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Research, development and adoption for the north Australian beef cattle breeding industry: an analysis of needs and gaps

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ABSTRACT

This review seeks to analyse and prioritise needs and gaps in research and development (R&D) for the north Australian beef cattle breeding industry, and to advise on options to increase rates of adoption and successful implementation of this R&D. The material reviewed includes the peer-reviewed literature as well as industry reports and other relevant publications in three targeted areas of R&D deemed to be important by industry leaders and supporting scientists: (i) breeding herd management, (ii) feedbase management, and (iii) management of environmental sustainability. For breeding herd management, the need for uniform definition and consistent utilisation of appropriate productivity metrics is highlighted, with emphasis on assessment of maternal reproductive efficiency in terms of weaning (or branding) rates. Priority is given to the urgent need for reliable means of remotely assessing causes of neonatal calf mortality to enable the development and application of management interventions that improve calf survival rates. The highest priority for feedbase management is to increase producer awareness and willingness to adopt stocking rates that are appropriately matched to the long-term carrying capacity of native rangeland pastures that predominate in northern Australia. Other opportunities include increasing the use of perennial, tropically adapted legumes, where conditions permit, to improve soil fertility and nitrogen intake of cattle, and devising strategies to overcome widespread phosphorus deficiency through diagnosis and supplementation, especially in the wet season. In order to enhance environmental sustainability in the face of climate change, priorities include improving producer awareness and use of increasingly robust tools for predicting key weather events, as well as developing genetic strategies to increase heat tolerance of cattle and evaluating management interventions to mitigate heat stress. Conclusions drawn from these sections are summarised and used to make recommendations on priorities for increasing adoption of existing research-proven practices and technologies, and for further R&D on selected topics.

Keywords: adoption, calf mortality, environmental sustainability, grazing management, heat stress, nutrient supplementation, performance metrics, reproductive efficiency.

Introduction

The north Australian beef industry spans Queensland, Northern Territory, and the Pilbara and Kimberley regions of the north of Western Australia. It comprises production enterprises that account for ~64% of Australia's national beef herd of some 23 million cattle (ABARES 2019), together with transport, processing and other supply chain infrastructure, including facilities for live cattle export. The total value of the industry is estimated to be ~A$5 billion per annum, mostly generated by export of processed product and live cattle, making it the most valuable agricultural sector in the northern half of the country. Importantly, much of this income is generated on land that cannot be used for other agricultural purposes, and the pastoralists involved have responsibility for stewardship of natural resources across ~60% of the land base of northern Australia, in addition to management of their beef enterprises.

As described by Greenwood *et al.* (2018) and Chilcott *et al.* (2020), the northern pastoral zone and its beef enterprises are diverse in terms of climate, soils, native and introduced pasture species, cattle genotypes, scale of enterprise, management systems and business ownership. Nevertheless, some general features and challenges clearly distinguish the northern beef industry from its southern counterpart. These include often extreme variation in climate within and between wet and dry seasons, with consequences for the feedbase, which features lower quality C_4 grasses and few legumes, and widespread phosphorus (P) deficiency. This limits cattle growth rates and carrying capacity, necessitating large-scale, extensive operations with a lower degree of stock control, exacerbated by the cost and limited availability of labour due to geographic distance. Heat stress and other factors limit stock-work during the summer wet season, with particular challenges for management of breeding herds. Other challenges include access to markets, constrained by distance and transport infrastructure, and the vulnerability of supply chains to external forces, most notably affecting the live export market on which much of the industry in Far North Queensland, the Northern Territory and northern Western Australia presently depends. Also, the widespread use of Brahman and composite breeds because of their disease resistance and ability to perform in harsh environments has brought trade-offs in terms of generally lower fertility and, to some extent, meat quality. The combination of climate, remoteness, cattle genotypes and market access, together with the need to protect against cattle ticks and numerous arboviruses, has resulted in internationally unique production systems that require specialised attention from the Australian scientific community.

Assessment of enterprise and industry performance has been approached in two ways. The first approach, and that traditionally used in earlier studies, was to collect biological and production data from herds in a region or several regions and to describe numerical trends. Since about 2014, large datasets from many individual properties have been collected. This includes studies in the Beef Cooperative Research Centre (CRC) (see Bunter *et al.* 2014) and in the CashCow project (see McGowan *et al.* 2014). In addition to biological and production data, business has been the focus of other studies (see Holmes *et al.* 2017), in which the authors used powerful statistical methods on their large datasets to describe parameters including production metrics and economic outcomes. The results are typically expressed as region-specific median values and the spread as quartile boundaries (e.g. top 25%). Impacts of different factors are expressed as percentage point impact or odds ratio. These studies benefit from the fact that they are built on systematically collected data and also from the power of the statistical analyses and the inferences so generated. The studies of Holmes *et al.* (2017) are limited to family-owned enterprises. Importantly, they report EBIT (Equity Before Interest and Tax) as a measure of herd productivity. This ideally serves the purpose of the present review because EBITs remove the complexity associated with land and animal asset value as well as market fluctuations, which are outside the control of farm management. A limitation of such an approach is that it requires data on a large number of animals (typically thousands) from industry-representative enterprises across multiple years. Also, these observational studies are inevitably retrospective in nature.

The second approach is to model a typical farm enterprise. The enterprise data used are a composite of data from observational studies such as those described above. These inputs are used in mathematical models that include well-developed simulations of pasture growth and animal performance to predict outcomes. Examples relevant to northern breeding herds include papers by Ash *et al.* (2015) and Bowen and Chudleigh (2021). An advantage of this approach is that the simulations can be run for decades so that the data generated are prospective. Therefore, researchers can ask 'what if' questions to investigate the predicted impact of a management change. However, a disadvantage is that the input values need to be accurate. Further, the stochastic nature of animal production means that models may not yet be sufficiently nuanced to enable reliable predictions. Outputs from models are usually validated in the field and the model is iteratively modified to try to reflect reality.

The challenges described above, together with factors beyond the influence of producers, processors and other industry participants, such as increasing government regulation and volatile international terms of trade over recent decades, have led to the assessment that well over half of northern production enterprises are economically unviable in the long term (Holmes *et al.* 2017; McLean *et al.* 2018). On a more optimistic note, those researchers have also reported a 10-fold difference in long-term profitability between the average and top 25% of beef production enterprises ($6 vs $62 per adult equivalent (AE)) (McLean and Holmes 2015). These analyses led to the identification of key factors that distinguished the top performers, as summarised by Fitzpatrick (2020):

- higher income per AE through greater productivity (kg beef/AE) as determined by
  - higher reproduction rates
  - lower mortality rates
  - higher sale weights
- lower enterprise expenses per AE, indicating more targeted herd expenditures
- lower overhead expenses per AE, due mostly to better labour efficiency
- lower asset values per AE.

The profit drivers listed above were ranked in the order reproduction, mortality, weight gain and cost of production (McLean and Holmes 2015), with reproduction found to be twice as important as mortality and turn-off weight, as long as cow mortality is not substantially higher than 2–3% (Holmes *et al.* 2017). Improvement of these production indexes has for decades been the goal of many well-funded research projects (Holroyd and O'Rourke 1989; Hasker 2000). This again raises the question of barriers to adoption of research and development (R&D) by the northern beef industry despite numerous successful research outcomes and their incorporation into feasible extension programs. Accordingly, the recently published 'Northern Australia beef situation analysis' has concluded that failure to adopt best management practices is the industry's major impediment to lifting performance (Chilcott *et al.* 2020). However, despite its comprehensive coverage of R&D challenges and opportunities, this large report did not do much to substantiate its conclusion about adoption with specific examples or analyses, nor did it seek to offer remedies to barriers to adoption.

With regard to breeding herd performance, the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) has collected data on branding rates; those from Queensland and Northern Territory over 40 years are presented in Fig. 1 (ABARES 2019). A small upward trend in branding percentages occurred in the late 1980s and early 1990s, but percentages later flattened to lie between 60% and 75%. Year-to-year variation is especially notable.

This review evaluates the present state of knowledge in three areas deemed by industry leaders and supporting scientists to be important drivers of productivity and profitability that are amenable to translation and adoption of existing and future research findings. These are: (1) breeding herd management, (2) feedbase management, and (3) environmental sustainability. Much of the content is drawn from a report commissioned and recently published by Meat & Livestock Australia (MLA) to inform the MLA-sponsored Northern Breeding Business (NB2) strategic partnership (Bell and Sangster 2022). The background, vision, objectives and work plan for this initiative, involving industry participants and multiple providers of scientific support for the northern beef sector, are detailed in another MLA report (Fitzpatrick 2020).

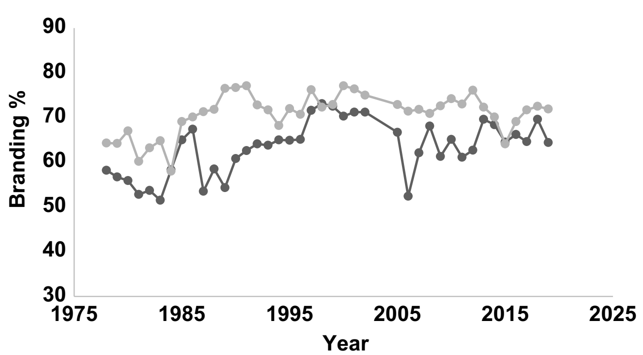

Fig. 1. Branding rates in Queensland (grey dots) and Northern Territory (black dots) between 1977 and 2019 (adapted from ABARES 2019).

Breeding herd management

Beginning in the 1950s, the rapid and widespread dissemination of *Bos indicus* (mostly Brahman or Brahman cross) cattle across northern Australia was driven by growing appreciation of their ability to survive and produce in challenging tropical environments. However, this initiative became tempered by concerns about their reproductive performance, initially based on anecdotal reports from producers and later supported by empirical research evidence (e.g. Seebeck 1973; Holroyd *et al.* 1979).

This section is prefaced by a summary of subsequent industry surveys of breeding herd performance, culminating in the relatively recent, comprehensive CashCow investigation (McGowan *et al.* 2014; McCosker *et al.* 2020*a*). This is followed by a review of current and past R&D on reproductive physiology, performance and management, including consideration of opportunities and challenges for genetic improvement of reproductive performance in northern herds. Management practices to improve reproductive performance and reduce mortality in the breeding herd are then discussed, with a particular focus on R&D needed to understand and reduce causes of calf mortality.

Surveys of breeding herd performance: what have we learnt?

Since the late 1980s, four major surveys of breeding herd performance in northern Australia have been undertaken. Of these, three were funded by MLA or its predecessors (Holroyd and O'Rourke 1989; O'Rourke *et al.* 1992; McGowan *et al.* 2014) and the other by CSIRO (Bortolussi *et al.* 2005*a*). For methodological details and results of these surveys, readers are referred to the original reports, and for a more comprehensive review, to our recent MLA Final Report (Bell and Sangster 2022).

The data of Holroyd and O'Rourke (1989) are of historical interest but are of limited use as a baseline for assessing changes in industry performance because of the widely varying time frame of their collection during a period of major changes in breed structures, operational changes and market opportunities in the northern industry.

The next survey by O'Rourke *et al.* (1992) was based on responses of producers to a detailed questionnaire sent in December 1990 to all beef enterprises in northern Australia that normally carried at least 300 cattle. This produced the best snapshot to that date of breeding management and other aspects of the north Australian beef industry and a useful baseline for judging future changes. However, the picture painted may have been somewhat rosier than that for the industry as a whole because the sample of respondents, representing about 33% of the total number of producers contacted, was self-selected and possibly biased towards the more progressive end of the industry.

The third survey of northern breeding herd performance and management was conducted in 1996 and 1997 by Bortolussi *et al.* (2005*b*), and reflected growth in live exports since the previous report. The authors' claim that their survey was representative of the whole northern industry is hard to verify because of lack of information on the process for selection of participating properties; certainly, the process was not random because of criteria described by Bortolussi *et al.* (2005*a*). The conclusion of this report noted the considerable variation in reproductive performance within and between regions but was generally optimistic about previous improvements and future opportunities to increase performance of breeding herds across northern Australia.

The most recent and detailed survey of reproductive performance in north Australian beef herds was the CashCow study (McGowan *et al.* 2014; McCosker *et al.* 2020*a*, 2020*b*), which reported data gathered on 72 commercial properties across four types of country: Southern Forest, Central Forest, Northern Downs and Northern Forest. Findings are further discussed in following subsections.

The above surveys have also been reviewed by Chilcott *et al.* (2020), who concluded that early progress in improvement of reproductive performance of northern breeding herds appears to have stalled. We cannot confidently endorse this claim because of important variations in sample selection, regions represented, and data analysis among the surveys of O'Rourke *et al.* (1992), Bortolussi *et al.* (2005*a*), Bunter *et al.* (2014) and McGowan *et al.* (2014). This point was reinforced in a recent meta-analysis of reproductive wastage (Chang *et al.* 2020*a*), which considered 43 articles on wastage published between 1936 and 2014. As indicated above, the metadata contained a wide range of data types, collection times and sampling periods, which limited the statistical power of the conclusions. However, if the commercially achievable level of performance can be represented by performance of the 75th percentile of mobs or cows, as proposed by McGowan *et al.* (2014), then clearly, regardless of historical trends, there is ample room for improvement in most indexes of breeding herd performance across northern Australia. In broad terms across the industry, a shift from the median to the 75th percentile could be expected to improve weaning rate from 67% to 80% (McGowan *et al.* 2014).

Snapshot of CashCow trends

Median values for performance variables, summarised for all eligible females across the four land types, are presented in Table 1. This summary demonstrates the variation among regions and the extreme of the Northern Forest, which is detailed in the following subsection. The other three regions are quite similar to each other for rates of pregnancy within 4 months of calving (P4M), annual pregnancy and calf loss. The weaning rate is 72–77% (branding rates *per se* were not reported in the CashCow survey but can be estimated by subtracting fetal/calf loss percentage from annual pregnancy rate percentage). As expected, these estimated values are similar to, or slightly lower than, reported values for weaner contribution and, considering differences among surveys in definition of regions or country type, not markedly different from the values for branding percentage reported by Bortolussi *et al.* (2005*b*). Liveweight production per cow is cited here as an enterprise measure of breeding herd productivity.

Northern Forest: nature's extreme

The Northern Forest includes parts of Western Australia, Northern Territory and Queensland, approximately north of a line between Proserpine and Broome, and includes country where eucalypt forest predominates across a range of landforms. The Northern Forest represents the environmental extreme typified by a native grass resource vulnerable to degradation, low rainfall over a range from arid regions to wet tropics, and high temperatures. Most cattle are exposed to tick and buffalo fly infestation. The Northern Forest is typified by low stocking rates, large properties (top 25% of sampled properties carry 11 000–22 000 AE, compared with 1100–6800 AE in other regions), challenges of remote management, and long distances. Year-round mating is common but maiden heifers are commonly run as a separate group, so tighter calving periods occur for this cohort.

In terms of median values for the four regions (see Table 1), the Northern Forest has the lowest values for P4M (15%),

Table 1. Median values for reproductive performance of all cows by country type.

Measure	Southern Forest	Central Forest	Northern Downs	Northern Forest	Overall
Pregnant within 4 months of calving (%)	67	68	66	15	47
Annual pregnancy (%)	85	85	80	66	79
Fetal/calf loss (%)	6.0	6.7	10.0	12.9	9.5
Contributed a weaner (%)	76	77	72	53	70
Pregnant cows missing (%)	8.3	7.9	6.6	10.6	8.4
Liveweight production (kg/cow)	188	197	141	89	150

Source: McGowan *et al.* (2014).

pregnancy rate (66%), and cows producing a weaner (53%). At the same time, the fetal/calf mortality is the highest (12.9%), as is cow mortality (10.6%). Liveweight production is lowest in the Northern Forest, at 89 kg/cow retained. Although the top 25% of Northern Forest properties sampled are superior to the region's median in every metric, each is worse than the median in all other regions. The Northern Forest appears to represent a quite different production system to the other regions and is an outlier in the CashCow analysis. For example, across the whole study, variation in P4M accounts for 60% of variation in breeding rates, but this does not hold for the Northern Forest. The environment affects the approach to management in fundamental ways.

Lower feed availability and N deficiency occur for more than half the year during the dry season, and P availability is marginal to severely deficient in most soils. The environment best suits cattle with predominantly Brahman content; other breeds do not thrive. Comparisons of the performance of Brahmans versus Tropical Composite (TCOMP) cattle have not been conducted in the Northern Forest owing to the low number of TCOMP cattle, but in the other three regions, the mean P4M was significantly greater in cows with <50% than those with >75% *B. indicus* content (68.3% vs 50.7%). Beef CRC research showed that Brahmans take longer to develop the first corpus luteum (mean 751 days) than TCOMPs (mean 651 days). In the second breeding season, Brahman herds had lower pregnancy rates (59% vs 76%), longer lactational anoestrus interval (134 vs 84 days) and greater number of days to calving (363 vs 344 days) than TCOMP herds (Johnston *et al.* 2009). In the Northern Forest, breed factors predicated by the environment lead to fewer herd pregnancies.

It is assumed that the higher median rate of calf loss (12.9%, Table 1) in this region is also associated with the environment and the constraints to management placed on properties under these conditions. In a further illustration, in Northern Forest herds, unlike herds from other regions, fetal/calf loss is unaffected by temperature–humidity index (THI; see McGowan *et al.* 2014). Calf loss is not significantly different among regions if THI is >79 for at least 2 weeks during the expected month of calving, whereas under lower THI conditions (≤79 for at least 2 weeks in this period), calf losses are reduced in all other regions. These data suggest that comparatively high fetal/calf loss in Northern Forest herds arises from the suite of factors prevalent in Northern Forest properties including heat and humidity. The meta-analysis of Chang *et al.* (2020*a*) calculated a calf mortality rate of 21.6% (compared with 12.9% in CashCow). Possible reasons for this discrepancy are (1) the CashCow data are a more contemporary assessment since the widespread introduction of Brahman cattle, and (2) the selection of properties and (necessary) human interventions during conduct of the CashCow trials may have led to improved herd performance.

