some species suited to multiple grazings over a longer growing season. In each replicate plot, two quadrats of 0.5 m by 1.0 m (i.e. 1 m^2) were cut to ground level and bulked for each replicate, dried at 80°C for 3–5 days to determine DM per ha. Below-ground components were not measured because no bulb-producing species were tested.

Root-lesion nematode populations

For Expts 2 and 3, root-lesion nematode populations were assessed at the end of the growing season under the forage brassicas and other forage crops. A susceptible crop control of wheat cv. Kennedy was used in Expt 2, and the surrounding field of chickpea (*Cicer arietinum* L.) cv. Hattrick in Expt 3. Bulked soil samples were taken in each replicate block at sowing and then from individual forage plots after final biomass cuts and harvest of grain-crop controls. In Expt 3, 10 surface-soil samples (0–150 mm) of 10 mm diameter were collected and analysed by the SARDI PREDICTA molecular diagnostics service (https://pir.sa.gov.au/research/services/molecular_diagnostics) to provide concentrations of specific combinations of DNA markers correlated with direct measures of *P. thornei* populations (Fanning *et al*. 2018).

In Expt 2, each plot had two 45-mm-diameter soil cores taken to a depth of 1500 mm with a vehicle-mounted hydraulic soil coring rig. Cores were separated into depth intervals (0–150, 150–300, 300–450, 450–600, 600–900, 900–1200 and 1200–1500 mm) and bulked within each plot. Samples were split to determine soil moisture and nematode populations throughout the whole soil profile. Gravimetric soil moisture content was measured from a 100-g soil subsample for each depth layer determined from mass of samples before and after drying in an oven at 105°C for 2 days. Samples for nematode determination were kept <20°C during the day of collection and were then refrigerated at 4°C until processing occurred (it took 14 days after sampling to process the 196 samples). Samples were broken into <10-mm fragments, and a 150-g subsample was used for nematode extraction following the Whitehead extraction method (Whitehead and Hemming 1965). Briefly, this involves submerging a soil sample of known weight in water to extract the nematodes and then capturing them over a 20-μm mesh sieve, before using a compound microscope to identify and count the populations of key nematode species. In this study, the root-lesion nematode *P. thornei* was the focus.

Commercial participatory evaluations

The commercial-scale evaluation sites were sown by the collaborating farmers as part of their field operations for sowing their forage cereals. A portion of the sown field (0.5–2 ha) was sown to forage brassica adjacent to the remainder sown to a forage cereal crop. Sowing rates for forage brassicas (2.5–3.0 kg/ha) and forage cereals (25–35 kg/ha) were lower than in the experiments, although some initial difficulties in adjusting seed-flow rates through commercial seeders meant that variable plant densities were achieved. No herbicide weed control was applied in these fields and no fertilisers were applied.

Biomass production at commercial evaluation sites was measured just before the initiation of grazing (70–100 DAS). At the Wallumbilla site, grazing exclusions were also sampled at the end of the grazing period to estimate the total growth both before and during the grazing period. Five or six paired quadrats (0.5 m by 1.0 m) were cut to ground level on either side of the junction between the forage brassica and the adjacent forage cereal. All samples were dried in an oven at 80°C for 4–5 days until they reached constant weight.

Statistical analyses

Biomass production data from Expts 2 and 3 were subjected to analysis of variance (ANOVA) in GENSTAT Release 19.1 (VSN International, Hemel Hempstead, UK) using block as a random effect. Expt 1 was analysed using ANOVA with a split-plot design. A Tukey's multiple comparison ($P < 0.05$) was used to determine differences in biomass production among genotypes. Commercial evaluations were subjected to a paired *t*-test to determine significant differences between forage brassica and cereal production. In Expt 2, nematode counts were not normally distributed and it was necessary to transform data logarithmically ($\ln(x + 367)$) before statistical analyses to address variance heterogeneity. Transformed *P. thornei* counts were subjected to ANOVA in GENSTAT Release 19.1 with crop, depth, sampling time, and their interactions as main effects, and the least significant difference (l.s.d.) was determined. The analysis was conducted using only data from the top 900 mm soil depth (that is, the top five layers), because 99% of the final *P. thornei* population was isolated from these layers. Because of similar results throughout the soil profile, an average population throughout the top 0–900 mm was also compared among crop types. In Expt 3, PREDICTA-B data were collected only in the surface 150 mm and were subject to ANOVA with only crop type as the main effect.

