Final report

Improving the use of forage brassicas in mixed farming systems

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Abstract

This project aimed to validate the potential of forage brassicas to fill feed gaps in livestock systems across the mixed farming regions of Australia. Multi-site evaluation of a diverse range of forage brassica types showed that several genotypes produced similar or higher yields of metabolizable energy than forage cereals. This was further confirmed with long-term simulations of productivity under a wide range of climatic conditions and environments. Incorporation of forage brassicas into pasture-dominant forage systems was predicted to reduce the frequency and magnitude of feed deficits by 20-45% or allow stocking rates to be increased by 10-20% without increasing risk. Despite the opportunities, forage brassicas can accumulate secondary compounds that present some animal health risks and grazing management challenges for producers. We demonstrated that glucosinolate concentrations, which influence animal palatability and intake can vary dramatically amongst genotypes, production environments and in response to management. Similarly, nitrate concentrations at concerning levels were common, but may be mitigated by high soluble carbohydrates in forage brassicas. The project has sparked growing interest and adoption of forage brassicas through communicating emerging information and recommendations widely and via 22 on-farm demonstrations where forage brassicas were tested in diverse livestock systems.

Executive summary

Background

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. In these hotter and drier environments, forage brassicas are more likely to fit as an 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. Preliminary experimental and commercial evaluations in subtropical Australia found production of some forage brassica genotypes were comparable or superior to widely used forage options. However, grazing forage brassicas does have some animal health risks and animal production can be reduced by the accumulation of several anti-nutritional compounds. To mitigate this constraint to production there is a need to further understand these animal health risks, their causes, and identify and test some possible solutions (*e.g.,* supplementation).

This project set out to further validate the potential of forage brassicas for wider use in mixed farming systems in Australia. Because this production environment is quite different from regions where current recommendations have been developed, further information was required by farmers, advisors and industry to guide recommendations in these new environments. In particular, there are several new genotypes that were thought to offer advantages in drier conditions, but evidence was required on which forage brassica genotypes were most suitable. The project partnered closely with forage seed industry (PGG Wrightson's Seeds, now DLF seeds), and used a participatory research approach with farmers and advisors across Australia's mixed farming zone.

Objectives

1. *Explore the potential of new forage brassica options to provide alternative options to fill feed gaps in mixed farming regions.* Multi-environment evaluation of diverse genotypes, coupled with development and application of simulation modelling enabled predictions of the productivity and relative performance of forage brassicas compared to current forage options across Australia's mixed farming regions.
2. *Understand factors influencing variable livestock performance and animal health risks when grazing forage brassicas*. Experiments focussed on the influence of brassica genotype and growing environment on animal behaviour and performance, and relationships with the presence of anti-nutritional secondary compounds.

Methodology

- Through multi-environment studies across 8 site-season combinations, the biomass production, ME and CP content and yield of 10 different forage brassicas were compared to a forage cereal and canola reference crops.
- Detailed physiological data from these studies was used to calibrate a new forage brassica model in APSIM and this was validated using 23 different datasets spanning Australia and New Zealand.
- Using historical climate data we simulated potential production of forage brassicas across diverse environments spanning Australia's mixed farming zone and examined how integrating 15% of forage brassicas to a pasture feedbase would alter the long-term whole-farm feed-balance and frequency and magnitude of feed deficits.

- Two grazing studies examined sheep performance and preferences when grazing forage brassicas, and via analysis of field surveys and controlled experiments the influence of glucosinolates and nitrates in forage brassicas on potential animal performance was investigated to understand their expression in response to management, genotype and environmental factors.

Results/key findings

- Forage rapes and raphnobrassica *cv.* Pallaton were found to perform well across many mixed farming regions, particularly under drier conditions, where they either matched or exceeded the yield of metabolizable energy provided by forage cereals.
- Simulation modelling showed that brassicas offer largest advantages over forage cereals in later sowing windows in medium rainfall regions, and where feed shortages during late winter and spring occur frequently.
- Incorporating 15% of the grazing area to forage brassicas across many different production systems has the potential to reduce the frequency of feed gaps by 25-40% or increase stocking rates by 10-30%.
- The accumulation of secondary compounds such as nitrates and glucosinolates are a widespread occurrence in many forage brassicas, posing animal health risks and reducing forage acceptability and hence animal growth. Crop nutrition, growing environment and genotype all seem to influence their expression, but these are difficult to predict.

Benefits to industry

This project has demonstrated the wider potential and benefits of using forage brassicas in mixed farming systems to diversify both forage and cropping systems and reduce the frequency and magnitude of feed gaps. Forage brassicas can often provide higher quality forage than forage cereals and produce more metabolizable energy per hectare thereby improving animal production. Our analysis and on-farm demonstrations suggest there is potential to safely increase farm stocking rates by 10-20% or reducing supplementary feed requirements by 20-45% by integrating forage brassicas into the current farm feedbase in many regions. Forage brassica seed sales have increased by 25% over the life of this project, indicating that already there is significant uptake by industry.

Future research and recommendations

This project has built a significant case for the wider application of forage brassicas in new regions and has initiated a program of on-farm demonstration to further validate the potential benefits on farm. An ongoing program of supported on-farm testing and evaluation, coupled with advisor training, would further assist wider adoption, and avoid potential pitfalls associated with implementing forage brassicas into livestock systems. Our engagement with industry and results from this work has highlighted three key research and development needs to support better management and avoid risks for producers adopting forage brassicas, including:

- deeper understanding of the mechanisms and management options for reducing risks of high nitrate and glucosinolates, and their subsequent impacts on animal health and performance;
- regional research to optimise the agronomy (*e.g.,* sowing rates) and nutrition of forage brassicas, as the existing recommendations were developed under higher productivity environments;
- examine forage mixtures that include forage brassicas for their potential to mitigate animal health risks, provide more balanced diets, and lengthen the grazing season compared to currently used monocultures.

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1. Background

1.1 System opportunity for forage brassicas

Forage brassicas (members of the Brassicaceae family) offer potential as an alternative forage break crop option for use across Australia's mixed crop-livestock farming zone. While 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 there are few profitable break crop options. While canola (*Brassica napus* var. *annua* L.) has been widely adopted in areas with reliable annual rainfall > 450 mm (Kirkegaard *et al.* 2016), 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 similar role 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 an increasing use of annual forage crops (*e.g.,* oats, 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 there are few annual forage crop options apart from forage cereals like oats (*Avena sativa* L.), meaning there is often limited crop rotation. 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.

The high climate variability across Australia's mixed farming zone also induces a high regularity of feed gaps (where livestock feed demands exceeds on-farm forage supply). These feed gaps impose a large cost to livestock production either through the need for expensive supplementary feeding or the need to reduce or maintain lower stocking rates (Bell *et al.* 2018). Depending on the region, feed gaps can occur during autumn-winter period when pasture growth is slow due to low temperatures or moisture limitations (*e.g.,* subtropics), and the summer-autumn, where much of southern Australia experiences a period of 'summer drought' of limited-no pasture growth (Moore et al, 2009). Forages that can provide high quality feed during these critical periods can be highly valuable additions to the farm feedbase (Bell *et al.* 2018). Forage brassicas have long been used 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 (Ward and Jacobs 2013; Barry 2013). For example, in New Zealand they are grown to provide a high-quality forage bank that can be used from early summer to late winter (de Ruiter *et al.* 2009b). A broad range of forage brassicas have been developed to fit different niches in these systems. Many are also available in the market in Australia but in many cases have received little evaluation outside similar systems to those used in New Zealand.

Research on the potential of forage brassicas outside the temperate humid zone (*i.e.,* where annual rainfall/potential evapotranspiration (aridity index) is > 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. A series of preliminary experimental and on-farm studies conducted in short growing season environments in southern Qld and northern NSW demonstrated that forage brassicas produced comparable biomass to other forage crop options in the region and were beneficial in managing pathogenic nematode populations (Bell *et al.* 2020). Farmers and advisors in the region and seed industry indicated their interest in investigating this further. This suggested there was a strong industry 'pull' for further information and evidence to demonstrate the wider potential of forage brassicas and to support their implementation. With this indicated potential, this project set out to investigate the wider potential of forage brassicas in mixed farming systems across Australia.

1.2 Research needs

1.2.1 Genotypic adaptation and suitability in systems

There is a wide range of plant types and genotypes of forage brassicas that can serve different roles and have different management needs (*e.g.,* leafy vs. bulbous types, erect vs. prostrate types, herbicide tolerance, single grazing vs. multiple grazing; Table 1). This diversity of choice has also been further widened with the commercialisation of newer cultivars (*e.g.,* herbicide tolerant types) and interspecific hybrid genotypes like raphanobrassica (a hybrid of *Brassica oleracea* (kale) and *Raphanus sativus* (radish)). It is anticipated that some of these new genotypes may have greater adaptation and application in the mixed crop-livestock zone than older genotypes. As many of these genotypes have been developed for wetter and cooler production environments, 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.* 2009b) suggest that leafy turnip is less able to handle periods of water-deficit than forage rape, which 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 is the opportunity 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 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 that 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 between 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.

1.2.2 Animal production and grazing management

While 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). Firstly, the 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.* 2020). This is likely to be of greater importance when forage brassicas are grazed for short and intensive periods, while in longer grazing periods slower growth during adaptation period are counterweighted by the high forage nutritive value. The production of anti-nutritional compounds and how this is influenced by genotype, 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 to 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). While there is some evidence that Cu, Se or I 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 mitigate them. 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 is needed to better quantify the relative animal production that can be achieved from forage brassicas compared to other possible forage options (*e.g.,* forage cereals, annual legumes, grazing canola) that could play a similar function in the livestock feedbase.

1.2.3. 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, identifying the periods when forage brassicas could provide the greatest forage value and how they fit into a broader farm feedbase is required to more fully understand their value to the grazing enterprise and the types of genotypes that would best fill different feed gaps (Chapman *et al.* 2006; de Ruiter *et al.* 2009a). 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 better guide the selection of brassica genotypes that would fit these different niches. Further, forage brassicas may have benefits for subsequent crops in rotations to either reduce costs or enhance yield (or both) that may need further evaluation to establish their whole-farm systems benefits.

2. Objectives

The project had two main objectives:

1. *Explore the potential of new forage brassica options to provide alternative options to fill feed gaps in mixed farming regions.*

This was achieved through a co-ordinated set of multi-site evaluations comparing biomass production, forage quality and system impacts on soil water, nitrogen, pathogens among multiple new and existing forage brassica genotypes with forage cereal controls across 8 site-year combinations spanning Australia's mixed farming zone. This data was then used to develop and validate simulation models that were used to extrapolate the potential production of forage brassica genotypes across a wider range of environments and climatic conditions capturing inherent climate variability. Outputs of this model were also used to explore how forage brassicas augmented other forage sources to fill gaps in feed supply across diverse production systems. Finally, 16 on-farm demonstrations sites were implemented across Australia to road-test priority forage brassica options with producers and advisors under different production systems.

2. *Understand factors influencing variable livestock performance and animal health risks when grazing forage brassicas*.

A set of 3 experiments examined factors influencing animal behaviour and performance upon introduction to different forage brassica types; how mineral supplementation may alter animal performance; and explored management options to mitigate animal health risks when grazing brassicas. To document the prevalence and possible environmental or management factors influencing the expression of anti-nutritional factors known to influence animal performance, they were measured on samples collected from field evaluation studies and from farmer fields.

3. Methodology

3.1 Multi-site evaluation of forage brassicas

3.1.1 Experimental design and locations

In 2018 and 2019, 8 independent field evaluation experiments were carried out at 4 locations in 2 years across environments spanning the mixed crop-livestock zone (Eastern and Western Darling Downs QLD, Central West NSW, and Wheatbelt WA; Figure 1). The details for each of the trial sites including location, soil type, sowing date, rainfall and irrigation received over growing season (mm), and N applied (kg/ha) is presented in Table 1.

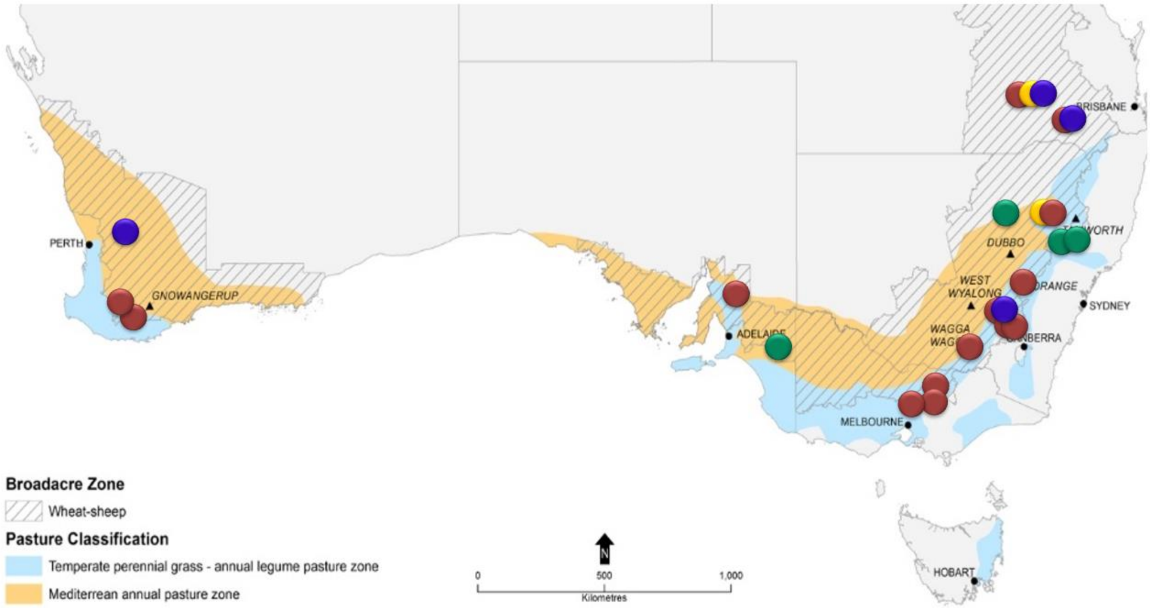


Figure 1. Forage brassica trial site locations for field evaluation experiments in 2018 and 2019 (blue), collaborative research sites with partners at CSIRO, Waite SA, and AMPS Research, Tamworth NSW in 2019 (green), and producer demonstration sites in 2019 (orange) and 2020 (red) managed together with PGG Wrightson Seeds.

The forages at all core sites were evaluated in replicated plots (n = 4 replicates/species, 50-60m^2 in size) in a randomised complete block design. Each field experiment examined 10 forage brassica genotypes, including some newly released genotypes and/or cultivars, compared to forage oats. Unfortunately, forage oats did not germinate at the York site in 2019 due to unforeseen reasons. A dual-purpose canola was also included at each experimental site. The canola and forage oat species used at each site were selected based on what was most relevant to the region (Table 2).

Three additional collaborative research sites were established in 2019 to compare a sub-set of forage brassica genotypes to common forage cereals in a randomised complete block design. At the Lameroo, SA site only forage rape *cv.* Goliath and raphanobrassica *cv.* Pallaton were sown and compared to barley *cv.* Spartacus (n = 4 replicate blocks). At the two northern NSW sites in Armatree (n = 4 replicate blocks) and Pine Ridge (n = 3 replicate blocks) forage rapes *cv.* Goliath, HT-R24 and Winfred, raphanobrassica *cv.* Pallaton, kale *cv.* Regal, bulb turnip *cv.* Rival, and forage radish *cv.* Graza were sown and compared to forage oats *cv.* Eurabbie and Flinders and barley *cv.* Moby. Total edible biomass was collected at each of these sites, but the frequency of collections at the northern

NSW sites was limited due to drought conditions. Due to the limited bulb produced at the northern NSW sites, only total edible aboveground biomass was collected. Start and end soil water was also collected at the Lameroo site.

Table 1. Site location, soil type, sowing date, growing season rainfall (and irrigation), and nitrogen (N) applied (N calculated in applied starter, urea and liquid fertiliser) for the four trial sites in the 2018 and 2019 field-evaluation experiments.

			2018			2019		
Site name	Latitude, Longitude	Soil type	Sow date	In-crop rain + irrigation (mm)	N applied (kg/ha)	Sow date	In-crop rain + irrigation (mm)	N applied (kg/ha)
Tummaville, QLD	27°84’88”S, 151°45’39”E	Black vertosol	20 Jun	193 + 135	6	12 Apr	30 + 128	103
Condamine, QLD	26°50’9”S, 149°59’51”E	Grey vertosol	11 Jul	132	6	04 Apr	26	6
Greenethorpe, NSW	34°07’68”S, 148°36’52”E	Red Kandosol	21 Jun	198	18	28 Mar	73	26
York, WA	31°91’07”S, 116°70’44”E	Grey sandy loam	26 Jun	233	84	28 Jun	135	88

Table 2. Forage brassicas, canola and forage oats included in the field-evaluation experiments at the different trial sites in 2018(■) and 2019 (□).

		Site			
Species	Cultivar	Tummaville, QLD	Condamine, QLD	Greenethorpe, NSW	York, WA
Forage oats	Flinders	■□	■□		■
	Eurabbie			■□	
Raphanobrassica	Pallaton	■□	■□	■□	■□
Forage rape	HT-R24	■□	■□	■□	■□
	Goliath	■□	■□	■□	■□
	Winfred	■□	■□	■□	■□
Bulb turnip	Green globe	■□	■□	■□	■□
	Rival	■□	■□	■□	■□
Leaf turnip	Hunter	■□	■□	■□	■□
Kale	Regal	■□	■□	■□	■□
Forage radish	Graza	■□	■□	■□	
Swede	Domain				■
Canola	Wahoo	■	■		
	45Y91CL			■	
	Bonito				■
	Hyola970CL	□	□	□	□

3.1.2 Crop agronomic management

The forage brassicas were sown at 20-50 mm depth, depending on soil moisture conditions, and on 25-30 cm row spacings. All core experimental and collaborative research sites were sown in autumn-winter, but the time of sowing differed at each location depending on rainfall and other sowing conditions to ensure site establishment. Nutrients were applied at sowing, and at some locations were also applied throughout the growing season to ensure no limitations (Table 1). Basal applications of P (20 kg/ha), K (20 kg/ha) and S (20 kg/ha) were also applied with the seed at sowing. Plants were monitored regularly for weed burdens, insect pressure and plant fungal infections and diseases. Appropriate management was implemented when needed.

3.1.3 Experimental measurements and procedures

Crop growth

The number of plants emerged were measured between 30 and 42 days after sowing (DAS). Plant stage was continuously monitored throughout the experimental period to identify key events including emergence date (50% emerged), stem elongation (initiation of reproductive stems at the plant crown), and flowering date (50% of plants commenced flowering).

Forage biomass cuts were taken approximately every 60, 90, 120 and 150 days after sowing (DAS) using a 0.5 m^2 quadrat. Two biomass cuts were taken in central plant rows within each replicated plot. For bulb producing species, both above and below ground portions were collected (when appropriate). All samples were dried at 60-80°C to determine dry weight.

Nutritive value

Samples collected for forage biomass were later prepared for nutritive value analysis. The dried samples (above and below ground portions, separately) were ground through a 1 mm screen for near infrared reflectance spectroscopy (NIRS) analysis at the CSIRO Rural Research Laboratory, Floreat WA to determine nutritive value including crude protein (CP), digestibility, and metabolisable energy (ME) content. All forage samples were further analysed for plant nitrates (NO_3 concentrations as nitrate) using flow injection analysis at the NSW Department of Primary Industries, Feed Quality Services, Wagga Wagga NSW as part of the livestock component of the project (as further described in section 3.2).

Soil water and nutrient use

Prior to or at sowing, 4-6 soil cores were taken at 1.8 m depth across each replicate block for soil water and nutrients. The soil cores were partitioned into the soil layers 0-15, 15-30, 30-60, 60-90, 90-120, 120-150 and 150-180 cm and split in half lengthwise. Half the core was used for soil water and the other for soil nutrients by placing in separate soil bags. The 4-6 cores taken within each replicate block were bulked to form one representative sample. The soil water samples were weighed (taring bag weight) immediately following collection.

For soil water and nutrients at the end of the experiment, 2-3 cores were taken per replicate plot. The cores were partitioned and separated into bags as previously described. Both start and end soil water samples were dried at 100-105°C for 3-5 days (until at constant dry weight). Once dried the samples were weighed again to determine gravimetric and volumetric soil water content. Both start and end soil nutrient samples were dried at 40°C for 3-5 days before being finely ground. Samples in the first 4 layers underwent a basic set analysis for soil characterisation (standard test at CSBP, including electrical conductivity, pH (water & $CaCl_2$), NO_3 and NH_4, Colwell P, Colwell K, Sulphur (KCl 40), organic carbon (Walkley Black). All other samples underwent analyses for NO_3 and NH_4 only.

Data analysis

Cumulative growing degree days (GDD) was calculated for each forage biomass cut taken at the core experimental and collaborative research sites. This was achieved using temperature data from each individual site and the base temperature zero (0) of canola in the vegetative stage of growth via the following equation:

GDD = average daily temperature (minimum + maximum temperature/2) - base temperature (0)

Cumulative GDD was considered the most appropriate method of comparing biomass production and nutritive value between and within site years at the core experimental sites and the collaborative research sites due to the differing sowing times and environmental conditions, in particular temperature, which affects plant maturity. Two GDD windows of 800-1300 GDD and 1600-2100 GDD were selected as these captured the most data points across all sites and were most relevant to the stage of plant growth.

At each of the core experimental sites, total edible biomass and yield of ME and CP in the two GDD windows were analysed with a linear mixed model using REML. The significance level for all analyses was set at $P \le 0.05$. A genotype x environment analysis using a Finlay & Wilkinson (1963) type analysis with REML was used to compare the biomass production within the two GDD windows for the species grown at both the core and collaborative research sites.