The Northern Forest environment clearly constrains production. However, despite the challenges of cattle production in this harsh environment, a business comparison across the northern beef industry concluded that the financial performance of properties in this area follows the broader industry pattern (Holmes *et al.* 2017). For example, mean EBITs of the top 25% properties in the Northern Forest ($4.0–8.6/AE) were in the same range as those in the other three northern regions considered in CashCow ($3.6–9.7/AE). This somewhat unexpected finding may be partly due to the greater scale of operation on most Northern Forest properties.

Measuring breeding herd productivity

The variation in data and analytical approaches cited above highlights that data on productivity should be collected and recorded in a practical and systematic way. Such data can be used to: set benchmarks; identify risks and patterns; understand opportunities for improvement; and measure progress or change over time. For the north Australian breeding industry, the major focus is on the breeding females in the herd and their calves. Examples of information collected include herd data (numbers, weights, body condition score (BCS) of each sex and age class) at particular times (weaning, branding, purchase/sale). Financial data such as business income, labour costs, depreciation and variable costs are also useful in understanding whole-of-enterprise positions. A challenge in northern Australia is that the environment makes the consistency of data and data collection difficult. A call for standardisation of data protocols (Chang *et al.* 2020*a*) was largely addressed in the CashCow project (McGowan *et al.* 2014; McCosker *et al.* 2020*a*). The ABARES data collection framework is also standardised.

Table 2 provides examples of the most commonly used physical measurements to derive the metrics that usefully describe breeding herd productivity. This table also defines several metrics used in research, in enterprise benchmarking, and for genetic selection, which is referred to later in this review. Note that weaning (or branding) percentage is the most useful single variable for assessing rates of pregnancy and calf loss. Branding rates are derived from whole-of-industry producer survey data collected annually by ABARES. It is important to adopt consistent use of metrics such as weaning rates, not only on individual properties but also across the industry. Standardisation and demonstrated use of appropriate and practical metrics should be a fundamental goal of programs such as NB2 that are designed to promote adoption of R&D outcomes. These parameters are targeted for use at enterprise level, so their value is in making year-to-year or cohort-to-cohort comparisons.

Data capture should be practical to the situation, collected in a timely fashion, recorded, and acted upon as appropriate. Data should be identified to individual animals by using National Livestock Identification System (NLIS) tags and linked to Data Capture Systems located crush-side and

Table 2. Measures that are important in recording and decision-making.

Type and name	Definition	Purpose, method
Physical data		
Body mass	Liveweight in kg, individual or presented as herd × type average	Weight gain, target weight for breeding. Measure with scales, girth tape
Body condition score	Five-point scale: 1 (poor) to 5 (fat)	Animal and herd evaluation, especially for breeding females
Cow/heifer age	By year of birth	Categorise into age cohorts for management. Often indicated by distinctive ear tag
Breed	Proportion of *Bos indicus* to *Bos taurus*	Provides understanding of herd genetics and options for selection
Pregnancy	Positive pregnancy diagnosis (PD)	Establishes percentage of herd pregnant
Lactation	Udder full at branding or weaning	Establishes percentage of herd feeding a calf
Production rates (%)		
Conception rate	Females conceiving during breeding season	Success/failure in fertilisation
Pregnancy rate	Mated females pregnant at PD	Conception rate minus embryonic and fetal loss
Cow mortality rate	Pregnant cows missing	Includes those which have lost tags
Mortality rates (as % of target group)		
Calf prenatal loss	Losses from conception to birth	Research interest: can be split into early and late embryonic, and fetal
Calf perinatal loss	Losses within 48 h of birth	A component of calf mortality
Calf postnatal loss	Losses between 2 days and weaning	A component of calf mortality
Calf mortality	Losses since positive PD	Fetal loss (%) in mid–late pregnancy plus calf loss (peri- and postnatal)
Branding	Calves at branding per 100 females bred	ABARES reported rate
Weaning	Calves weaned per 100 females bred	
Additional herd productivity measures used in CashCow (McGowan *et al.* 2014)		
Annual weaner liveweight	kg	Individual or herd basis
Weaner production	kg/cow.year	Liveweight of weaners per cow retained
Annual liveweight production	kg/cow.year	Weaner production plus weight gain in cows, adjusted for mortality
Liveweight production ratio	kg produced/kg cattle	
P4M	Pregnant within 4 months of calving (%)	Used as denominator of calf loss percentage (excludes early fetal loss)
Weaner production vs steer weight gain	Surrogate for weaner production as a rough guide	Measure of capacity of cattle to grow on the same country
Genetic parameters		
Estimated breeding value		Difference between genetic merit of an individual animal and the genetic base (e.g. breed average) to which it is compared
Heritability		Estimate of the degree of variation in a phenotypic trait in a population that is due to genetic variation between individuals in that population

coupled to weighing machines. Results such as pregnancy diagnosis and BCS should also be entered into the data system. Subsequent analysis is achieved by downloading records and processing through management software.

In addition to the measures listed in Table 2, other data are relevant to productivity, such as:

- bull semen and soundness evaluations to ensure successful mating by bulls
- plasma inorganic P (PiP) to assess the need to supplement animals with P in the wet season
- data on disease investigations and vaccination history at a herd level
- pasture feed availability and budgeting 'on the ground' or via remote systems
- breeding records such as rates of females per bull, and purchase of bulls with known estimated breeding values (EBVs) chosen to meet productivity goals.

Challenges and opportunities for genetic improvement of reproductive performance

Economic modelling of northern beef productivity in different regions predicted the potential benefit from improved weaning rate on farm returns. Ash *et al.* (2015) predicted that an increase in weaning rate of 5% achieved through genetic gain would increase profits by 13% in South East Queensland, by 20% in northern Queensland, and by 27% in the Victoria River District of Northern Territory. By contrast, in the modelling study of Bowen and Chudleigh (2021), a 6% increase in weaning rate was predicted to provide a small economic gain in the Northern Gulf region of Queensland and no gain in other regions. The modest results in the latter study were attributed to the model's inclusion of the cost of transition to superior genetics, such as the purchase of elite bulls, which was not accounted for in the model of Ash *et al.* (2015). Nevertheless, longer term productivity benefits are expected to accrue from genetic improvement in reproductive traits.

Genetic improvement of reproduction in the tropically adapted beef breeds used in northern Australia has been limited by difficulties in recording appropriate performance metrics and slow selection responses (Johnston 2013), as well as the long-term inclination of seedstock and commercial breeders to select for type rather than performance traits. In addition, heritability of the key maternal production trait, lifetime weaning rate, is low (Meyer *et al.* 1990). An important, overarching limitation continues to be nutritional and other environmental constraints on genetic expression of selected traits. Nevertheless, selection-line experiments have demonstrated that significant improvement in reproduction rates is possible in Droughtmaster (Davis *et al.* 1993) and Brahman (Schatz *et al.* 2010) breeds, as has the practical experience of astute and well-informed producers such as Alf Collins (Anon 2019). Recently, the genetic bases for these outcomes have become much better understood through research conducted by the CRC for Beef Genetic Technologies, particularly on defining the degree of genetic control for component physiological traits that underpin overall reproductive performance.

The Beef CRC Northern Breeding Project was a large, multi-site investigation of the genetics of growth and reproductive performance of Brahman and TCOMP cattle that are broadly representative of genotypes of beef cattle used in northern Australia. For full details of the objectives, scope and design of the project, see Barwick *et al.* (2009*a*, 2009*b*) and Johnston *et al.* (2009). Genetic analyses of performance of females confirmed previous reports of the low heritability of lifetime reproduction traits, with estimates of 0.11 and 0.07 for lifetime annual weaning rate in Brahmans and TCOMPs, respectively (Table 3; Johnston *et al.* 2014*a*). However, component traits of early reproductive performance each had moderate to high heritability, especially in Brahmans. These included age at puberty as determined by age at first observation of a corpus luteum (Table 3; Johnston *et al.* 2009) and, most notably, length of the post-partum anoestrous interval in 3-year-old cows (Table 3; Johnston *et al.* 2014*a*). Importantly, genetic correlations between early-in-life measures and lifetime traits were moderate to high, particularly the correlation between post-partum anoestrous interval and lifetime annual weaning rate (Table 3; Johnston *et al.* 2014*a*). The authors concluded that these results highlight an important opportunity for genetic improvement of weaning rates in tropically adapted beef cows by focusing recording and selection on early-in-life reproduction traits, particularly in Brahmans for traits associated with post-partum anoestrus.

The Beef CRC project also included evaluation of reproduction traits in young bulls up to 24 months of age (Corbet *et al.* 2013). Scrotal circumference was among the most highly heritable traits in both Brahmans and TCOMPs, but genetic correlation of this trait with semen quality traits, including percent normal sperm, varied with breed and age. Thus, a single, reliable indicator of bull fertility was not identified. However, the lack of antagonism among bull traits means that selection for improved semen quality should not adversely affect other production traits. Genetic associations between reproductive traits of young bulls and female traits also were investigated (Johnston *et al.* 2014*b*). Semen quality traits were genetically correlated with short duration of post-partum anoestrus in first-lactation cows and lifetime cow reproduction traits in both genotypes, but magnitudes of relationships varied with bull age. Thus, inclusion of some bull measures in selection indexes may

Table 3. Heritabilities (estimated value ± approximate standard error) of lifetime annual weaning rate, age at puberty and post-partum anoestrous interval, and genetic correlations between early-in-life traits and lifetime weaning rate, in Brahman and Tropical Composite (TCOMP) cows.

Trait	Heritability		Genetic correlation	
	Brahman	TCOMP	Brahman	TCOMP
Lifetime annual weaning rate[A]	0.11 ± 0.06	0.07 ± 0.06	–	–
Age at puberty[B,C]	0.57 ± 0.12	0.52 ± 0.12	−0.36 ± 0.21	−0.29 ± 0.23
Post-partum anoestrous interval[A]	0.51 ± 0.18	0.26 ± 0.11	−0.62 ± 0.24	−0.87 ± 0.32

[A]Johnston *et al.* (2014*a*).
[B]Johnston *et al.* (2009).
[C]Johnston *et al.* (2014*b*).

indirectly help to improve female reproduction in tropical breeds.

Cessation of the Beef CRC in 2012 was followed by the northern beef Repronomics™ project, a large, MLA-funded breeding and genotyping study that combined intensive recording of early-in-life female reproduction phenotypes with dense genotyping of all project animals (Johnston *et al.* 2017). The project used Brahman, Droughtmaster and Santa Gertrudis breeds at three different research stations, located in central and northern Queensland, and Northern Territory, respectively. The overarching goal of the project was to drive the development of new, genomics-enhanced BREEDPLAN evaluations specific to the most numerous tropically adapted beef breeds across typical northern environments.

Preliminary reports published have focused on development of conventional genetic and genomic approaches to enhance rates of genetic improvement for female reproductive traits. These include elaboration of the potential use in BREEDPLAN of more heritable early-in-life reproductive measures in bulls and cows, discussed above, as correlated traits to predict the easily recorded trait of days to calving (Johnston and Moore 2019), and the use of intensively recorded phenotypic reference data and genotypes to increase the accuracy of genomic selection of young bulls (Moore *et al.* 2019). An important, recently completed milestone was the whole-genome sequencing of 55 sires from the three focal breeds that, cumulatively, have >3300 progeny born and recorded in the project. Another example of the substitution of easily measured traits to overcome the challenges of acquiring sufficient, accurate phenotypic data for primary traits in *B. indicus* and *B. indicus*-infused cattle is the use of reproductive maturity score as a proxy for age at puberty, the primary trait for which is age at appearance of the first corpus luteum (Engle *et al.* 2019).

Successful completion, translation and commercial demonstration of the applicability of the above research on development of genomic EBVs will be especially important to restore industry confidence in genetic technologies that has been lost due to inaccuracy and variability of quantitative trait EBVs in BREEDPLAN.

Analysis of reproductive wastage

Wastage can occur at many points in the breeding cycle. Aspects such as attainment of puberty and ovulation are processes driven by a range of factors including genetics and nutrition. From that point on, there are multiple sources of reproductive inefficiency that can affect a cow's ability to wean a calf. These inefficiencies can be broken down into fertilisation failure, embryo/fetal mortality and perinatal/postnatal calf loss as summarised by Burns *et al.* (2010), and viewed in the context of overall breeding performance (branding or weaning percentage), they have not changed in northern Australia during the past 30 years (Fig. 1; ABARES 2019).

Fertilisation failure can be assessed only through analysis of oestrus cycle components, but it is a significant component of loss. Historical estimates of losses in Queensland range from 12% to 19%. Subsequently, lactational anoestrus significantly reduces pregnancy rates, especially in first-lactation heifers and older cows that have lost condition during pregnancy and lactation.

Variation in bull fertility related to semen quality in terms of percentage of normal spermatozoa (Fitzpatrick *et al.* 2002), libido intensity (Bertram *et al.* 2002) or structural defects (McGowan *et al.* 2002) also contributes to variation in cow fertilisation rates in *B. indicus* herds in northern Australia.

Embryo mortality covers the period between fertilisation and Day 24 ('early'), and from Day 25 to Day 45 ('late'). For this period, reported losses are highly variable in the northern environment and means range from 17% to 75%. Early loss appears to contribute in the range 25–30% and late loss 10–15%. In some cases, especially with early losses, cows may be able to return to service and successfully become pregnant. Fetal losses (after Day 42) account for 2–8%.

In commercial herds, fertility and embryo/fetal losses are difficult to measure, but 100 minus the pregnancy rate (%) in joined females taken at pregnancy diagnosis provides an estimate of wastage to that point (McGowan *et al.* 2014). As shown in Table 1, median pregnancy rates (excluding Northern Forest) across years in all age classes of females are in the range 80–85%, suggesting that the practical degree of loss on an annual basis is 15–20%. The top 25th percentiles in these categories are 90–92%, which suggests that 10% loss is the minimum effect, a level which is common in the beef industry internationally (Burns *et al.* 2010).

Opportunities for improvement include puberty management, nutrition management (rising plane to initiate ovulation), genetic selection and disease management. In many cases these factors are fixed or slow to change; therefore, the more immediate gains on offer are through reducing calf loss. The goal of reducing calf loss can be justified on several fronts including the potential financial benefits, that the risk factors have been quantified, that some aspects are under management control, and the opportunity to improve animal welfare. An additional source of wasted productivity is cow mortality, which, across the whole northern industry, is believed to average 9% per annum.

As an example of the financial benefits (in kg/AE), McLean and Holmes (2015) used farm economic data to assess the relative impact costs of three proposed improvements. For the stated improvements, the equivalent benefit is estimated as follows:

- A 1% increase in reproduction rate leads to a 1.5 kg/AE response.
- A 1% reduction in mortality leads to a 2.28 kg/AE response.
- A 1 kg increase in turn-off leads to a 0.18 kg/AE response.

How these benefits accrue is worth exploring under different scenarios. A cow that produces a live calf to weaning is the ideal and adds value to all three elements. A non-pregnant cow can gain weight and, without a calf to raise, can often reach a BCS sufficient to breed in the next year, providing a delayed but positive benefit. Cows that lose a calf may gain additional weight and condition and have a quicker return to oestrus because they are not producing milk. Dead cows and calves not only cost the enterprise inputs but also provide no return. As in the biological analysis, the financial analysis indicates that the major benefits will be achieved through reductions in both cow and calf mortality. Cow mortality and calf mortality are discussed in turn below.

Cow mortality

Estimating cow mortality is difficult. In CashCow, the 'number of cows missing at muster' was used as a practical approach to estimating mortality (Table 1). Percentage mortality rates vary among regions, seasons and properties, but accounting for other factors, a mean of ~9% is a conservative estimate across the four regions surveyed in CashCow (Fordyce *et al.* 2022). Currently, the number of cattle in northern Australia is estimated to be ~14 million, and assuming that half of those are cows, then >630 000 die each year. Of course, every cow will die in time, but the aim is to cull cows before they become unproductive. Furthermore, breeding old cows reduces the potential for genetic gain in a herd.

Mortality rates from multi-season studies reveal two trends: herds in harsher environments have higher mean mortality (e.g. Brigalow Station 2.3%, Kidman Springs 11.3%; Mayer *et al.* 2012); and rates differ between age classes of cows (2 years of age 27.5%, 3–7 years 2.8–8.9%, 8 years 11.9%, 9 years 14.2%; O'Rourke *et al.* 1995). The CashCow data (Table 1) reported a median cow mortality of 8.4%, although the multivariate analysis in that study (McGowan *et al.* 2014) predicted means of 8.9–18.1%. The major determinants of loss appear to be location and nutrition:

- Harsh vs milder conditions (e.g. Northern Forest vs Northern Downs) can account for 9.2% points.
- Mortality is highest in first-calf heifers and cows >7 years of age.
- The difference between BCS 1 and 5 accounts for 7.8% points.
- Low dry-season biomass of <2000 vs >2000 kg/ha accounts for 5.4% points.
- Time to follow-up rain >30 days at the start of the wet accounts for 4% points.

The gaps between the median and 25th percentile (see data and discussion below in *Potential gains in addressing calf loss: benchmarking the top 25%*) show that there is opportunity for gains across the industry in the order of 5 percentage points. In order to address heifer mortality, separate management of this cohort to improve nutrition and BCS is essential, as is providing the best possible conditions for calving. Opportunities to reduce mortality of aged cows include providing nutrition to increase BCS, and culling for age (>7 years), bottle teats and failure to raise a calf. An alternative is to remove the pressure of pregnancy on older cows by sterilising them, and then fattening them for sale.