Results and discussion

Biomass production

Across the three experiments conducted in southern Qld, DM production of several forage brassica cultivars was similar to that of cereal crops (forage oats, barley or dual-purpose wheat) and often greater than forage legume options (Fig. 3). In Expts 1 and 3, forage brassica genotypes did not differ significantly in DM accumulation, whereas in Expt 2, forage rape cvv. Interval and Leafmore produced more DM than other forage brassicas. Dry and hot seasonal conditions following the winter sowing at Expt 2 saw the leafy turnip cv. Hunter senesce many of its leaves before sampling at the end of September. All forage pea and vetch (*Vicia* spp.) genotypes produced biomass similar to the forage brassicas in Expt 3 under very dry conditions (only 83 mm rain from sowing to final biomass cut).

Despite the drier than average winter (i.e. <170 mm rainfall compared with long-term mean of 260 mm) at all experimental sites, forage brassicas consistently produced 5–8 t DM/ha in 100–120 days, with growth rates of 50–70 kg DM/ha.day from sowing. Biomass production from several forage brassica genotypes was equivalent to, or exceeded, that of forage cereal or legume benchmarks in each of the experiments, indicating significant potential as alternative forage options in these growing environments. Although we did not measure the relative nutritive value of forages, the forage brassicas would be expected to have higher nutritive value than the forage cereals when harvested at the same time (see Fig. 1). Hence, this even further enhances the prospects that forage brassica would provide higher nutritive value during critical periods of feed deficit during winter in these subtropical regions.

Production levels were also significantly higher than those reported in the past under similar growing conditions (Table 3; French *et al*. 1988; Spurway *et al*. 1974; Wheeler 1963). These levels of production were achieved from direct drilling all forages with limited follow-up rain after sowing (at Expts 1 and 2 in particular) and with dry conditions during their growing season (<170 mm rain from sowing to final harvest). These growing conditions suggest that forage brassicas can be established and go on to achieve effective biomass production under conditions with limited follow-up rain. Samples were not taken after forage harvest to determine the extent of soil-water extraction, which would have allowed for comparisons of forage water-use efficiency among forages, but use of soil-water accumulated before sowing was an important contributor to this growth. Although the plant-available water at sowing was not determined here, extraction of soil-water accumulated during the prior fallow in addition to the in-crop rainfall would result in estimates of forage water-use efficiency of 23–35 kg DM/ha.mm for the best performing forage brassicas in these studies, comparable to those reported in New Zealand (Fletcher *et al*. 2010*a*).

Root-lesion nematode populations

Both Expts 2 and 3 found that forage brassicas did not build root-lesion nematode populations, and hence, they provide possible benefits as a rotation crop. In Expt 2, the populations of *P. thornei* were highest after the susceptible wheat crop cv. Kennedy at all depths in the soil profile, significantly higher ($P < 0.01$) than after the forage brassicas (Fig. 4). In the first 150 mm soil depth, populations were also higher ($P < 0.01$) after wheat cv. Mackellar than after the brassicas, but there was no significant difference at deeper layers of the soil profile (Fig. 4). When averaged across the whole soil profile, oats and leafy turnip maintained the same populations of *P. thornei*, and hence are suggested to be resistant to hosting *P. thornei*. Populations of *P. thornei* were 1.6–2.1 times higher after the other forage brassicas, but this was significantly less ($P < 0.01$) than the nearly 8-fold increase under the susceptible wheat control (cv. Kennedy), whereas the increase under wheat cv. Mackellar was intermediate and not significantly different from the other forage brassicas.

