Final report

Needs and gaps analysis for NB2

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Prepared by: Alan Bell, Nick Sangster

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Meat and Livestock Australia Limited
PO Box 1961
NORTH SYDNEY NSW 2059

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Abstract

This report reviews existing Australian and appropriate overseas research and development (R&D) material to identify needs and gaps that are directly relevant to the Northern Breeding Business (NB2) program. Material reviewed includes the peer-reviewed literature, as well as industry reports and other relevant publications in three targeted areas of R&D: breeding herd management, feedbase management, and management of environmental sustainability; a fourth section on pathway to practice focuses on barriers to adoption of research-proven technologies and practices, using specific examples to identify possible avenues to overcome these barriers. The final sections summarise conclusions drawn from the needs and gaps analysis and offer specific recommendations on R&D needs and priorities; adoption targets, systems and capacity; and options for NB2 delivery.

The present report is not a replacement for sources of information such as printed or online material or expert advice that focus on farm management and financial planning or decision-making.

Executive summary

The purpose of this report is to audit and evaluate the present state of knowledge in three areas of R&D deemed by industry leaders and supporting scientists to be important drivers of productivity and profitability for northern beef breeding businesses: breeding herd management, feedbase management, and environmental sustainability. A fourth section on pathways to practice addresses barriers to adoption and identifies possible avenues to overcome these barriers. The report was commissioned to assist the planning of work and identification of gaps relevant to the NB2 strategic partnership between industry participants and multiple providers of research, development and adoption (RD&A) for the northern beef sector, sponsored by Meat and Livestock Australia (MLA).

Breeding herd management

The findings of four major surveys of breeding herd performance in northern Australia, conducted since the late 1980s, suggest that overall performance, as indicated by calf branding rates, has improved little during the past 30 years. The most recent and comprehensive survey is the CashCow study by McGowan *et al*. (2014), which reported weaning rates of 72-77% in three of the four regions surveyed (Southern Forest, Central Forest, Northern Downs) but only 53% in the harsher Northern Forest region. Regardless of historical trends, if the commercially achievable level of performance is represented by that of the 75th percentile of cows, as proposed by McGowan *et al*. (2014), there is ample room for improvement in most indices of breeder performance across northern Australia.

Wide variations in environmental conditions and management practices present challenges to the consistency and accuracy of data collection. We have tabulated a range of physical measurements that should be used to derive metrics that describe breeding herd productivity. Among the most useful metrics is weaning (or branding) %. These measurements should be practical to the situation, collected in a timely manner and recorded with individual animals identified by NLIS tags and linked to crush-side data capture systems.

Genetic improvement of reproductive performance of northern herds has been limited by difficulties in recording appropriate metrics (see above) and slow responses to selection related to low heritability of key production traits such as lifetime weaning rate. However, Beef CRC research has identified underlying component traits that have moderate to high heritabilities, especially age at puberty and length of post-partum anoestrus interval in 3-year-old cows which are captured in the estimated breeding value (EBV) for days to calving. Subsequent and ongoing work in the MLA-funded Repronomics™ project aims to greatly enhance application of these findings by developing genomics-enhanced BREEDPLAN evaluations for the most numerous tropically adapted beef breeds used across northern Australia. A key industry objective is to greatly increase adoption of these tools by demonstration of their positive impact in selected seedstock and commercial breeding enterprises. Even though the time to impact is several years, incorporation of genetic improvement into farm and adoption plans in NB2 is essential.

The physiological components of reproductive wastage include fertilisation failure, early and later embryo mortality, and fetal mortality during later gestation. Avenues for improvement include puberty management, nutrition, genetic selection and disease management. However, reduction of neonatal and later calf mortality appears to offer the greatest potential gains in overall reproductive performance. Risk factors for calf mortality include calf factors (sex and birthweight) and maternal factors (breeding status, teat and udder scores, age, breed, nutrition (especially phosphorus (P) deficiency). A major challenge for the development of intervention strategies to reduce calf mortality is identifying the time and location of birth, and subsequent physical and behavioural events. Various technical options for remote surveillance of cows and calves are presently under development.

Rates of cow mortality can be as high as those of calf mortality and represent a largely hidden issue for the industry with both large financial impacts and animal welfare-related risks. Major contributing factors include cow age (especially heifers and aged cows) and body condition score (BCS), with opportunities to alleviate by separate nutritional management of heifer, nutrition to increase BCS of older cows, and culling for age, bottle teats and failure to raise a calf. Implementation of these practices are also likely to have positive outcomes for calf survival.