Calf mortality

Data from successive surveys suggest that rates of calf loss in northern beef herds have been unchanged for several decades. Although industry-wide fetal/calf loss is recorded as 9%, it is known to be as high as 20% in some areas in certain years, especially in heifers. Burns *et al.* (2010) summarised data on losses from studies undertaken in regions of northern Australia between 1983 and 2009. The extremes for fetal/calf loss were from Queensland's Brigalow Belt (7–18%) and regions of Northern Territory (several regions >20%, with others 3.4–14%). Perinatal loss (within 48 h of birth) accounts for 2–12 percentage points and postnatal mortality (between 48 h and weaning) contributes 0.3–15 percentage points. Holroyd (1987) considered that 12% would be an acceptable level of loss, comprising 5% prenatal, 4% perinatal and 3% postnatal losses. Losses averaged 9.5% across the five Queensland research stations sampled in the Beef CRC trials (Bunter *et al.* 2014), which may underestimate losses on commercial properties.

Risks for calf mortality. Two independent studies published in 2014 drew conclusions from analyses of large datasets (Table 4). Although these studies provide excellent industry-wide views, it should be noted that individual properties may have a subset of the risks, or the impact of each risk may differ from the regional trend.

Bunter *et al.* (2014) analysed factors contributing to calf mortality over 9 years in Brahman and TCOMP breeds on research stations across different regions in Queensland. The data comprised a range of animal metrics and breeding timings, and udder and teat scores were included. Using multivariate analysis, an odds ratio (OR) was generated for each factor. In this context, an OR of 2, for example, indicates that a factor increases the probability of calf mortality two-fold. The lack of association of calf loss with maternal BCS was attributed to better management on research farms than on commercial properties, where BCS was likely to be more variable (Bunter *et al.* 2014) and therefore limiting. Factors such as location, adverse environment and year, which were significant sources of variability, are not listed in Table 4 because these factors are not under management control. Several husbandry activities were not considered, probably owing to them being regarded as standard procedures (e.g. castration) or where data were fragmentary (e.g. cow spaying).

Table 4. Odds ratio (OR) of a factor affecting calf mortality, or estimated impact on mortality.

CRC Qld dataset (Bunter *et al.* 2014)			
Risk factor	**Description and attributed OR quantum**	**Regions/other comments**	**Actionable response**
Calf sex	Female calves two times more likely to die (OR ~2)		No
Low calf birth weight (BW)	<32 kg increased risk vs >39 kg (OR 1.5–2.8)		Nutrition, genetics
Cow breeding status	Higher loss in heifers vs 4–7-year-olds (OR 2.6–5.6) No calf in previous year (OR 2.5)		Nutrition, genetics Cull cows >4 years old that do not produce a weaner
Teat score	Size, indicating bottle teats (OR 2)		Cull
Udder score	Small vs large (OR 5)		Small has poor lactation, cull
Cow age × calf BW	Interaction of small calves born to cows <4 years old (OR 1.8–5.6)		Nutritional
Breed	Mortality higher in Brahmans (10.5%) than TCOMPs (8.6%) (OR 1.5)	'Toorak', 'Belmont' comparison	Cull, genetics/breed
Horned vs polled	Higher risk if horned (OR 8.4)	Post-branding dehorning 1.5% mortality	Use polled genetics, analgesia with procedures

CashCow dataset (McGowan *et al.* 2014)			
Risk factor	**Description and estimated increase in mortality (percentage points, pp)**	**Regions/other comments**	**Actionable response**
Low BCS	Lower pregnancy rates for 2nd lactation heifers and low calf BW (8 pp)		Herd segregation and feeding, genetic selection against low birthweight
P deficiency	P:metabolisable energy ratio <500 (1–10 pp)	Especially Central Forest, Northern Forest	Diagnose and supplement
Low crude protein	Lowers BCS (up to 4 pp)		Nutrition, supplements
THI	>79 for >15 days (4–6 pp)	Southern Forest, Central Forest, Northern Downs	Shading, calving facilities
Mustering	Mustering <90% effective (9 pp) 1st lactation cows mustered within 2 months of calving (9 pp)	May impact when calving is year-round	Tighter mating period and planned muster dates
Hip height	>140 cm (3.7 pp)		More common in older cows, so cull as required
Mother's age	Overall 'heifer gap' compared with other ages (also see Table 5) (3–4 pp)	All regions	Heifer management, genetics
No calf in previous year	(3.6 pp)	Commonly related to teat and udder problems	If no calf in sequential seasons, cull
Disease	Only with recent infection: pestivirus (8 pp), *Campylobacter fetus* (7 pp). Akabane virus not tested	All regions	Vaccinate when at risk
Presence of wild dogs	Unsubstantiated, but estimated (6–11 pp)	All regions	Bait

Country type is not included, because, while it is a major component, it cannot be changed.

The CashCow study ran over 3–4 years consecutively and collected animal and property data on mainly commercial properties across four regions (McGowan *et al.* 2014). This allowed a large number of parameters to be calculated and many factors to be estimated through statistical analysis and models using multivariate analysis. The factors are ascribed percentage points of effect on calf loss. From these data, a ranking of effects, clustered with likely origin across the industry, was:

1. deficient nutrition, which also has direct impact on BCS
2. heifer management issues such as mismothering, abandonment of calves, low-birthweight calves

3. risks such as bottle teats that could be resolved by culling cows
4. temperature/humidity impacts
5. aspects amenable to genetic control.

Causation of calf loss. Causal webs of calf loss have been generated by McGowan *et al*. (2014, 2017). Although they are helpful in general understanding of possible impacts, those acting at property level may vary in importance. Despite these and earlier investigations, the causes of calf mortality remain poorly understood, partly because mothers cannot be observed around the time of calving. Fetuses and dead or weakened calves are rarely found, let alone made available for investigation of the cause of death. Even when observations are possible, it has been estimated that about one-third of the deaths have an unknown cause (O'Rourke *et al*. 1995). Similarly, Bunter *et al*. (2014) stated that 'despite regular observation the reason for mortality ... was still essentially unknown'. As a result, most presumed causes are not known or estimates that exist are based on a handful of studies or are assumed to arise from a particular risk factor.

Causes of prenatal fetal loss are especially difficult to identify. Some infectious agents that cause infertility or early abortions include *Campylobacter fetus*, *Neospora caninum*, *Tritrichomonas foetus*, Akabane virus, bovine herpes virus, bovine pestivirus and bovine ephemeral fever virus (see summary in Burns *et al*. 2010). Disease agents that tend to affect older fetuses, including causing abortions in late pregnancy, are *Leptospira* spp., *Neospora caninum* and Akabane virus.

The majority of deaths occur during or within 48 h of birth. An estimated 67% of deaths observed during the Beef CRC longitudinal study occurred within a day of calving (Bunter *et al*. 2014). Based on limited observations, some causes of death during this period included dystocia, congenital defects, cow mortality, sick and weakened calves that failed to suckle (some due to bottle teats), heat stress and predation, with 43% unknown (Holroyd 1987). Calves with low vigour are less likely to suckle in the perinatal period, resulting in dehydration, starvation, and low immunity due to lack of colostrum.

In the later postnatal period, between 48 h and weaning, death may occur through predation, and wound infection following castration, branding and dehorning. However, although anecdotal reports exist of significant losses to dogs on individual properties, survey data suggest that predation is not a major industry-wide issue (Allen *et al*. 2020).

To address the major gap in direct evidence of causation, research is needed that can monitor herds during the breeding season, mother up cows and calves, find dead calves and fetuses, and diagnose their conditions in order to categorise causes of death, over several seasons and, ideally, across multiple regions. A further challenge is that research methods should minimise disruption of cow–calf bonds while collecting data. The aim of such work is to link causation to risk factors and use that information to develop and evaluate interventions for improving calf survival. In place of direct physical observation that has been used to date, modern telemetry and positioning systems offer the opportunity to undertake remote surveillance to determine causation.

Remote surveillance: opening opportunities to understand causation. Remote surveillance of cattle is a developing technology. This discussion covers several techniques categorised into fixed and mobile data collection systems. The main focus is the use of technology in a research environment to study causation of mortality. However, in time, such technologies may be deployed as useful herd-management tools.

Fixed systems include static data-collection devices coupled with sophisticated data analysis. The best example is walk-over weighing (WOW), which enables cows to be weighed as they enter or leave watering points and the data to be used to estimate weights, growth rates, mothering up and potential calving events (Menzies *et al*. 2018*a*, 2018*b*). These systems generally require little maintenance, operate for long periods and are autonomous. They are ideal for determining herd trends, but are only as good as their frequency of use by cows and the sophistication of the algorithms. They do not allow attribution of causes of calf loss but have been used to estimate herd BCS and other relevant aspects of the herd.

Mobile systems include ear tags or collars that allow monitoring of an individual cow's physical position and behaviour over time by sending information back to researchers. GPS-enabled ear tags are available that signal position at various intervals (e.g. 15 min) and communicate via the internet or satellite. Ear tags incorporating accelerometers can inform on additional activities such as calving behaviours (Chang *et al*. 2020*b*). An intravaginal device, Calf Alert, that is ejected at birth, can signal time of birth (Stephen and Norman 2021) and location can be estimated from triangulation of signals, or the GPS signal from the cow's ear tag, if fitted. Using methods such as these, it is possible (but still challenging) to record the cow's identity, find the birth location and time, then tag and clinically evaluate the calf. If the calf is dead, the cause of death can be investigated by laboratory post-mortem. Stationary GPS signals can also indicate cow death (or lost tags).

Even with well-resourced research programs, the measuring of causes of calf loss in a typical production system remains a challenge. Some challenges are physical (e.g. internet coverage, frequency of reporting, loss of tags), others are human (e.g. coverage at night and in rugged terrain), or due to the animal (e.g. an aggressive cow). Herd size is another challenge. At least 200 cows need to be tagged and tracked over several months. This number is required because there is some loss of data and, even in the best circumstances, only causes with an incidence >5% can be measured with sufficient accuracy. Seasonal variation and sporadic events such as disease outbreaks means that several seasons of data are required.

These methods could be supplemented with multifunction ear tags (location, behaviour) and technologies such as drone-based predator spotting. At present, these are cutting-edge research tools, but as future costs fall, some of the components may be deployed in commercial herds to assist management. Research work has commenced in this area with the Calf Watch project (FutureBeef 2020), which is building on the earlier trialling of WOW, accelerometers and intravaginal devices to identify causation, especially in the perinatal period.

Potential gains in addressing calf loss: benchmarking the top 25%. As observed earlier, property data, aggregated regional data and longitudinal data collected from the cattle industry are highly variable. Because the calf-loss datasets discussed above are large and have been collected in a consistent fashion, the reported trends have a sound statistical basis, and it has been common to present those data and their analyses as 25th and 75th percentiles about a median. The 75th percentile represents the best performing properties in terms of productivity (or 25th percentile for mortality data) and is considered an achievable benchmark for properties with physical similarities in the same region. A thorough industry analysis (Holmes *et al.* 2017) examined financial performance of properties against productivity in northern beef enterprises. Three production items recurred as typical characteristics of northern beef properties in the top 25%. These were: (1) higher reproductive rate, (2) lower mortality rate, and (3) higher sale weight. These insights broadly align with the physical herd data from the CashCow project (McGowan *et al.* 2014) where farm productivity drivers were: (1) cows pregnant (%); (2) fetal/calf loss (%) (or weight of weaned calves); (3) liveweight change in cows/heifers; and (4) herd mortality (%). Some examples of the 25th percentile target for mortality are shown in Table 5.

Knowledge of risks and causes and how to mitigate them should focus on opportunities to reduce calf loss. For the industry, risks that contribute 2 percentage points of loss, which are associated with an OR of >1.5, should be a high priority for mitigation. On the other hand, the percentage point losses and OR of the risks in Table 4 are industry trends, which may not be translated to a particular property where some risks may be more important or more readily mitigated than others. Nevertheless, the set of aspirational benefits are increases in productivity of:

- 6% in heifers across all regions (reducing the 'heifer effect')
- 3.2% for second-lactation cows in Southern, Central and Northern Forests (with opportunities to improve return to in-calf the priority in all regions)
- 2.4–4.1% for older cows in all regions.

Holmes *et al.* (2017) claim that half of northern beef production comes from properties already at or above the 75th percentile level, and that even these would benefit from gains. Achieving such gains across half of the industry, including those properties placed between the 25th and 75th percentile, could lead to a 1–2 percentage point reduction in calf loss.

Genetic options to improve calf survival. The influence of maternal genetics on rates of calf loss was studied in the Beef CRC (Bunter and Johnston 2014). Heritability of calf death before weaning was low in both Brahman (0.09) and TCOMP (0.02) cattle. However, much higher values for heritability of maternal traits contributing to calf mortality were obtained, including birthweight (0.48), udder score (0.49) and teat score (0.38). Therefore, the authors recommended selection for the maternal contribution to birthweight, while avoiding very high birthweights that may predispose to dystocia, with the more accessible, genetically correlated measurement of weaning weight considered an acceptable proxy when birthweight is not known. They further recommended that selection for birth and weaning weights should be accompanied by recording of teat and udder characteristics to assist in preventing undesired correlated effects on teat or udder size, which can also have detrimental outcomes for calf survival. Genetic links to maternal behaviour, including flight time and mothering score, as well as calf vigour traits, were not deemed to be useful traits on which to base selection to improve calf survival (Johnston *et al.* 2019).

Table 5. Target 25th percentile fetal/calf loss values for different ages of females and cow mortality cited as the aspirational management goal, and the deviation from median (in parentheses) as a measure of the required potential gain (from McGowan *et al.* 2014).

	Southern Forest	Central Forest	Northern Downs	Northern Forest	Overall
Fetal/calf loss (%)					
1st lactation heifers	3.9 (5)	3.7 (6.5)	7.3 (7.6)	10.8 (5.6)	5.1 (6.0)
2nd lactation heifers	0.7 (3.9)	3.5 (3.8)	4.3 (0.4)	5.4 (4.1)	3.3 (3.2)
Mature cows	2.2 (2.4)	3.8 (2.4)	3.3 (3.6)	9.4 (4.1)	4.1 (4.0)
Cow mortality (%)	3.3 (5)	1.8 (6.1)	3.8 (2.8)	5.8 (4.8)	3.8 (4.6)

Feedbase management

The beef industry in northern Australia depends heavily on a feedbase consisting of mostly native perennial grasses growing in a range of semi-arid to tropical savanna rangeland environments as categorised by Tothill and Gillies (1992) and Bortolussi *et al.* (2005*c*). These environments feature generally poor soils and wide variation in rainfall within and between seasons, resulting in highly variable quantity and nutritional quality of pastures. Length of the non-growing season and quality of pasture are especially important influences. As discussed in the previous section, these environmental factors and the availability of adequate nutrition for cattle have significant impacts on the reproductive performance of breeding females, as well as on the growth patterns and market readiness of animals destined for slaughter.

This section briefly reviews past and present R&D on the production and utilisation of native and naturalised forages, and considers options for improving quality and management of the northern feedbase. In particular, the primary importance of appropriate grazing management practices to maintain and, if necessary, rehabilitate natural grasslands is emphasised. Additional options to increase pasture production and breeding herd performance in more favoured regions are also considered, including establishment and management of perennial legumes; potential for irrigation to increase forage production at the enterprise level; development of feasible, cost-effective supplementation strategies; and potential for greater use of conserved forages.

Grazing management

Pasture utilisation

A simple but important concept in grazing management is that of 'pasture utilisation', defined as the percentage of pasture growth per unit time (usually season or year) that is consumed by cattle (Chilcott *et al.* 2020). Understanding and application of this concept are central to best practice in all types of grazing systems. However, its importance is critical to the sustainable management and long-term productivity of perennial native grasses in northern Australia, which are especially sensitive to overgrazing (Hunt 2008).

Almost all studies of pasture utilisation in northern Australia have used cattle growth rate as the animal production performance metric, including those discussed below. However, a large modelling study is under way to determine levels of pasture utilisation required for optimal breeding-herd performance in northern Australia as judged by pregnancy rate, P4M, calf mortality and weaning percentage (Cowley *et al.* 2019). This project aims to relate cow performance datasets from 28 commercial properties across Northern Territory and northern Queensland to rates of pasture utilisation predicted by the GRASP pasture growth model and to use the CSIRO's Crop Livestock Enterprise Model (CLEM) (Meier *et al.* 2019) to predict bioeconomic outcomes.

In intensively managed grazing systems, pasture growth, the denominator in the calculation of pasture utilisation, has been estimated by applying technologies that use sward height as a proxy for pasture biomass, such as rising plate meters, pasture sleds and, more recently, multispectral sensors mounted on unmanned aerial vehicles (Alvarez-Hess *et al.* 2021). However, these technologies are inapplicable on extensively managed northern beef properties because of the heterogenous distribution of ground cover, pasture species diversity and vast paddock sizes. A promising alternative approach to remote sensing of pasture biomass and ground cover may be high-resolution satellite imagery, initially developed by the CSIRO and Department of Agriculture and Food Western Australia (Donald 2021), and since refined and commercialised by Cibo Labs (https://www.cibolabs.com.au/). Using 2000 field calibration sites, Cibo Labs provides an Australia-wide service for estimating feed on offer at 10-m resolution every 5 days with a median prediction error in pasture biomass of 295 ± 8 kg/ha derived from 100 training episodes involving ~16 000 estimates (Donald 2021).

A recent study conducted under extensive commercial conditions in the Victoria River Downs region of Northern Territory found significant positive relations between various indexes of pasture availability assessed by satellite imagery and liveweight change of breeding cows assessed remotely by WOW over a 2-year period (Pearson *et al.* 2021). Further, machine-learning predictive modelling was used to show that liveweight change could be predicted with reasonable confidence by a combination of information on pasture availability, calendar date and rainfall.