Predicta-B samples taken at the end of the growing period in Expt 3 showed *P. thornei* populations to be lowest after kale, forage pea and a dual-purpose pea cultivar, significantly lower ($P < 0.05$) than the highest populations found after forage rape cv. Leafmore; other forages were intermediate (Table 6).

These findings suggest that forage brassica genotypes may differ in their resistance to root-lesion nematodes but would provide rotational benefits compared with growing susceptible crops (e.g. wheat). Similar variation in nematode propagation has been observed in canola genotypes, which are considered to be resistant to *P. thornei* and maintain their populations at levels similar to, or slightly higher than, maintaining a cropless fallow (Owen *et al*. 2010). The data here suggest that forage brassicas are no better or worse in terms of *P. thornei* management benefits than other resistant rotation-crop options such as oats or forage pea (Owen *et al*. 2013).

Commercial participatory evaluations

The DM production levels achieved in commercial evaluations were far lower than those observed at the experimental sites, with <2 t DM/ha produced by 75–100 DAS in three of the five trials, particularly where in-crop rainfall was low (<100 mm) (Table 7). At two sites, the forage brassicas produced more DM than the cereal control, whereas at the other three sites, the DM yields were 50–70% of the cereal yields. The reasons for the large differences in production potential for forage brassicas achieved experimentally and in on-farm evaluations are unclear. Likely reasons may include sowing techniques, suboptimal plant densities (either too high or too low), lack of fertiliser applications, and/or soil fertility constraints.

Future needs and opportunities for research and development

Whole-of-system impacts

Integrating new forage species into a farm feedbase requires complex analysis of animal forage demand and supply and the dynamics of this through time (Bell *et al*. 2018). Hence, it is necessary to identify the periods when forage brassicas could provide the greatest forage value and how they fit into a broader farm feedbase in order to understand more fully their value to the grazing enterprise and the types of