3.2 Modelling forage brassica performance in forage systems

To complement the multi-site field evaluations, we have used data collected in the project to develop models of forage brassica genotypes in APSIM (Step 1) which were then used to make predictions of the production potential of forage brassicas across a wider range of locations and historical climatic conditions (Step 2) and finally outputs from these simulations will be used in a whole-farm feed-base calculator to analyse how forage brassicas could be used to complement existing forage sources to reduce frequency and size of feed deficits across 5-6 different production systems (STEP 3) (Fig. 2).

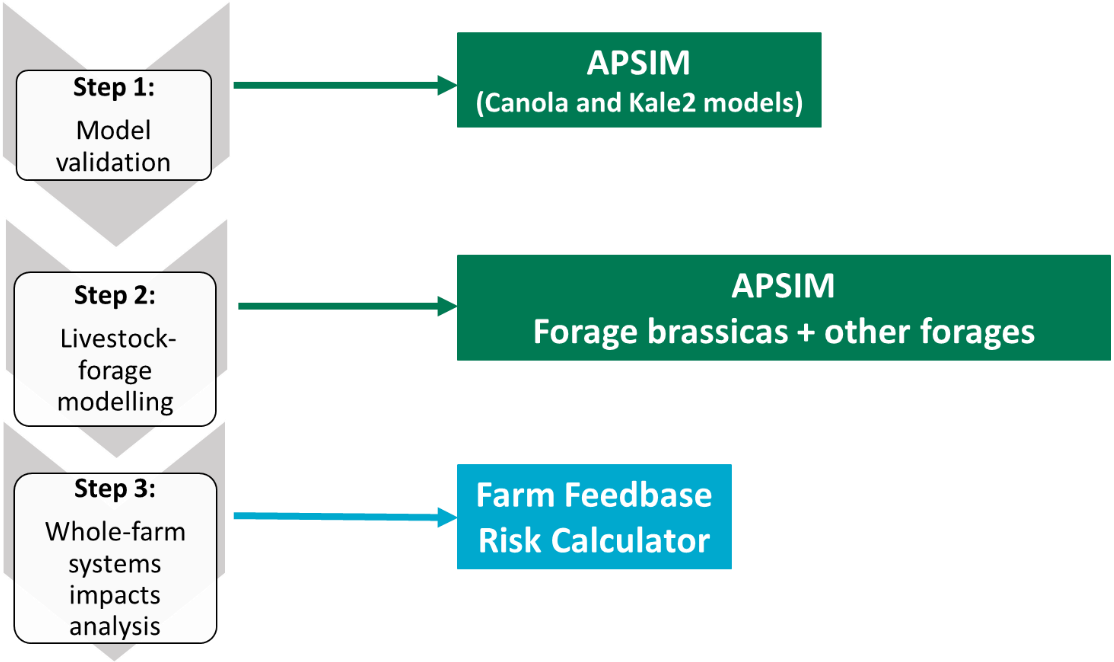


Figure 2. Steps involved in the development and implementation of a simulation model of forage brassicas in APSIM (Holzworth *et al.* 2014).

3.2.1 Model calibration

The first calibration stage used a dataset collected over two site-years (the experiments conducted at the Tummaville site in southern Queensland in our multi-environment evaluations (Table 3). Data collected included a combination of multiple measures of biomass and its components, forage nutritive value of plant components, leaf and canopy development, and observations of crop phenological development (i.e., vegetative, buds visible, flowering). Soil water, nitrate-nitrogen (NO3-N) and ammonium-nitrogen (NH4-N) concentration were measured at the start and end of each experimental site year (as outlined in section 3.1.3). This data was available for the several forage brassica genotypes as well as the reference canola crop. This enabled the simulations to be characterised using canola and then model parameters to be modified to accurately predict the growth of each forage brassica genotype. For more details see Watt *et al.* (2022).

Table 3. Summary of the observations of different plant growth attributes from two experimental years used for the calibration of each forage rape cultivar (*cv.* Goliath, HT-R24 and Winfred), raphanobrassica *cv.* Pallaton and the reference crop canola.

	No. of observations for:		
Plant growth attributes measured	Forage rapes	Raphanobrassica	Canola
Biomass			
Total biomass	10	10	10
Green biomass	10	10	10
Senesced biomass	5	5	4
Leaf/petiole biomass	8	8	7
Stem biomass	8	7	7
Nutritive value [a]			
Whole plant	8	8	7
Leaf/petiole	7	7	6
Stem	7	5	6
Leaf and canopy development			
Leaf number (mainstem)	15	15	15
Leaf area index	11	12	11
Radiation interception	11	12	11
Distribution of individual leaf size	2	2	2
Specific leaf area	2	2	2
Water and nitrogen uptake			
Start/End soil water	2	2	2
Start/End soil mineral N	2	2	2

[a] Dry matter digestibility (DMD) and crude protein (CP) content

The calibration stage aimed to produce a functional forage brassica model by making only minor modifications to the generic crop parameters in the APSIM-canola model (APSIM Initiative 2021) to improve the fit between predicted and observed data for each genotype. Initial parameters for the forage brassicas genotypes were based on the winter canola *cv.* Taurus because of its high vernalisation requirement. Adjustments to parameters were made using observed data where possible and then by exploring the sensitivity to changes in their values, and refinements were made iteratively until a point was reached that optimised model agreement with observed values. The process targeted crop parameters for which experimental data were clearly different between canola and forage brassica genotypes (*i.e.,* phenological development, leaf appearance rate, leaf size, specific leaf area). Model parameterisation was conducted stepwise, firstly focussed on crop phenology, then on canopy development and biomass partitioning, and finally on parameters driving nutritive value predictions.

3.2.2 Model evaluation

The second evaluation stage involved testing the newly derived set of parameters for each genotype across a wider range of production environments, climatic conditions, and agronomic management practices. Using data from previous studies from Australia and New Zealand, simulations were developed for 23 experimental site-years where data on plant biomass (220 individual observations) and nutritive value (i.e., dry matter digestibility (DMD) and crude protein content (CP)) (102 individual observations) were available for these genotypes (or similar varieties). The model test set included data on diverse forage brassicas from: 1) multi-environment experiments conducted in this project across a range of agro-climatic zones of Australia's mixed farming zone, (Watt *et al.* 2021; Flohr unpubl. data); 2) forage rapes grown for comparison with dual-purpose canola in temperate sub-humid (Kirkegaard et al., 2008a), and temperate cool-season wet environments (Kirkegaard unpubl. data); 3) forage rape evaluations in temperate cool-season wet environments of southern Australia and previously used for modelling in APSIM (Pembleton et al., 2013); and 4) forage rape experiments in temperate cool-season wet environments of New Zealand (Chakwizira et al., 2014; Fletcher and Chakwizira, 2012a) (Table 4).

Simulations for each of the 23 experiments were built in APSIM using management and soil information documented for each of these studies. Simulation outputs were tested against observed data for biomass, ME yield, and total plant DMD and CP, although many data sets were limited to biomass data only. Where possible, reference crops were used to check that simulation of water and N resources were reasonable, and in some cases, soil N availability was adjusted in order to adequately simulate growth of the reference crop. Statistical analyses were used to evaluate the performance of the model simulations of biomass, ME yield, and total plant DMD and CP content. Analyses were carried out for each forage brassica genotype and partitioned to test the performance in each agro-climatic zone. This enabled sources of variability within the broader model testing data set to be identified.

Table 4. Summary of data sets used for the model testing of forage brassica genotypes parameterisations using APSIM.

Site Characteristics			**No. observations**		
Location (lat, long)	Agro-climatic zone	Soil type	Biomass	DMD/ CP	Reference
Tummaville, QLD[1] (-27.85, 151.45)	Sub-tropical, sub-humid	Black Vertosol	10	8	Watt *et al.* (2021)
Pilton, QLD (-27.52, 151.59)	Sub-tropical, sub-humid	Brown Vertosol	1		Bell *et al.* (2020)
Formartin, QLD (-27.27, 151.25)	Sub-tropical, sub-humid	Black Vertosol	1		Bell *et al.* (2020)
Tulloona, QLD (-29.00, 150.02)	Sub-tropical, sub-humid	Grey Vertosol	1		Bell *et al.* (2020)
Iandra, NSW (-34.08, 148.37)	Temperate, sub-humid	Red Kandosol	2	2	Watt *et al.* (2021)
Wagga Wagga, NSW (-35.06, 147.21)	Temperate, sub-humid	Red kandosol	2		Kirkegaard *et al.* (2008)
York, WA (-32.91, 118.23)	Dry Mediterranean	Grey sandy loam	6	4	Watt *et al.* (2021)
Lameroo, SA (-35.20, 140.30)	Dry Mediterranean	Sand over loam (midslope)	3	3	Flohr (unpubl. data)
Delegate, NSW (-37.03, 148.56)	Temperate, cool season wet	Podosol	6		Kirkegaard (unpubl. data)
Elliott, TAS[d] (-41.06, 145.46)	Temperate, cool season wet	Clay loam	58	22	Neilsen (2005)
Stonehouse, TAS (-42.18, 147.40)	Temperate, cool season wet	Medium clay	1	1	J. Lynch (unpubl. data)
Cambridge, TAS (-42.51, 147.26)	Temperate, cool season wet	Medium clay	1	1	J. Lynch (unpubl. data)
Mawbanna, TAS (-41.00, 145.22)	Temperate, cool season wet	Clay loam	4	1	K. Pembleton (unpubl. data)
Stanley, TAS (-40.45, 145.16)	Temperate, cool season wet	Clay loam	5	1	K. Pembleton (unpubl. data)
Terang, VIC[e] (-38.15, 142.54)	Temperate, cool season wet	Sandy clay loam	12	12	Jacobs and Ward (2011)
Mt Gambier, SA[f] (-37.52, 140.45)	Temperate, cool season wet	Sandy loam	1	1	K. Boston (unpubl. data); DairySA (2009)
Hastings, NZ[g] (-39.38, 176.50)	Temperate, cool season wet	Silt clay loam	25		Chakwizira *et al.* (2014)
Lincoln, NZ[h] (-43.38, 172.29)	Temperate, cool season wet	Silt loam	18		Fletcher and Chakwizira (2012a)

3.2.3 Model extrapolation & feed system analysis

Multi-site simulation design

Twenty-two simulation locations were selected based on a broad distribution of landscapes and climates across the mixed farming zones, and higher rainfall livestock regions using the Interim Biogeographic Regionalisation for Australia v.7 (Department of Agriculture 2020) and the agro-climatic classification of Hutchinson *et al.* (2005) as a guide (Figure 3). Soils for each location were selected from the APSoil database (https://www.apsim.info/apsim-model/apsoil/) and the Soils and Landscapes Grid of Australia (Grundy *et al.* 2015) and the SoilMapp iPad app (CSIRO 2020) were used to identify a representative soil in the database on the basis of soil type and depth for each location (Table 5). Meteorological for all locations was sourced via SILO Long Paddock database (Jeffrey *et al.* 2001).

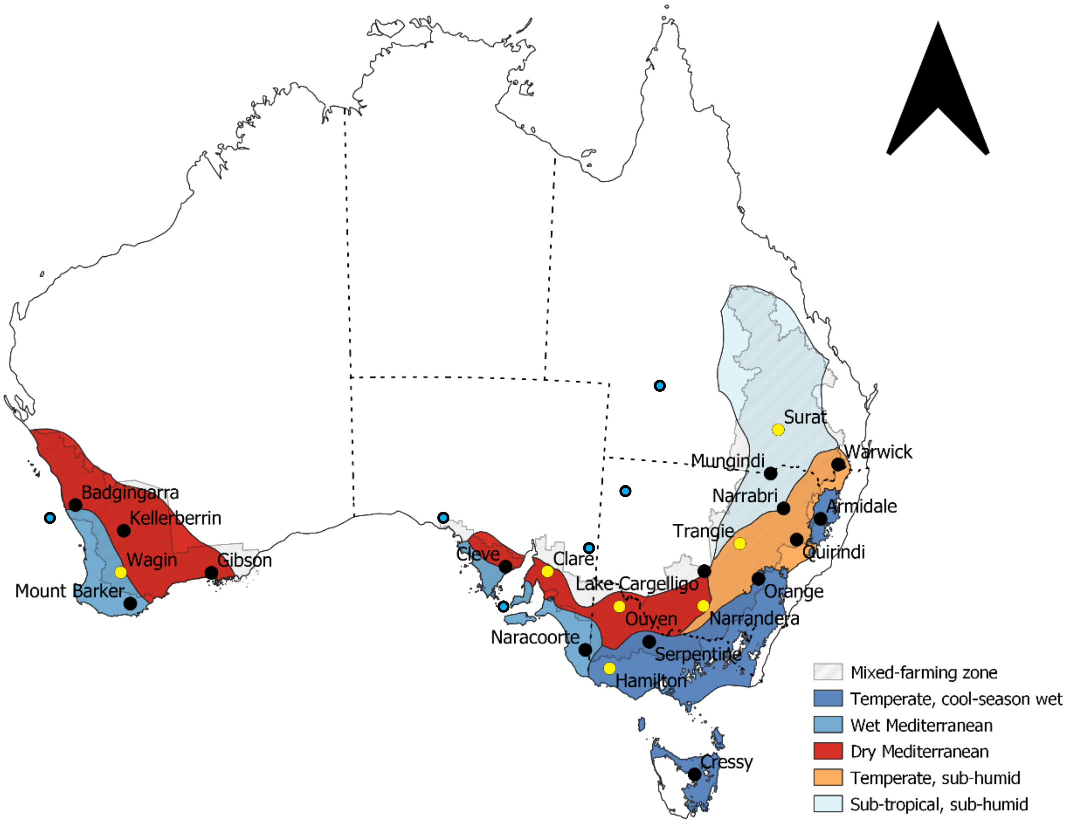


Figure 3. Distribution of the 22 simulated locations across different agro-climatic regions of Australia's mixed-farming regions. Yellow points on the map indicate the seven locations included in the on-farm feedbase analysis.

Simulated crop management

All simulations were set up using the same crop management with the only differences being soil and meteorological data. Simulations were run over a 60-year period (1960-2020). Starting soil water and nitrogen were reset on 15 January of each simulated year. Starting soil water was set at 30% of the plant-available water-capacity that was filled from the top to bottom to mimic conditions that would be expected following a cereal crop sown the previous year. Rainfall and evaporative processes after the reset date were able to 'play-out' in a realistic way prior to sowing. Starting soil nitrate-N was set at 50 kg/ha that was distributed in the first 1000 mm of soil. Sowing depth for all genotypes was set at 30 mm with a row spacing of 250 mm. At sowing, 200 kg/ha of urea-N was applied and a further 100 kg/ha of urea-N was applied when the crop reached APSIM stage 4.9. Plant density varied between genotypes with canola, Goliath and Winfred set at 60 plants/m^2 (sown a 3 kg/ha), and HT-R24 and Pallaton set at 50 plants/m^2 (sown at 3 kg/ha and 6 kg/ha, respectively).

Table 5. Summary of average rainfall, soil type selected and soil characteristics of the 21 simulated locations across Australia's mixed farming zone and higher rainfall livestock regions.

No.	Location	Latitude, longitude	Average rainfall (mm)	Soil type (APSoil no.)	Soil PAWC (mm)
1	Kellerberrin, WA	-31.62, 117.72	329	Red clay (415)	237
2	Mount Barker, WA	-34.63, 117.64	727	Duplex sandy gravel (1237)	172
3	Gibson, WA	-33.68, 121.83	618	Duplex sandy gravel (448)	100
4	Wagin, WA	-33.31, 117.34	430	Deep sandy duplex (403)	80
5	Badgingarra, WA	-30.34, 115.54	538	Brown deep sand (904)	113
6	Naracoorte, SA	-36.96, 140.74	578	Silty loam (1250)	113
7	Cleve, SA	-33.70, 136.49	400	Red sandy clay loam (316)	98
8	Clare, SA	-33.82, 138.59	634	Clay loam (285)	207
9	Ouyen, Vic	-35.07, 142.31	328	Loam - swale (642)	214
10	Serpentine, Vic	-36.41, 143.98	507	Clay loam (524)	202
11	Hamilton, Vic	-37.65, 142.06	617	Clay (632-YP)	261
12	Narrandera, NSW	-34.71, 146.51	433	Brown Chromosol (174)	191
13	Lake Cargelligo, NSW	-33.28, 146.37	417	Red Dermosol (1196)	199
14	Orange, NSW	-33.32, 149.08	910	Sandy clay loam (703)	131
15	Trangie, NSW	-31.99, 147.95	493	Clay (684)	193
16	Mungindi, NSW	-28.98, 148.99	502	Grey Vertosol (1279)	204
17	Quirindi, NSW	-31.51, 150.68	680	Black Vertosol (1166)	214
18	Armidale, NSW	-30.52, 151.67	792	Red Chromosol (236)	153
19	Narrabri, NSW	-30.32, 149.83	659	Grey Vertosol (97)	218
20	Surat, Qld	-27.16, 149.07	573	Black Vertosol (1282)	289
21	Warwick, Qld	-28.21, 152.10	688	Black Vertosol (31)	245

The sowing window for all genotypes was from 1 March to 31 May each year, before crops were sown if an earlier sowing event had not been triggered. A sowing event was triggered when rainfall exceeded potential evapotranspiration over a 7 day period and when available soil water status was greater than 50 mm. Different cultivars of wheat and canola were selected throughout the sowing window based on previous analysis of the optimal sowing windows: Wheat - Wedgetail (1-Mar - 1-May), Gregory (1-May - 31-May); Canola - Taurus (1-Mar - 19-Apr), CBI406 (19-Apr - 31-May).

On a monthly basis, net biomass production (*i.e.,* sum of daily biomass growth) and potential metabolizable energy (ME) yield were calculated for each of the forage brassicas, forage wheat and dual-purpose canola. For forage brassicas and wheat, this was accumulated up until flowering (APSIM stage 6.0), while for dual-purpose canola to account for timing of lock-up from grazing this was only calculated until bud-elongation (APSIM stage 4.9) to estimate total annual forage production potential.

Whole-farm feed-base risk analysis

At a selection of six locations spanning different agro-climatic regions across the mixed farming zone (see Figure 3), an additional analysis examined the potential for forage brassicas to complement the existing feed-base to improve the continuity of forage supply and support a representative livestock enterprise. This was conducted using the Farm Feed-base Risk Calculator, a simple spreadsheet model that computes the metabolizable energy balance of a farm to predict the frequency and size of monthly feed surpluses and deficits over the long-term (see Bell *et al.* 2018 for details). In brief, the annual cycle of monthly energy demand of a representative livestock enterprise is derived from widely used calculations of energy requirements for each class of stock accounting for their annual growth, lactation and pregnancy cycles (see Table 6). This is compared against long-term simulations (1960-2010) of monthly production and quality for forages and their relative contribution to the feed-base (*i.e.,* % area of farm) to calculate the metabolizable energy available (Table 6). To account for carry-over of forage, two-thirds of any surplus forage is carried forward to the next month. Using this model, we estimated the frequency, size and timing when forage supply was insufficient to meet livestock demand; that is, when livestock numbers either must be reduced, or supplementary feeding provided. Similarly, we also computed when the available biomass fell below a threshold of 500 kg DM/ha, which is an indication that animal intake, and hence performance, is likely to be reduced.

The *Baseline* feed-base analysed in each region reflected the main pasture or forage sources available (Table 6), and area allocations to each, chosen based on those reported previously obtained through consultations with local producers (see Thomas *et al.* 2018). In each *Baseline* scenario, the stocking rate of the livestock enterprise was adjusted to achieve a median annual utilisation of the farm feed-base of around 40-45%, to allow for reasonable comparisons of the feed-base risk impacts amongst regions. In comparison to this baseline scenario, three additional feed-base scenarios were compared where the farm stocking rate was maintained constant (*i.e.,* same number of breeding units per grazed ha including any additional forages). The first, involved an additional 15% of the farm area allocated to a forage brassica (*+forage brassica*). The second, involved an additional 15% of the farm area allocated to a forage cereal (+cereal). The third, involved adding a combination of an additional 15% each of both the forage brassica and forage cereal (*+both*). These scenarios used inputs of monthly forage production and quality derived from the long-term simulations described above for forage rape *cv.* Winfred and forage wheat.

Finally, while the previous scenarios maintained a constant stocking rate, an additional analysis used the farm feed-base risk calculator to calculate the potential to increase the stocking rate of the farm while achieving a similar level of risk when forage brassicas only were introduced into the farm feed-base. This was done by adjusting the stocking rate per grazed hectare until the same net farm feed deficit was achieved over the long-term simulation. At this point, both the previous *Baseline* scenario and the *+forage brassica* scenario were deemed to have equivalent risk of a feed gap.

Table 6. Details of the representative livestock enterprises, baseline farm feed-base simulated for the six diverse regions for which whole-farm feed-base risk analysis was conducted. Derived based on Thomas *et al.* 2018.

Region	**Maranoa, Qld**	**Central West, NSW**	**Riverina, NSW**	**South-west, Vic**	**Mallee, Vic**	**Mid-North, SA**	**Great Southern, WA**
Location	Roma/Surat	Trangie/Condobolin	Narrandera	Hamilton	Birchip	Clare	Katanning/Wagin
Livestock system specification							
Enterprise	Bos indicus X cows, store weaners	Merino ewe, fat lambs	Dual-purpose ewes, store lambs	First-cross ewe, fat lambs	Merino ewe, store lambs	Merino ewe, fat lambs	Merino ewes, store lambs
Calving/lambing window	1 Nov-15 Dec	15-Aug- 15 Sep	15 Jun – 15 Jul	15-Aug- 15 Sep	15-Aug- 15 Sep	1 Jun – 15 Jul	1 Jun – 15 Jul
Weaning date	30 May	1 Nov	1 Sep	1 Nov	1 Nov	1 Sep	1 Sep
Progeny sale date	30 May	15 Mar	1 Dec	15 Mar	1 Jan	1 Feb	1 Dec
Stocking rate* (BU/grazed ha)	0.35	1.56	2.75	3.80	1.87	3.35	2.91
Baseline farm feed-base							
Feed-base composition (% area)	Buffel grass 80 Panic grass + medic 20	Subclover + barley grass 30 Phalaris 40 Lucerne 30	Subclover + barley grass 40 Lucerne 30 Phalaris 30	Phalaris 33 Tall fescue 33 Lucerne 33	Medic + barley grass + capeweed 100	Medic + barley grass + capeweed 100	Subclover + ryegrass + capeweed 100
Median forage utilisation (%)	*44*	*42*	*44*	*44*	*40*	42	40

*Stocking rates were tailored to achieve an average utilisation of 40-45%, breeding units (BU) included all adult animals producing progeny.