Principles of sustainable grazing management

Numerous modelling studies and long-term grazing trials have established the principles of sustainable grazing management, as reviewed by Hunt *et al.* (2014) (Table 6). Among these studies, the 'Wambiana' grazing trial stands out because its 20-year time span has allowed collection of comprehensive biological and economic data over the gamut of climatic events and market variations likely to be encountered by the northern beef sector (O'Reagain *et al.* 2018). The key findings of this study, conducted on a commercial property near Charters Towers, were that a fixed, moderate stocking rate at long-term carrying capacity for growing steers allowed pasture and land condition to be maintained and that it maximised individual animal production. Over the long term, it also was more profitable than fixed, heavy stocking. In general, these findings confirmed and reinforced those of earlier grazing trials conducted in the Victoria River District of Northern Territory (Dyer *et al.* 2003) and in Central Queensland (Burrows *et al.* 2010). It also is encouraging to note that outcomes of the Wambiana trial were predicted with reasonable accuracy by an earlier modelling study that simulated a hypothetical

Table 6. Principles and guidelines for grazing management in northern Australia (adapted from Hunt *et al.* 2014).

Principle 1. Manage stocking rates to maintain land condition and economic returns
Guideline 1.1. Set stocking rates to match long-term carrying capacity
Guideline 1.2. Regularly assess the need to adjust stocking rates in response to current and anticipated forage supply and quality
Guideline 1.3. Management factors other than forage supply also determine the need to vary stock numbers, such as land condition trend, ground cover, grazing pressure from other herbivores, and economic risk
Principle 2. Rest pastures to maintain them in good condition or to restore them from poor condition so as to increase pasture productivity
Guideline 2.1. Rest pastures during the growing (wet) season, commencing after sufficient rain (38–50 mm), to initiate herbage growth at the beginning of the growing season
Guideline 2.2. Rest pastures for the whole growing season if possible, or at least for the first half of the growing season
Guideline 2.3. Pastures need to be rested for two growing seasons to improve by one ABCD condition class (where A is good and D is very poor, (Chilcott *et al.* 2003), and for longer if the initial condition is less than B (fair)
Principle 3. Devise and apply fire regimes that enhance grazing land condition and livestock productivity while minimising undesirable impacts
Guideline 3.1. Use fire to manage woody species, using a minimum fuel load of 2000 kg/ha
Guideline 3.2. Use fire to change the composition of the herbaceous layer in certain pasture types (e.g. Mitchell grasslands and black speargrass pastures) by killing less desirable plants such as wiregrass (*Aristida* spp.)
Guideline 3.3. Use fire to change grazing patterns by temporarily increasing the attractiveness of previously ungrazed areas and providing rest to previously grazed areas
Principle 4. Use fencing and water points to manipulate grazing distribution
Guideline 4.1. Smaller paddocks and additional water points can achieve more effective use of pastures. In extensive grazing areas, aim for paddocks of 30–40 km^2 with two water points and a maximum distance to water of 3–4 km. In more intensive regions, aim for paddocks of 20 km^2 with two water points. Cattle numbers should be limited to <300 per water point
Guideline 4.2. Smaller paddocks and additional water point do not overcome uneven pasture utilisation within paddocks at the plant community or patch scale. Other methods (e.g. fire, selection of water point locations) may be necessary
Guideline 4.3. Property development can generate significant increases in livestock production only where it results in more effective pasture utilisation by increasing carrying capacity
Guideline 4.4. Fencing and water points can be used to help protect preferred land types and sensitive areas from overgrazing

property in the Charters Towers district (MacLeod *et al.* 2004). However, unlike the Wambiana trial, economic assessment in that study was based on breeding herd performance as well as steer growth rates.

A trial into long-term grazing strategies has been ongoing since 2010 at Old Man Plains Research Station, south-west of Alice Springs (FutureBeef 2021a). Final results have yet to be published but the researchers are encouraged that long-term carrying capacity determined by using Grazing Land Management methodology appears to have been central to the maintenance of good land condition and consistent production over a range of seasonal extremes in this arid/semi-arid environment.

Technical guides to best management practices for grazing management to optimise land condition, animal production and profitability in the Barkly Tablelands (Walsh and Cowley 2014*a*), Victoria River Downs (Walsh and Cowley 2014*b*) and Alice Springs (Walsh *et al.* 2014) regions of Northern Territory are generally aligned with the recommendations of Hunt *et al.* (2014). These publications additionally identify specific knowledge gaps related to stocking rates, pasture spelling, landscape restoration, prescribed burning and infrastructure development that are directly relevant to issues discussed in the rest of this section. The steps required to determine long-term carrying capacity, including assessment of land condition and estimation of safe rates of pasture utilisation, have recently been summarised in practical terms (Walsh and Paton 2020).

Despite the clarity and consistency of the advice cited above, its widespread communication to northern beef producers, and well-documented examples of the successful adoption of advice to commercial enterprises (e.g. Walsh and Cowley 2016), overgrazing continues to be a major concern, with ongoing rangeland degradation and declining profitability of beef enterprises as demonstrable negative consequences. Factors contributing to the mismatching of cattle stocking rate and the native forage resource were analysed by Stafford Smith *et al.* (2007). These included the unpredictability of short- and long-term variations in both climatic and market conditions, and lack of knowledge of technical and other (e.g. risk-management) options to aid decision-making about grazing pressure. Ironically, although understanding of the impacts of grazing pressure has increased, innovations such as the introduction of *B. indicus* cattle and feed supplementation have enabled greater rates of pasture utilisation and perceived carrying capacity, with long-term detriment to land condition and enterprise profitability (Stockwell *et al.* 1991; Ash *et al.* 2011). Macro-industry factors that place a high value on the herd, such as property valuation and bank lending practices, also contribute to the mismatching of stocking rates and carrying capacity (Bowen and Chudleigh 2021). The focus of many producers (and some advisors) on production per hectare rather than production per animal exacerbates this problem (Holmes 2022).

Another key practical issue is the tendency of many graziers to retain stock for too long during a drought event before taking action to sell or agist cattle (Landsberg *et al.* 1998). The lead author of that paper and other progressive graziers have successfully managed this risk by setting hard turn-off dates if it has not rained by a certain predetermined date. Other options for managing grazing pressure are discussed below.

The concept of wet-season spelling of native pastures is based on observations of the particular sensitivity of tall-grass communities in northern Australia to grazing selectivity of cattle and defoliation during early forage growth (Ash and McIvor 1998). Effects of wet-season resting on vegetation dynamics and land condition were examined at three sites in north-eastern Queensland with differing levels of soil fertility and two contrasting classes of land condition (Ash *et al.* 2011). This comprehensive study clearly showed that either conservative stocking (25% pasture utilisation) year-round or moderate stocking (50% pasture utilisation) with some wet-season resting maintained land in a desirable state or helped transition from a less desirable to a more desirable state for sustainable production and rangeland condition. Results of other studies into the effects of resting have been more equivocal; however, in some cases, they were confounded by effects of various other factors, or lacked controls. After reviewing all of the available literature, Hunt *et al.* (2014) concluded that, in most circumstances, resting pastures during the early growing season will have positive effects on subsequent growth and botanical composition of native pastures. They recommended that the rest period should commence immediately after rainfall sufficient to initiate forage growth (i.e. 38–50 mm) at the beginning of the growing season or, if paddock access is difficult after rain, before the wet season starts (Table 6).

Longer term spelling of rangeland pastures over one or more growing seasons also has been advocated as a means of sustaining their productivity and ecological stability or remediating degraded land (Hunt *et al.* 2014), based on research findings (Orr and Paton 1997; Post *et al.* 2006) and the experiences of commercial practitioners (e.g. Landsberg *et al.* 1998). The recommended duration of resting varies with initial land condition and seasonal growing conditions.

Optimising distribution of grazing pressure

On extensively managed northern properties, distribution of grazing pressure within very large paddocks with few water points also may be an issue for optimising pasture use and cattle production, and minimising land degradation (Hunt *et al.* 2007). Proximity of water points may be especially important because, although cattle can range large distances from water, activity declines markedly beyond 3–4 km (Fisher 2001; Hunt *et al.* 2013; Cowley *et al.* 2020). This can lead to overgrazing near water points and underutilisation of more remote pasture. Therefore, Hunt *et al.* (2014) concluded that a grazing radius of 2.5–3 km (i.e. ~5–6 km between water points) should ensure acceptable levels of forage utilisation across the landscape and reduce the overgrazing of pastures near water points, as long as the number of cattle per water point is <300 (Table 6).

Hunt *et al.* (2014) also found that reduction of paddock size can improve grazing distribution; however, the cost of fencing increases markedly for paddock sizes less than ~30 km^2. Accordingly, those authors recommended that, on more extensive northern properties, producers should aim for paddocks of 30–40 km^2 in area with two water points, and a maximum distance to water of 3–4 km. For more intensively managed properties in north-eastern Australia, the recommendation was paddocks of 20 km^2 with two water points to optimise grazing distribution (Table 6).

The principles established by Hunt *et al.* (2014) are being applied in a current MLA-funded project aiming to assess the influence of paddock area and distance to water on reproductive performance and calf wastage in beef heifers on two commercial properties in the Barkly Tableland and north-western Queensland (Walsh and McCosker 2019). The ultimate goal of the project is to refine and test a user-friendly spreadsheet tool to enable producers to compare the benefits and costs of different infrastructure options on their own properties.

Rotational or cell grazing continues to be promoted as a means of more efficiently using rangeland pastures in northern Australia despite an abundance of research findings to the contrary. For example, 30 years ago, O'Reagain and Turner (1992) concluded that there was little difference between continuous and rotational grazing systems in terms of effects on rangeland condition or animal production in South Africa. More recent Australian studies have supported this conclusion (Hunt *et al.* 2013; Hall *et al.* 2014, 2016; Schatz 2019), as have comprehensive reviews of the international literature (Briske *et al.* 2008; Hawkins 2016). Therefore, it is not surprising that cell grazing was found to be much less profitable than set stocking because of its additional capital and operational costs, including the opportunity cost of labour (Hunt *et al.* 2013). Nevertheless, rotational/cell grazing continues to be practised and advocated by experienced commercial producers in northern Australia and elsewhere. Possible reasons for the dichotomy between experimental evidence and producer experience have been reviewed by Teague *et al.* (2013), who offered three hypothetical explanations: (1) failure of experimental treatments to take account of 'accepted' principles of plant health and animal intake; (2) lack of commercial scale of controlled grazing trials; and (3) failure of researchers to optimise the integration of ecological, economic and social contexts and conditions. This suggests that quality of management is a central issue that should not be discounted when assessing the relative merits of continuous versus rotational grazing systems.

Self-herding has been proposed as a less expensive potential alternative to paddock-based rotational grazing. This approach, which uses feed rewards linked to visual, auditory and olfactory cues to modify cattle grazing behaviour and distribution, was evaluated recently in a project conducted at Kidman Springs, Northern Territory (Revell 2019). Positive outcomes included the attraction of cattle into previously undergrazed areas, more even distribution of grazing pressure in large paddocks, improvement of feed quality by removing dry, rank grasses, and associated reduction of fire risk. This trial used breeding cows of mixed age without deliberate inclusion of bulls. However, stray bulls that were intermittently present used the self-herding attractant stations together with the breeders. Further research is required to confirm and extend these findings under a range of conditions before self-herding telemetry technology can be offered as a reliable alternative to conventional rotational grazing systems.

Production and utilisation of native and naturalised forages

Most native grasses in northern Australia are tropically adapted C_4 species that feature more efficient photosynthetic processes than temperate C_3 grasses and relatively high biomass production during the growing season. However, the feeding value of these grasses is poorer owing to their lower concentration of soluble nutrients, especially non-structural carbohydrates, and lower digestibility associated with their more fibrous leaf structures (Wilson and Hacker 1987; Van Soest 1994). With these species, seasonal variation in nutritional value can be as important as pasture abundance, particularly the decline in nitrogen (N) content and dry matter (DM) digestibility during the dry season in dry tropical regions. The utility of faecal near-infrared reflectance spectroscopy as a tool to assess pasture quality and improve the nutritional management of northern breeding herds has been reviewed by Dixon and Coates (2007).

To varying extent, the native feedbase has been augmented by deliberate or inadvertent introduction of exotic grass and legume species, beginning as early as the late 19th Century, as reviewed by Clements and Henzell (2010). Notable early examples include buffel grass (*Cenchrus ciliaris*), Townsville stylo (*Stylosanthes humilis*) and leucaena (*Leucaena leucocephala*). These and related species can, in more favourable regions of northern Australia and with appropriate management, offer substantial opportunities for increased productivity of beef herds. However, their introduction should be considered only where conditions allow and after the basic principles of grazing management of native pastures have been implemented, as discussed above. The relative productivity of a range of introduced pasture species in Queensland is summarised in Table 7.

Table 7. Average commercial steer performance on a range of pasture systems in Queensland (adapted from Noble *et al.* 2000).

Forage system	Av. stocking rate (ha/steer)	Annual liveweight gain (kg/head)	Av. age at 600 kg LW (months)
Native pasture, North Qld	10	80–100	>55
Native pasture, Central Qld	4	100–140	>50
Native pasture/ stylo, North Qld	5	130–165	45
Native pasture/ stylo, Central Qld	3.5	140–170	42
Buffel grass, new	2	170–190	40
Buffel grass, run down	3	140–150	45
Leucaena/buffel grass	1.5	250–280	30

Introduced grasses

Early production responses to the sowing of introduced grasses, particularly buffel grass on fertile soils cleared of brigalow and gidgee scrub, were substantial and have continued to boost the productivity and profitability of beef enterprises in regions such as Central Queensland (Table 7; Peck *et al.* 2011). However, since the late 1980s, it has been apparent that the productivity of sown grass pastures declines over time, mostly due to a progressive decrease in available soil N (Myers and Robbins 1991; Tothill and Gillies 1992). For example, cattle liveweight gains for 6 months from June 1989 at Brian Pastures Research Station in South East Queensland were 78 kg/head on 2-year-old pasture, 37 kg/head on 5-year-old pasture, and 20 kg/head on 8-year-old pasture (Myers and Robbins 1991).

A more recent review of this problem estimated that pasture decline reduces production by ~50%, with a projected industry cost exceeding $17 billion over 30 years, and concluded that the best long-term solution is to establish a range of adapted legumes in the existing grass-dominant pastures (Peck *et al.* 2011). A main concern was restoration of the productivity of buffel grass pastures, which were estimated to be 'dominant' on 5.8 Mha and 'common' on a further 25.9 Mha in Queensland, mostly in central and southern regions.

Pasture dieback affecting introduced and some native grasses has been identified as an emerging problem across wide areas of northern and eastern Queensland. Early trials have demonstrated that perennial legumes are unaffected and should be part of the solution to restoring pasture productivity in affected areas (FutureBeef 2021*c*).

Although most of the recent R&D on new pasture species and cultivars for the tropics and subtropics has centred on adapted perennial legumes, ongoing work in North Queensland is evaluating a range of promising, recently developed *Panicum* grasses, with an initial focus on optimising seed production (Cox *et al.* 2019).

Tropical legumes

Stylosanthes. The most widespread tropical legumes in northern Australia are the *Stylosanthes* species, most notably *S. scabra* cv. Seca (shrubby stylo) and tetraploid *S. hamata* cv. Verano, which by the end of the 20th Century were being regularly oversown into about 1 Mha of native pastures (Noble *et al.* 2000). Both of these cultivars are adapted to seasonally dry environments and most soil types of northern Australia other than heavy clays. In addition, both are relatively tolerant of Australian strains of the fungus *Colletotrichum gloeosporioides*, the cause of anthracnose disease, which devastated previously well-established and widespread communities of Townsville stylo (*S. humilis*) and common stylo (*S. guianensis*) in the 1970s (Edye 1997).

Grazing studies during the early 1990s demonstrated that oversowing of either or both stylo cultivars (cvv. Seca and Verano) across a range of northern environments consistently supported higher cattle growth rates than native pastures alone and extended cattle growth for several months beyond that achieved by many native pastures (Coates *et al.* 1997). For example, at Lansdown, south of Townsville, steers grazing native pastures oversown with Verano gained more than steers grazing native grasses alone, by 50 kg/head.year, during the period 6–12 years after pasture establishment (McCaskill and McIvor 1993). Similar responses to inclusion of Seca in native pastures were observed at two sites in Central Queensland studied over periods of 4 or 5 years (Middleton *et al.* 1993). These results support the conclusion of Coates *et al.* (1997) that stylo-based pastures have the potential to allow feeder or grass-finished cattle to meet market specifications and markedly improve breeder performance. However, positive responses to stylo inclusion may be reduced by prolonged drought or pre-existing adequate levels of soil N (e.g. Jones *et al.* 2000).

The destruction of *S. humilis* and *S. guianensis* cultivars by anthracnose in the 1970s led to an integrated research program over two decades to improve anthracnose resistance in stylos. Much of this work focused on development of durable resistance in *S. scabra*, using cross-breeding of lines carrying different resistance genes (Cameron *et al.* 1996; Chakraborty 2004). Australian research in this area then lapsed. However, genetic lines of *S. seabrana* and *S. scabra* have been recently reselected from old evaluation sites in the humid tropics of North Queensland and are being screened for anthracnose resistance (Gorman *et al.* 2019). Preliminary results suggest that at least two of the 19 new lines tested appear considerably more resistant than the other new lines and commercially available cultivars.