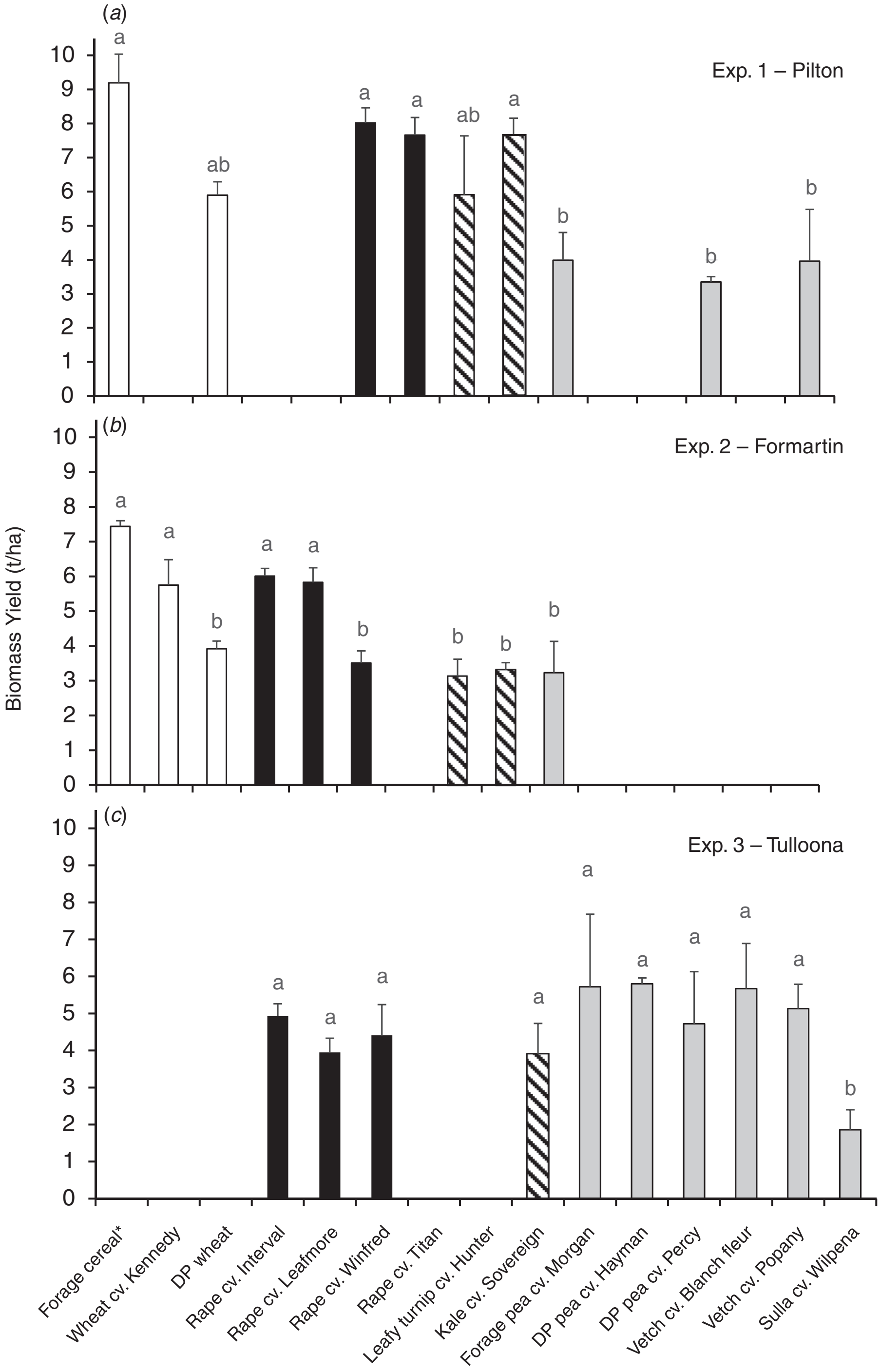

Fig. 3. Biomass production of forage brassicas compared with other crop options at three experimental sites: (*a*) Expt 1, 114 days after sowing (DAS); (*b*) Expt 2, 111 DAS; (*c*) Expt 3, 99 DAS. Cereal crops, open bars; forage rape, black bars; other forage brassicas, hashed bars; forage legumes, grey bars. Forage cereals used were oats cv. Genie at Formartin and barley cv. Urambie at Pilton; dual-purpose (DP) wheat cultivars were Wedgetail at Pilton (Expt 1) and Mackellar at Formartin (Expt 2). Capped lines are standard errors.