3.3 Livestock performance and health risks when grazing brassicas

3.3.1 Exp. 1: Animal performance on brassicas and supplementation response

Several studies have noted a delay in liveweight gain when introducing livestock to brassicas, but this phenomenon is not consistently observed (Barry 2013). Differences in intake delays and liveweight gain by livestock grazing brassicas could be partly explained by genotypic differences between brassica cultivars. Using Merino ewe lambs naïve to brassicas, we aimed to test whether variation in lamb performance could be attributed to nutritional differences between brassica genotypes. We selected four forage brassicas representing the major leafy-types (in contrast to bulb-types) currently on the Australian market: dual-purpose canola (*Brassica napus cv.* Hyola 970CL); forage rape (*B. napus cv.* Titan); kale (*B. oleracea cv.* Sovereign) and raphanobrassica (*B. oleracea* x *Raphanus sativus cv.* Pallaton).

Site management

Experiment 1 was conducted in the drought summer of 2018-2019 at the CSIRO Ginninderra Experiment Station in Hall, Australian Capital Territory (35°12’01” S 149°05’02” E, 592 m a.s.l.). Three 0.1-ha plots were sown to each genotype in a complete randomised block design on 24th October 2018. Canola, rape and kale were sown at 4.7 kg/ha, and the larger-seeded raphnobrassica at 6.6 kg/ha (PGG Wrightson Seeds Australia), using a row spacing of 24 cm. We simultaneously applied CropRite fertilizer (Incitec Pivot) at 110 kg/ha, providing16 kg/ha N, 13 kg/ha P and13 kg/ha S. At sowing, the site was also treated with the pre-emergent herbicide Treflan at 1.7 L/ha (active ingredient, a.i. 480 g/L trifluralin; Dow Agrosciences). Due to drought conditions, the crop was grown under irrigation, with the first ~15 mL of water applied four days after sowing. Emergence of kale was very poor; kale plots therefore underwent a second sowing at 6.2 kg/ha between existing rows on 30 November.

By early November, leaf damage from caterpillars was evident across all plots. We applied Lorsban at 900 mL/ha (Dow AgroSciences; a.i. 500g/L chlorpyrifos) and Fastac Duo at 250mL/ha (Nufarm; a.i. 100g/L alpha-cypermethrin) on 16 November. To control damage by gastropods in the north-eastern part of the site, we applied 3.6 kg of Baysol Snail and Slug Bait (Bayer; a.i. 20 g/kg methiocarb) over the affected area on 23 November. We reapplied Fastac Duo across all plots at 400 mL/ha on 11 December and 2 January.

To maintain a healthy crop for grazing in January, we mowed all plots on 21 December. This removed 63 – 68 % of DM from plots, based on three replicate samples taken from each treatment before and after mowing. Prior to grazing, we erected two herbivore-exclusion cages (2.25 m^2) per plot. We also took six biomass cuts in each plot using randomly placed quadrats and removing plant material at ground level. Plant material collected from plots was kept cool, separated into brassica and weed components, weighed and sub-sampled; subsamples were oven-dried at 70°C for 96 hours to determine DM, and then ground in a Cyclotec mill with a 1 mm screen for use in chemical analyses. Biomass cuts were repeated weekly once grazing commenced; when grazing ceased in a plot, six quadrats were cut in the plot area and two within each exclusion cage.

Animal management

Merino ewe lambs (six months old) were kept on pasture with *ad libitum* pelletised sheep feed, composed of wheat, triticale, barley, lupins, canola meal, mill mix, fava hulls, oat hulls, lime, bicarb soda, magnesium oxide, salt, vitamins, minerals and zeolite (Conqueror Milling Company). Lambs were weighed and condition-scored on 17 January 2019. We selected 68 animals within a fasted liveweight range of 28.0 – 35.0 kg, and a minimum condition score of 2. We systematically allocated sheep to plots to achieve an even distribution of weights, with plot means ranging from 31.1 – 31.3 kg. Six animals were allocated to each plot except to two of the kale plots, where the number was reduced to four because available DM was below 2 t/ha.

To determine whether LWG could be improved by correcting a potential micro-nutrient deficiency in brassicas, half of the animals on each plot were drenched with a selenium, copper and iodine drench (Iodine Combo Drench for Sheep and Goats, Vetpak). The drench was diluted to 12.5 % by volume in water, according to manufacturer's directions, and applied at a dose rate based on the lightest animal in the flock (*i.e.,* 1.9 mL for 28.0 kg liveweight). The maximum delivery of trace minerals per kilogram of liveweight was 0.003 mg Se, 0.017 mg Cu, 4.2 mg I, 0.0025 mg Co and 0.005 mg Zn. The levels of Se and Cu applied were thus well below recommended limits (Freer, Dove *et al.* 2007, Suttle 2010). The risk of toxic effects was further mitigated by using vaccines without supplementary Se, and by ensuring that Se, Cu and nitrate concentrations in both the pasture and brassica treatment plots were within safe levels. Blood samples were taken from the jugular vein of one drenched and one undrenched animal from each plot at the start of the grazing trial.

Animals were placed on plots on 22 January (12 weeks after sowing) and weighed once per week after fasting overnight. Plots were de-stocked when brassica stem height reached ~10cm (≤59 days). We removed animals from plots for fasting in the early evening (1600 – 1700 h), fasted them overnight in pens, weighed each animal, took a second blood sample from the previously sampled animals, and returned them to pasture.

All procedures involving animals were approved by the 'CSIRO Wildlife and Large Animal' Animal Ethics Committee (AEC no. 2018-32) and were performed in accordance with the 'Australian code for the care and use of animals for scientific purposes' (NHMRC 2013) and territory legislation.

Chemical analyses

Ground forage samples were analysed by near-infrared spectroscopy (NIRS) in the CSIRO Rural Research Laboratory (Floreat WA), using procedures described by Norman *et al.* (2020) to determine crude protein (CP), metabolisable energy (ME) and neutral detergent fibre (NDF). Nitrates were analysed by CSIRO Black Mountain Analytical Services (Acton ACT). A health panel analysis was performed on blood samples by Regional Laboratory Services (Benalla VIC).

Statistical analyses

All statistical analyses were performed using R v. 3.6.1 (R Core Team 2019). We constructed linear mixed effects models using the lme4 package ((Bates *et al.* 2015) to test fixed effects with block as a random effect.

3.3.2 Exp. 2: Animal diet selectivity when introduced to grazing brassicas

In Experiment 2, we evaluated selective consumption by lambs of genotypically-diverse brassica cultivars in a cafeteria trial that included cereals as controls. Animals were free to choose amongst the full complement of forages and we hypothesised that (1) some cultivars would be consumed preferentially over others, and (2) preferences would be related to nutritional quality.

Experimental design

In late March 2019, we sowed 14 forage crops including 12 brassicas and 2 control cereals in Greenethorpe, NSW (one entry, fodder beet, failed to establish). Cultivar details are given in section 3.1. Plots (2.2 m x 25 m) were arranged in a complete block design with four replicate blocks. Each block was individually fenced and contained a water trough.

On 6 June, we introduced 13 Merino lambs (45-55 kg) to each block (0.16 ha) and allowed them to graze for 10 days (*i.e.,* ~812 Dry Sheep Equivalent grazing days / ha). We estimated the available dry matter (DM) before and after grazing using a pair of quadrat cuts (1m^2 each) of above-ground material in each plot; plant material was dried at 70℃ for 72 h, weighed, and ground for nutritional quality analyses. All plots were slashed on 26 June to remove excess biomass, and urea was applied at 200 kg/ha (= 92 kg N/ha) in mid-July. Due to dry conditions, drippers were used to apply approximately 25 mm of water to the trial in mid-August, followed by 50 mm in late August. In late September, plants were again sampled as above before grazing of regrowth commenced using 29 Merino lambs for 4 days. Chemical analyses of plant samples were conducted as described in section 3.3.1.

All procedures involving animals were approved by the 'CSIRO Wildlife and Large Animal' Animal Ethics Committee (AEC no. 2018-07) and were performed in accordance with the 'Australian code for the care and use of animals for scientific purposes' (NHMRC 2013) and territory legislation.

Statistical analyses

To quantify selective consumption by lambs, we calculated the difference between pre- and post-graze DM as a percentage of pre-graze DM. We analysed the data in R using the linear mixed effects model function (lmer) within the package lme4 (Bates *et al.* 2015). We tested the fixed effects of cultivar and levels of metabolisable energy (ME), crude protein (CP), neutral detergent fibre (NDF) and nitrate, with block included as a random effect.

3.3.3 Exp. 3: Plant nutrition effects on plant secondary metabolite accumulation

Brassicas have a relatively high demand for both N and S to reach yield potential but in excess they can lead to elevated production of nitrates, glucosinolates and S-methyl sulphoxide (Fletcher *et al.* 2010b; Barry 2013; Almuziny *et al.* 2016; Groth *et al.* 2020; Gugała *et al.* 2020). The plant response to fertilizer application is dependent on the growth environment. Experiment 3 addresses our limited understanding of how PSMs vary in response to N and S availability in the summer environment of southern NSW, a region where the use of forage brassicas is expected to expand significantly.

Site management

Experiment 3 was conducted at the CSIRO Boorowa Agricultural Research Station (BARS) in Boorowa, NSW (34°28'05''S 148°41'56''E). Weather data was collected at an on-site weather station recording measurements every minute during the growth period (Table 7).

Table 7. Weather conditions at the study site during the trial (September 2020 - February 2021).

	September	October	November
Mean Max. Daily Temp. (°C)	19.9	21.7	27.3
Mean Min. Daily Temp. (°C)	4.7	8.1	10.4
Total Precipitation (mm)	41.3	103.8	58.7

Soils at the site are kurosols (Department of Planning, Industry and Environment 2020). Soil cores to 1.7 m were collected on 5th August 2020 (Table 8). The study site was split into 12 sections (approx. 6 m x 16 m) with two soil cores taken from each section and separated into seven depth increments; the two cores from each section were bulked by depth.

Table 8: Soil characteristics at the study site ("Paddock 4", Boorowa Agricultural Research Station, August 2020)

Depth (cm)	Nitrate N (mg/kg)	S (mg/kg)	P (mg/kg)	K (mg/kg)	pH ($CaCl_2$)	Conductivity (dS/m)
0-10	11.2 ± 0.6	6.3 ± 0.3	33.1 ± 1.8	230.2 ± 8.5	6.3 ± 0.1	0.061 ± 0.003
10-20	9.3 ± 0.6	7.6 ± 0.5	21.6 ± 2.0	148.1 ± 6.7	5.3 ± 0.1	0.035 ± 0.002
20-50	10.4 ± 0.6	6.4 ± 0.5	4.8 ± 0.4	108.2 ± 2.9	5.9 ± 0.1	0.041 ± 0.004
50-80	11.2 ± 0.1	6.4 ± 0.4	3.1 ± 0.1	95.6 ± 3.0	5.5 ± 0.1	0.031 ± 0.001
80-110	5.6 ± 0.3	4.6 ± 0.3	2.7 ± 0.1	116.6 ± 6.5	5.9 ± 0.1	0.027 ± 0.001
110-140	2.9 ± 0.2	2.4 ± 0.2	2.0 ± 0.0	136.7 ± 5.3	6.6 ± 0.1	0.043 ± 0.005
140-170	2.6 ± 0.2	1.8 ± 0.2	3.3 ± 0.2	150.1 ± 5.5	7.0 ± 0.1	0.063 ± 0.008

Experimental design

We used a replicated split-plot design to test the effects of brassica cultivar (3 levels), N fertilizer (3 levels), S fertilizer (2 levels) and their interactions, on the production of DM, nitrates and glucosinolates. The field trial comprised 72 plots (6.4 m x 1.75 m) including four replicates (blocks) of each cultivar x N x S combination. Brassica cultivars used in this study were *Brassica napus* (Canola *cv.* Hyola 970CL and Rape *cv.* Titan) and a kale-radish cross, *Brassica oleracea* x *Raphanus raphanistrum* (Raphanobrassica *cv.* Pallaton). Sites were sprayed with Trifluralin 480 at 1.5 L/Ha and Roundup UltraMAX at 1.9 L/Ha prior to sowing to control weeds. Crops were sown as 7 rows at 0.25 m spacing, resulting in 1.75 x 6.4 m plots. Canola Hyola 970CL was sown at 5 kg/ha, Rape Titan was sown at 6.7 kg/ha and Raphno Pallaton was sown at 8 kg/ha (sowing rates adjusted for germination rate and seed size). All crops were sown with 100 kg/ha of MAP which provided a 10 kg/ha baseline nitrogen level. Nitrogen was applied in the form of urea and sulphur was applied in the form of gypsum. The levels of nitrogen were 0 kg/ha for the 'low' treatment, 50 kg/ha for the 'medium' treatment and 100 kg/ha for the 'high' treatment. Sulphur was applied at 0 kg/ha for the 'low' treatment and 50 kg/ha for the 'high' treatment. At 4 and 6 weeks after sowing, 30 mL/ha of Trojan was applied to control caterpillars.

Data collection

Forage cuts were taken approximately 9 weeks after sowing. Brassica plant material was collected from 2 quadrats (50 cm x 125 cm) from each plot and the plant matter from both quadrats was combined; dead leaves were excluded. Fresh weight (FW) of the sample was recorded. Two subsamples were taken (approximately 6 plants per subsample) for nitrate or glucosinolate analysis.

Plant matter for nitrate analysis was dried in a 70°C oven for a period of 4-7 days. These samples were weighed to record dry matter percentage. Following this, plant matter was ground into 1 mm pieces using a Foss CT 293 Cyclotec^{TM}. Two samples of ground plant material were taken and sent to NSW DPI Laboratory Services for nitrate analysis via wet chemistry and to CSIRO Floreat for forage quality analysis via near infra-red spectroscopy.

Chemical analyses

Plant matter for glucosinolate analysis was stored at -80°C and then freeze dried. Plant matter was then ground into 1 mm pieces using the Foss CT 293 Cyclotec^{TM}. We weighed 70 mg (± 2 mg) of plant matter into a 10ml falcon tube for each plot. The glucosinolate extraction process followed the experimental protocol outlined in Grosser and van Dam (2017). A 1 cm x 1 cm piece of glass wool was pushed to the bottom of a glass Pasteur pipette. We added 0.5 ml of G-25 Dextran gel to each glass pipette to form a column. Each column was flushed with 1ml of ultrapure water. To each tube containing plant matter, we added 1 ml of 70 % methanol and vortexed the tube before placing it in a 91°C bath until the samples boiled. We then placed the tubes in an ultrasonication bath for 15 minutes and centrifuged them at 2,700 x g for 10 minutes at room temperature. Supernatants were removed and added to individual columns. We added 1 ml of 70 % methanol to each tube containing plant matter and vortexed. Samples were placed in an ultrasonication bath again for 15 minutes and were then centrifuged for 10 minutes at 2,700 x g at room temperature. Supernatants were added to their respective columns. Each column was then washed twice with 1 ml 70 % methanol, once with 1 ml of ultrapure water and twice with 1 ml of 20 mM sodium acetate buffer (pH 5.5). Eppendorf tubes (2 ml) with a hole pierced through the lids were then placed under each column and 20 µl of sulfatase was added to the columns, followed by 50 µl of sodium acetate buffer. Columns were covered with aluminium foil and left overnight. Each column was flushed twice with 0.75 ml ultrapure water and Eppendorf tubes were then capped and placed in a -80°C freezer for ~1-3 hours. Samples were then freeze dried for 20-22 hours. Each sample was dissolved in 1 ml of ultrapure water and vortexed. Dissolved samples were then transferred to HPLC filter vials for analysis.

Quantification with High Performance Liquid Chromatography (HPLC): Thermo Scientific Q Exactive Plus coupled to an UltiMate 3000 UHPLC (Ultra High-Performance Liquid Chromatography) platform. Pump flow on 0.400 mL/min, injection volume 10.00 µL.

Data analysis

Nitrate data was transformed using a square root function to correct skewness. Linear mixed effects models were used to model the response of forage yield and of nitrates to cultivar, nitrogen treatment and sulphur treatment. A linear model was run to model the response of total glucosinolate concentration (measured as total ion current) to cultivar, nitrogen treatment and sulphur treatment. All models contained block as a random effect. ANOVA was run on each model to determine any significant relationships. All statistics were performed in R (version 4.0.2) using the package lme4.

3.3.4 Field survey and cross-site analysis of plant-secondary metabolites

Ruminant livestock are more likely to suffer from nitrate toxicity when the feed source is high in nitrates and low in readily fermentable carbohydrates. While brassicas can accumulate high levels of nitrate in plant tissue, they also tend to be high in non-structural carbohydrates, potentially lowering the grazing risk (Guillard et al. 1995). We hypothesised that the accumulation of nitrates and non-structural carbohydrates are a function of brassica genotype, N inputs and DM productivity. We tested this by analysing both above- and below-ground biomass samples from field trials at York WA, Greenethorpe NSW, Condomine and Tosari QLD. Nitrates and total non-structural carbohydrates were analysed by the NSW DPI Feed Quality Service. Over winter 2020, we also sampled brassica crops on-farm within a 3-hour radius of Canberra where animal ill-health effects had been reported to the NSW Local Land Services veterinarian.

We analysed the data in R using the linear mixed effects model function (lmer) within the package lme4 (Bates *et al.* 2015). We tested the fixed effects of cultivar, total available N (sum of total mineral N in soil to 90cm and N applied as fertilizer), and DM production, with collection date and block nested within site included as random effects.

3.4 On-farm demonstration sites

In collaboration with PGG Wrightson's seeds, a series of 22 on-farm demonstration sites were identified and sown with forage brassicas. However, not all sites were successfully established (due to flooding, poor establishment, herbicide issues and drought) or produced useful data or insights. Of the 16 sites established in 2020/21, 14 of these sites were sown in autumn and the other 2 were sown in spring. Hence, in 2021/22 fewer sites were implemented to allow for regular communication and more focussed monitoring to be provided by the team. Travel restrictions over this period hampered the ability of the team to regularly visit and collect the intended data. In the second year, all site hosts and the project team met online at monthly intervals over the growing season to review progress, discuss and trouble-shoot management issues as they emerged.

Sowing time was determined by the participating farmer based on the best fit in their system for filling feed gaps. While interesting observations and lessons were evident at most sites, 10 produced useful comparative results on the performance of forage brassicas on farm.

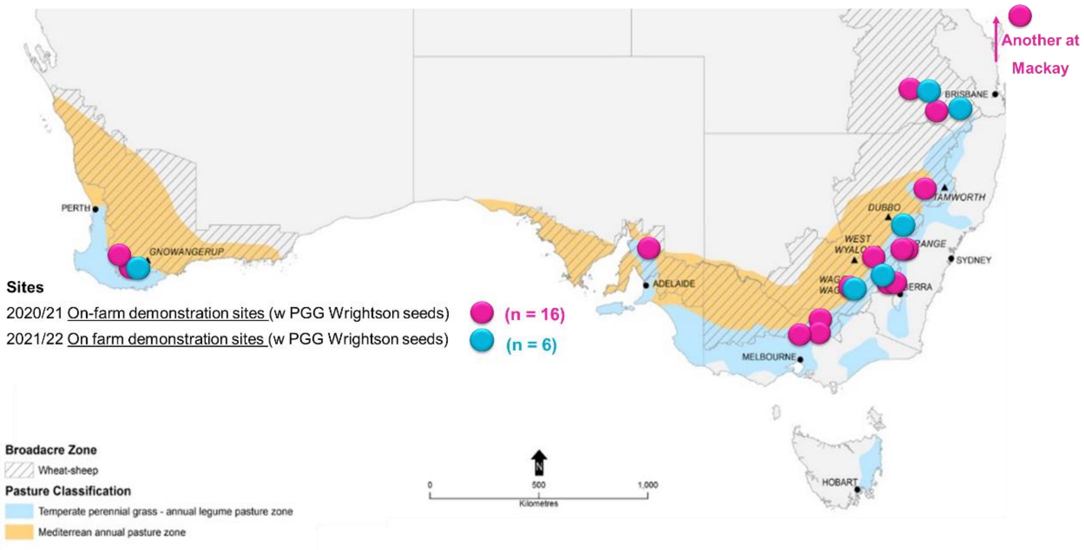


Figure 4. Locations of on-farm demonstration sites testing forage brassicas in different production systems and environments.

The CSIRO team developed a protocol to collect information on the number of grazing days and grazing intervals, animal growth rates, regular photos of the site, biomass prior-to and after grazing and information on agronomic management applied at each site. All sites had baseline soil nutrient analysis conducted prior to sowing. Seed was provided by the PGGW, a simple 1-page management guideline was developed and distributed. We also produced and developed a grazing management aide (akin to one used in New Zealand), *i.e.,* a traffic cone (see adjacent image) to help guide grazing management of the crops.

After being involved in the on-farm demonstrations in the first year, each of the collaborating farmers/advisors was interviewed to collect their perspectives and experiences. This involved the following questions put to each of them. This has been initiated in the second year, but not yet collated fully at this stage.

Basic questions asked in post-demonstration interviews:

- After this year, do you think you would you consider planting brassicas again – interest long term?
- How can you see brassicas fitting into your system?
- Based on what you know now, is there anything you would do differently?
- Have you had any issues or problems that you think we need to address if we are to continue these sorts of demonstration opportunities?