Leucaena. In contrast to the relatively widespread use of stylo legumes by north Australian beef producers, adoption of leucaena, a highly nutritious and productive tree legume, has been slow despite the sustained research efforts of scientific proponents (e.g. Shelton 2019) and the positive experiences of leading producers (e.g. Heatley 2019). Thus, despite the availability of grazing cultivars since the 1960s and repeated research demonstrations of the production, profitability and environmental benefits of the legume (e.g. Bowen *et al.* 2018), the total area sown to leucaena across northern Australia is estimated to be no more than ~130 000 ha, mostly in Central and southern Queensland (Buck *et al.* 2019*a*). This is miniscule considering a conservative estimate that >8 Mha of land in Queensland alone is potentially suitable for growing leucaena (Peck *et al.* 2011).

The slow rate of adoption has been attributed to multiple factors including: lack of awareness of or confidence in the plant's productive potential; concerns about the negative effects of mimosine toxicity on cattle health and performance; high rates of crop failure related to inadequate knowledge of the environmental and agronomic requirements for the successful establishment and management of leucaena; and high upfront cost of establishment and ongoing cost of management (Buck *et al.* 2019*a*, 2019*b*). Additional factors include susceptibility of the most used leucaena cultivars to the psyllid insect *Heteropsylla cubana*, especially in more humid growing regions (Lemin *et al.* 2019), and environmental concerns about the potential of leucaena to establish as a weed in native ecosystems (Campbell *et al.* 2019; Revell *et al.* 2019).

The problem of mimosine toxicity in non-adapted Australian cattle was believed to have been solved by the discovery of a rumen bacterium, *Synergistes jonesii*, that effectively degraded mimosine and its toxic ruminal metabolites, 3,4-dihydroxypyridine (3,4-DHP) and 2,3-DHP (Jones and Megarrity 1986). Cultured strains of *S. jonesii* were introduced into Australia in 1982, leading to the development and commercial release in 1995 of a mixed-culture bacterial inoculum that could be administered as an oral drench (Klieve *et al.* 2002). Doubts have been raised about the efficacy of the inoculum (Halliday *et al.* 2019) and the necessity of its use in non-adapted cattle (Shelton *et al.* 2019). However, most cattle fed leucaena in Queensland continue to perform well and do not display clinical symptoms of mimosine/DHP toxicity. In the absence of conclusive evidence for widespread reduction in efficacy of the bacterial inoculum, it would seem premature to discontinue the practice of inoculation, particularly for cattle not previously exposed to leucaena.

Past and present research on leucaena breeding in Australia, and possible future opportunities, have been recently reviewed by Dalzell (2019). The review highlighted the use of interspecific hybridisation among the 24 known species of the genus *Leucaena* to improve psyllid resistance and cold and frost tolerance of cultivars used for grazing, without sacrificing forage yield and cattle growth performance. Ongoing research to breed sterile cultivars of leucaena also was briefly reviewed.

Redlands, a psyllid-resistant hybrid leucaena cultivar bred by University of Queensland scientists, was commercially released in 2017 after 15 years of research. The cultivar was developed by progressive backcrossing of psyllid-resistant lines of *L. pallida* to the commonly used commercial cultivar *L. leucocephala* ssp. *glabrata* cv. Wondergraze. Resulting breeding lines were assessed for psyllid resistance and *in vitro* forage quality. Performance of cv. Redlands in terms of psyllid resistance and cattle growth is being assessed against Wondergaze in a large grazing trial at 'Pinnarendi' station in the Atherton Tablelands (Lemin *et al.* 2019). Results so far have confirmed the psyllid resistance of Redlands and demonstrated that its ability to support cattle growth matches that of Wondergraze. This trial also has identified challenges to the establishment of leucaena in less-than-ideal environments.

In some regions of Australia, including pastoral leasehold land in Western Australia and Northern Territory, establishment of commercial plantations of leucaena is forbidden, owing to concerns about environmental weed risk. In other regions, such as parts of Northern Territory and northern New South Wales, it has been discouraged for the same reason. Development of sterile varieties of leucaena would obviate this risk and enable expanded opportunities for graziers to take advantage of the benefits of leucaena–grass pasture systems. Current efforts to breed sterile cultivars involve development of male or female sterility via mutagenesis (McMillan *et al.* 2019) or gene editing to prevent flowering (Real *et al.* 2019). Interspecific hybridisation to produce sterile triploids also is being evaluated (Real *et al.* 2019). As well as reducing or eliminating the weed potential of leucaena cultivars, sterility may enhance forage yield because plant resources will not be diverted from vegetative growth to seed production (Dalzell 2019).

Desmanthus. Stylos are the preferred legume option for broadacre pasture improvement on lighter northern soil types, and leucaena is best suited to the more fertile soils of Central and southern Queensland. However, until recently, the vast areas of semi-arid clay soil rangelands of northern Australia, such as the Mitchell Grass Downs Bioregion, have had no commercially available or adapted sown pasture legume (Gardiner 2016). Among numerous legumes tested, *Desmanthus* species were found to be among the best long-term survivors on cracking clay soils in this region (Hall and Walker 2005). Earlier grazing trials had demonstrated high DM production and grazing tolerance of several accessions of *D. virgatus* grown on heavy soils over 7 years in subtropical subcoastal Queensland (Jones and Brandon 1998). More recently, increased liveweight gains have been observed in steers grazing mixed buffel grass–desmanthus pastures compared with those grazing buffel grass only during the dry season in Central Queensland (Gardiner and Parker 2012; Collins *et al.* 2016). However, these promising preliminary studies need to be extended and replicated under the harsher northern conditions in which it is hoped desmanthus will be of greatest value. As with leucaena and other tropical legumes, establishment of desmanthus can be challenging and producers are advised to adhere strictly to seed manufacturers' guidelines, preferably with professional agronomic advice.

The practice of re-visiting abandoned former pasture evaluation sites to assess long-term survival and persistence of tropical legumes has led to the discovery, selection, further evaluation and commercial release of several varieties of desmanthus that are able to persist under heavy grazing on northern clay soils (Gardiner 2016). The most notable example is Progardes™, a composite of five cultivars (JCU 1–5) derived from three species of *Desmanthus* (*D. virgata*, *D. bicornutus*, *D. leptophyllus*) that was commercially released in 2012 by Agrimix. By 2019, some 35 000 ha had been sown to Progardes™, mostly across Queensland but also in northern New South Wales and Northern Territory, with the targeted soils being Vertosols and related neutral to alkaline clay soils in semi-arid environments (Gardiner *et al.* 2019); this short update also noted progress with development of four new desmanthus cultivars (JCU 6–9) and the discovery and evaluation of further well-adapted accessions across inland northern inland Australia. Other research has included intra- and interspecific crossing of *Desmanthus* species to yield novel plants with softer, more erect growth, later maturity and greater cold tolerance (Stuart and Kempe 2017).

Other legumes. During the latter half of the 20th Century, there was a sustained effort by Australian scientists to assemble, characterise and evaluate a tropical forages resource collection, which, by 1996, contained ~17 000 legume accessions and almost 5000 grass accessions (Hacker 1997). However, after the mid-1990s, this work essentially ceased due to perceived diminishing returns on R&D investment in exotic tropical forages, especially legumes, and by the early 2000s both the germplasm repository in the Australian Tropical Forages Collection (ATFC) and the scientific knowledge base were in danger of being lost. To mitigate the latter risk, an online interactive tool, Tropical Forages (see www.tropicalforages.info) was developed in 2005 that allowed access to information on 180 tropical and subtropical forage species, their adaptation and potential. Content has been revised and updated, with modernised IT access (Cook *et al.* 2020). This resource was complemented by a comprehensive stocktake and analysis of legume evaluations for tropical pastures in Australia, which was collated into a database with >180 000 individual records collected from 567 sites across northern Australia (Bell *et al.* 2016). In 2000, custody of the ATFC was transferred from the CSIRO to the Queensland Department of Primary Industries, and then, in 2014, to the newly created Australian Pastures Genebank, in Adelaide (Hughes *et al.* 2017). This resource, together with plants extant in earlier trial plots, can provide plant stocks that may be useful in particular environments and potentially suitable for changing and variable climates.

The project undertaken by Bell *et al.* (2016) was prompted by the renewed interest of the northern beef industry in expanding the range of adapted tropical legumes available for use in different northern soils and climatic environments, particularly those currently devoid of sown-pasture options. The approach involved both re-evaluation of previous work, including re-visiting abandoned pasture evaluation trial sites, and identification of opportunities to develop new, elite cultivars. The authors concluded that the highest priorities for further legume development are: legumes that persist in competitive grass pastures in the subtropical semi-arid inland; legumes for clay soils in the northern tropical regions; legumes for lighter sandy and duplex soils in the inland subtropics; and more robust ley legume options for use in mixed farming systems. Several species and accessions were identified that had previously shown promising advantages over existing commercial varieties but have yet to be commercialised. These included cultivars of *Desmanthus*, *Stylosanthes*, *Macroptilium* and *Aeschynomene*.

Re-examination of old sites of plant evaluation also has led to commercial release of cultivars of several other legume species for pastures on clay soils, including *Clitoria ternatea*, *Macroptilium bracteatum* and *Stylosanthes seabrana* (Cox 2016). Each of these cultivars is intended to occupy different production niches according to climate, soil type and grazing strategy. However, adoption of these cultivars has been slowed by lack of promotion, mismatch of seed supply and demand, and difficulty of establishing legumes in pastures dominated by some key grass species.

Irrigation potential

In much of northern Australia, abundance and quality of pasture is limited by lack of water, especially later in the dry season and early in the wet season. This gives intuitive appeal to the idea of integrating small-scale, dispersed (mosaic) irrigation systems into extensive beef production systems where local environment and groundwater resources permit. Early predictions of the potential benefits of mosaic irrigation were optimistic, albeit with caveats regarding need for government assistance (Grice *et al.* 2013), and there are now examples of commercial implementation significantly increasing forage production and animal performance (Heatley 2019; Kimberley Pilbara Cattlemen's Association 2020). However, the costs of establishing and operating such schemes are substantial and their net economic benefit has yet to be empirically tested across a range of northern environments and production systems (Chilcott *et al.* 2020).

A recent benefit–cost analysis of implementing mosaic irrigation to increase forage production has relied on bioeconomic simulation modelling of irrigation development scenarios in three contrasting regions of northern Australia: the Burdekin, the Barkly Tableland and the Kimberley (MacLeod *et al.* 2018). As expected, predicted growth rates of cattle destined for slaughter were increased by irrigation in all three regional scenarios, with positive implications for rates of turnoff and access to more lucrative target markets. Nevertheless, the projected return on investment for irrigation was, in most cases, marginal at best, except when market prices were historically high. Interestingly, this modelling study also predicted that changes in herd structure due to the use of irrigated forage to enable early weaning and preferential feeding of calves and breeding cows could be at least as valuable as changes in liveweight gain of growing and finishing cattle. However, this prediction has been challenged by a subsequent economic evaluation of various management strategies for beef enterprises in different regions of Central and northern Queensland and Northern Territory (Bowen and Chudleigh 2021). This modelling study found that neither genetic nor nutritional strategies, including irrigation, aimed at improving breeding-herd performance were likely to improve enterprise profitability significantly, owing to the high costs and time required for implementation.

Supplementation strategies

Use of nutritional supplements has long been advocated and, to variable extent, adopted by northern beef producers to address deficiencies of energy and N in tropical pastures, especially later in the dry season, and of P during the wet season. By far the most common practice to overcome energy/N deficiency has been to offer grazing cattle loose licks or blocks containing urea as a cheap source of non-protein N, incorporated with molasses as a readily available source of energy (Winks *et al.* 1976; McLennan *et al.* 1981). Calcium phosphate in different forms has been the most common vehicle for inclusion in licks of P supplement (Winks 1990; Dixon *et al.* 2020). Although N is generally considered to be the first limiting nutritional factor for growing cattle grazing low-quality forages (Leng 1990; Poppi and McLennan 1995), N and energy will be considered together because of their metabolic interdependence and because most supplementary feed sources contribute to requirements for both (McLennan *et al.* 1995).

Nitrogen and energy

Decisions on whether to supplement N and energy, and with what feed sources, will depend on the animal performance response to supplementation, cost of commercially formulated supplements, and the ease with which they can be effectively delivered under extensive grazing conditions. In general, northern producers have relied on urea supplementation to meet cattle requirements for rumen degradable protein but have been unable to justify use of more expensive sources of rumen undegradable protein such as protein meals to increase productivity further. As argued by McLennan (2014), supplementation strategies for growing cattle should be viewed in the context of a growth path to a defined market or slaughter weight, which, in most regions of northern Australia, will encompass at least two dry seasons. McLennan (2014) further cautioned about the riskiness of high levels of supplementation in the first dry season because compensatory growth during the subsequent wet season can obviate the advantage of earlier supplementation. Rather, it was recommended that the less risky option would be targeted supplementation towards the end of the growth path and, if possible, use of leucaena-based systems or other special-purpose pastures or crops as alternatives to dependence on supplements. Although this advice may be appropriate for growing steers, it does not address the need for heifers to reach a critical mating weight to reach puberty and become pregnant early in the wet season in order to calve early in the following wet season and then reconceive in timely fashion. In regions where heifer weight gain is adequate, this should not be an issue. However, in harsher regions such as the Northern Forest, supplementation may be essential for achieving reproductive goals.

Most studies of cattle growth responses to N and/or energy supplements in northern Australia have been limited to only one or two levels of feeding (see Poppi and McLennan 1995). This limitation was addressed by studies in which growth response profiles to varying intakes of a range of protein meals and energy-rich carbohydrate feed sources were established in young (~6 months) (McLennan *et al.* 2017*a*) and older (10–12 or 33–36 months) (McLennan *et al.* 2017*b*) Brahman × Shorthorn (75% *B. indicus*) steers fed low-quality tropical grass hays *ad libitum*. Most notably, low levels of N supplementation produced steep growth responses that plateaued with higher levels of supplementation, typical of classical growth responses to level of dietary protein. This was consistent with the notion that N is the primary deficiency for growing cattle grazing mature dry-season grasses, and clearly demonstrated the biological efficacy of protein supplementation. The response curves obtained by McLennan *et al.* (2017*a*) provide a practical framework for formulation of N and energy supplements for growing cattle grazing low-quality tropical forages, including heifers for breeding, and for benefit–cost analysis of the case for using different types of supplement. This approach was followed in a recent study of the effects of supplementation of weaned Brahman crossbred (≥75% Brahman) heifers with varying amounts of copra and maize on body growth and reproductive performance (Silva *et al.* 2022). Results were used to develop a model which predicted that 2-year-old heifers of this genotype need to achieve a pre-mating liveweight of ~300 kg in October–November in order to achieve a probability of pregnancy of 80%, regardless of weaning weight.

The supplements used in the above studies included cottonseed meal, copra meal or fishmeal for N, and molasses, sorghum, maize or barley for energy. With the exception of fishmeal, which can no longer be used in Australia, these represent commercially available supplements of varying rumen degradability. A comprehensive survey of more novel, and mostly untested, options to enhance rumen function and improve weight gain of cattle grazing low-quality northern pastures recommended investigation of a range of potential supplements including bacteriocins, probiotics, fibrolytic enzymes and protein-rich microalgae (Lean *et al.* 2011). Of these, only microalgae have been systematically investigated under conditions relevant to the northern beef industry. These studies found that, in steers fed a low-N hay, the rate and efficiency of microbial protein production, and feed intake, were enhanced to a greater degree by supplementation with *Spirulina platensis* than by supplementation with non-protein N sources fed at an equivalent level of rumen-degradable N (Panjaitan *et al.* 2015). A later study confirmed the growth-promoting effectiveness of *S. platensis* and another species of microalgae, *Chlorella pyrenoidosa*, as potential N supplements for cattle grazing low N pastures (Costa *et al.* 2016). The authors suggested that the most feasible source of microalgae as supplements would come from the development of on-farm, open-pond production and harvesting systems. The capital and operational costs of such systems have yet to be determined.

In a study in the Victoria River District, Northern Territory, re-conception rates of first-lactation Brahman heifers were increased markedly by feeding high-protein supplements for at least 100 days until green forage was available at the start of the wet season (Schatz 2015). Liveweight at calving and re-conception rates were increased by supplementation in each of three consecutive years, with the overall mean advantages being >20 kg for liveweight and 42% for re-conception rate. In supplemented heifers, the magnitude of the re-conception response also was linearly related to liveweight at calving. Nevertheless, caution was advised regarding the need to evaluate carefully benefit versus cost of supplementation and to tailor strategies for increasing pre-calving weight of first-lactation heifers to the specific situations of individual properties.

Supplementation strategies for growing cattle in northern Australia are almost always intended to address nutritional deficiencies. However, positive responses have been observed to energy supplementation of rapidly growing young cattle grazing leucaena–grass pastures in the Ord River Irrigation Area (Petty *et al.* 1998; Petty and Poppi 2012). More specifically, the average daily gain of *B. indicus*-cross yearling heifers was increased from 0.7 kg/day in unsupplemented controls to 1.1 kg/day in animals fed 2.5 kg/day of molasses (Petty and Poppi 2012). This was attributed to increases in efficiency of utilisation of degradable protein and rate of production of microbial protein in the rumen and the associated increases in metabolisable energy intake. Heifer growth responses declined with higher levels of supplementation; this was due to a substitution effect on herbage intake. Such an effect might allow more stock to be supported on a limited area or quantity of leucaena. However, as cautioned by Harper *et al.* (2019), the economics of such a strategy would need to be assessed in relation to growth response curves such as those established by Petty *et al.* (1998) and Petty and Poppi (2012).