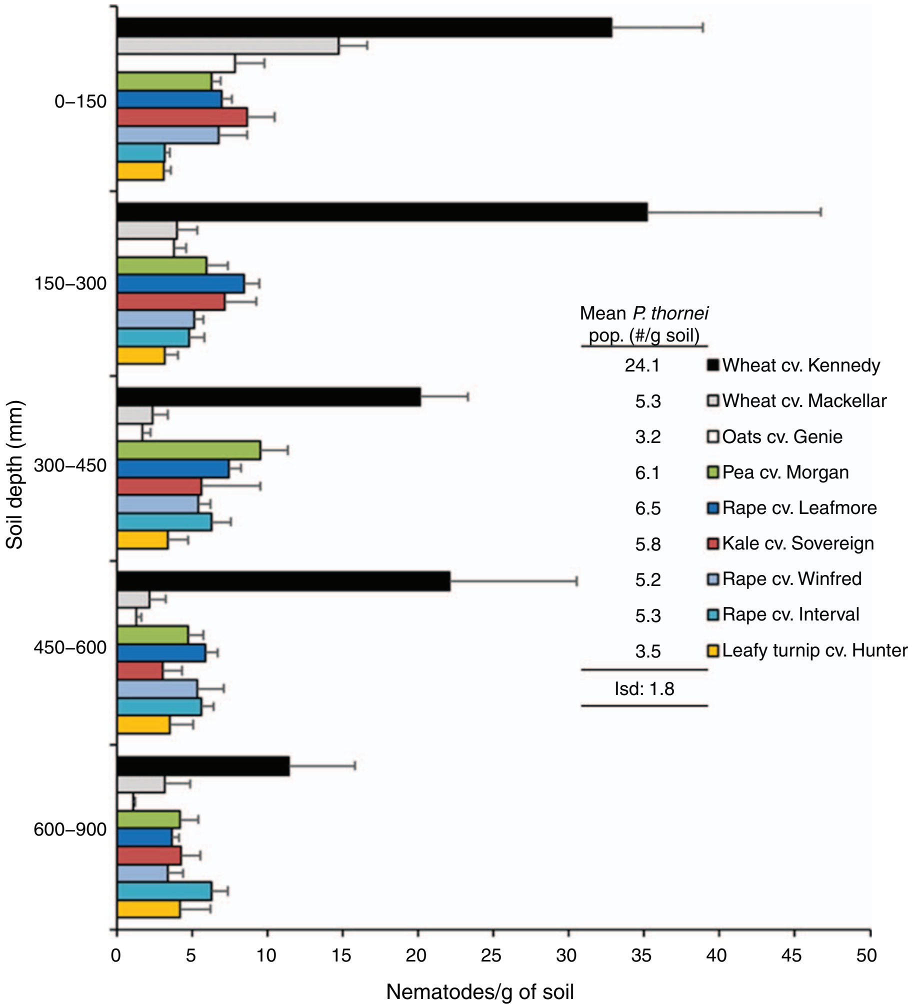

Fig. 4. Populations of *Pratylenchus thornei* (no./g soil) throughout the soil profile and averaged across 0–900 mm depth (inset table) at harvest after different forage brassica genotypes and alternative forage crops and a susceptible wheat check (cv. Kennedy) in Expt 2.

Table 6. Root-lesion nematode (*Pratylenchus thornei*) populations, determined by using Predicta-B, after forage brassicas compared with other forage crop options in Expt 3 (Tulloona, NSW)

Values followed by the same letter are not significantly different ($P > 0.05$)

	Post-crop *P. thornei* (no./g soil)
Rape cv. Interval	3.4ab
Rape cv. Winfred	3.9ab
Rape cv. Leafmore	18.6b
Kale cv. Sovereign	2.1a
Pea cv. Morgan	2.8a
Dual-purpose pea cv. Hayman	8.4ab
Dual-purpose pea cv. Percy	2.7a
Common vetch cv. Blanchefleur	10.8ab
Purple vetch cv. Popany	4.1ab
Sulla cv. Wilpena	4.1ab
Surrounding cropped field (chickpea)	5.5ab

genotypes that would best fill different feed gaps (Chapman *et al*. 2006; de Ruiter *et al*. 2009*a*). In the mixed-farming zone, filling winter feed gaps with dual-purpose crops can greatly alter the 'safe' carrying capacity or move the period of feed deficit to other times of the year (Bell *et al*. 2015). However, the timing of feed deficits will vary across regions and production systems, and hence, a broader understanding and consideration of these opportunities is needed to provide better guidance of the selection of brassica genotypes that would fit these different niches. Further, forage brassicas may have benefits for subsequent crops in rotations, either to reduce costs or to enhance yield (or both), which may need further evaluation to establish their whole-farm systems benefits.

Genotypic adaptation and suitability in systems

A wide range of plant types and genotypes of forage brassicas can serve different roles and have different management needs

Table 7. Biomass production (mean ± s.e.) of forage brassicas compared with a forage cereal sown in five on-farm participatory evaluations in southern Queensland

Established plant density, measurement date and days after sowing (DAS) at each site are provided where possible