4 Results

4.3 Multi-site evaluation of forage brassicas

The growing conditions at all sites were very challenging due to well-below average annual rainfall conditions and in-crop rainfall ranging from 26-233 mm. At some sites, decile one drought conditions were reported. Some irrigation was applied at the Tummaville 2018 and 2019 sites; however, total water received by these sites was similar or just below the average growing season rainfall. This set of different production environments resulted in a wide range in forage productivity potential with the mean edible biomass production across the sites ranging from 2.0-6.4 t DM/ha in the early grazing window, and 0.6-8.5 t DM/ha in the late grazing window (Tables 9 and 10).

4.1.1. Productivity of forage brassica genotypes compared to benchmark species

Early grazing window

At all sites sampled within the early grazing window (800-1300 growing degree days after sowing), at least 6 of the forage brassicas produced similar or higher *(*$P \leq 0.05$) edible biomass and ME yield than oats. More forage brassicas (8 or all 9 genotypes) produced similar or higher *(*$P \leq 0.05$) CP yield than oats across these sites (Table 9). A clear example of where forage brassicas outperformed oats in this early window was at the Tummaville 2019 site where the top 3 forage brassicas outperformed oats by around 1.8 times for yields of ME (94 vs. 51 GJ/ha) and CP (1670 vs. 963 kg/ha) (Table 9). This was also evident at the Iandra 2019 site (lower mean site production) where forage brassicas outperformed oats by around 1.9 times for yields of ME (41 vs. 22 GJ/ha) and CP (770 vs. 408 kg/ha) (Table 9). When compared to dual-purpose canola, forage brassicas also ranked well for all productivity measures, with at least 7 forage brassicas producing similar or higher *(*$P \leq 0.05$) yields at 4 out of the 5 sites, and at least 4 of the forage brassicas at the other site (Table 9).

Of the forage brassicas, the best performing genotypes in this early grazing window were Green Globe and Rival turnip, and HT-R24 forage rape, which consistently ranked above the site mean across all sites for all productivity measures by around 15%. The one exception was for Rival that performed poorly at the Tummaville 2018 site. Across at least 3 of the 5 sites sampled, Goliath forage rape and Hunter leafy turnip also ranked above the site mean for all productivity measures. Regal kale performed poorly across all sites in this early grazing window and was on average 40% lower than the site mean for all productivity measures (Table 9).

Late grazing window

In the late grazing window (1600-2100 growing degree days after sowing), oats often produced more edible biomass (ranking 44% higher than the site mean) than the forage brassicas (Table 10). However, the forage brassicas had higher nutritive value than oats and during this late grazing window, yields of ME and CP for oats was only 22% and 1% higher than the site mean, respectively. Within this late grazing window, at least 7 of the forage brassicas produced similar or higher *(*$P \leq 0.05$) edible biomass as oats at 3 of the 6 sites, but very few (if any) of the forage brassicas outperformed oats at the other 3 sites. Pallaton was the only forage brassica to produce similar *(*$P \leq 0.05$) edible biomass as oats at the York sites (2018 and 2019). On the other hand, the forage brassicas performed relatively better for CP yield, with 8 or all 9 of the forage brassica genotypes producing similar or higher *(*$P \leq 0.05$) CP yield as oats at 4 out of 6 sites, and 4-6 of the forage brassicas at the other 2 sites (Table 10). This was most evident at the Tummaville 2019 and both years at Condamine, where the CP yield of oats was around 20% lower than the site mean, and the top 3 performing forage brassica genotypes at these three sites produced between 1.5 to 2 times more CP yield than oats (Table 10). In the late grazing window, there were some instances where dual-purpose canola was reproductive, particularly in the 2018 season; in these cases, the ME content of canola was lower compared to the forage brassica genotypes (Table 12). When compared to dual-purpose canola, several forage brassicas (ranging from 3 to all 9 genotypes) produced similar or higher *(P* ≤ 0.05) edible biomass and ME yield as canola. Many more of the forage brassicas yielded similar or higher *(P* ≤ 0.05) CP yield as canola (ranging from 5 to all 9 genotypes) across all sites in this late grazing window (Table 10).

The best performing forage genotypes in the early grazing window were not the best performing genotypes in the late grazing window. Oats performed the best for edible biomass, but in terms of yields of ME and CP the best performing genotypes (i.e., those ranked most consistently > than the site mean) were Goliath and HT-R24 forage rapes, Pallaton raphanobrassica and canola, which all produced on average 16% higher yields than site means. The lowest performing genotypes were Hunter leafy turnip, Green Globe turnip and Regal kale, which produced around 22% less than the site mean for all productivity measures (Table 10).

Table 9. Early grazing window (800-1300 growing degree days after sowing) edible biomass (bulb, stem and leaf portions), and yields of metabolisable energy yield and crude protein (*i.e.,* biomass × ME or CP content) produced by forage brassicas, canola and forage oats at 5 experiments across the Australian mixed farming zone. Each genotype was ranked as a % of the site mean of all genotypes and the mean and range of these ranks across sites is provided.

	Tummaville		Iandra	York		Mean rank (%)	Site rank range (%)
	2018[1]	2019	2019	2018	2019		
	Edible biomass (t DM/ha)						
Green Globe turnip	-	8.2	3.2	2.5	2.0	117	104-127
Rival turnip	1.1	8.1	3.8	2.9	2.6	116	53-142
HT-R24 rape	2.6	8.0	3.1	2.3	2.2	116	103-125
Goliath rape	2.4	7.0	2.9	2.5	1.9	108	95-112
Winfred rape	2.5	6.2	3.2	2.1	2.0	106	90-125
Hunter leafy turnip	2.6	7.3	2.8	2.2	1.7	105	86-122
Canola	2.0	6.4	3.4	2.2	2.0	105	95-131
Oats	2.6	5.3	1.9	2.3	-	95	76-123
Pallaton raphano.	1.8	5.2	2.2	2.3	2.2	94	81-114
Graza radish	2.2	4.5	2.1	-	-	86	70-106
Regal kale	1.4	4.4	1.2	1.4	1.0	60	48-69
Site mean	2.1	6.4	2.7	2.3	2.0		
LSD	*0.78*	*2.14*	*0.47*	*0.36*	*0.72*		
P-Value	*< 0.01*	*< 0.01*	*< 0.001*	*< 0.001*	*0.02*		
	Metabolisable energy yield (GJ/ha)						
Green Globe turnip	-	95.0	39.2	30.1	22.9	121	103-135
Rival turnip	13.7	95.2	46.4	34.4	29.3	121	55-154
HT-R24 rape	31.2	91.2	37.4	26.7	24.6	119	102-130
Goliath rape	28.5	77.0	34.8	29.6	21.0	110	95-121
Winfred rape	29.7	69.7	39.2	23.3	23.1	109	89-135
Hunter leafy turnip	31.0	84.6	34.2	25.6	19.3	108	87-123
Canola	23.6	73.3	40.7	23.8	22.9	106	91-142
Pallaton raphano.	21.9	60.5	28.0	27.0	25.0	96	83-113
Graza radish	27.1	51.5	26.2	-	-	90	71-108
Oats	27.1	50.7	22.3	24.1	-	88	70-108
Regal kale	17.3	49.4	15.1	16.8	11.3	61	51-69
Site mean	25.1	72.6	33.0	26.1	22.2		
LSD	*9.25*	*24.5*	*5.45*	*4.78*	*8.16*		
P-value	*< 0.01*	*< 0.001*	*< 0.001*	*< 0.001*	*0.02*		
	Crude protein yield (kg/ha)						
Green Globe turnip	-	1802	757	354	333	121	111-132
Rival turnip	320	1583	833	386	408	116	63-142
Canola	554	1374	710	366	293	109	99-122
HT-R24 rape	560	1504	645	336	315	108	105-110
Hunter leafy turnip	604	1622	644	320	249	106	84-119
Goliath rape	578	1494	648	307	268	104	90-114
Pallaton raphano.	492	1258	572	337	351	102	92-118
Winfred rape	501	1271	725	289	291	101	91-124
Graza radish	595	1132	524	-	-	97	83-117
Oats	479	963	408	275	-	80	70-94
Regal kale	386	1026	295	224	166	66	50-76
Site mean	507	1336	615	319	297		
LSD	*170*	*507*	*105*	*82.9*	*113*		
P-Value	*0.03*	*0.04*	*< 0.001*	*0.02*	*0.01*		

[1] Based on aboveground biomass only as bulbs were insufficient in size for collection.

Table 10. Late grazing window (1600-2100 growing degree days after sowing) edible biomass (bulb, stem and leaf portions), and yields of metabolisable energy and crude protein (*i.e.,* biomass × ME or CP content) of forage brassicas, canola and forage oats at 7 experiments across the Australian mixed farming zone.

	Tummaville		Condamine		Iandra	York		Mean rank (%)	Site rank range (%)
	2018	2019	2018	2019	2018	2018	2019		
Edible biomass (t DM/ha)									
Oats	7.5	9.4	2.6	0.8	3.6	5.1	-	144	110-180
Canola	5.5	8.0	1.8	1.2	2.5	4.1	2.7	124	94-201
Pallaton raphano.	5.1	7.9	2.3	0.5	1.7	4.5	3.9	114	83-181
HT-R24 rape	3.5	9.7	1.8	1.1	2.0	3.8	2.3	112	84-191
Goliath rape	3.3	11.2	3.0	0.7	2.2	3.4	2.3	109	80-140
Rival turnip	3.6	9.4	2.2	0.5	1.7	3.6	1.9	94	81-110
Winfred rape	2.8	7.9	2.5	0.6	1.9	2.9	1.9	92	67-120
Graza radish	5.0	5.5	1.8	0.5	2.1	-	-	91	65-119
Regal kale	5.2	8.4	1.6	0.0	1.7	2.3	1.9	77	8-124
Green Globe turnip	3.1	8.3	2.0	0.2	1.2	3.8	1.6	76	32-104
Hunter leafy turnip	1.7	8.1	1.6	0.3	1.7	3.2	1.0	69	40-96
Site mean	*4.2*	*8.5*	*2.1*	*0.6*	*2.0*	*3.7*	*2.2*		
LSD	*1.1*	*2.2*	*0.9*	*0.7*	*0.5*	*0.9*	*0.5*		
P-Value	*<0.001*	*<0.01*	*0.05*	*0.03*	*<0.001*	*<0.001*	*<0.001*		
Metabolisable energy yield (GJ/ha)									
Oats	63.0	88.8	24.1	8.5	37.2	44.9	-	122	92-163
Pallaton raphano.	60.7	93.5	28.0	6.0	18.8	53.8	47.6	121	83-192
Canola	-	94.3	19.3	14.1	25.8	29.9	31.0	117	77-208
HT-R24 rape	41.7	110.1	21.8	12.7	23.3	43.6	26.6	115	89-187
Goliath rape	39.5	124.9	35.5	7.6	25.6	37.9	25.5	113	87-145
Rival turnip	43.2	110.0	26.8	6.0	19.1	40.0	20.7	97	84-114
Winfred rape	33.6	90.9	30.6	7.0	24.2	32.5	21.5	96	74-126
Graza radish	54.2	63.3	21.4	5.8	23.1	-	-	92	66-120
Green Globe turnip	36.7	97.8	23.5	2.2	14.3	42.8	17.9	80	32-111
Regal kale	59.4	92.4	19.2	0.5	18.8	26.4	20.5	78	8-131
Hunter leafy turnip	20.6	97.1	18.7	3.7	20.6	34.3	11.3	72	45-101
Site mean	*45.3*	*96.6*	*24.4*	*6.7*	*22.8*	*38.6*	*24.7*		
LSD	*11.3*	*24.8*	*10.4*	*7.5*	*5.1*	*10.2*	*5.8*		
P-Value	*<0.001*	*<0.01*	*0.05*	*0.01*	*<0.001*	*<0.001*	*<0.001*		
Crude protein yield (kg/ha)									
Canola	-	1808	386	232	368	441	338	124	88-195
Pallaton raphano.	912	1807	512	112	285	443	476	116	90-159
HT-R24 rape	630	1835	378	255	291	373	280	112	83-214
Goliath rape	658	2240	620	136	330	264	314	108	77-142
Graza radish	1018	1415	406	106	357	-	-	102	82-135
Rival bulb turnip	783	1924	452	115	314	327	312	102	95-112
Oats	872	1296	375	97	344	495	-	101	75-143
Winfred rape	596	1483	547	133	329	219	256	93	64-125
Green Globe turnip	858	1845	403	42	251	368	291	90	35-113
Regal kale	812	1612	371	10	314	310	285	82	9-107
Hunter leafy turnip	437	1653	366	62	312	211	147	72	49-98
Site mean	*758*	*1720*	*438*	*118*	*318*	*345*	*300*		
LSD	*236*	*415*	*182*	*131*	*87*	*146*	*54*		
P-Value	*<0.001*	*<0.001*	*0.10*	*0.01*	*0.28*	*<0.01*	*<0.001*		

4.1.3. Forage quality of forage brassicas

The higher forage quality provided by the forage brassicas was a key driver of their higher yields of crude protein and metabolizable energy and was a clear advantage over the benchmark forage comparisons of canola and forage oat (Tables 11 and 12). In the vegetative growing phase, the forage brassicas often contained around 1.0-1.6 MJ/kg DM higher metabolizable energy content than forage oats, and in some cases, this was also superior to canola when it had reached early reproductive development (Table 11). Crude protein content was also consistently > 2% higher in the forage brassicas than the forage oats.

This difference in forage quality was increased at the later grazing window when the forage oats had started to become reproductive (Table 12). Forage oats often had ME content < 10 MJ ME/kg DM compared to forage brassicas maintaining ME content > 11.5 MJ ME/kg DM. Similarly, the crude protein content of forage oats was typically around 5% lower than the forage brassicas. This ability of the brassicas to maintain or only show modest declines in their forage quality at later grazing periods is likely to be a distinct advantage over forage cereals or dual-purpose crops.

Table 11. Metabolisable energy and crude protein content of forage brassicas (bulb, stem and leaf portions), canola and forage oats in early grazing window (800-1300 growing degree days after sowing) at 5 site years across the Australian mixed farming zone (years 2018 and 2019).

	Tummaville		Iandra	York		Mean rank (%)
	2018[1]	2019	2019	2018	2019	
Metabolisable energy content (MJ/kg DM)						
Rival turnip	12.1	11.7	12.2	11.9	11.4	102
Pallaton raphano.	12.2	11.6	12.4	11.7	11.3	102
Green globe turnip	-	11.7	12.3	11.9	11.2	102
Graza radish	12.1	11.5	12.3	-	-	102
Hunter leafy turnip	11.9	11.6	12.4	11.7	11.4	101
HT-R24 rape	12.2	11.4	12.2	11.4	11.4	101
Regal kale	12.2	11.2	12.3	11.8	11.1	101
Winfred rape	12.1	11.2	12.3	11.4	11.5	101
Goliath rape	12.0	11.1	12.1	11.8	11.3	100
Canola	11.5	11.5	12.2	10.9	11.5	99
Oats	10.4	9.6	11.4	10.6	-	90
Site mean	*11.9*	*11.3*	*12.2*	*11.5*	*11.3*	
LSD	*0.23*	*0.23*	*0.27*	*0.77*	*0.12*	
P-Value	*< 0.001*	*< 0.001*	*< 0.001*	*0.02*	*< 0.001*	
Crude protein content (% DM)						
Graza radish	26.8	25.1	24.7	-	-	111
Pallaton raphano.	28.0	24.4	25.6	14.7	16.0	109
Regal kale	27.7	23.2	24.2	15.6	16.2	108
Canola	27.0	21.5	21.3	16.7	14.6	103
Green globe turnip	-	22.1	23.7	13.6	16.4	103
Rival turnip	28.4	19.3	22.0	13.5	16.0	100
Hunter leafy turnip	23.2	21.6	23.3	14.6	14.7	99
Goliath rape	24.7	21.5	22.6	12.2	14.3	96
Winfred rape	21.1	20.4	22.7	14.0	14.4	95
HT-R24 rape	21.8	18.9	21.1	14.4	14.6	93
Oats	18.5	18.4	20.8	12.1	-	84
Site mean	*24.7*	*21.5*	*22.9*	*14.1*	*15.2*	
LSD	*3.64*	*2.21*	*2.12*	*3.09*	*1.58*	
P-Value	*< 0.001*	*< 0.001*	*< 0.001*	*0.12*	*0.03*	

[1] Based on aboveground biomass only as bulbs were insufficient in size for collection.

Table 12. Metabolisable energy and crude protein content of forage brassicas (bulb, stem and leaf portions), canola and forage oats in the late grazing window (1600-2100 growing degree days after sowing) at 7 site years across the Australian mixed farming zone (years 2018 and 2019).

	Tummaville		Condamine		Iandra	York		Mean rank (%)
	2018	2019	2018	2019	2018	2018	2019	
Metabolisable energy content (MJ/kg DM)								
Pallaton raphano.	12.0	11.8	12.0	11.9	11.2	11.9	12.1	105
Winfred rape	12.0	11.5	12.0	11.2	12.0	11.2	11.4	103
Hunter leafy turnip	12.0	11.9	12.0	11.9	11.8	10.9	10.8	103
Green globe turnip	12.0	11.7	12.0	11.7	11.5	11.2	11.1	103
Goliath rape	12.0	11.1	12.0	11.8	11.6	11.3	11.3	102
Rival turnip	12.0	11.8	12.0	11.6	11.6	11.0	10.9	102
HT-R24 rape	12.0	11.4	12.0	11.2	11.5	11.3	11.4	102
Regal kale	11.2	11.0	11.8	11.6	11.2	11.6	11.1	100
Graza radish	11.0	11.5	11.8	11.6	11.3	-	-	100
Canola	-	11.8	10.5	11.8	10.3	7.1	11.7	93
Oats	8.5	9.6	9.3	10.7	10.2	8.8	-	84
Site mean	*11.5*	*11.4*	*11.6*	*11.5*	*11.3*	*10.6*	*11.3*	
LSD	*0.34*	*0.34*	*0.30*	*0.45*	*0.40*	*0.58*	*0.38*	
P-Value	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	
Crude protein content (% DM)								
Green globe turnip	27.9	22.6	21.0	22.0	20.3	9.6	18.2	116
Graza radish	20.5	25.6	22.3	21.6	17.4	-	-	109
Regal kale	15.6	19.3	23.1	22.6	18.6	13.8	15.3	108
Rival turnip	21.6	20.6	20.3	23.1	18.9	9.0	16.6	106
Hunter leafy turnip	25.7	20.2	23.0	19.3	18.1	7.2	14.3	102
Pallaton raphano.	17.9	22.9	22.0	22.2	16.8	9.7	12.3	101
Canola	-	22.7	21.1	20.1	14.7	10.2	12.8	99
Winfred rape	21.0	18.7	21.6	22.2	16.0	7.8	13.6	97
Goliath rape	19.6	19.9	20.9	21.4	14.9	7.7	13.9	95
HT-R24 rape	17.9	19.0	21.2	22.8	14.2	9.6	12.1	95
Oats	11.7	14.1	14.6	12.3	9.4	9.7	-	69
Site mean	*19.9*	*20.5*	*21.0*	*20.9*	*16.3*	*9.4*	*14.3*	
LSD	*2.40*	*1.85*	*2.38*	*2.15*	*2.32*	*2.94*	*1.83*	
P-Value	*< 0.001*	*< 0.001*	*< 0.01*	*< 0.001*	*< 0.001*	*< 0.01*	*< 0.001*	

4.1.3. Genotype by environment interactions

Across the range of production environments measured here, the multi-environment trial analysis revealed limited genotype by environment interactions in the early grazing window but in the later grazing window a number of genotype-by-environment interactions were found for the various productivity measures. In the early grazing window, there were no genotype by environment interactions for edible biomass, but there were some slightly negative correlations for yields of ME and CP, particularly for CP yield. In this early grazing window, these slightly negative correlations between sites were isolated to the Tummaville 2018 site which were strongly related to the lower performance of Rival at the Tummaville 2018 site which was inconsistent with the other sites. Within this early grazing window, all genotypes, other than Rival, had a stable performance ranking across the range of production environments. Relative to the other genotypes, Rival was shown to be highly responsive in higher production environments, that it increased its productivity relatively more than other genotypes as indicated by a steeper regression (Figures 5a, b and c). To illustrate, Goliath had similar relative ME yield compared to Rival in low production environments, but a much lower relative performance in a higher production environment (Figure 5b).