As discussed in the previous section, *Breeding herd management*, prolonged post-partum anoestrus and low pregnancy rates in first-lactation heifers are a recurring problem in many breeding herds in northern Australia, especially when bodyweight and/or BCS at calving are reduced by inadequate nutrition during the preceding dry season. Expected positive responses to pre-partum N/energy supplementation were confirmed in some earlier studies (Siebert *et al.* 1976; Dixon *et al.* 1996; Fordyce *et al.* 1997) but not in others (Siebert *et al.* 1976; Fordyce *et al.* 1996, 1997; Dixon *et al.* 1997*a*, 1997*b*). Failure to respond in the latter cases usually was associated with a lack of effect of supplementation on pre-partum liveweight of heifers under unusually good or poor dry-season nutritional conditions, or with premature cessation of supplementation and loss of earlier liveweight gains (see Dixon 1998). However, even when clearly positive effects of supplementation on pregnancy rates were observed at Swans Lagoon, these were much less than effects of early weaning in the same experiments on second-lactation Droughtmaster cows (Dixon *et al.* 2011*a*, 2011*b*). Positive effects of N supplementation on liveweight loss of older cows during late pregnancy were observed while the cows were fed low-quality hay before calving. These effects were not maintained when the cows subsequently grazed high-quality grass–stylo pasture during lactation (Dixon and Mayer 2021). However, the high levels of compensatory growth observed in these cows would not necessarily be expected on most commercial properties where lactating breeders must graze lower quality native pastures.

The complex issue of whether or when to supplement N and/or energy for breeding cows was addressed by Dixon (1998), who stated that consideration of these and other management options should be based on their capacity to achieve desirable conceptus-free liveweight and BCS at the end of the dry season. Possible strategies included non-protein N (urea) supplementation, time of weaning, cow BCS at the start of the dry season, and, if necessary, 'crisis feeding' of molasses/urea in the late dry season to reduce cow mortality. These strategies are summarised in Fig. 2, as adapted from Dixon (1998).

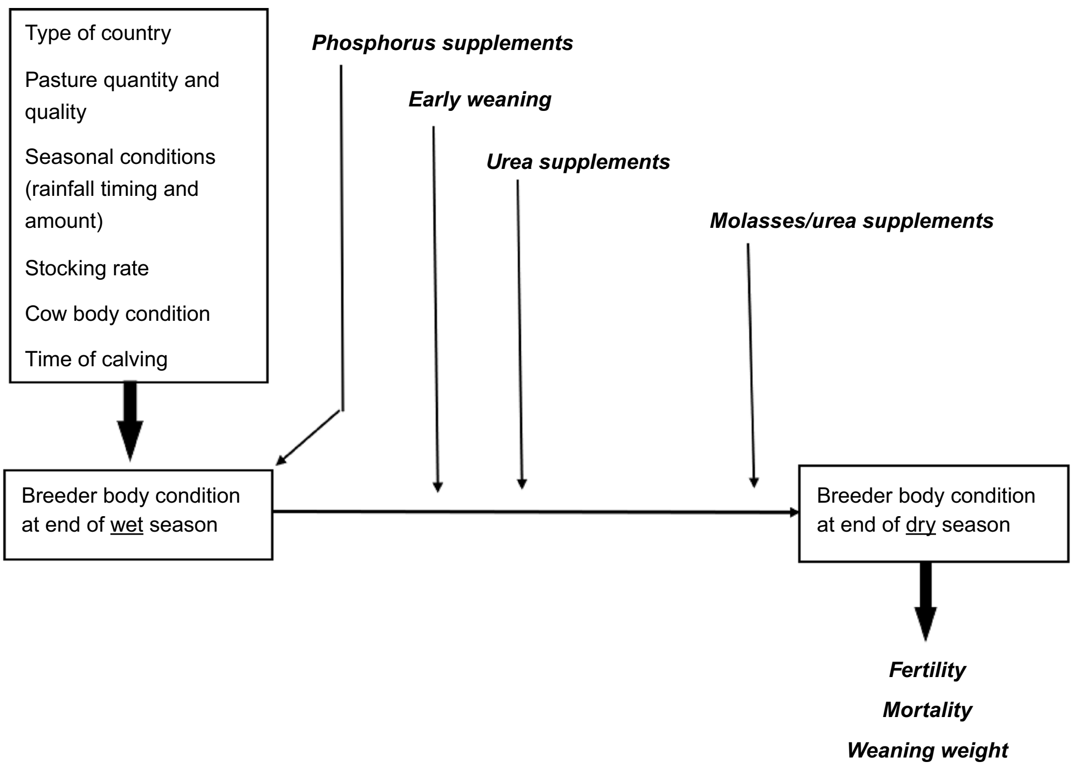

Fig. 2. Schematic representation of factors that influence productivity of breeding cows in a northern semi-arid environment (adapted from Dixon 1998).

Phosphorus

Phosphorus deficiency is a serious impediment to the performance of growing and breeding cattle in much of northern Australia, due to the variably low P status of many rangeland soils. Use of P fertilisers to address this problem is generally not cost-effective on large, extensively managed properties in the seasonally dry tropics, making direct supplementation of P the only feasible strategy to alleviate its deficiency in grazing cattle. This is important because provision of P to cattle grazing acutely deficient pastures is the single most effective strategy to improve both productivity and profitability of beef production under such conditions (Bowen *et al.* 2020).

The management of P nutrition of beef cattle in northern Australia has been comprehensively reviewed by leading experts in the field (Dixon *et al.* 2020), with topics including P requirements and availability in forages and different forms of inorganic supplements; consequences of P deficiency for productivity of growing and breeding cattle; and diagnosis of P status in grazing cattle. This subsection will focus on several key issues regarding supplementary feeding of P.

Use of the P status of soils and grazed forages to assess the likelihood of P deficiency in grazing cattle is complicated by the spatial diversity of soil types, even within individual paddocks on large properties, and by wide variation in P concentration among pasture species and their morphological components. The latter is exacerbated by the tendency of P-deficient cattle to select plant material with higher P concentration (Coates and Le Feuvre 1998) and by variation between years in seasonal conditions affecting plant levels of available P (Coates *et al.* 2019). As discussed by Dixon *et al.* (2020), existing soil maps are insufficiently detailed to inform decisions about the need for P supplementation on properties with heterogeneous soils. Recent development of remote-sensing techniques for high-resolution soil mapping may help to overcome this limitation (Forkuor *et al.* 2017). For example, a map of bicarbonate-extractable P levels in surface soils at a 1-ha pixel resolution of Queensland's grazing lands has been published recently (Zund *et al.* 2022).

Approaches to the assessment of animal P status include evaluation of cattle behaviour and production; measurement of faecal P concentration; measurement of PiP and other blood markers; and measurement of bone P in biopsy samples or obtained post-mortem from animals suspected to have deficiency (Dixon *et al.* 2020). Each of these approaches has limitations, especially for the diagnosis of less severe or subclinical P deficiency. For example, although faecal P may be a useful indicator of extremes of dietary P concentration, its utility for assessment of responses to P supplementation is limited (Wadsworth *et al.* 1990; Quigley *et al.* 2015; Dixon *et al.* 2018). Concentrations of PiP are considered to be a most reliable diagnostic test for young breeder cows and growing cattle on a positive plane of nutrition (Wadsworth *et al.* 1990; Dixon *et al.* 2017). However, use of this blood marker to assess the P status of mature pregnant or lactating cows is complicated by the P demands of the conceptus or mammary glands and the cow's ability to mobilise and later replenish bone P (Dixon *et al.* 2017). Substantial individual variation of PiP in breeding herds of mixed age and reproductive history presents an additional challenge (Dixon *et al.* 2019), as does lack of access to resources for the processing, refrigerated transport and laboratory analysis of blood samples. The latter limitations highlight the need for development of a sufficiently robust and accurate crush-side test for PiP.

During the dry season, growth responses to P supplementation of cattle grazing pastures on P-deficient soils are usually muted, because the first limiting nutrient is likely to be N or, possibly, energy. However, during the wet season, when pasture growth is rapid and cattle intakes of N and energy are relatively high, P is likely to become the primary limiting nutrient (Dixon *et al.* 2020). Therefore, producers are generally advised to offer P supplements during the wet season despite the logistical and other challenges associated with this practice.

Notwithstanding the extent of P deficiency across north Australian rangelands and the demonstrated efficacy of P supplementation in numerous controlled experiments, adoption of the practice has been relatively low (Dixon *et al.* 2011*c*; Niethe 2011). This may be partly explained by some of the above-discussed challenges regarding diagnosis of deficiency and wet-season delivery of supplements, as well as incomplete understanding of the consequences of P deficiency for productivity and profitability of beef enterprises. These issues were addressed in a study of the effects of P supplementation on growth and reproductive performance of Brahman heifers grazing acutely P-deficient pastures over three successive seasons (2017–19) in a demonstration trial at the Victoria River Research Station, Kidman Springs, Northern Territory (Schatz *et al.* 2023). Results are summarised in Table 8.

Treatments were applied after the heifers were weaned in June 2014. During the dry periods (May–October) in 2014 and 2015, there was no effect of P supplementation on heifer growth rate; however, the supplemented group grew significantly faster during the wet seasons of 2014–15 and 2015–16. Thus, at first mating in May 2016, mean weight of the supplemented heifers was 65 kg greater than that of the unsupplemented heifers. This growth advantage was amplified over subsequent years (Table 8). Effects of P supplementation on reproductive performance were equally impressive, with the supplemented females maintaining superior pregnancy and weaning rates, as well as faster growth rates in their progeny. These outcomes translated to total weaner weights that were 55%, 54% and 87% greater in the supplemented than the unsupplemented group in 2017, 2018 and 2019, respectively (Table 8). Most notably, the trial had to be stopped in May 2019 because of the extremely poor condition of >30% of the unsupplemented cows.

Table 8. Effect of phosphorus supplementation on growth and reproductive performance of Brahman females grazing phosphorus-deficient pastures in the Victoria River District, Northern Territory (from Schatz *et al.* 2023).

	2017		2018		2019	
	+P	−P	+P	−P	+P	−P
Cow PiP (mmol/L)	1.81	0.71***	1.23	0.66***	1.73	0.65***
Liveweight (kg)	380	262***	426	357***	430	324***
Pregnancy rate (%)	30	5***	60	21***	72	10***
Calf mortality (%)	20.6	22.0	17.6	23.7	12.9	20.4
Weaning rate (%)	56	48	47	36	69	57*
Av. weaner weight (kg)	173	139***	185	172	202	157***
Total weight of weaners (kg)[A]	8634	5564	7949	5145	12 936	6912

*$P < 0.05$; ***$P < 0.001$: indicating that mean values for −P group are significantly lower than those for +P group.
−P cows had not been fed any P supplement since weaning. Cow data are for lactating animals at the May muster. PiP, plasma inorganic P concentration.
[A]Assumes that both treatments started with 100 heifers; not subjected to statistical analysis.

Bowen *et al.* (2020) used the data from this trial to model the economics of P supplementation on an average-sized property in the Katherine region of Northern Territory and estimated a return on investment in P supplementation of 172%. Similar positive results were found when predicted outcomes in the Fitzroy Natural Resource Management Region of Central Queensland were modelled. These predictions of the profitability of P supplementation, together with the empirical findings of Schatz *et al.* (2023), summarised above, highlight the need for more effective translation of research findings into feasible management practices. This should include appropriate consideration of the regional diversity of P deficiency and the likelihood of minimal responses to supplementation in more productive areas of Central and southern Queensland.

Forage conservation

In contrast to dairy and beef farms in southern Australia, forage conservation is not normally an integral part of the annual production cycle on most extensively managed northern beef properties. Thus, although hay making may occur opportunistically if conditions allow late in the wet season, overall, reliance on home-grown or purchased fodder for breeding and growing cattle is relatively low and mostly used to mitigate effects of drought. Exceptions occur in regions such as southern and coastal Queensland where reliable rainfall and fertile soils permit more intensive management, and on a few irrigated properties in the Pilbara and Kimberley regions of Western Australia (Kimberley Pilbara Cattlemen's Association 2020). Non-irrigated hay-making enterprises around Katherine and other specific locations in the Top End of Northern Territory also have been developed, mostly to serve needs of the live export industry (North Australian Agribusiness Management 2016). With the specific exception of the feedlot sector, mostly located in south-central Queensland, the use of silage by northern cattle producers is very low.

Much of the above commentary is based on the results of a comprehensive survey of the production, use and trade of hay and silage by the Australian fodder industry during the period from 2002–03 to 2006–07 (Martin 2009). The northern beef industry would clearly benefit from a similar, updated analysis of trends during the past decade. Fact sheets describing best practices for making hay and silage under tropical and subtropical conditions have been prepared by relevant state agencies and Rural Research and Development Corporations. These are useful technical aids; however, an economic case for greater and more strategic use of conserved forages by the northern beef industry has yet to be made. Specific questions should include, but not be limited to:

- What are the attitudinal and technical barriers to more widespread production and use of conserved forages on extensively managed pastoral properties?
- Should silage making be a more seriously considered option, especially under environmental conditions that are suboptimal for hay making, such as mid–late wet season?
- Could increased production of conserved legumes (e.g. cavalcade, desmanthus, dolichos, lablab) offer a cheaper alternative to existing concentrate sources for N supplementation during the dry season?
- Considering earlier questions about the profitability of grazing beef on irrigated pastures, is there a financially compelling case for more widespread production of conserved fodder under irrigation where cost and availability of water permit?
- Conversely, and considering that irrigated fodder costs up to 10 times more to produce than rainfed fodder, what and where are the opportunities for substantially increasing the quantity and quality of rainfed fodder?

- Should forage plant species not currently used in Australia, but of proven value in foreign tropical systems, be considered (e.g. cassava)?
- With regard to specific needs of the northern breeding industry, what are the opportunities to improve hay quality for use in early weaning feeding systems?

Management of environmental sustainability

The Australian Beef Sustainability Framework defines sustainability as the production of beef in a manner that is socially, environmentally, and economically responsible (Red Meat Advisory Council 2021). Social aspects include public attitudes to animal welfare with implications for the social licence to produce beef. Examples of opportunities to improve current practices in the northern breeding herd are discussed earlier, in the section *Breeding herd management*, including alternatives to aversive practices such as surgical dehorning, and reducing the incidence of calf and cow mortality. Opportunities to reduce the negative effects of poor nutrition are discussed in the section above (*Feedbase management*), and heat stress is considered in the present section. The profitability of northern beef enterprises is clearly an important aspect of sustainability, and recently has been assessed by experts in farm business management and northern beef production (McLean *et al.* 2020). Therefore, this section focuses on aspects of environmental sustainability.

The north Australian beef industry is challenged by a natural environment that is characterised by a highly variable and unpredictable climate, nutrient-deficient soils, animal pests, weeds and toxic plants. The predicted influence of climate change on average temperatures, frequency and severity of droughts, and incidence of extreme weather events is likely to exacerbate these natural environmental challenges. The built or managed environment includes the further challenges of long distances to markets and to necessary services, and lack of supply-chain infrastructure. This section addresses management strategies to promote resilience and offset the impacts of these factors on the productivity and health of breeding herds in the north, as well as to ensure the sustainability, long-term productivity and biodiversity of the rangeland systems in which they graze. These strategies are discussed in the context of the environmental priorities of Red Meat 2030, the current strategic plan of the Australian red meat industries (Red Meat Advisory Council 2019).

Managing climate variability for northern pastoral systems

Predicted changes in the climate of northern Australia will accentuate the already pressing need to increase the genetic resilience of both pasture plants and the cattle that graze them. Features of climate change projected for northern Australia include increased average temperatures for all seasons with greater incidence of extremely hot spells in the summer wet season. Rainfall patterns also are predicted to change with increased incidence of extreme rainfall events, interspersed with prolonged and severe droughts.

Adaptation of forages to climate change

Heat tolerance and drought resistance have long been priorities for the genetic selection or accession of tropically adapted grasses and legumes, and this will need to be further emphasised to combat a hotter and intermittently drier climate. These adaptive characteristics, together with tolerance of low N, are more evident in the C_4 grasses that predominate in northern pastoral systems. The likely key driver of climate change, elevated levels of atmospheric CO_2, also may influence the future balance of C_4 versus C_3 pasture species, particularly in intermediate and subtropical pastures. Early studies indicated that the ability of C_4 plants to increase rates of photosynthesis in response to elevated CO_2 is much less than that of C_3 plants (Ehleringer *et al.* 1997). However, those experiments were short-term, and more recent results of studies conducted over 20 years have shown that this pattern of response was reversed after 12 years (Reich *et al.* 2018). Part of this later increase in CO_2-induced growth of C_4 grasses was attributed to increased rates of mineralisation of soil N by C_4 but not C_3 plants. Thus, there is evidence that long-term effects of climate change on northern pasture communities may change the present balance between C_4 and C_3 plants to favour C_4 grasses further. This has implications for biomass production (likely positive), forage quality (likely negative), and, perhaps, the successful establishment and maintenance of C_3 legumes (possibly negative).

Heat stress and breeding herd performance

Effects on reproductive physiology. The most significant non-nutritional environmental stressor affecting the productivity of breeding herds in northern Australia is heat stress. Exposure of cattle to high ambient temperatures around mating and during early pregnancy can have direct negative effects on development and quality of male and female gametes and on early embryo development and survival (Hansen 2009, 2013; Abdelatty *et al.* 2018), although such effects appear to be less pronounced in *B. indicus* than *B. taurus* breeds (Rocha *et al.* 1998). Heat exposure during the first half of pregnancy also can impair placental growth and functional development, with consequences for later fetal growth, birthweight and calf survival (Ouellet *et al.* 2021). Emerging evidence additionally suggests that heat stress of cows during late pregnancy may negatively affect mammogenesis, lactogenesis and later milk yield, at least in dairy breeds, and also may have a negative carryover effect on milk yield of heifer progeny during their first lactation (Ouellet *et al.* 2021). Finally, whereas most of the above effects are considered to be mediated by direct effects of heat stress on cellular and molecular functions in the testis, ovary, placenta and mammary gland, the secondary effects of heat-induced inappetence and reduced energy balance must be considered, as well as largely independent effects on post-absorptive metabolism (Baumgard and Rhoads 2013).