Location	Species, cultivar	Established density (no. of plants/m^2)	Sampling Date	Sampling DAS	Biomass (t/ha)
Meandarra	Barley	–	15 Sept. 2012	92	1.83 ± 0.69
	Rape cv. Winfred	–			0.94 ± 0.30
Delungra	Oats cv. Genie	–	25 June 2013	74	1.43 ± 0.39
	Rape cv. Leafmore	–			0.96 ± 0.21
Wallumbilla	Oats cv. Warrego	91	10 Sept. 2013	176	5.20 ± 0.26
	Rape cv. Interval	136			3.01 ± 0.48
Roma	Oats cv. Warrego	61	27 June 2013	108	1.33 ± 0.10
	Rape cv. Interval	32			1.82 ± 0.27
Chinchilla	Oats cv. Genie	–	1 June 2014	85	1.63 ± 0.25
	Rape cv. Winfred	–			3.82 ± 0.70

(e.g. leafy vs bulbous types, erect vs prostrate types, herbicide tolerance, single vs multiple grazing; Table 1). This diversity of choice has been further widened with the commercialisation of newer cultivars (e.g. herbicide-tolerant types) and interspecific hybrid genotypes (e.g. raphanobrassica). Some of these new genotypes may have greater adaptation and application in the mixed crop–livestock zone than older genotypes. Many of these genotypes have been developed for wetter and cooler production environments; hence, there is a need to test their adaptation and relative DM production potential across environments in Australia's mixed crop–livestock zone. Under more frequent water stress in these regions, some forage brassica species or cultivars are likely to perform less reliably. For example, the experimental data presented here and general literature from New Zealand (de Ruiter *et al*. 2009*b*) suggest that leafy turnip is less able to handle periods of water-deficit than forage rape, and this is likely to limit its application in more arid regions.

Further, how these different genotypes would fit into different production systems and regions where feed gaps occur at different times also needs to be considered (Moore *et al*. 2009). A clear opportunity in many regions exists to grow a standing fodder bank over autumn and winter that can be used in combination with other forage types to fill feed gaps during this period or even into spring and early summer. This would require the ability to use as stand-over forage without loss of nutritive value. In high-rainfall and cooler environments, forage brassicas sown in spring are used to finish livestock over summer, but it is uncertain whether this application will work in the drier and hotter climes of the mixed crop–livestock zone. These two different forage-use patterns are likely to require different forage brassica genotypes and management approaches. Given that the forage brassicas would also be expected to deliver break-crop benefits to subsequent crops, quantifying and understanding differences among genotypes in their tolerance or resistance to key diseases or pests and how this relates to levels of these pests in subsequent crops is needed. For example, it is known that canola genotypes vary in their resistance to root-lesion nematodes and forage brassicas are also like to vary; it should also not be assumed that all forage brassicas will offer high resistance levels.

Animal production and grazing management

Although forage brassicas are known to provide forage of high nutritive value and offer the potential for improved animal production, factors contributing to suboptimal animal performance and animal-health risks require better understanding. This will be even more important on larger, less intensively managed livestock enterprises in the mixed-farming zone than in more intensive grazing systems where forage brassicas have been traditionally used (e.g. dairy). First, a delay or lag in animal performance after being introduced to canola and forage brassicas is widely reported, and proven management options to mitigate this effect are required (McCormick *et al.* in press). This is likely to be of greater importance when forage brassicas are grazed for short and intensive periods, whereas in longer grazing periods, slower growth during the adaptation period is counterweighted by the high forage nutritive value. The production of anti-nutritional compounds and how this is influenced by genotype and environmental conditions such as water stress and temperature, and the subsequent effect on forage palatability and animal feeding response, require examination. If plant stress promotes the accumulation of these anti-nutritional compounds, these issues will likely be of greater importance if forage brassicas are grown in drier and hotter conditions. Understanding this would not only help to minimise the risks to animal production but also optimise the role of forage brassicas in crop rotations by using periods of grazing aversion to shift pressure onto other, more palatable weeds (e.g. ryegrass). Although there is some evidence that Cu, Se or iodine mineral nutrition may be suboptimal for livestock grazing forage brassicas, there is no conclusive evidence that mineral supplementation improves animal performance on forage brassicas. These grazing issues may be important when forage brassicas are grown in pure swards, but the possibility of integrating them with other forage species in multi-species mixtures may help to mitigate these issues. However, there is currently little understanding of how these mixtures influence the nutritional value of the forage crop, or animal grazing behaviour and performance. Finally, data are needed for better quantification of the animal production that can be achieved from forage brassicas compared with other possible forage options (e.g. forage cereals, annual legumes, grazing canola) that could play a similar function in the livestock feedbase.