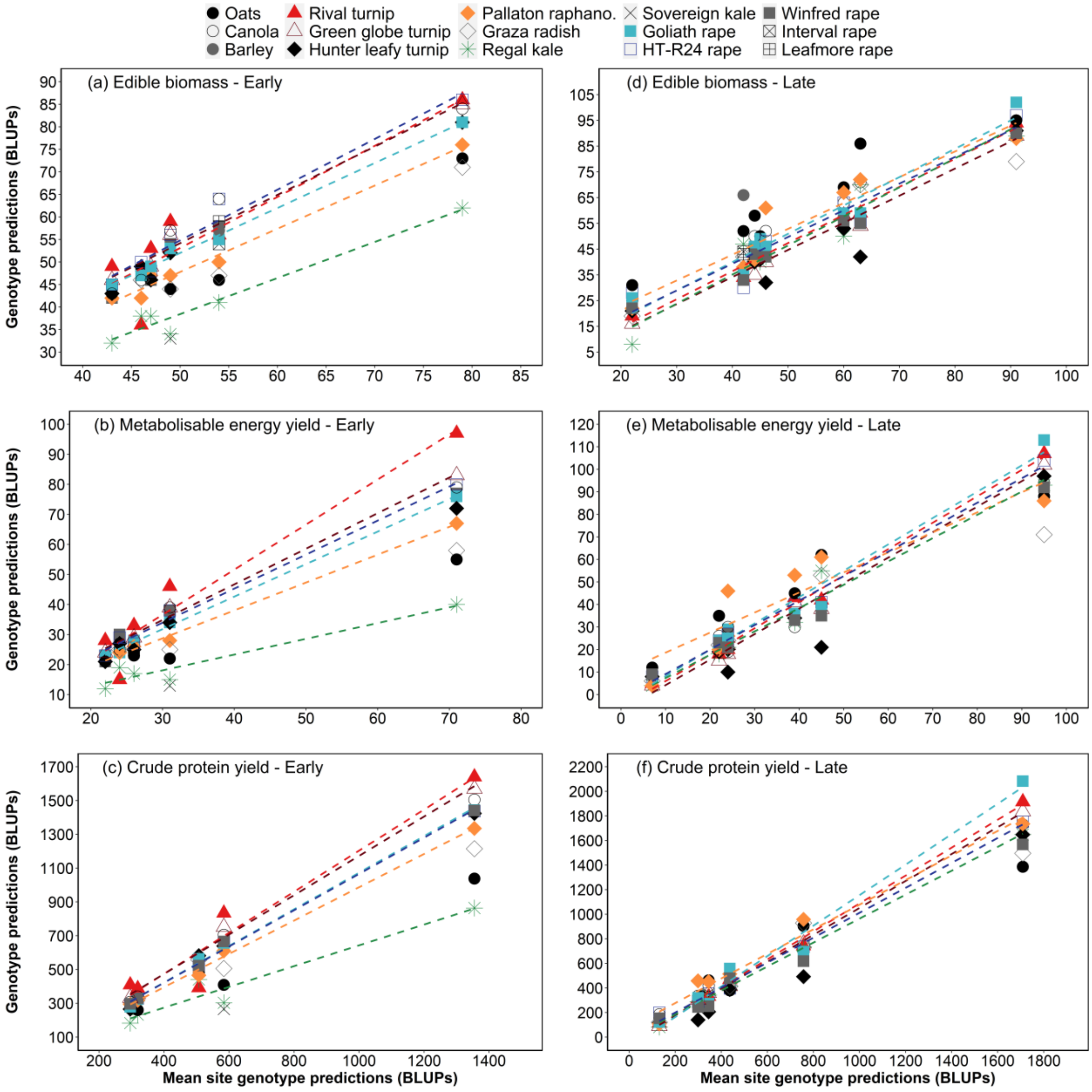


Figure 5. Relationships between forage genotype and environment using best linear unbiased predictors (BLUPs) obtained from multi-environment trial analyses for a diverse range of forage brassica genotypes, canola and cereal crops for edible biomass (a and d), metabolisable energy yield (b and e), and crude protein yield (c and f) within an early (800-1300 growing degree days after sowing; a-c) and late grazing window (1600-2100 growing degree days after sowing; d-f).

In the late grazing window, some moderate negative correlations between experimental sites were identified, particularly for yields of ME and CP. The multi-environment trial analyses showed that in the later grazing window there was no-single forage brassica genotype that was ranked consistently across all production environments for any of the productivity measures. Moderate negative correlations for ME yield were mostly related to the Tummaville 2019 site, whilst the moderate negative correlations for CP yield were related to both the Tummaville 2019 and Condamine 2018 sites. These indicate that several of the forage genotypes ranked very differently within the Tummaville 2019 experiment compared to their ranking at the sites that had lower production potential (Figures 5e and f). This was most apparent for Hunter leafy turnip that performed poorly for all productivity measures in environments with low-moderate production potential but quite favourably at the Tummaville 2019 site (Figures 5d, e and f). This revealed that some genotypes, such as Hunter, are better suited to higher production environments, compared to low production environments (i.e., drier environments) where they are poorly adapted. The moderate negative correlations for CP yield related to the Condamine 2018 site were due to the relative ranking of several genotypes including oats, Graza, Winfred and Goliath, which varied considerably at this site compared to the York 2018 and Iandra 2018 sites (Figures 5d, e and f). It is unknown why these genotypes responded so differently as they were all grown in low-moderate production environments. Of the forage brassicas, Pallaton had high relative productivity at sites with low-moderate mean production but was far less responsive at sites with high production potential in the late grazing window (Figures 5d, e and f).

4.4 Modelling forage brassica performance in forage systems

4.2.1 Model evaluation

The newly calibrated models for forage brassica genotypes were shown to perform adequately across a broad range of production environments, seasonal conditions and management scenarios (Figure 6). When model performance was tested against an independent multi-environment data set, the biomass for all genotypes was reasonably well predicted as indicated by the high NSE score (0.61–0.72), $R^2 > 0.73$, and RMSE values ranging from 1.4 to 1.7 t DM$\cdot$ha^{-1}. The PBIAS values for all genotypes were < 25% and early rape genotype was close to optimal, indicating low model bias, but predicted biomass for late rape genotype (e.g., Goliath) and raphanobrassica were often underestimated and overestimated, respectively. Although there were differences in model performance between the agro-climatic zones, all sites had relatively low RMSE values ranging from 0.6 to 2 t DM$\cdot$ha^{-1}. Overall, the model predicted biomass with only a 0–39% difference to the observed data at 18 out of the 23 sites and this was distributed broadly across the agro-climatic zones.

Predictions of plant DMD and CP content were poor for all genotypes, often achieving negative NSE scores and R^2 values well below 0.50 ($R^2 < 0.10$ in most instances). This finding was also consistent across agro-climatic zones and cultivars. Although DMD predictions for the forage brassicas were improved by the iterative modifications made to the green leaf and stem DMD parameters during the calibration stage (Fig. 6d), many of the statistical analyses indicated potential to further improve model performance, especially the need to better capture the variability in DMD over time and across environments. While model performance statistics here were generally poor for DMD, observed data captured a relatively small range, mainly during the vegetative growth stage, when grazing is most likely. Further, in reality DMD values above 70% are likely to have minimal impact on animal dry matter intake and thus, animal production outcomes (Blaxter et al., 1961) and observed DMD values in our model testing set were above this value.

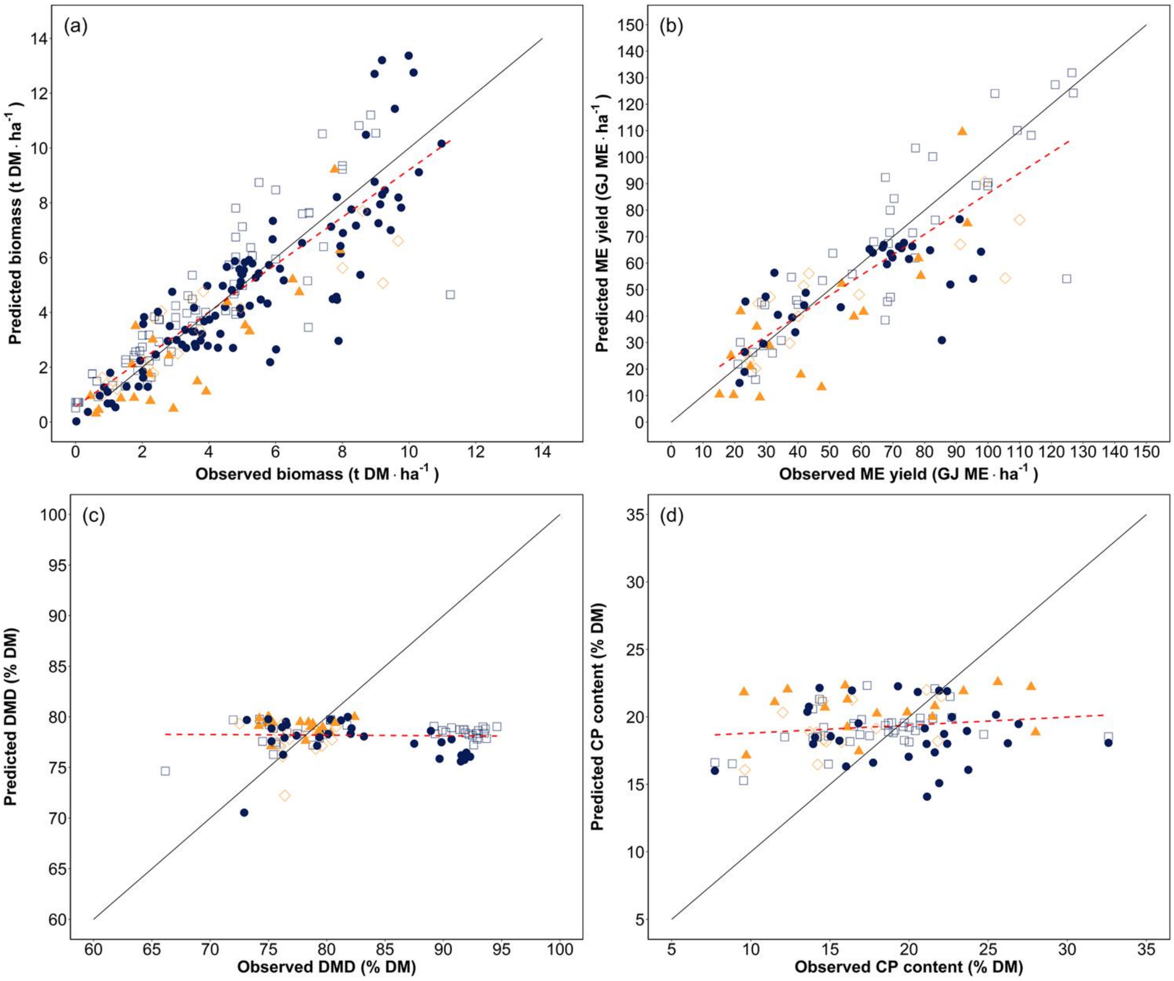
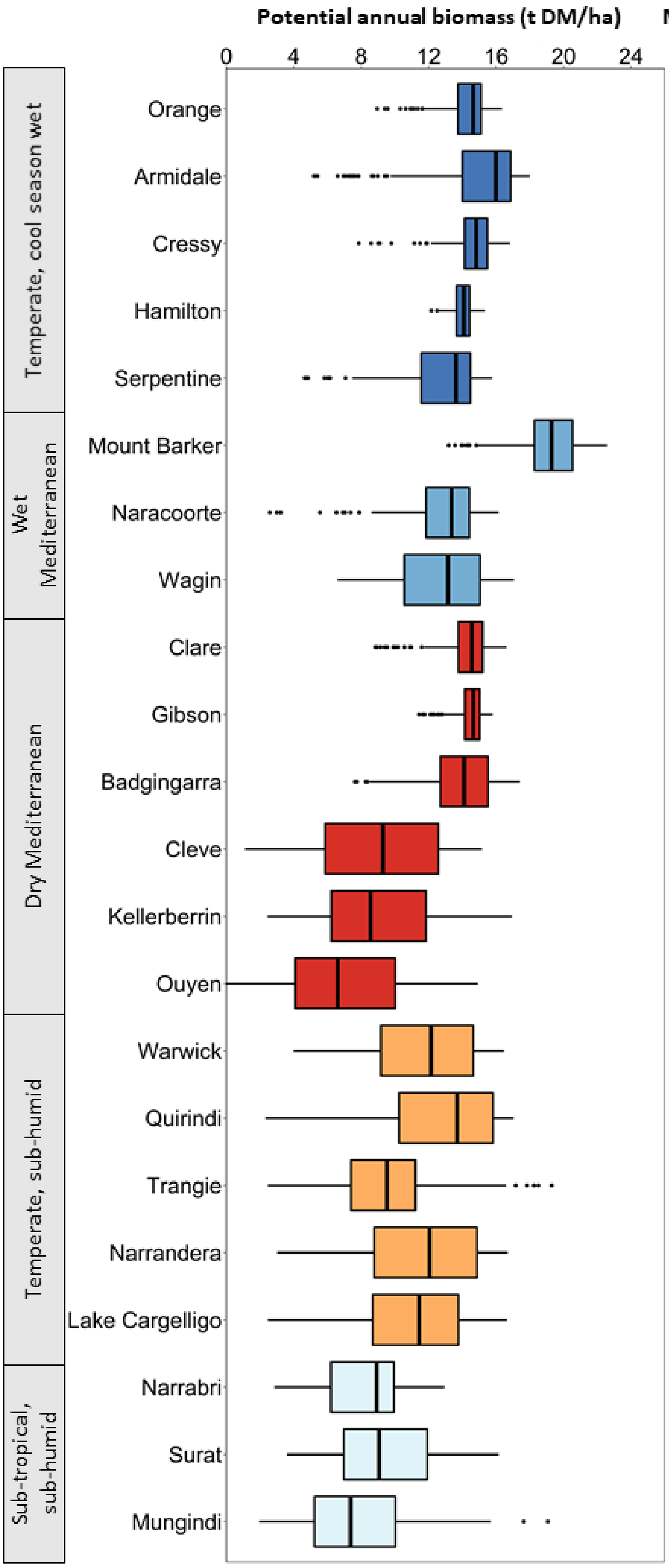


Figure 6. Observed *vs.* predicted (a) biomass, (b) metabolisable energy (ME) yield, (c) dry matter digestibility (DMD), and (d) crude protein (CP) content of forage brassica types: early rapes (blue solid circles), late rapes (blue open squares), raphanobrassica (orange solid triangles) and HT rape (orange open diamonds). Solid line represents 1:1 line and red dotted line the linear regression.

4.2.2 Predictions of forage brassica productivity across climatic conditions

The predicted productivity of forage brassicas was highest (> 14 t DM/ha/year on average) in those locations with a winter/uniform rainfall distribution and annual rainfall exceeding 600 mm average, and hence a longer growing season for winter-growing crops. Simulated annual forage production was surprisingly similar across a range of the temperate, cool-season wet environments and higher rainfall Mediterranean environments (Figure 7), with growth in locations with cooler winters (e.g., Cressy, Orange) often limiting winter growth. These locations all had relatively consistent production amongst years, with 50% of years varying around the median by only 2-3 t DM/ha/year. While demonstrating similar upper growth potential to other locations in these agro-climatic zones, the drier locations such as Serpentine, Wagin and Badgingarra, had higher variability in production, because they likely to incur water stress that limits their growth in drier seasons. Simulated productivity potential of the forage brassicas was lower (11.2 t DM/ha/year average) and more variable still in the lower rainfall (< 500 mm) locations in the dry Mediterranean (e.g., Cleve, Kellerberrin, Ouyen) and temperate, sub-humid agro-climatic regions (Figure 7), where water limitations are more likely to limit forage growth. Here, annual production varied significantly, with 5-8 t DM/ha/year variance between the upper and lower quartiles of simulated seasons. Simulated production potential was lowest and equally variable in the sub-tropical, sub-humid (8.4 t DM/ha/year average) locations where winter rainfall is less and more variable.



	Mean pot. annual biomass (t/ha)	Sowing window	
Orange	14.3	04-Mar	04-Apr
Armidale	14.8	02-Mar	04-Apr
Cressy	14.6	18-Mar	12-Apr
Hamilton	14.0	20-Mar	19-Apr
Serpentine	12.8	26-Mar	17-May
Mount Barker	19.2	22-Mar	07-May
Naracoorte	12.8	04-May	31-May
Wagin	12.8	28-Mar	17-May
Clare	14.2	28-Mar	05-May
Gibson	14.5	20-Mar	01-May
Badgingarra	13.8	20-Apr	31-May
Cleve	9.0	20-Apr	31-May
Kellerberrin	9.0	03-Apr	24-May
Ouyen	6.9	11-Apr	31-May
Warwick	11.5	04-Mar	28-Apr
Quirindi	12.8	07-Mar	24-Apr
Trangie	9.3	11-Mar	05-May
Narrandera	11.6	28-Mar	11-May
Lake Cargelligo	10.9	20-Mar	03-May
Narrabri	8.2	08-Mar	06-May
Surat	9.5	04-Mar	15-May
Mungindi	7.6	11-Mar	06-May

Figure 7. Summary of simulated potential annual biomass production and sowing window for forage brassicas (forage rape *cvv.* Goliath, Winfred and HT-R24, and raphanobrassica *cv.* Pallaton) across environments in Australia's mixed farming zone. Variation over the 60-year simulation is shown by the box (25th and 75th percentile) either side of the median, and whiskers (5th and 95th percentile). Sowing window represents dates where 50% of sowing opportunities occur (1st and 3rd quantiles).

There were negligible differences in the predicted annual production amongst the four forage brassica genotypes, under the simulated crop management used here where differences in grazing response were not captured (Figure 8). The only exception was at Mount Barker where the simulated production of Goliath forage rape and Pallaton was higher by around 20-30 GJ ME yield per year (approximately 1.5-2.5 t DM/ha) (Figures 8f). There were some small differences in the timing of forage production through the year, with the raphnobrassica having lower production in the cooler months but then higher production in spring (not shown here).

Using the 60-year simulated period, the sowing window of the forage brassicas for each location was established based on the date when at least 50 mm of available soil water, and rainfall exceeded pan evaporation over a 7-day period. This highlighted significant regional and locational differences in the probable sowing window of the forage brassicas (*i.e.,* between which 50% of sowing opportunities occur). Early and consistent sowing opportunities occurred during early autumn (early March to early April) in the temperate, cool season wet locations (*e.g.,* Orange, Armidale, Cressy and Hamilton). The higher rainfall Mediterranean climates (*e.g.,* Mount Barker, Wagin, Clare, Gibson) were sown later, most often sowing from late-March until early/mid-May. Similarly, the southern locations with more winter dominant rainfall in the temperate, sub-humid climates (*i.e.,* Trangie, Narrandera, and Lake Cargelligo), tended to have a sowing window from mid/late-March until early/mid-May (Figure 7). By comparison the drier Mediterranean environments (*e.g.,* Ouyen, Cleve, Badgingarra) had much later and shorter sowing windows, starting from late-April until end-May (Figure 7). In contrast to these winter-dominant rainfall regions, the fives most northern locations (*i.e.,* the sub-tropic, sub-humid locations, and Warwick and Quirindi) had a very wide sowing window (early/mid-March until early/mid-May) reflecting their highly variable autumn and early winter rainfall (Figure 7).

4.2.3 Relative productivity of forage brassicas compared to alternatives

The forage productivity potential of the forage brassicas was nearly always greater than dual-purpose canola (data not shown). These differences reflect the much longer vegetative growing season of forage brassicas, after which grazing would stop on the dual-purpose canola. The production advantage for the forage brassicas over dual-purpose canola varied amongst sites and seasons, often associated with the length of growing season of that season and location. In temperate, cool-season wet, wet mediterranean environments the forage brassicas produced 50-120 GJ ME/ha more than the dual-purpose canola. These advantages were less (commonly around 30-80 GJ ME/ha higher) in the shorter season environments in the drier mediterranean climates, the temperate, sub-humid, and sub-tropical, sub-humid environments.

The relative difference in potential annual ME yield produced by the forage brassicas compared to forage wheat varied between locations and was inconsistent within different agro-climatic environments (Fig. 8). Nonetheless, at over half of the locations the forage brassicas regularly exceeded the predicted ME yield of forage wheat. The forage brassicas were predicted to produce higher annual ME yield compared to forage wheat in more than 80% of simulated years at six of the 22 locations: Cressy (Fig 8c), Hamilton (Fig. 8d), Mount Barker (Fig. 8f), Naracoorte (Fig. 8g), Cleve (Fig. 8l) and Ouyen (Fig. 8n). At another seven locations the forage brassicas produced more than forage wheat in most seasons (i.e., 60-80% of years) but there were some years where the forage wheat was predicted to be superior: Serpentine (Fig. 8e), Wagin (Fig. 8h), Clare (Fig. 8i) Badgingarra (Fig. 8k), Kellerberrin (Fig. 8m), and Narrandera (Fig. 8r). At the remaining sites (10 of 22) forage brassicas only exceeded the annual ME yield of forage wheat in 10-30% of simulated years, meaning that forage wheat was consistently more productive. These locations were not consistently associated with particular agro-climatic zones, with this occurring at locations in the cool season wet region (e.g., Armidale and Orange), Mediterranean climates (e.g., Gibson) and at most of the temperate, sub-humid, and sub-tropical, sub-humid environments. These locations represented very different agro-climatic environments and differences in relative productivity potential cannot be explained by annual average rainfall or its seasonality alone. However, what is apparent is that the relative performance of forage brassicas compared to wheat was influenced significantly by sowing date across locations

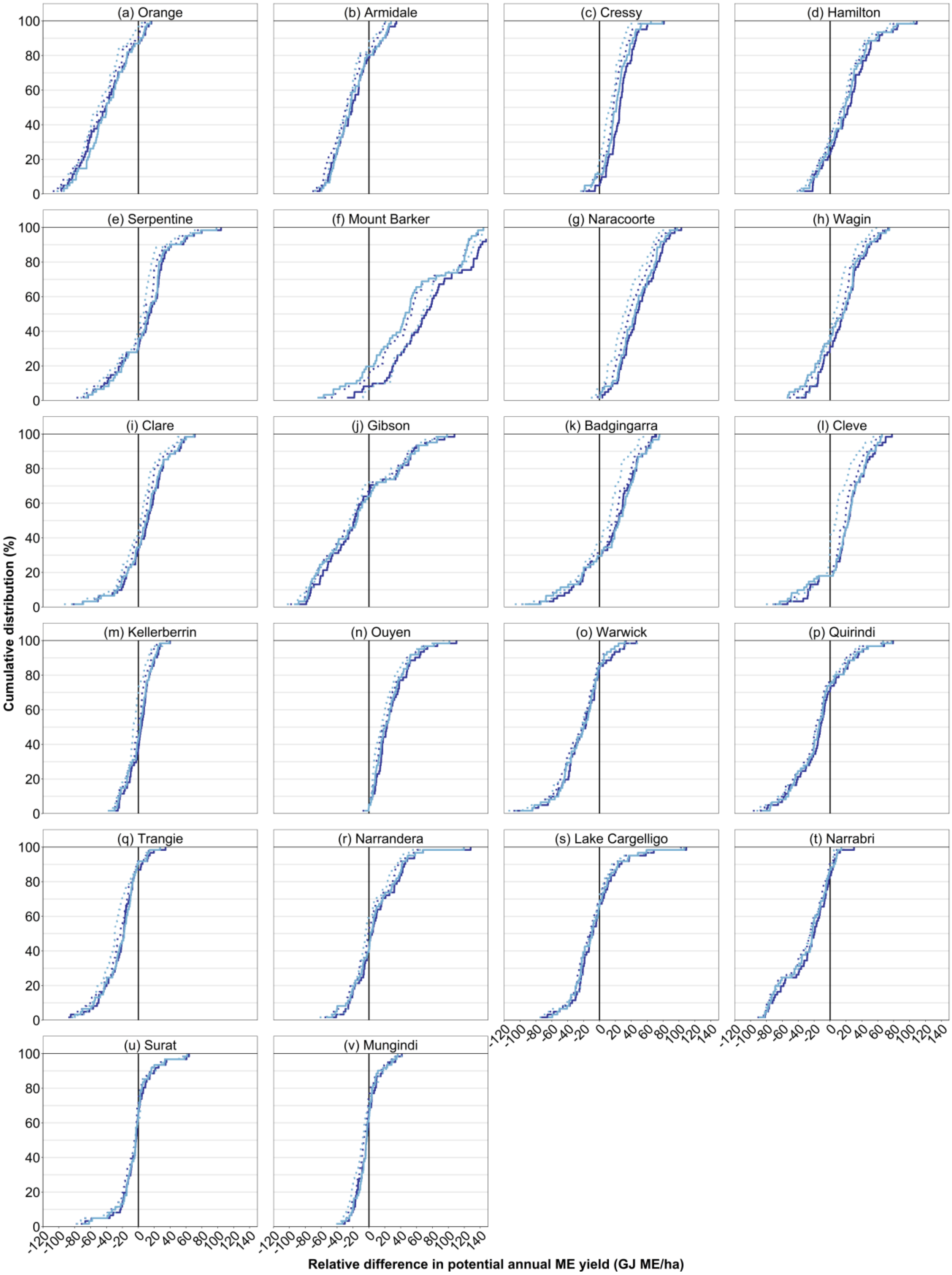


Figure 8. Relative difference in simulated annual metabolisable energy yield (GJ ME/ha/year) of Goliath (dark blue; solid), Winfred (light blue; solid), HT-R24 (dark blue; dotted), and Pallaton (light blue; dotted) compared to forage wheat (black; solid) over 60 simulated years across environments in Australia's mixed farming zone.