Genetic selection for heat tolerance. There is considerable genetic variance for heat tolerance between and within cattle breeds. The substantially greater tolerance of *B. indicus* than *B. taurus* breeds is well known (e.g. Beatty *et al.* 2006; Gaughan *et al.* 2010*a*) and, together with tick resistance, was a major reason for the introduction of Brahmans to northern Australia in the mid-20th Century. However, taurine breeds such as the Shorthorn and Hereford that were selected for their ability to produce in the tropics became substantially more heat-tolerant than their unselected counterparts, albeit less so than indicine genotypes (Frisch 1981). This heat tolerance and genetic improvement in other aspects of tropical adaptability, including tick resistance, led to the development of a synthetic taurine breed, the Adaptaur, at 'Belmont', the CSIRO's Cattle Research Station near Rockhampton, during the 1980s and 1990s (O'Neill *et al.* 1998). However, despite impressive reproductive and growth performance (O'Neill and Frisch 1998), industry uptake of the Adaptaur was poor and the breed is now almost defunct (CJ O'Neill, pers. comm.).

Other examples of tropically adapted taurine breeds available to northern beef producers include the Belmont Red and Senepol, which were developed by infusion of African *B. taurus* genetics into British breeds (Belmont Red: Africander × Hereford × Shorthorn, O'Neill and Frisch 1998; Senepol: N'Dama × Red Poll, O'Neill *et al.* 2010), and the Tuli, a pure African Sanga breed. In cross-breeding studies comparing Tuli × Hereford with Brahman × Hereford and Boran × Hereford steers, the heat tolerance of the Tuli crossbred steers was shown to be similar to that of the two indicine crossbreeds (Gaughan *et al.* 1999).

The above breeds are widely used by the major pastoral companies to create their own proprietary tropical composite breeds based roughly on the combination of one-third Brahman (and other *B. indicus* breeds), one-third tropically adapted taurine, and one-third British and European breeds (mostly Shorthorn and Charolais but with increasing interest in Angus and Wagyu) (Porto-Neto *et al.* 2014). However, it is recognised that higher proportions of *B. indicus* genetics are likely to be optimal for animals in harsher environments (Burrow 2012). In a modelling study, the economic values of using such tropically adapted composite genotypes or a terminal crossbreeding system based on Brahman cows were compared to that of a straightbred Brahman herd as used by much of the northern industry (Burrow *et al.* 2003). The simulated composite herd was predicted to be considerably more profitable than the crossbred enterprise, with both outperforming the straightbred Brahman herd. Much of the superior performance of the composites was attributed to their higher weaning and turnoff rates, the latter due to greatly increased growth rates of progeny.

Despite experimental evidence for the value of using TCOMP genotypes, and their successful utilisation by the pastoral companies, adoption of crossbred cattle by the broader northern industry has been limited. Reasons for this are not clear but possibly include lack of access to the professional genetic advice necessary for successful introduction and maintenance of complex cross-breeding programs.

An important consideration when selecting for adaptability traits such as heat tolerance is the possibility of antagonistic relationships between adaptive and productive traits (Burrow 2012). However, genetic correlations between resistance to heat stress and reproduction traits are generally positive (Turner 1982; Burrow 2001), indicating that selection for heat tolerance is likely to be associated with improved reproductive performance. Also, a large study of genetic associations between adaptive and productive traits, including growth rate and age at puberty, in Brahman and TCOMP heifers led to the conclusion that selecting for reduced age at puberty is unlikely to have negative effects heat tolerance or other tropically adaptive traits (Prayaga *et al.* 2009).

Non-genetic strategies to mitigate heat stress. Non-genetic management options for mitigating heat stress in cattle include provision of shade, ensuring an adequate water supply, and nutritional manipulation (Henry *et al.* 2012). Research on physiological, behavioural and production responses to application of these options has focused mainly on intensively managed dairy and feedlot beef systems (Blackshaw and Blackshaw 1994; Gaughan *et al.* 2010*b*). For extensively managed northern cattle, provision of adequately spaced watering points with good supply has already been discussed in relation to grazing management. Provision of natural or artificial shade at or near these points and ensuring that paddocks have sufficient tree cover would appear to be achievable management interventions. However, this assumes that the firmly held industry paradigm that 'trees and cattle don't mix' (Arbuckle 2009) can be overcome by existing research evidence that open woodland with a grass–legume feedbase provides both effective shade (González *et al.* 2013) and superior animal performance (O'Neill *et al.* 2013). Other management options proposed to reduce environmental or metabolic heat load in dairy and beef feedlot enterprises, such as artificial cooling or dietary manipulation (Gaughan *et al.* 2008*a*; Gonzalez-Rivas *et al.* 2018), are infeasible for extensively managed northern beef operations.

Using advanced forecasting of key weather events to manage risk and aid decision-making

A major challenge for northern beef producers is managing the risk posed by year-to-year variation in the onset, intensity and duration of the summer wet season; this situation is likely to be exacerbated by emerging climate change (Cobon *et al.* 2020*a*). A key issue affecting cattle productivity is the number of days in the year when pasture is green, which, according to a recent analysis, is affected more by the number of days of rainfall than by total precipitation because the latter is dominated by extreme events when most rainfall is lost as runoff (Brown *et al.* 2019). That study concluded that an ideal forecasting system would predict the number of rain days when the soil is dry; incorporate soil moisture content at the beginning of the wet season; determine the probability of an early break to the wet season; and establish the interaction of El Niño Southern Oscillation (ENSO) with other climate modes. The Northern Rainfall Onset (NRO) model has been used by the Australian Bureau of Meteorology since 2015 to predict the date when an accumulation of 50 mm of rainfall is reached after the beginning of September. More recently, the Bureau has developed a multi-week to seasonal model, ACCESS-S1, which became operational in 2018. A recent evaluation of this model found a significant improvement in its ability to forecast interannual variation in the NRO, with further improvements expected in the forecasting of high-frequency rainfall events as the wet season progresses (Cowan *et al.* 2020). The economic value of using more skilful and accurate forecasting models to set cattle stocking rates before onset of the wet season was assessed to be most important when pasture availability was low at the end of the dry season (Cobon *et al.* 2020*b*).

Reducing the impact of beef production on the rangeland environment

Optimising stocking rates for long-term productivity and sustainability

As discussed in the section *Feedbase management*, the setting of appropriate stocking rates is crucial to the sustainable management of northern rangeland agro-ecosystems to ensure long-term productivity as well as maintenance of land condition and biodiversity of native flora and fauna. Most of the studies that have demonstrated the economic and environmental benefits of moderate stocking rates have used cattle growth rate as the performance metric. Although it is unlikely that the general principles established by these trials, as reviewed by Hunt *et al.* (2014), will be different for breeding herds, there is a clear need for specific aspects, including optimal rates of pasture utilisation, to be integrated into recommended best management practices for northern breeding management systems. This is the central objective of a large modelling study currently under way aiming to relate cow performance datasets from 28 commercial properties across the Northern Territory and northern Queensland to predicted rates of pasture utilisation (Cowley *et al.* 2019).

Although not specific to breeding herds, the issue of drought management is likely to become an even more urgent priority with predicted changes in the climate of northern Australia. As recently discussed by Niethe and Holmes (2020), the key elements of a sound drought management plan should be preservation of native pastures and land condition.

Reducing the contribution of the northern breeding herd to greenhouse gas emissions

The contribution of the northern breeding herd to national emissions of greenhouse gases (GHG) and possible strategies to mitigate this likely source of global warming also need to be addressed. According to the latest Australian National Greenhouse Accounts (Australian Government 2022), enteric methane, mostly emitted by cattle and sheep, accounts for ~68% of agricultural GHG emissions and just over 9% of Australia's total GHG emissions. The contribution of the northern beef herd is not precisely known but is assumed to be substantial because of herd size (~58% of the national herd) and the fact that cattle grazing low-quality tropical grasses produce relatively large volumes of methane per kg DM consumed (Kennedy and Charmley 2012). Confidence in the ability to predict methane emissions from Australian cattle has been boosted by the derivation of a universal equation relating methane production to DM intake in dairy and beef cattle fed temperate forages and in beef cattle fed tropical forages (Charmley *et al.* 2016). It also should be noted that the current IPCC method for assessing the warming potential of enteric methane, based on a 100-year time frame (GWP100), results in values that are substantially greater than those estimated by the radiative forcing approach, which takes account of the short half-life of biogenic methane compared with that of GHGs derived from the combustion of fossil fuels (Ridoutt 2021).

Among the wide range of nutritional, pharmacological and immunological strategies to mitigate ruminal methane production that have been investigated in recent decades, by far the most promising are dietary inclusions of small amounts of *Asparagopsis* spp. (red seaweed) or a synthetic compound, 3-nitrooxypropanol (Eckard and Clark 2020; Black *et al.* 2021). These should be readily applicable to intensively managed dairy and lot-fed beef cattle. However, their suitability for extensive northern beef production systems will require the development of practicable feeding strategies such as inclusion in salt or molasses licks, or administration via slow-release rumen boluses. More modest reductions in methane production under tropical conditions have been observed in cattle fed the tropical legumes leucaena (Stifkens *et al.* 2022) and *Desmanthus* spp. (Suybeng *et al.* 2020), which should provide additional benefits such as increased plant and soil carbon sequestration (Radrizzani *et al.* 2011). In addition to the as-yet-unfulfilled potential of these strategies for reducing total methane emissions from individual animals, major benefits of increased reproductive efficiency and turnoff rates for reducing GHG emissions intensity have been predicted by comprehensive life-cycle analyses (Wiedemann *et al.* 2015) and substantiated by retrospective commercial case studies. For example, detailed analysis of the records of a leading breeding enterprise in the Barkly region of Northern Territory has shown that increases in weaning rate (46%) and annual liveweight turnoff (71%) and an 82% decrease in breeder mortality, which were achieved by managerial innovation and investment between 1981 and 2013, led to a 43% decrease in GHG emissions intensity (Walsh and Cowley 2016). However, these increases in productive efficiency enabled the property to increase carrying capacity and size of the breeding herd, thereby increasing total GHG emissions by ~50%. Therefore, advocacy of increased productive efficiency to reduce the carbon footprint of the northern breeding industry may need to be accompanied by incentives or disincentives to control animal numbers.

Other significant sources of GHG emissions from northern rangelands include deforestation and uncontrolled wildfires. Data on these sources are included in the Australian National Greenhouse Accounts (Australian Government 2022), but the likely major contributions of the northern beef industry are not specified, let alone those attributable to the breeding sector. However, the preponderance of breeding operations in the northern forests and savannas means that they should have an important role in the implementation of strategies to mitigate GHG losses from land clearing and wildfires. These could include limitation of clearing to the removal of woody regrowth and use of cool burning early in the dry season to reduce the likelihood of later, more intense and uncontrolled fires.

In addition to the mitigation strategies discussed above, northern breeding properties have the option of garnering credits by increasing carbon sequestration through reforestation of previously cleared land. If barriers to widespread establishment and maintenance of perennial tropical legumes such as leucaena and desmanthus can be overcome, graziers should be able to benefit from the development of new methods to measure increases in soil carbon content over space and time (Australian Government 2021).

Management and amelioration of environmental stressors

Heat stress

Genetic and non-genetic managerial options to combat heat stress in northern breeding herds have been discussed earlier in this section. Considerable research has been done on practical assessment of heat stress and the development of heat load indexes for intensively managed dairy cattle (Lees *et al.* 2018) and lot-fed beef cattle (Gaughan *et al.* 2008*b*). However, in their present form, these methods are inapplicable to free-ranging cattle in extensive pastoral systems. There is a clear need to develop techniques for remote monitoring of the animal and microclimatic variables needed for real-time calculation of heat loads in extensively managed breeding herds in northern Australia. Recent innovation of advanced and robust telemetric technologies makes this a more feasible objective than it would have been only a few years ago (Lewis Baida *et al.* 2021).

Weeds and pests

Breeding herds suffer loss of production through a range of weed and pest species, including disease agents. The impacts of several diseases are listed below as factors that contribute to reproductive wastage through failure to conceive, abortion, and death of cows and calves. The weeds, invasive animal species and diseases have impact on herd productivity in general, but are mentioned briefly here because under some circumstances they can impact breeding herd productivity. One example is land degradation by pigs, which is responsible for grazing land loss, gully erosion and silting waterways. Another is the potential for predation of calves by dogs, as discussed in the subsection *Calf mortality*.

Weeds, ectoparasites and arboviruses are additional factors that may impact breeding herds due to intoxication or disease in breeding animals. Problems caused by weeds, ectoparasites and arboviruses are likely to become more prominent in the future through the impact of factors such as transportation and climate change, which have already changed the geographic distribution of weeds and diseases.

Some weeds affect productivity by reducing access to food. In addition to outcompeting grass, thorny plants such as prickly acacia (*Vachellia nilotica* subsp. *indica*) are a particular problem when they grow in dense thickets and the scrub becomes impenetrable. Toxic plants such as *Pimelea* spp. can cause disease through ingestion of the toxin simplexin, which can be fatal.

The most economically important diseases of cattle in northern Australia are caused by cattle tick (*Rhipicephalus australis*) and buffalo fly (*Haematobia exigua*), together causing losses of $250 million per annum. Ticks are endemic north of a line near the Tropic of Capricorn and extending down the coastal regions of Queensland into northern New South Wales. They do not thrive in drier, central areas. Ticks also transmit tick fever, a potentially fatal disease. Brahman breeds and tropical composites have a higher natural resistance to ticks than *B. taurus* cattle and this partially explains why *B. indicus* breeds predominate in northern Australia. The increase in popularity of southern-sourced Angus bulls for cross-breeding means that more of those animals are at risk and need to be monitored for infection and treated. During years of heavy infestation, ticks may contribute to a 30% decline in conception rate of cows and an average decrease of 24 kg in calf weaning weight (Holroyd *et al.* 1988). Ticks are currently controlled by dipping animals with acaricide and enforcing quarantine zones to limit cattle movements. Quarantine lines are maintained at cattle yards on highways where dipping is mandated and along secure cattle fence lines. However, both approaches of control are under pressure, the former from emergence of acaricide resistance, and the latter from climate change that is allowing ticks to survive south of the quarantine lines. Climate modelling suggests that the number of ticks and their geographic extent is set to increase. Buffalo flies are endemic over a wider range than ticks, and both the range and intensity of infection increases in rainy years. Quarantine is of little use in restraining a flying insect, and so insecticidal treatments are a common practical method of control. The mouthparts of the fly pierce the hide of animals and cause pain; this 'fly-worry' reduces time spent feeding, leading to weight loss as well as hide damage. Buffalo fly is considered an animal welfare problem.

Arboviruses, including the bluetongue virus, cause disease with a range of impacts. In most years, bluetongue is a mild disease but its range expands in wet years when the range of insect vectors increases. The prime importance of bluetongue is that its presence creates a trade barrier whereby animals in a variable range of northern Australia are banned from live export to disease-free areas such as northern China. Climate change may also increase the chances of the introduction and spread of other insect-borne infectious agents such as lumpy skin disease.

Opportunities to increase adoption and productivity

General observations

The largest gap in delivering productivity gains in northern Australia is in translation of research through adoption of beneficial practices. In the context of breeding herds, an important step is to identify practices for which research has shown potential for a significant quantum of improvement, that are practical in their application, and that offer an attractive return on investment. The process of adoption should be underpinned by knowledge exchange, skills development, demonstration in the region, and the application of metrics and tools to demonstrate benefits, for example, on calf survival rates.

Successful adoption of novel technologies and practices has occurred at different rates in the industry, and many initiatives have taken a long time to achieve peak adoption. Some were top-down, such as the botulism vaccine and solar pumps with telemetric tank level monitoring, which were driven by commercial interests. Others were more organic and followed the efforts of pioneering producers. Examples are helicopter mustering, yard feeding of weaners and growing steers for live export.

Over time, MLA has invested in adoption and, in the process, has a developed a framework comprising five elements. Four of these are designed to demonstrate sequential improvements in producer engagement and sophistication; the fifth is an enabling initiative. They provide a range of service-delivery options that can be tailored to personal preference and needs, including:

- resource materials such as printed guides, decision tools, websites (e.g. Future Beef https://futurebeef.com.au/)
- awareness activities such as BeefUp Forums, which are also used to direct producers towards adoption opportunities
- short-term skills training courses such as the EDGE suite of programs
- participatory projects and mentoring activities, such as Producer Demonstration Sites and Profitable Grazing Systems courses offering benefit though groups of producers working together.

The enabling activity is intended to build livestock advisory capacity through advisor updates, training of new consultants, future consultant sponsorship and mentoring by experienced operators.

Nevertheless, rates of adoption have been slow and there is a need to identify and develop means to overcome barriers to adoption. Specific barriers are diverse and vary among individual enterprises and over time. They can be loosely classified as social, technical and financial. Whereas technical and financial aspects may be more easily defined, social aspects can be broad and complex, including default bias, education/understanding and time pressures. Such issues can only be addressed by application of social science skills and insights, which are outside the scope of this review. However, in the MLA report by Bell and Sangster (2022) from which much of the content of this paper is drawn, we offered examples of adoption of new practices and technologies by the northern beef industry, including perceived barriers to adoption. Several examples follow.

- Leucaena has proven benefits for cattle performance when grown in suitable geographic regions. Trial plantings have had variable success, affecting return on investment and the time delay for that return, so that the barriers to adoption are financial. Thus, a major objective of The Leucaena Network initiative has been to lower the financial barrier to adoption by sharing knowledge and collaborative producer support.
- Phosphorus supplementation in the wet season has clear financial benefits in areas of P deficiency. MLA has recently funded a Producer Demonstration Site to demonstrate benefits and 'ease' of feeding methods. This exposed that a critical barrier to adoption is the practicability of PiP testing to diagnose the P status of cattle and thereby aid decision-making. A resulting goal is to develop a simple, robust crush-side testing system. Modelling of the financial benefit of herd-level interventions for the Katherine region in Northern Territory suggest that benefits from P supplementation are likely to be greatest in the Northern Forest region, where there is widespread incidence of moderate to severe deficiency of P in its soils (Bowen *et al.* 2020).