Agronomic and physiological understandings

The agronomic management of forage brassicas is well established for temperate humid environments (de Ruiter *et al*. 2009*b*); however, several issues, outlined below, are likely to require some revision or adjustment so that location-specific information can be provided to optimise forage brassica production and minimise risk for growing them in drier production environments.

First, economically viable sowing rates in lower rainfall regions are likely to be lower than those used under the higher rainfall conditions where current recommendations have been developed. When production potentials are lower, high seed-input costs are also likely to be mitigated by lower sowing rates. For these reasons, understanding the forage production trade-offs across a diversity of plant densities and production potentials would help to guide these decisions.

Second, the small seed size of most forage brassicas will require establishment of optimal sowing depths and techniques. Risks for shallow sowing of small-seeded species are likely to be higher in drier and warmer conditions with less reliable follow-up rain. Hence, the capacity is needed to sow seeds deeper into soil moisture to reduce risk of surface drying after initial germinations. Like canola, forage brassicas will probably be sown dry before the opening of the winter rains (Fletcher *et al*. 2016); problems with establishment of canola under drying conditions and into retained cereal crop residues are known and are likely to apply to forage brassicas (Bruce *et al*. 2006).

Third, Australia's cropping zone has a wide diversity of soil types with low or variable fertility, and particularly common are constraints such as soil acidity, salinity and sodicity (Dang *et al*. 2010). The suitability or tolerance of forage brassicas to these challenging soil types requires attention, especially because farmers are more likely to consider a forage crop as a viable alternative to a grain crop where soil constraints limit the range of viable break crops.

Fourth, although fertiliser recommendations for forage brassicas are available, these are typically tailored to higher production regions, whereas more conservative fertiliser applications matched to production potential will be needed in lower rainfall regions. A better understanding of the critical P and K levels is required, because these nutrients are known to limit production in many regions across Australia's mixed crop–livestock zone (Gourley *et al*. 2019). Further, few herbicides are currently registered for use in forage brassicas in Australia. Management options for important weed species in cropping systems, especially other broad-leaf weeds (e.g. wild radish, wild turnip, fleabane, sowthistle, etc.) will be critical. It is likely that much of the work on suitable herbicides has been done elsewhere, but effort to register these products in Australia will be needed. The potential to integrate herbicide-tolerance technologies (e.g. glyphosate or triazine) like those in canola into forage brassicas would further widen their opportunities in crop rotations.

Finally, if forage brassicas are to be grown in warmer and drier environments, this is likely to change the phenological development rate and hence the appropriate sowing and grazing windows for these crops. There will be a need to understand phenological development responses across environments, especially when vernalisation or photoperiod requirements may or may not be met, so that grazing opportunities can be maximised and reproductive development that reduces nutritive value can be avoided. This is likely to vary for different species and genotypes.

Conclusions

Forage brassicas are a common component of intensive livestock systems in temperate, higher rainfall zones; however, there is significant evidence of potential roles for them in broadacre mixed crop–livestock systems. Several forage brassicas have attributes that would make them highly suitable alternative break crops in rotation with cereal grains and able to be used to provide forage of high nutritive value at critical periods of the year. Preliminary studies here show promising production from current forage brassica genotypes in subtropical regions, but wider testing is needed in other regions to validate this. Their broader potential will be realised through further research to understand better the fit of different forage brassica genotypes across environments and production systems; in addition, agronomic recommendations will need revision to match these lower productivity environments.

Conflicts of interest

The authors declare no conflicts of interest.

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