4.2.3 Whole-farm feed-base risk analysis

Across representative livestock and forage-based feed systems simulated representing seven diverse regions, there was significant differences in the impacts of integrating autumn-sown forage brassicas. At five of the seven systems, adding 15% of the farm forage area to forage brassicas reduced the frequency of farm feed deficits by 35-50% (Table 3). At these sites the frequency that edible biomass fell below a threshold of 500 kg/ha was also reduced by 20-40%. Some of these benefits were derived by the increase in feed-base production when the forage brassicas were added compared to the simulated baseline pasture feedbase (ranging from 20-35% more GJ ME/ha/yr across these sites), but there were also benefits from the timing of forage supply (discussed below). The south-west Victoria and Mallee Victoria feed-base systems were predicted to have much smaller benefits for reducing the frequency of feed-gaps (10-20% reductions). The relative gain in feed-base productivity predicted was also smaller at these sites (around 15%).

At most sites, both forage brassicas and forage cereals grown under similar management achieved similar impacts on reducing feed gaps in these livestock enterprises. At a few locations (Riverina, Mallee and Great Southern), there was some small advantage of the brassicas over the forage cereals for reducing the frequency of farm feed deficits, often owing to the higher quality of the brassica crops in spring. In four of the seven simulated systems there was also complementary benefits of having both forage brassicas and forage cereals in combination (Table 3).

Despite large differences in seasonality of growth of the baseline pasture feed-base, and hence timing and frequency of feed deficits, across the different regions simulated here, the incorporation of forage brassicas (and forage cereals) consistently reduced late autumn to late spring feed gaps across all locations. Clearly this benefit was greatest in locations with frequent feed deficits at this time of the year (e.g., Maranoa, Qld, Fig. 5a), but even at other locations where winter and spring feedgaps were less common there were significant reductions in the frequency of farm forage deficits during this time (e.g., Riverina, Mallee, Fig. 5c). One more surprising prediction was the extent that adding this additional productive feed source to the farm feed-base over winter was able to mitigate feed deficits that occur in late summer and autumn in the locations with a Mediterranean climate (i.e., Great Southern WA and Mid-North, SA, Fig. 5e and 5f). In these regions over summer, livestock often rely on dry residue grown during the previous spring, and while the forage brassica did not directly produce forage at this time its addition meant that more forage was conserved and subsequently available over the summer period. In southern Victoria, where the simulated system very rarely had feed deficits from late autumn (May) to spring, the autumn-sown brassicas have little benefit; in fact, they may exacerbate farm feed deficits in early autumn, at a time of the year where other pastures are in shorter supply and the autumn-sown forage brassicas are yet to contribute to forage supply of the farm.

Table 13. Frequency (percent of months) of a farm feed deficit or reduced edible biomass occurring, and the average feed-base productivity (t DM/ha/yr and GJ ME/ha/yr) under the baseline pasture system compared to systems adding 15% forage brassica, forage cereal or a combination of both. The stocking rate per grazed ha (i.e., including all pastures and forage crops grazed) is held constant in all scenarios.

Region	Maranoa, Qld	Central West, NSW	Riverina, NSW	South-west, Vic	Mallee, Vic	Mid-North, SA	Great Southern, WA
Farm feed deficit frequency (*i.e.,* feed supply insufficient to meet stock demand)							
Baseline	16.1	19.3	13.8	4.1	17.8	7.7	13.4
+ forage brass.	8.0	12.4	8.8	3.6	14.4	3.9	6.9
+ forage cereal	8.1	12.3	9.8	3.4	16.5	2.3	9.5
+ both	7.3	10.3	8.7	3.8	14.7	2.0	5.7
Available edible biomass falls below 500 kg/ha							
Baseline	48	55	40	20	51	33	42
+ forage brass.	33	43	32	17	47	28	34
+ cereal	35	41	35	17	50	27	37
+ both	28	37	30	17	47	25	33
Average feed-base productivity (t DM/ha/yr)							
Baseline	4.3	3.6	6.2	9.6	4.5	6.9	6.6
+ forage brass	4.9	4.4	6.9	10.2	4.9	8.0	7.4
+ forage cereal	5.0	4.6	6.8	10.0	4.6	7.8	7.3
+ both	5.6	5.2	7.4	10.5	4.9	8.7	8.0
Average feed-base productivity (GJ ME/ha/yr)							
Baseline	37	30	53	74	37	58	59
+ forage brass	47	41	64	86	44	74	72
+ forage cereal	46	43	61	82	40	71	70
+ both	54	51	70	92	46	84	80

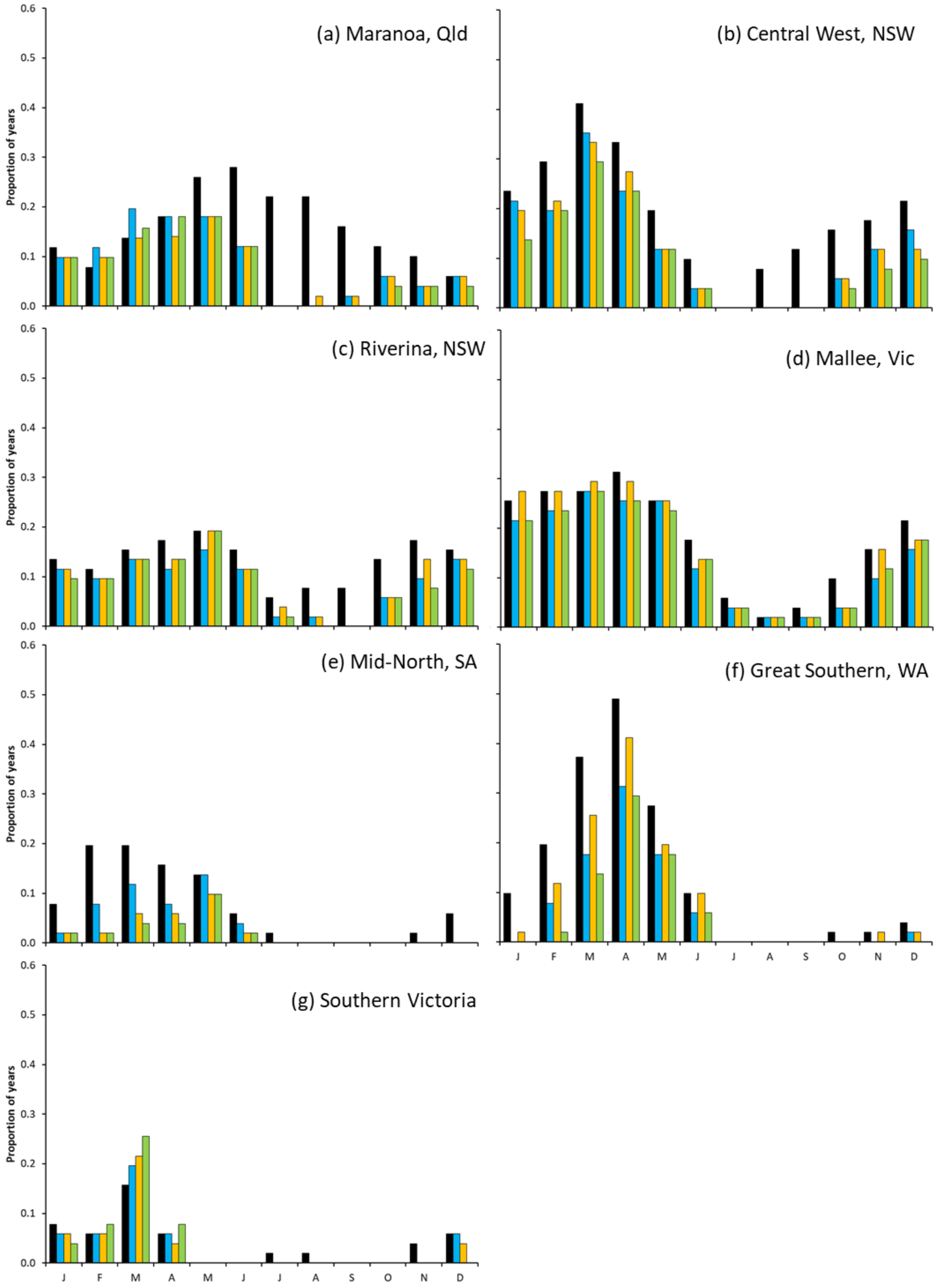


Figure 9. Frequency of predicted farm feed deficits throughout the year over 50 years (1960-2010) under the baseline pasture-only feed-base (black), or when 15% (by area) of forage brassica (blue) or forage cereal (yellow) or a combination of both (green) are added to the farm feed-base at seven locations spanning Australia's mixed crop-livestock zone.

While one benefit of forage brassicas may be to reduce feed deficits, this means there may also be potential to increase stocking rates while maintaining the same risk of feed deficits. Table * demonstrates that for a feed system that integrates 15% of grazed area to forage brassica, this has the potential to increase the stocking rate that can be maintained by 10-30%, depending on location. As above, the least benefits were obtained in south-west Victoria, but large increases in safe stocking rates (>20%) could be achieved in summer-dominant rainfall regions (*e.g.,* Maranoa, Qld and Central West NSW) or Mediterranean climates (Mid-North SA and southern WA). While this increase in stocking rate is unlikely to translate into a direct gain in farm profit due to other associated costs, it does show that increases in returns of livestock enterprises of >10% are likely to be achievable using forage brassicas.

Table 14. Stocking rate (breeding units per grazed ha) that achieves the same predicted net farm feed deficit (GJ ME) using a pasture-only farm feedbase compared to one including 15% forage brassica.

Region	Baseline	+ 15% Forage brassica	% change
Maranoa, Qld	0.35	0.45	28
Central West, NSW	1.56	2.00	28
Riverina, NSW	2.74	3.19	16
South-west, Vic	3.81	4.17	9
Mallee, Vic	1.87	2.15	15
Mid-North, SA	2.92	3.63	24
Great Southern, WA	3.33	4.45	33

4.3 Livestock performance and health risks

4.3.1 Exp. 1: Animal performance on brassicas and supplementation response

The brassica genotypes differed significantly in DM production (raphanobrassica = canola > rape > kale) but not in nutritional values (Table 15). Nitrate concentrations did not differ significantly between treatments at the beginning of the trial but increased markedly in kale as the trial progressed (Fig. 10). Notably, plant material in more than half of the plots at any time had nitrate levels above the 10000-ppm recommended as the safe limit for grazing but did not appear to affect animal health. Rates of LWG differed between weeks and brassica genotypes but was not affected by available DM or nutritional quality (Table 15). Across all genotypes, lambs lost weight during the first three days after introduction, during which biomass on all plots increased (i.e., intake was very low). Subsequent rates of LWG were higher on rape and canola than on kale and raphanobrassica. Lambs that received the micro-nutrient drench did not perform better overall than un-drenched lambs regardless of cultivar (Fig. 11). Blood concentrations of gamma glutamyl transferase, total bilirubins and creatinine increased significantly between the start and end of grazing in sampled sheep, suggesting some adverse effects on liver and kidney function, but none were outside the normal range (Table 16).

Supplementary feeding appears to be necessary to avoid weight loss of lambs when they are first introduced to forage brassicas. The DM production, plant nutritional value, and micro-nutrient supplement did not affect LWG. Lambs showed greater rates of LWG on genotypes of *B. napus* (canola and rape) than *B. oleracea* (kale and raphanobrassica), but this was not reflected in rates of DM intake.

Table 15. Dry matter (DM) production and nutritional quality of four genotypes of spring-sown forage brassica before grazing commenced in summer 2019, and associated intake and liveweight gain (LWG) in Merino ewe lambs. Values represent mean ± SE. Superscripts denote significant differences between cultivars *(P* < 0.05). DM intake calculations account for plant growth.

	Canola	Rape	Kale	Raphanobrassica
DM available (t/ha)	3.6 ± 0.2^{A}	1.8 ± 0.3^{B}	1.0 ± 0.3^{C}	4.0 ± 0.4^{A}
DM digestibility (%)	71.4 ± 0.9	70.6 ± 0.3	70.9 ± 1.2	72.6 ± 0.7
Metabolisable energy (MJ/kg DM)	10.6 ± 0.1	10.5 ± 0.0	10.4 ± 0.2	10.8 ± 0.1
Crude protein (% DM)	21.8 ± 1.4	24.7 ± 1.6	18.8 ± 1.2	21.7 ± 1.3
Neutral detergent fibre (% DM)	32.0 ± 1.3	31.4 ± 0.2	32.0 ± 1.2	29.0 ± 0.6
DM intake (kg/head/day)	1.3 ± 0.3^{AB}	1.1 ± 0.2^{B}	1.7 ± 0.2^{A}	1.2 ± 0.1^{AB}
LWG Day 0-3 (g/head/day)	-511 ± 74	-462 ± 44	-648 ± 62	-563 ± 62
LWG Day 4 onward (g/head/day)	132 ± 12^{A}	139 ± 16^{A}	97 ± 12^{B}	103 ± 8^{B}
Grazing days (/ha)	1880 ± 208^{B}	1220 ± 140^{C}	1847 ± 256^{B}	3280 ± 262^{A}

Figure 10. Nitrate concentrations in plots over time by cultivar.

Table 16: Blood screening results from lambs before and after grazing brassicas. Asterisks indicate significant differences between pre- and post-graze samples.

Indicator	**Normal range**	**Pre-Graze**	**Post-Graze**	**P < 0.05**
Gamma Glutamyl Transferase (U/L)	0 - 55	43.9 ± 3.4	54.8 ± 4.5	*
Total Bilirubins (µmol/L)	0.0 - 6.8	2.2 ± 0.3	4.2 ± 0.5	*
Creatinine (µmol/L)	0 - 265	82.2 ± 1.6	75.9 ± 1.4	*

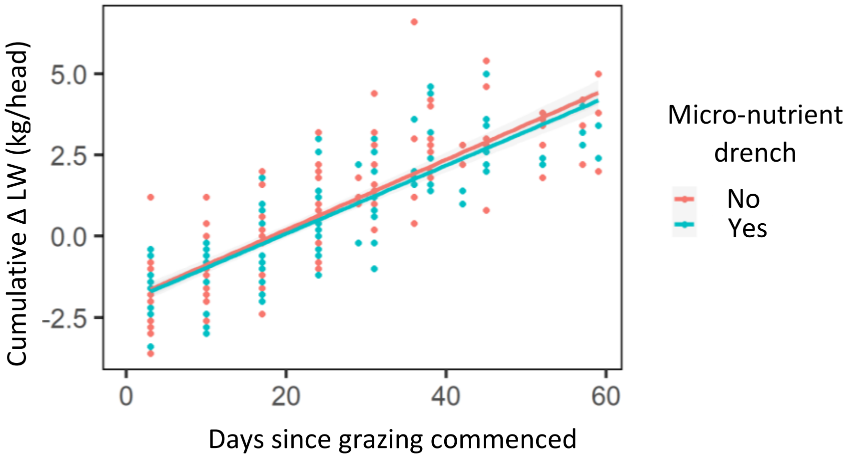


Figure 11. Cumulative liveweight gain of lambs grazing brassicas with or without an oral micro-nutrient (Se, Cu, I) supplement administered.

4.3.2 Exp. 2: Animal diet selectivity when introduced to grazing brassicas

Cultivar was a significant predictor of selectivity by lambs (*P* < 0.001; Table 17). Oats, kale and raphanobrassica (kale × radish) were most strongly selected for, whilst turnip foliage was largely avoided (we recorded an increase in available DM in most plots over the grazing period). There was no significant effect of ME, CP, NDF or nitrate content on the proportion of available DM consumed by lambs (*P* > 0.2; Table 17).

Table 17. Change in DM after first grazing in June (as a percentage of available DM) and DM concentrations of ME, CP, NDF and nitrate, by forage cultivar. Values are arithmetic means ± SE; letters indicate significant differences at *P* < 0.05.

Cultivar	Δ DM (%)	ME (MJ/kg)	CP (%)	NDF (%)	Nitrate (g/kg)
Oats *cv.* Eurabbie	-78 ± 8 ^{A}	11.4 ± 0.0	21.6 ± 0.4	31.3 ± 0.8	5.2 ± 1.6
Kale *cv.* Regal	-75 ± 4 ^{A}	12.3 ± 0.1	24.1 ± 0.7	15.2 ± 1.6	18.5 ± 1.5
Raphanobrassica *cv.* Pallaton	-67 ± 18 ^{A}	12.4 ± 0.1	25.6 ± 0.9	13.6 ± 0.3	13.6 ± 1.9
Kale *cv.* Sovereign	-64 ± 9 ^{AB}	12.4 ± 0.1	25.1 ± 1.4	15.3 ± 1.2	21.7 ± 1.9
Rape *cv.* Winfred	-48 ± 4 ^{ABC}	12.3 ± 0.1	22.7 ± 0.9	16.9 ± 0.9	14.0 ± 1.1
Triticale *cv.* Endeavour	-46 ± 30 ^{ABC}	11.2 ± 0.1	21.6 ± 0.9	32.2 ± 0.3	4.1 ± 1.3
Rape *cv.* HT-R24	-41 ± 4 ^{ABC}	12.2 ± 0.1	21.1 ± 0.8	16.9 ± 1.4	19.7 ± 2.0
Canola *cv.* Hyola 970CL	-38 ± 8 ^{ABC}	12.2 ± 0.1	21.3 ± 1.0	18.2 ± 0.9	17.3 ± 2.5
Rape *cv.* Goliath	-38 ± 9 ^{ABC}	12.1 ± 0.2	22.6 ± 0.9	18.0 ± 1.3	26.6 ± 7.2
Radish *cv.* Graza	-35 ± 12 ^{ABC}	12.3 ± 0.1	24.7 ± 0.4	17.1 ± 1.0	8.8 ± 1.8
Bulb Turnip *cv.* Rival	2 ± 6 ^{BC}	12.2 ± 0.1	23.2 ± 0.3	17.3 ± 0.6	26.3 ± 2.2
Bulb Turnip *cv.* Green Globe	9 ± 5 ^{C}	12.3 ± 0.1	24.4 ± 1.1	15.8 ± 1.0	15.7 ± 4.2
Leafy Turnip *cv.* Hunter	17 ± 21 ^{C}	12.4 ± 0.1	23.3 ± 0.4	15.4 ± 1.2	20.3 ± 5.4

This study demonstrated that lambs prefer some brassica cultivars over others, and these preferences may have a genotypic basis. The preferred brassicas were all kale or kale crosses (*Brassica oleracea* var. *acephala*), while the least preferred were turnip and turnip crosses (*Brassica campestris* var. *rapa*). We found no relationship between selectivity and the nutritional quality parameters we assessed. Selective intake could be influenced by plant secondary metabolites found in brassicas, such as glucosinolates and sulphur-methyl cysteine sulphoxide (Barry 2013). Further work is needed to quantify these compounds across forage brassica cultivars to determine whether they are drivers of selectivity by lambs.

4.3.3 Exp. 3: Plant nutrition effects on plant secondary metabolite accumulation

DM yield

There was a significant interaction between the N applied and cultivar (Table 18). DM yield of the raphanobrassica was not affected by N treatment while canola and forage rape showed a reduced forage yield under the low nitrogen treatment (Figure 12). The results indicate no significant impact on forage yield of cultivar alone or sulphur treatment (Table 19).

Table 18. The effects of cultivar, nitrogen, sulphur and their interactions on forage yield.