- The potential benefits of remote feedbase monitoring on rangeland management are large. Past barriers to adoption were technical, arising from limitations to the system's predictive power. There is now an opportunity to sell the benefits and user-friendliness of more advanced systems by educating producers and advisors in the use of tools and addressing inadequate internet connections. This technology has potential benefits in all north Australian regions.
- Measurement and mitigation of environmental impacts on fertility, and demonstration of the benefits of intervention, are difficult and complex issues. Despite ongoing demonstration trials and model development, barriers such as implementation of changes in management, cost of building infrastructure such as fences and watering points, and the property-specific nature of possible changes will be difficult to overcome for many producers.

Research projects that have produced important data and insights into northern breeding herd management include:

- The Wambiana Grazing Trial, which has been running for >20 years and has provided valuable data on stocking rates and land condition across seasons including three droughts, as well as economic analysis of the enterprise. Major insights have been that excessive stocking rates lead to lower productivity and profitability over time and land condition also suffers.
- CashCow and the Beef CRC studies, which benchmarked breeder productivity metrics and identified risks associated with cow and calf mortality. Some interventions to improve survival rates and enhance breeder productivity have been prompted by these data including P-supplementation, feedbase management and heifer management.

The rest of this section considers future opportunities to improve adoption of R&D on breeding herd management, feedbase management and management of environmental sustainability.

Breeding herd management

Many of the potential gains in metrics such as pregnancy rates and mortality could be influenced by improvement in feedbase management as previously discussed. Research has shown that improving pregnancy rates can be tackled through breed selection and genetic improvement, especially bull selection. Genetic gain in the north has yet to take advantage of the new technologies that have been developed, including robust EBVs suitable for genomic testing in Santa Gertrudis and Brahman breeds, and those under way for Droughtmaster. Rapid and effective deployment of superior genetics through bull selection is an urgent requirement, and a plan needs to be promulgated. In addition, there is a direct adverse genetic effect of low birthweight, large teats and small udders on calf growth and survival (Bunter *et al.* 2014). Progress towards improved birth/weaning weight and teat and udder size as selection goals in cows is expected to be rapid because of the high heritability values for birth (0.48) and weaning (0.39) weights, and udder (0.49) and teat (0.38) scores. Genetic links to behaviour, including flight time and mothering score, as well as calf vigour traits were not found to be useful traits on which to base selection (Johnston *et al.* 2019). An important caveat for investment in genetic improvement of the northern breeding herd is the overriding imperative to ensure that feedbase management and thus, cow nutrition, is adequate to allow genetic expression of desirable reproductive and other traits.

Mitigation of calf loss can leverage the knowledge that is now available on risks. Studies on causation are under way as described above, and it is hoped that they will close the knowledge gap. Together, they will point to areas where improvement through reducing risks and removing causes can occur. The major research, development and adoption (RD&A) tasks ahead for the industry are in mitigation of calf loss through practical and cost-effective interventions. Interventions should be designed by considering several questions such as: are they researchable, is a large quantum of effect expected, are they practical to apply, is there a clear dollar benefit and return on investment, and do they also improve animal welfare? In terms of quantum, we have already noted (Table 4) that removing some individual risks may yield benefits of 3 or 4 percentage points across a region, and possibly more on a single property. A gap in research lies in demonstrating the return on investment that can be achieved so that the barrier of high infrastructure costs of changes in herd structure can be justified.

Examples of interventions that could have impact are:

- improving shade to reduce effects of THI and improve maternal effects
- smaller paddock size or shorter distance to water to reduce heat impacts
- herd management with a special focus on heifer management, but also managing older cow cohorts
- reducing the mating period to optimise feed utilisation and cluster calving times.

Practices to increase fertility and enhance pregnancy rates also provide opportunities to increase weaning rates. These parameters are linked to improved BCS and quicker return to oestrus, which themselves hinge on feedbase management, especially of the native pasture resources. Quantity, quality and timing are important aspects and, where financially viable, feeding supplements. A rising plane of nutrition, referred to as flushing, can also be used to induce ovulation. For some properties, the management of breeding focuses around the 'green date' when significant rain leads to a build-up of feed after onset of the wet season.

As discussed earlier, the issue of decision-making strategies for supplementation of breeding cows is complex and certainly not amenable to a 'one-size-fits-all' approach. Nevertheless, strategies to increase weight at mating and reduce time to return to oestrus in first-calf heifers should provide benefits of increased rates and better timing of conception in most cases. In particular, the benefits for delivering calves at the right time of year and not missing a season can have large impacts on weaning rates. We note that a recent modelling analysis predicted that supplementary feeding of heifers will provide little economic benefit to breeding enterprises across northern Australia (Bowen and Chudleigh 2021). This conclusion is inconsistent with conclusions of most empirical studies and industry observations, highlighting the need for further studies to endorse or refute the modelling predictions.

Feedbase management

It has been difficult to find a quantitative assessment of the adoption of advice to use moderate stocking rates based on long-term carrying capacity, despite the abundance of persuasive empirical evidence and the considerable efforts by researchers and extension specialists to demonstrate and disseminate the economic and environmental benefits of such practices. However, scientific leaders involved in these efforts concur that across the northern beef industry, the overall level of adoption has been disappointing (e.g. P. O'Reagain and D. Smith, pers. comm.). We do not purport to have the answers to this problem, which surely must be influenced by the complex array of factors that determine decision-making of primary producers, including logic, intuition and emotion (Nicholson *et al.* 2015). However, we believe that finding solutions to this challenge should be especially amenable to the facilitated small-group learning approach, particularly if groups include respected producers who have had long-term success with adoption of more conservative stocking rates (e.g. Landsberg *et al.* 1998). For example, for the NB2 initiative, a feedbase learning program has been prepared that includes a list of achievements expected of participating producers, such as ability to assess ABCD land condition, estimate groundcover percentage, and identify key pasture species, as well as other key skills related to feedbase and grazing management (D. Walsh, pers. comm.).

It is generally agreed that the realisation of opportunities for great improvement in the performance of breeding and growing cattle in northern Australia by including tropically adapted perennial legumes in native or sown grass pastures has not fulfilled the promise offered by many research trials and extension demonstrations. This applies particularly to leucaena, which has a passionate following among its protagonists in the scientific and production communities but has yet to be widely adopted by the industry at large. The multiple reasons for this disappointing level of adoption have been discussed in the earlier *Feedbase management* section (Buck *et al.* 2019*a*, 2019*b*), the principal of which are inadequate knowledge of the environmental and agronomic requirements for, and cost of, successful establishment and long-term maintenance of leucaena plantations. Clearly, exposure of producer groups to peers who have overcome these obstacles should help to overcome negative attitudes such as 'I'm a grazier not a farmer'. Relevant case studies include the positive experiences of North Queensland producers such as Don Heatley (Heatley 2019) and Brett and Theresa Blennerhasset (Meat & Livestock Australia 2020). However, exposure to these positive examples should be accompanied by financial literacy training and technical support to ensure that producers have (1) a clear view of financial risks and benefits, and (2) access to appropriate agronomic expertise. Some of the required tools and sources of advice are already publicly available; however, future provision of such assistance should be a significant opportunity for private consultancies.

Despite the considerable evidence that P deficiency is perhaps the most significant limitation to productivity of breeding and growing cattle in many parts of northern Australia, especially the Northern Forest region, the level of adoption of wet-season supplementation remains unsatisfactory (Bowen *et al.* 2020). Part of the problem appears to be lack of awareness of the substantial economic benefits of supplementing deficient animals despite evidence from case studies of commercial properties (e.g. Jackson *et al.* 2012) and regionally relevant modelling studies of long-term business productivity and profitability (Bowen *et al.* 2020). Identification of the needs of individual enterprises should lend itself to assessment of the benefits of P supplementation at the property level. This should begin with assessment of soil P levels, assisted by improved analytical and mapping techniques (Zund *et al.* 2022) and animal P status, preferably by blood collection and laboratory measurement of PiP levels (Dixon *et al.* 2020), followed by expert advice on supplementation strategy and assessment of responses. Development of a crush-side test for PiP would be an important innovation where access to preparation, refrigerated transport and remote laboratory analysis of blood is a serious limitation. The diagnostic data generated should then be used in benefit–cost ratio analyses for the enterprise in question. A specific practical issue that may require further technical development is the devising of effective strategies for feeding out P supplements during the wet season when P is likely to be the first limiting nutrient in cattle grazing abundant forages that provide relatively high levels of N and energy but are deficient in P. This might include design of home-made lick sheds, provision of online tools for calculating target P intakes and managing the cost of supplementation, and advice on training animals to eat supplements (FutureBeef 2021*b*). Recommendations should focus on feeding P for as much of the wet season as feasible, and offering some P during the rest of the year to replenish animal bone reserves.

Management of environmental sustainability

In this review, it has been convenient to discuss separately the R&D needs and gaps for management of the breeding herd, feedbase and environmental sustainability. However, the multifactorial influences on breeding herd performance and sustainability that cross over in all three areas are most apparent when considering environmental issues and management. For example, the need to match stocking rates to appropriately estimated long-term carrying capacity of native and naturalised pastures, discussed in the *Feedbase management* section, is of central importance to both animal nutrition and the environmental sustainability of rangelands. Likewise, goals for reduction in GHG emissions intensity can be addressed largely by changes in management to improve reproductive efficiency and turnoff rates. Also, aspirations for the genetic improvement of reproductive performance of the northern breeding herd need to be integrated with those for genetic improvement of heat tolerance and other aspects of environmental adaptability. Finally, management options to mitigate heat stress should be considered together with broader aspects of grazing management, such as spacing of watering points, paddock size, and provision of natural and artificial shade.

More specific opportunities to reduce impacts of environment on breeding herd performance include (1) technologies for remote assessment of effects of environmental stressors, especially heat, on animal physiology and production under extensive pastoral conditions; and (2) meteorological tools to predict climatic variation, including the occurrence of extreme weather events and the timing of wet-season onset. The technologies for remote assessment are still under development but producers should be made aware of the benefits of being able to gauge the status of their cattle remotely during extreme heat and other climatic events. Regarding meteorological tools, there has been recent, significant improvement in meteorological models to predict climatic variation, especially timing of the onset of the wet season (Cowan *et al.* 2020). Raising awareness of these tools and providing training in their operation could be considered as an example of 'low-hanging fruit' to promote their adoption.

Conclusions and recommendations

Guiding principles for research, development and adoption

The following points should be borne in mind when determining priorities for future funding of R&D and strategies for increasing adoption of new technologies and practices by the northern breeding industry:

- Increasing adoption of existing research outputs should be the highest priority and has the potential to deliver the quickest gains.
- Opportunities for participatory research involving producers should be central to all phases of the RD&A process, starting from identification of the problem through to delivery of the solution. This bottom-up approach will need to be complemented by guidance and scientific input from trusted researchers and extension professionals with intimate knowledge of the northern breeding industry.
- Partnership with private companies should be especially important for the ongoing development and adoption of technologies such as satellite monitoring of pasture availability and land condition, and remote sensing of cattle behaviour and performance. Future uptake of these promising technologies will require significant improvements in their ease of use, integration and demonstrated economic value, which should not be a high priority for public funding.
- Marketing-based approaches to address the differing needs and appetite for change of individual enterprises could include profiling producers, matching profiles to preferred communication methods, understanding work routines, and using appropriate mentoring and coaching techniques, including peer-to-peer influencing, to promote change. Meeting the needs of tech-savvy younger producers will present particular challenges and opportunities related to data analysis and management, and development of user-friendly decision-making tools.

Selected examples of research-driven adoption activities

In our recently published MLA report (Bell and Sangster 2022), we detailed selected examples of adoption activities in relation to research background, aims and potential, adoption plan and execution, measurement of success (or otherwise), and barriers to adoption. These examples were intended to illustrate possible approaches to extension and adoption of research findings rather than prescribe specific priority topics for adoption. They included:

- phosphorus supplementation in the wet season
- remote sensing technologies for feedbase budgeting
- planting of regionally suitable legumes to enhance nutrition of breeding cows
- genetic selection of polled cattle
- mitigation of environmental impacts on fertility and mortality.

Data for these examples were obtained from MLA project reports, including that of The Centre for International

Economics, AgStrat Associates Pty Ltd and ISJ Investments Pty Ltd (2016), and publicly available websites such as http://mla.com.au, http://futurebeef.com.au and http://genetics.mla.com.au. Where available, assessment of ex-ante and ex-post benefit–cost ratios were included.

Priority recommendations

The following six recommendations are intended to address priority needs, some of which could have short-term impact, whereas others, even if immediately adopted and implemented, will take longer to generate impact but do offer tangible benefits. They are not necessarily listed in order of importance because needs and applicability will vary among regions and individual businesses.

1. The goal of identifying and implementing appropriate and uniform metrics for assessing breeding herd performance is strongly advocated. This will be essential to the establishment of baseline data from which responses to changes in management can be measured and benchmarked against peer enterprises. Accurate measurement of herd performance is also essential to sound economic management and will be central to producer involvement in research activities.
2. Studies on the causes of calf and cow mortality should be continued to improve understanding of the linkages between risk, causation and death, and thus enable the design of interventions to break the linkages. This work should include field-testing of practical methods for electronic tracking of cow movement and behaviour, initially for research usage but with a goal of eventual commercial application for remote management of breeding herds. Interventions to mitigate calf loss should be designed with the following questions in mind:
   - Are they researchable?
   - What quantum of effect is expected?
   - Are they practical to apply?
   - Is there a clear economic benefit and return on investment?
   - Will there be publicly demonstrable improvements in animal welfare?
3. Strategies to promote the demonstrated economic and environmental benefits of sustainable grazing management practices should be the primary focus of work on feedbase RD&A. These should include the upskilling of producers to assess ABCD land condition, and to estimate pasture biomass and other key variables. Specific R&D priorities should include: (i) further development and deployment of tools for remote sensing of land condition, feed on offer and pasture growth rate, including iterative involvement of end users to ensure that the tools are user-friendly and clearly beneficial; and (ii) integration of the principles of sustainable grazing into best management practices for the northern breeding herd (e.g. MLA 'Sweet Spot' project).
4. Promotion of P supplementation in P-deficient regions/locations should be considered as a high priority example of 'low hanging fruit' because of the clear evidence of major, measurable effects and early impacts on breeding herd performance. Key elements of approaches to increasing adoption should include: (i) increasing awareness of, and access to, diagnostic tools for identifying soil/plant and animal deficiencies (an R&D objective could be development of a crush-side test for PiP); (ii) development and demonstration of practical and effective wet-season feed-out practices (e.g. MLA 'Easy P' strategy); and (iii) use of appropriate production metrics and economic analysis to demonstrate impacts on herd performance and profitability.
5. There is opportunity to broaden levels of adoption of research-proven management practices that have already been successfully implemented by segments of the breeding industry. These include:
   - controlled mating to enable seasonal breeding
   - evidence-based culling of older cows to reduce cow and calf mortality
   - early weaning to enhance cow fertility by reducing the duration of post-partum anoestrous
   - further development of supplementary feeding practices such as spike feeding to achieve target mating weights and reduce post-partum anoestrus.
   - Advertising of case studies such as those posted on the MLA website and use of commercial demonstration sites should be part of the process. For some practices, these should be accompanied by access to professional expertise to evaluate benefit–cost ratios and whole-farm impacts of changing specific management practices on individual properties. For example, a decision to introduce early weaning would need to be informed by understanding of the needs and capacity to feed adequately and otherwise manage younger calves, such as access to good-quality hay. On the other hand, development of general and specific guidelines for culling cows should be a high priority because the gains will be immediate and readily apparent.
6. Research, development and adoption of genomic selection to improve genetic traits such as reproductive efficiency, heat tolerance, tick resistance and polledness should continue to be a priority for the northern breeding industry. While there has been some impressive research success, the path to market and adoption of the genomic tools developed so far, and those yet to come, needs to be more clearly defined and implemented. For example, realistic modelling of anticipated rates of progress and economic benefits, especially for northern seedstock enterprises, should be a key element. Once again, this highlights the

imperative to collect and compile accurate data on animal performance.

Other recommendations

The recommendations listed below include additional, potentially positive opportunities for RD&A as well as advice on aspects that are not considered to warrant further industry investment at this stage.

7. Testing of approaches to herd management and risk assessment in the face of an increasingly variable climate should include development and dissemination of clear guidelines to aid decision-making for drought management. These should be accompanied by promotion of awareness and utilisation of increasingly robust tools for predicting important meteorological and climatic events such as timing of the onset of the wet season.
8. R&D on mitigation of heat stress in breeding herds should include development of tools for remote assessment of the physiological status of sentinel animals and benefit–cost analysis of various infrastructure options to provide shade and access to water.
9. Among the existing options to use tropically adapted perennial legumes to enhance the feedbase and improve nutrition of the breeding herd, the stylos, desmanthus and leucaena stand out, with each suited to different regions across northern Australia. Efforts to fulfil the potential of these legumes should include increasing producer awareness of both their productive benefits and potential challenges to their establishment and maintenance. Access to professional agronomic advice and demonstrations of successful adoption should be important components of this work.
10. There are few compelling data that suggest further investment in animal disease research or control of predators will significantly benefit the northern breeding industry. Therefore, such work should be a lower priority.
11. Development of practical methods to reduce ruminal methane production with efficacious dietary additives is warranted. Also, awareness of the win–win benefits of improved reproductive efficiency and increased turn-off rates on emissions intensity at the herd or enterprise level should be emphasised and promoted.

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