Fixed effects	X^2	DF	P-value
N	28.1280	2	**< 0.0001**
S	0.8755	1	0.35
Cultivar	4.2724	2	0.12
N x S	3.3331	2	0.19
N x Cultivar	11.3676	4	**0.022**
S x Cultivar	2.1941	2	0.33
N x S x Cultivar	1.0610	4	0.90

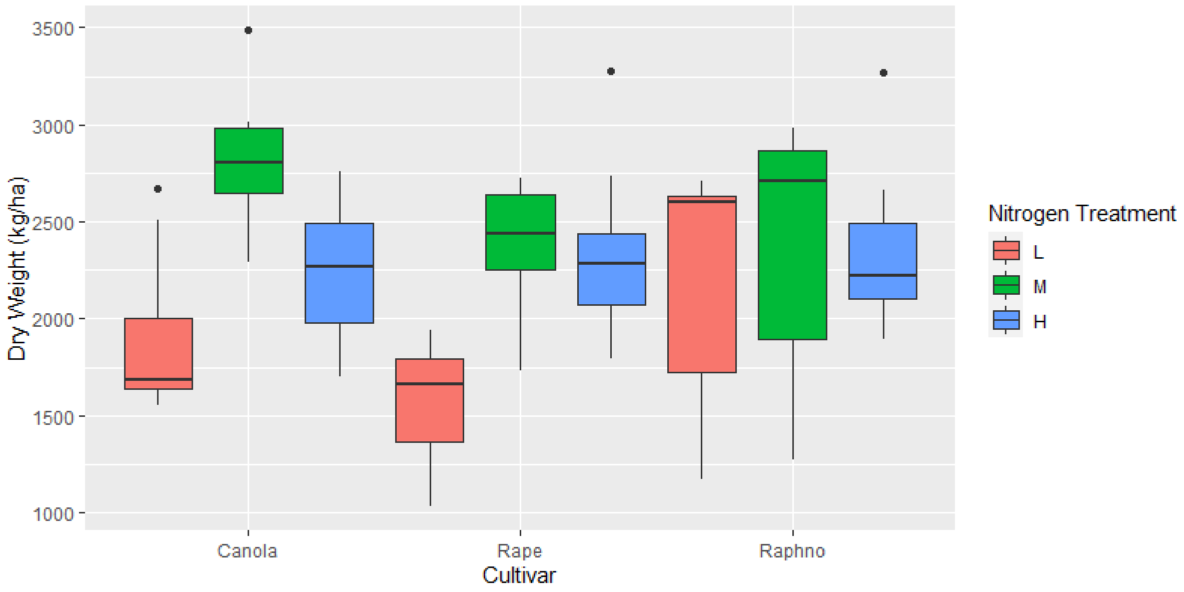


Figure 12. DM yield of three brassica cultivars *Brassica napus* (Canola and Rape) and *Brassica oleracea* x *Raphanus raphanistrum* (Raphno) in response to three levels of nitrogen fertilisation (low = L, medium = M and high = H).

Standard Forage Quality Measures

Analysis of quality of our forage brassicas showed that neutral detergent fibre ranged from 19.3-26.8 %, acid detergent fibre ranged from 11.6-16.9 %, metabolizable energy ranged from 11.0-12.4 %, dry matter digestibility ranged from 74.1-82.3 %, ash ranged from 9.1-13.2 % and crude protein ranged from 11.8-20.2 %. Overall, the chemical composition of the brassicas appears to remain relatively consistent across the various cultivars (Table 4).

Table 19. Comparison of means for digestibility and chemical composition of three forage brassicas: Canola, Forage rape and Raphanobrassica.

	Canola	Rape	Raphanobrassica
Neutral Detergent Fibre (%)	22.9	23.6	23.1
Acid Detergent Fibre (%)	14.0	14.0	13.8
Dry Matter Digestibility (%)	79.4	78.5	79.0
Metabolizable Energy (MJ/kg Dry Matter)	11.9	11.8	11.9
Ash (%)	11.1	10.6	11.6
Crude Protein (%)	16.0	15.9	17.0

Nitrates

Crop nitrate concentrations responded to the different levels of nitrogen fertilisation, increasing as the level of nitrogen fertilisation increases (Figure 3). However, no response in nitrates was found for different levels of sulphur fertilisation or when a synergistic effect of the two fertilisers was considered (Table 5). Cultivar also appears to have a significant effect on the levels of nitrates present (Table 5).

Table 20. The effects of cultivar, nitrogen, sulphur and their interactions on nitrate.

Fixed effects	X^2	DF	P-value
N	209.81	2	**< 0.0001**
S	0.28	1	0.60
Cultivar	9.43	2	**0.009**
N x S	1.66	2	0.43
N x Cultivar	3.42	4	0.49
S x Cultivar	0.36	2	0.84
N x S x Cultivar	3.52	4	0.47

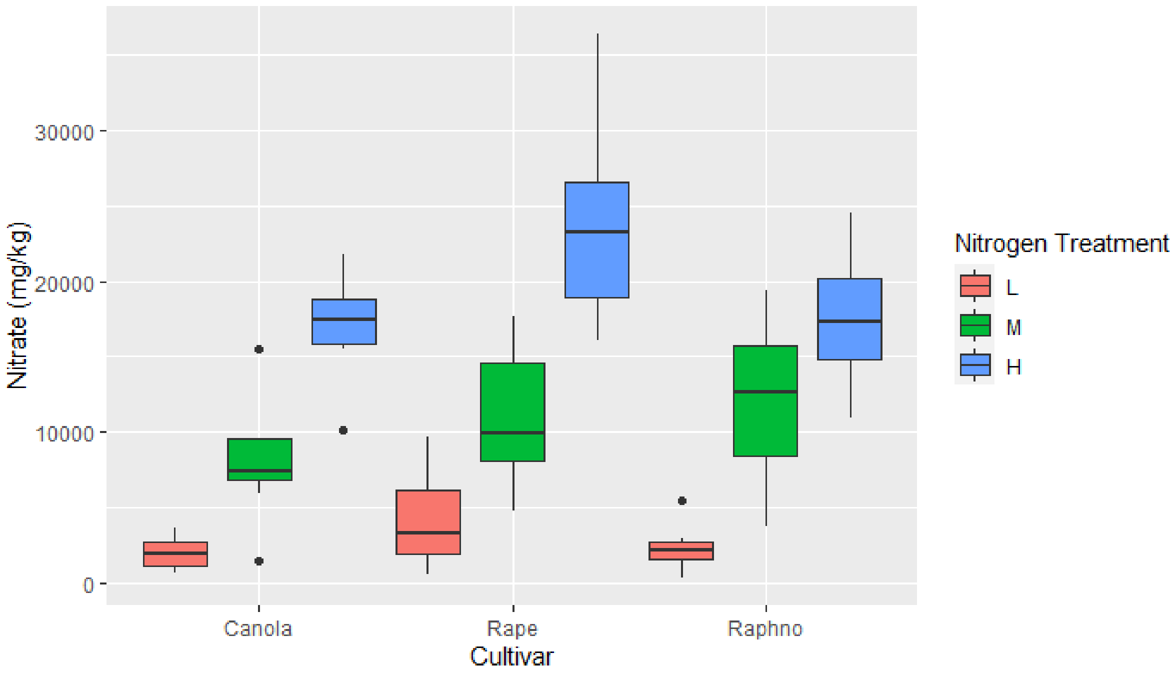


Figure 13. Nitrate (mg/kg) response to three levels of nitrogen fertiliser treatment (L=Low, M=Medium, H=High) across three brassica cultivars Brassica napus (Canola and Rape) and Brassica oleracea x Raphanus raphanistrum (Raphno).

Glucosinolates

The rates N and S fertilizer application had an interactive effect on the production of glucosinolates, while there were no significant effects of cultivar. At both high and medium N fertilizer rates, applying S resulted in an increase in glucosinolate production (**Fig. 4**).

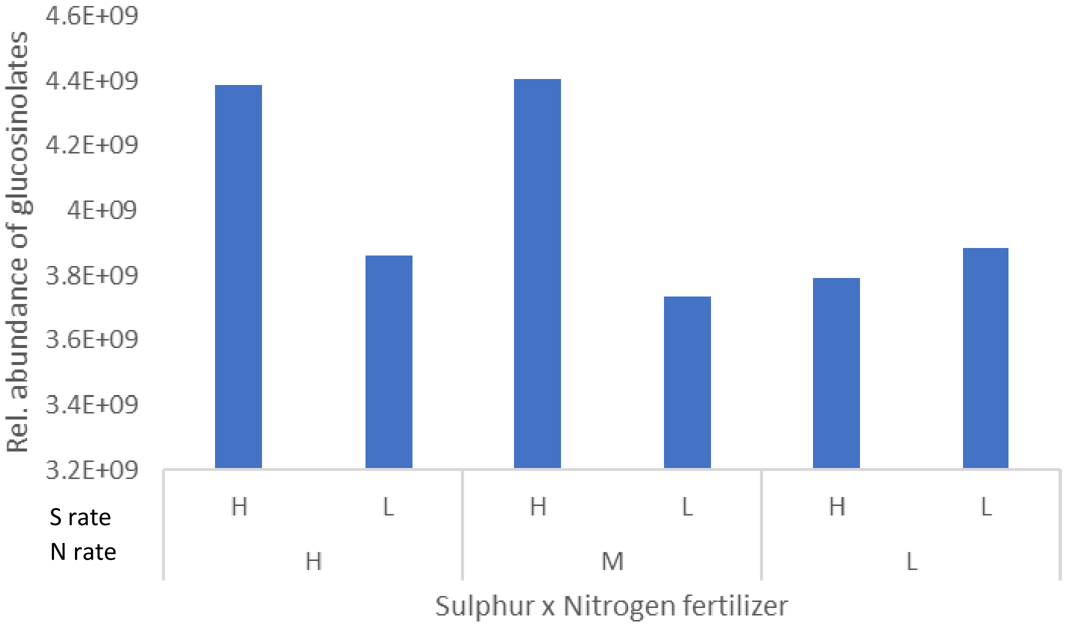


Figure 14. Relative abundance of glucosinolates in response to nitrogen (N) fertiliser treatment and sulphur (S) fertiliser rate across 3 forage brassica genotypes.

4.3.4 Field survey and cross-site analysis of plant secondary metabolites

Across the 8 experimental site-seasons, nitrate concentration in above-ground biomass was significantly affected by brassica cultivar ($\chi^2 = 157.4$, df = 14, $P < 0.0001$; Table 15) and total N available to the crop ($\chi^2 = 3.9$, df = 1, P = 0.049), while DM production had no effect ($\chi^2 = 0.3$, df = 16, P = 0.61). All cultivars exceeded the critical level of 10 000 ppm NO_3 except canola *cv.* 45Y91CL; all samples from the latter were collected from Greenethorpe NSW in 2018. Nitrate concentrations in above-ground tissue of bulb turnip *cv.* Rival and fodder beet *cv.* Jamon were exceptionally high. In bulb-type brassicas, nitrates were generally higher in the above-ground material than the below-ground material, except for in radish *cv.* Graza.

Table 15. Nitrate concentration of above- and below-ground edible plant tissue across brassica species and cultivars grown in Qld, NSW and WA in 2018/2019, with cereals for comparison.

		Above-ground biomass		Below-ground biomass	
Species	**Cultivar**	***N***	**Nitrate (ppm)**	***N***	**Nitrate (ppm)**
Oats	Eurabbie	8	2792 ± 1210		
	Flinders	32	9803 ± 1755		
Triticale	Endeavour	4	3788 ± 1435		
Canola	45Y91CL	4	639 ± 235		
	Hyola 970CL	28	14875 ± 2669		
	Wahoo	12	17679 ± 2997		
Rape	Goliath	48	17934 ± 2579		
	HT-R24	48	13309 ± 1970		
	Winfred	46	14184 ± 2133		
Kale	Regal	48	19231 ± 2549		
	Sovereign	4	21662 ± 1870		
Raphanobrassica	Pallaton	48	14190 ± 1963		
Radish	Graza	40	13518 ± 1815	28	17417 ± 1658
Bulb Turnip	Green Globe	43	18861 ± 2378	35	15944 ± 1889
	Rival	48	27177 ± 3081	36	20612 ± 2649
Leafy Turnip	Hunter	48	17544 ± 2566	27	12612 ± 3446
Fodder Beet	Jamon	24	32851 ± 2028	19	15206 ± 1901

Samples with nitrate concentrations exceeding 9000 ppm were further tested for total non-structural carbohydrates (Table 16); this included only above-ground tissue. Total non-structural carbohydrate concentrations differed significantly between brassica cultivars ($\chi^2 = 171.6$, df = 12, $P < 0.0001$) and increased with total N available to the crop ($\chi^2 = 5.8$, df = 1, P = 0.016). DM production and nitrate concentration had no effect ($\chi^2 = 2.5$, df = 1, P = 0.11).

We also surveyed brassica forage associated with animal ill-health on five NSW farms in winter 2020 (Table 17). The most common problem was photosensitisation in lambs. Nitrates were generally within in safe limits in leaf material but high in stems, highlighting the need to carefully manage grazing to avoid a high proportion of stem in animal diets.

Table 16. Total non-structural carbohydrate concentration of above- and below-ground edible plant tissue across brassica species and cultivars grown in Qld, NSW and WA in 2018/2019, with cereals for comparison.

Species	Cultivar	*N*	Total non-structural carbohydrates (% DM)		
Oats	Eurabbie	1	23.7		
Oats	Flinders	15	15.1	±	1.7
Canola	Hyola 970CL	16	16.7	±	0.6
Canola	Wahoo	8	4.9	±	0.9
Rape	Goliath	28	13.4	±	0.7
Rape	HT-R24	22	17.5	±	0.8
Rape	Winfred	26	14.8	±	0.7
Kale	Regal	25	10.5	±	0.8
Kale	Sovereign	4	16.0	±	1.4
Raphanobrassica	Pallaton	25	14.6	±	0.8
Radish	Graza	18	11.0	±	0.8
Bulb Turnip	Green Globe	29	9.6	±	0.8
Bulb Turnip	Rival	36	9.9	±	0.7
Leafy Turnip	Hunter	25	14.6	±	1.0
Fodder Beet	Jamon	24	6.6	±	0.7

Table 17. Details of farm sites surveyed in southern NSW and concentrations of nitrates where animal ill-health was reported when grazing brassicas in winter 2020.

FARM 1		
Area	Payten's Ridge NSW	
Issue	Photosensitization	
Rate	40/1000 lambs showed symptoms after 4 days	
Animals on paddock	Merino whethers + 1st X lambs (8-9 months old)	
Date occurred	mid-May	
Cultivar	DP Canola Hyola 970CL	
Crop height	90% at 60cm, 10% at 30cm	
Alternative feed	~10% of area in oats + couch, hay bale + supplement (Ca, lime, Mg) provided	
Previous feed	Oats	
Soil type	Red loam	
Date sampled	29/05/2020	
	Leaf	Stem
Nitrates (ppm)	61	17440
TNSC (% DM)	18	24

FARM 2	
Area	Thuddungra NSW
Issue	Photosensitization
Rate	30/480 lambs showed symptoms after 2 grazings of 5-11 days
Animals on paddock	325 breeding ewes (1st X) + 480 lambs (2nd X; 6-8 weeks old))
Date occurred	Early May
Cultivar	DP Canola Hyola 970CL
Sowing	mid-Feb dry sown with 80kg/ha MAP, applied N after 2nd grazing
Alternative feed	None but on rotation with wheat; salt, Mg, lime lick provided all year.
Previous feed	Lucerne -> canola (18/4/2020)-> wheat (29/4/2020) -> canola (10/5/2020) -> wheat *cv.* Kittyhawk (15/5/2020)
Soil type	Red loam
Date sampled	29/05/2020

	Leaf	Stem
Nitrates (ppm)	646	12458
TNSC (% DM)	19	26

FARM 3	
Area	Mandurama NSW
Issue	Bloat deaths
Rate	14/400 cattle died
Animals on paddock	Steers
Date occurred	10-15/04/2020
Cultivar	Forage rape Greenland + Radish Tillage
Sowing	20/02/2020; anhydrous ammonia (82% N) applied inter-row @ 60kg N/ha, grazed 8 weeks after sowing
Alternative feed	Some paddocks with access to grass for slow introduction, one without. Straw and Ca Na Mg lick provided.
Previous feed	Wheat -> brassica -> Italian ryegrass
Soil type	Red basalt clay loam, lighter acidic sandy loam; lime added, pH ~5
Date sampled	29/05/2020

	Species	Leaf	Stem	Root
Nitrates (ppm)	Radish	971	12398	16769
	Rape	3386	30	
TNSC (% DM)	Radish	16	18	22
	Rape	30	35	

FARM 4	
Area	Mundarlo NSW
Issue	Photosensitization
Rate	2-3% lambs with droopy ears
Animals on paddock	1000 ewes + 1000 X-bred lambs (2-8 weeks old)
Date occurred	early May (on for ~2 weeks)
Cultivar	DP Canola Hyola 970CL (retained seed)
Sowing	Early March sown with 80kg/ha MAP + 80kg/ha urea.
Crop height	50-70cm (35-55 cm on hill with adult ewes + no problems)
Alternative feed	None (some grasses on hill)
Previous feed	
Soil type	Light sandy loam
Date sampled	28/05/2020

	Leaf	Stem
Nitrates (ppm)	6084	54486
TNSC (% DM)	14	27

FARM 5			
Area	Eurongilly NSW		
Issue	Photosensitization (mild)		
Rate	1-2% lambs with puffy faces		
Animals on paddock	X-bred lambs (8-9 months old)		
Date occurred	early May (on for 3 days)		
Cultivar	DP Canola Hyola 970CL (paddock 1 + 3) + Phoenix CL		
Sowing	30 kg/ha urea + 55kg/ha MAP at sowing, 140kg/ha urea topdress on 8/04/2020		
Crop height	Paddock 1: 45-60 cm; Paddock 2 45-50cm; Paddock 3: ~50cm; Paddock 4: 15 cm (regrowth)		
Alternative feed	None		
Previous feed	Wheat / subterranean clover / lucerne-sub		
Soil type	Red clay loam		
Date sampled	28/05/2020		
	Species	Leaf	Stem
Nitrates (ppm)	Canola Hyola 970CL	2872	41257
	Canola Hyola 970CL regrowth	9888	51589
	Canola Phoenix CL	3768	52076
TNSC (% DM)	Canola Hyola 970CL	18	28
	Canola Hyola 970CL regrowth	15	22
	Canola Phoenix CL	16	29

4.4 On-farm demonstrations

4.4.1 General observations/insights

Soil & nutritional constraints

Across all on-farm demonstration sites, 70% of sites had acidic (pH 5.5-6.5) or strong acidic (<5.5 pH) soils. Lime was not applied at any sites and hence soil acidity is likely to be a constraint to productivity in many regions (as it is with canola). Manganese toxicity, induced by low soil pH, was also observed at some locations.

Soil nutrition and fertiliser management was also highly variable across locations. Most on-farm trials were sown with some starter fertiliser (60-100 kg of MAP or Granulock 15), but the soil mineral N status at sowing was highly variable and most N fertiliser applications were around 45-85 kg N/ha applied over the whole growing season (most often as a single application at sowing). Hence, at several sites N deficiencies were evident which reduced the productivity potential of the forage brassicas.

Lamb growth rates

No animal health issues were reported at any on-farm sites. However, animal growth rates were highly variable, particularly on the forage brassicas (Table 18). Very high growth rates of over 300 g/day were observed from some flocks of lambs grazing forage brassicas, but others were significantly reduced compared to this potential. Overall, the average animal growth rates were similar across the forage brassicas and forage cereals, where they were included as comparisons (Table 18).

Table 18. Growth rate data collected across six sites that represent both fat lambs and Merino lambs of mixed sex.

	Pallaton raphno	Titan rape	Hyola970 canola	Forage cereal
Average daily gain (g/head.day)	207	238	213	203
Range in LWG	92-300	173-304	46-343	190-216
No. observations	9	2	3	2

Animal grazing preferences were evident

At the Iandra site, raphno-brassica and Titan rape were sown in alternating strips. After the first grazing of these crops by a common mob of sheep, which were not naïve to grazing brassicas, there was strong preference for the raphnobrassica observed (see photo below). This result was consistent with observations in our livestock grazing studies and samples were collected to compare the concentrations of secondary compounds between the two forages.

Matching livestock numbers to growth rates was critical

Adjusting grazing management to maximise the value provided by the forage brassicas was a challenge at many on-farm research sites. This was particularly the case in spring when growth rates of the forage brassicas increased, and farmers often struggled to allocate sufficient stock numbers to maximise their utilisation of the forage available. This was clearly shown at the Holbrook site (Fig. 15), where the farmer was able to achieve 80% utilisation in winter, but in the spring grazing only utilised 25% of the biomass available and hence could have potentially obtained another 2500-3500 DSE days/ha.

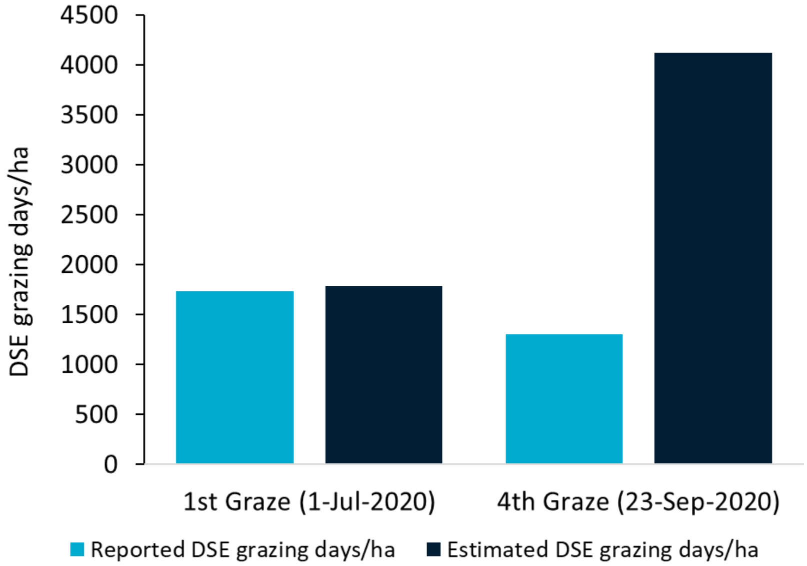


Figure 15. Estimated DSE grazing days/ha based on an estimated feedbase utilisation of 80% for Pallaton compared to the reported DSE grazing days/ha that were achieved at the Holbrook site in the 1st (July) and 4th Graze (September).

Resilience to seasonal conditions

The resilience and responsiveness of forage brassicas was demonstrated at the Millmerran on-farm demonstration site in southern Queensland. After a particularly dry spring, the forage brassicas fully senesced in early October, but after a rainfall event of 32 mm in mid-October, they quickly responded to produce significant biomass in a short period of time (see photos below).

4.4.2 Productivity and comparisons with other forages

A goal of the on-farm demonstrations was to generate information on the grazing potential they could provide over the winter-spring period. However, large variability in productivity achieved across on-farm demonstration sites (Table 19). This was partially driven by weather conditions but also was clearly related to management. Below it can be seen that at one location Pallaton raphnobrassica produced over 10 000 DSE grazing days per ha over 6 grazings at a site in southern NSW; with the grazing period extending from winter through to the autumn the following year. On the other hand, under very dry conditions in southern Qld very little grazing was obtained (though this was similar to forage oats in that season).

Table 19. Summary of grazing provided by forage brassicas across on-farm demonstration sites.

Site	Field size (ha)	Sow date	In-crop rainfall (mm)	Grazing days obtained (DSE.d/ha)	# of grazings	Grazing interval
Elong Elong, NSW	5	8 May	495	10 800	6	Early Aug-late March
Holbrook, NSW	11	13 Apr	366	4 650	4	Early Jul-late Sept
Mt Barker, WA	3	10 Jun	548	3 200	3	
Clare, SA	15	6 Apr	305	800	2	
Condamine, Qld	36	27 Mar	30	320	1	

On average the forage brassicas achieved twice the number of grazing than canola and forage cereals, owing to their longer growing season. Forage brassicas were often grazed into late spring and early summer, while the dual-purpose canola was not grazed beyond mid-August. When compared directly, this longer grazing window meant that the forage brassicas produced significantly more grazing potential than the dual-purpose canola (see Fig. 16).

At sites where Pallaton was grown in comparison with a dual-purpose canola or forage rape it was very clear that Pallaton had significantly lower (30-60% slower) growth rates during winter than the forage rapes and dual-purpose canola (Table 20). This was also demonstrated with less grazing offered at this time of year (*e.g.,* Figure 16b, below). However, after the winter period and during early spring Pallaton demonstrated significantly higher growth rates (Fig. 16), such that in some cases it was difficult to apply sufficient grazing pressure to maintain the plant in optimal growth phases for animals to utilise, seeing the crop either elongate or potentially become reproductive, which significantly reduced it longevity for subsequent grazing.

Table 20. Comparison of winter biomass between Pallaton raphnobrassica and forage rape or canola at 3 on-farm demonstration sites.

	Mountain Crk, SNSW		Iandra, SNSW		Dederang, NE Vic		
	Pallaton	Hyola970	Pallaton	Hyola970	Pallaton	Winfred	Hyola970
Biomass (t DM/ha)	1.8	2.6	1.0	2.7	1.4	2.5	2.1
Date	23-Aug		11-Jun	18-May	10-Aug		
Days after sowing	112		74	64	110		

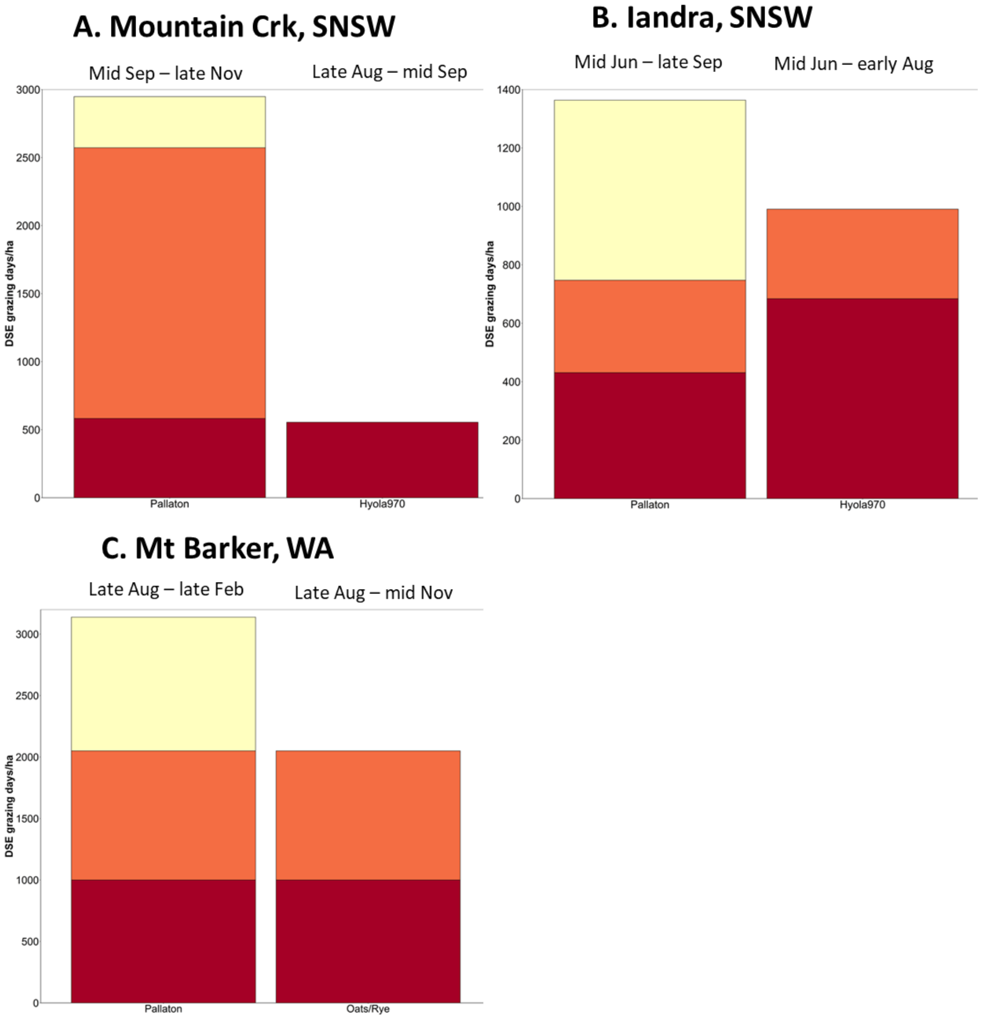


Figure 16. Comparison of the amount of grazing per hectare (DSE days/ha; red = 1st graze, orange = 2nd graze, cream = 3rd graze) provided by Pallaton raphnobrassica compared to either dual-purpose canola or a forage cereal (C.) sown under the same conditions at 3 on-farm research sites.

4.4.3 Post-evaluation feedback

At the end of the evaluation period, farmers and advisors involved in the on-farm demonstrations were interviewed to gauge their willingness to continue to test or grow forage brassicas, how they felt it would fit in their system and things or problems they encountered that require further attention. From these interviews four main issues or messages emerged were:

1. **Better crop management guidelines needed** (particularly in areas where canola is not commonly grown).
    a. Time of sowing
    b. Pests and disease management
    c. In-crop herbicide options
2. **Better grazing management guidelines needed.**
    a. Grazing residual threshold (feedbase utilisation)
    b. Animal health concerns
3. **Pallaton is considered a highly suitable feed in mixed farming systems, particularly late in the winter season through into early summer.**
4. **Establishment costs are high relative to other options (e.g., retained canola seed).**

5 Conclusion

This project has clearly demonstrated a much wider role for forage brassicas, and greatly increased awareness and knowledge of their potential benefits across the mixed farming regions of Australia. During the project, the team has responded to strong interest from industry in this research with a continued strong engagement and investment from seed industry, updates of forage brassica management guidelines, and a range of on-farm demonstration activities.

5.4 Key findings

Multi-site field experiments provided further evidence that forage brassicas can produce equivalent or higher yields of metabolizable energy than currently used forage cereals across many environmental and climatic conditions. Autumn-sown forage brassicas provide higher quality forage for longer into spring than forage cereals and provide a longer grazing window than dual-purpose crops. The new hybrid genotype of raphanobrassica *cv.* Pallaton and forage rapes were the most consistent performers and offered the best relative performance, particularly in drier growing conditions. While this project examined genotypes representing broader forage brassica types, it did not evaluate or compare amongst the broad range of varieties that current exist on the market.

By developing and then applying a simulation model of forage brassica genotypes in APSIM this allowed extrapolation beyond these limited growing situations. This confirmed wide application of forage brassicas across many parts of the mixed farming zone and identified situations, such as later planting windows particularly in medium rainfall environments, where they are likely to offer the greatest productivity advantages over forage cereals. Whole-farm modelling also showed that forage brassicas on 15% of the farms grazed area can complement existing pasture-based feed-base and could reduce the frequency and magnitude of farm feed deficits by about 25-40% at the same farm stocking rate. Alternatively using forage brassicas provides the potential to increase farm stocking rates by between 10-30% per grazed hectare at the same time as maintaining the same frequency and magnitude of farm feed deficits.

Development of the forage brassica model in APSIM provides an opportunity to understand and refine agronomic management practices and identify the potential role of forage brassicas to complement the existing livestock feed-base. We have parameterised a model for three forage rape genotypes and a raphanobrassica that can predict their vegetative biomass and nutritive value characteristics across a broad range of agro-climatic zones (e.g., sub-tropic, semi-humid *cf.* temperate, cool season wet environments), and agronomic management practices. This model is significantly more robust and broadly applicable than other forage brassica models, such as DairyMod (Johnson, 2016). This new capacity adds considerably to the complement of forage and crop models available in the APSIM framework. Having this capability in APSIM allows broader exploration of forage brassicas in the farming system, including their interactions with available soil water and nutrients, production risk in the face of climate variability, and interactions with other crops and forages in rotation. However, further model developments may be required for more sophisticated integrated forage-livestock simulations where aspects such as biomass partitioning, regrowth after grazing, and nutritive value parameters in later stages of plant growth are critical.

Our research experiments and on-farm comparisons regularly showed significant variability in animal performance on forage brassicas, the causes of which are still unclear. Animal grazing preferences for certain forage brassica genotypes were evident, but these were inconsistent across environments and grazing events. The accumulation of secondary compounds is implicated in some of these grazing behaviours. Across experimental sites, and in farmer fields, we found frequent high levels of nitrates at concentrations that would indicate high risks for grazing livestock. However, high levels of soluble carbohydrates are likely to mitigate these risks in forage brassicas. Further, glucosinolates were found to vary significantly amongst genotypes and growing conditions, and these are likely to influence animal grazing preferences and/or impact their forage intake and performance. We explored supplements as a way to mitigate risks of mineral deficiencies induced by these secondary compounds but found no compelling evidence that they were beneficial for animal performance. Overall, this work has uncovered likely causes of animal production variability and health risks when grazing brassicas, however, the extent that cultivar choice, crop agronomic management or grazing management might be able to mitigate these risks still needs further work to maximise animal performance and overcome this constraint to wider adoption.

The numerous on-farm demonstration sites distributed across Australia has sparked significant further interest in adoption of forage brassicas and provided valuable testbeds to gather livestock production data as well as identify critical management constraints or issues. These sites have validated the potential greater grazing that can be obtained from forage brassicas but showed that grazing and agronomic management are critical to maximising their potential. While the on-farm demonstrations have proven to be a very effective way of raising awareness and interest, the collection of rigorous and consistent data from these activities was challenging. These on-farm evaluations have confirmed that further work to refine industry-ready crop agronomic management guidelines would facilitate wider adoption. In particular, information on optimal time and rates of sowing for these environments, pest, weed and disease management options, and grazing guidelines to optimise utilisation and strategies to reduce animal health risks (e.g., mixtures).

5.5 Benefits to industry

During the project we have built significant capacity and knowledge amongst a network of advisors, growers, and industry organisations. The team has presented key findings to over 600 producers and advisors across the target regions and published several farmer-oriented media articles. A legacy of the project will be several industry-oriented knowledge products available online to support growers and advisors with guidelines and information on how to use forage brassicas more effectively in their production systems. A key next step is to also ensure these information sources are made available on-line for access by next users of this information. We have seen several champion farmers, increasingly introducing forage brassicas into their production systems as they gain further confidence in their application and benefits. To capitalise on this momentum, further support to facilitate further demonstrations and participatory on-farm research activities would greatly enhance the rate and scale of adoption across the industry.

As a result of this project, the forage seed industry is now more confidently promoting forage brassica genotypes outside its traditional uses in the higher rainfall livestock and dairy systems, and they see this market growing over the coming 5 years. Already over the life of this project (since 2016), forage brassica seed (excluding dual-purpose canola) sales have increased by 25%, indicating significant industry uptake already (Blair McCormick, DLF seeds). This project has been pivotal in establishing the broader value proposition of forage brassicas for industry investment and has seen them more seriously consider commercialisation of new (but costly) technologies such as herbicide tolerant forage brassicas in the Australian market (Dumbleton *et al.* 2012).

Based on an independent impact assessment conducted on this project, it is estimated that integrating forage brassicas could increase farm gross margins by 10-12% in either fat lamb or steer finishing systems with an average farm profit increase of around $46/ha adopted compared to systems without them. This matches the increases in farm stocking rates or reductions in supplementary feed needs predicted in section 4.2.3. With predictions of the scale of potential adoption possible of up to 300 000 ha (i.e., 0.5% of the mixed farming zone, 60 M ha), this would increase net returns across the red meat sector by around $13.8 M per year. Over a 20-year period, the wider adoption of forage brassicas is estimated to increase the net returns of livestock producers across the mixed farming regions by over $230 M.

6 Future research and recommendations

While this project has effectively demonstrated the broader potential role of forage brassicas in drier mixed farming systems this has highlighted several key research and development needs to support their wider use and overcome barriers to adoption. These include:

Refine agronomic management guidelines for forage brassicas require review and development using local evidence and information in these new environments. Current recommendations were developed in higher rainfall and more productive environments (*e.g.,* Gramshaw and Crofts 1969, Jacobs *et al.* 2006) and overall productivity are lower in more arid regions. This means that guidelines on optimal sowing rates, crop nutrition, and other input requirements are likely to differ and need testing to build wider industry confidence in altering such recommendations.

Weed and pest management is likely to be an important barrier to adoption (particularly when using forage brassicas in crop rotations) and there are few registered herbicides for use on forage brassicas. Hence, development and testing of herbicide packages to validate their safe application in forage brassicas is required.

Testing other patterns of use & system applications. While this project has demonstrated some potential for forage brassicas to be used as autumn-sown options in the mixed farming systems, there is a range of patterns of use that farmers have proposed to fit into their various forage-based grazing systems. For example, questions such as when and where could spring-sowing work?, what conditions are needed for sowing?, what are suitable mixtures or other species that could complement forage brassicas?. These require participatory on-farm research activities to explore, coupled with some analysis to generalise findings across regions and farming systems.

Animal health risks and sub-optimal animal performance of livestock grazing forage brassicas are one of the most important barriers to adoption of forage brassicas and dual-purpose canola. Our work has shown that risks of high nitrate can be frequent in forage brassica crops, but this may be mitigated by high levels of soluble carbohydrates, which may explain why more frequent animal health issues are not reported. While breeding programs commonly screen for anti-nutritional compounds, there is clearly genotypic variation in secondary compounds such as glucosinolates. It is also likely that seasonal growing conditions and more stressful environments may alter these, yet these processes are poorly understood.

Adoption and training program. Knowledge, understanding and experience with forage brassicas amongst advisors and farmers is limited in the mixed farming zone. There is a clear need to provide further upskilling, particularly of advisors, on the fit of forage brassicas, their agronomy and how to mitigate risks or issues when growing and grazing them. Coupled with on-farm demonstrations where networks of farmers can test the application and fit of forage brassicas will build significantly more confidence in using them effectively. Such a programme will be critical to support wider adoption and mitigate risks of farmers trying forage brassicas and failing due avoidable problems.

7 References

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8 Appendix

8.1 Summary of scientific & industry publications & communication

Table 8. Scientific journal articles and conference proceedings published or forthcoming produced from research conducted in association with this project.

Journal articles published

1 Bell LW, Watt LJ, Stutz RS (2020). Forage brassicas have potential for wider use in Australia's drier mixed crop-livestock farming systems. Crop and Pasture Science 71, 924-943.

2 Watt LJ, Bell LW, Cocks B, Swan T, Stutz R, Toovey A, De Faveri J. (2021) Productivity of diverse forage brassica genotypes exceeds that of oats across multiple environments within Australia's mixed farming region. Crop and Pasture Science 72, 393-406.

3 McCormick JI, Paulet JW, Bell LW, Seymour M, Ryan M, McGrath SR. (2021) Dual-purpose crops - the potential to increase cattle liveweight gains in winter across southern Australia. Animal Production Science 61, 1189-1201.

4 Watt LJ, Bell LW, Pembleton KG. (2022) A forage brassica simulation model using APSIM: model calibration and validation across multiple environments. European Journal of Agronomy 137, 126517. https://doi.org/10.1016/j.eja.2022.126517

Journal articles drafted or forthcoming

5 Stutz, Bell, Devilla, Swan, Watt. Phytochemical drivers of sheep selectivity between brassica forages. Animal Behaviour

6 Stutz, Watt, Bell. Nitrates and non-structural carbohydrates pose significant risks for grazing forage brassicas in Australia. Crop and Pasture Science.

7 Bell, Watt. Productivity potential and fit of forage brassicas in feed-base systems across Australia's mixed crop-livestock zone: a simulation analysis. Crop and Pasture Science.

8 Stutz, Cain, Culvenor, Bell, Swan, Carroll. Soil nutrition and fertiliser effects on production of plant secondary metabolites in forage brassicas. Plant and Soil

9 Stutz, Watt, Bell. A geometric framework for balancing livestock nutrition when grazing forage brassicas. Animal Production Science.

Conference publications

1 Watt L, Bell L, Cocks B, Swan T, Toovey A (2019) The potential of forage brassicas to produce herbage for mixed farming systems. In 'Proceedings of the 19th Agronomy Australia Conference', 25 – 29 August 2019, Wagga Wagga, Australia. www.agronomyaustralia.org/conference-proceedings

2 Stutz R, Watt L, Swan T, Bell L (2021) Understanding anti-nutritional compounds in forage brassicas to improve livestock production. 2021 Australian Brassica Conference https://conferences.com.au/2021-abc/

3 Watt L, Bell L (2021) Forage brassicas have a role in filling feed gaps in mixed farming systems. 2021 Australian Brassica Conference https://conferences.com.au/2021-abc/

4 Stutz RS, Bell LW, Culvenor RA, McDonald SE, Richardson AE (2021) Brassica as summer feed for lambs in southern New South Wales. Animal Production in Australia 33, clxxxiv.

5 Watt LJ, Hunt PW, Horton BJ, Bell LW (2021) Dual-purpose crops fill the winter feed-gap in prime lamb systems in Northern Tablelands NSW and reduce flystrike incidence. Animal Production in Australia 33, lxiii.

6 Stutz RS, Swan AD, Watt LJ, Bell LW (2022) Lamb selectivity amongst grazing brassicas: a cafeteria trial. Animal Production in Australia 34, cxviii.

7 LJ Watt, LW Bell, PW Hunt (2022) Autumn lambing systems that integrate dual-purpose crops provide benefits across environments. Animal Production in Australia 34, cxxiii.

8 Bell LW, Watt LJ, Stutz R (2023) Diverse forage brassica genotypes have potential to augment forage supply on drier mixed crop-livestock farms across Australia. Proceedings of International Grasslands Congress, Kentucky USA, 14-19 May 2023.

Table 9. Summary of presentations delivered (and scheduled) with farmers and advisors

Date	Description	Attendance
14 Nov 2018	CSIRO Experiment Station Field Day, Hall ACT	30
26 Jun 2019	Canola Crop Walk, Iandra Castle, Greenethorpe NSW	20
9 Aug 2019	Field walk/research update with farmers and agricultural advisors	15
9 Aug 2019	Agribusiness Today Forum, Greenethorpe NSW	20
16 Aug 2019	Field walk with Elders agronomists (Tummaville QLD)	20
6 Sep 2019	Animal Health Issues of Grazing Canola Workshop, Wallendbeen NSW	80
18 Nov 2019 & 12 Apr 2021	Project updates for PGG Wrightson Research and National sales team	4
19 Nov 2019	CSIRO Experiment Station Field Day, Hall ACT	30
3 Nov 2020	Livestock Productivity Partnership Pasture & Forage Online Webinar (Northern regions). Made available on YouTube via the NSW DPI Agriculture.	44
16 Mar 2021	Sheep growth & preference across brassica cultivars, Southern Central NSW Agronomy Conference, Nutrien Ag Solutions	60
28 Jan- 1 Feb 2022	DLF Seeds Roadshow updates – Cootamundra, Cowra, Harden, Grenfell, Molong, Orange, Eugowra NSW. Retail agronomists/sales teams (Nutrien, Elders, Delta, Emerge Ag, CRT, AgNVet)	40
9-11 Feb 2022	DLF Seeds Roadshow update (online). Nutrien & Elders Agronomists/sales team (national audience)	96
1 Jun 2022	LLS Pasture Research and Innovation Updates – Wagga Wagga & Whitton	235
19 Aug 2022	PGG-Wrightson's Research team project final update & workshop	8

Legacy materials

- Pasture Research Update Recording - https://youtu.be/sxxC6YsYxhA
- Livestock Productivity Webinar – Dual-purpose crops and forage brassicas https://www.youtube.com/watch?v=cvfo7IG8eVQ
- Forage brassica management guidelines – to be published online in 2023.