Feedbase management

Grazing management to optimise (not maximise) pasture utilisation is critically important for the sustainable productivity of the northern feedbase. Numerous long-term studies have established the principles of sustainable grazing management, with cattle growth rate the usual performance metric. However, a current modelling study, using data from 28 properties across northern Queensland and the Northern Territory, is relating breeding herd performance to levels of pasture utilisation. Another ongoing, MLA-funded project is assessing the influence of paddock size and distance to water on the reproductive performance and calf wastage in beef heifers on commercial properties in the Barkly Tableland and north-western Queensland. Its goal is to develop a user-friendly spreadsheet tool to enable producers to compare benefits and costs of different infrastructure options. A recently completed project also evaluated feed-rewarded self-herding to modify the grazing behaviour and distribution of breeding herds, with promising results. Nevertheless, overgrazing, including by breeding herds, remains a widespread problem in the north and demands innovative approaches to convince herd managers of the long-term economic, as well as environmental, benefits of moderate stocking rates. Refinement of affordable, user-friendly technologies for remote monitoring of the feedbase, as well as training in economic evaluation of grazing management outcomes, should be part of the toolkit.

The northern feedbase depends heavily on native perennial C4 grasses growing in a range of semi-arid to tropical savanna environments characterised by poor soils and wide variation in rainfall within and between seasons. To a varying extent this has been augmented by introduction of exotic grasses (e.g. buffel grass) and legumes (e.g *Stylosanthes* spp, leucaena, *Desmanthus* spp).

Buffel grass continues to be a highly valued and dominant component of pastures in central and southern Queensland but decreased productivity due to progressive decline in available soil nitrogen (N) is an identified problem. The most obvious solution is the inclusion of adapted perennial legumes to increase soil N through N fixation, as well as to offer additional nutrition to grazing cattle.

Stylosanthes spp are the most widespread tropically adapted legumes used in northern Australia, especially on lighter soils. Anthracose disease, which devastated the widely used Townsville stylo in the 1970s, continues to be the focus of breeding trials to identify fungus-resistant stylo varieties. Despite decades of research and demonstrations of large productivity gains, the adoption of the highly nutritious tree legume, leucaena, has been limited by lack of awareness of or confidence in the plant's productive potential and inadequate knowledge of the environmental and agronomic requirements for, and costs of, successful establishment and management. Additional factors include susceptibility of the most widely used cultivars to psyllid insects, especially in more humid regions, and environmental concerns about the potential weediness of leucaena in native ecosystems. Each of these issues and concerns has demonstrated or potential solutions, discussed in this report, with communication to and support of producers being the major barrier to adoption.

Neither the stylos nor leucaena are suitable for use in the vast areas of heavier clay soils in the northern rangelands. Progardes™, a composite blend of five cultivars from three *Desmanthus* species, is showing promising results under these conditions. However, as with leucaena, establishment of desmanthus in grass-dominant pastures has presented challenges.

Much of the northern feedbase is typified by progressively increasing N deficiency as pastures dry and mature during the dry season and P deficiency that is exposed by increased availability of N and energy during the wet season. Supplementation of N in the form of various high-protein feed sources has been found to be efficacious in growing heifers but is limited by cost and availability compared to the non-protein N source, urea. In wetter regions, the use of well-adapted, perennial legumes, especially leucaena, should be considered as a first option to redress the impact of N deficiency on breeding herd performance. Fertilisation of P-deficient pastures is not economically feasible on most extensive northern breeding properties, leaving direct animal supplementation as the only viable option. Numerous studies have demonstrated dramatic responses in animal performance, including reproduction, to P supplementation in regions with moderate to severe soil P deficiencies, with substantial economic benefits. Nevertheless, adoption of P supplementation has been relatively low due to lack of clear definition of the problem on individual properties, limited access to tools for physical measurement and economic evaluation of the impact of supplementation, and availability of effective strategies for feeding P supplements, especially during the wet season.

Environmental sustainability

A broad definition of sustainability of beef production enterprises includes social and economic, as well as environmental, aspects. In this report we have focused on the latter while acknowledging the importance of the former aspects in the context of the Australian Beef Sustainability Framework.

Anticipated changes in the climate will accentuate the need to further enhance the resilience of pasture plants and grazing animals. Limited evidence suggests that increased levels of atmospheric CO_2 may favour the growth of C4 grasses over that of C3 plants in the north, with positive implications for biomass production but negative consequences for forage quality and the successful establishment and maintenance of C3 legumes.

The negative effects of heat stress on multiple aspects of female and male reproduction will increase the need to enhance the heat tolerance of northern breeding herds, and investigate feasible options for mitigation of the effects of high ambient temperatures and extreme weather events. It has been shown that genetic selection for heat tolerance is likely to be associated with improved reproductive performance. Non-genetic management options for mitigating heat stress include provision of natural and(or) artificial shade and ensuring adequate water supply.

Challenges to management of the risk of variation in the onset, intensity and duration of the summer wet season are likely to be exacerbated by climate change. Recently, the Bureau of Meteorology has significantly increased its ability to forecast interannual variation in the onset of the wet season, with further improvements anticipated for the forecasting of high-frequency rain events as the wet season progresses.

Impacts of beef production on the rangeland environment include the negative effects of overstocking on land condition, biodiversity and, ultimately, long-term productivity of northern pastoral systems, as discussed above, as well as contributions of enteric emissions of methane to greenhouse gas (GHG) emissions. The precise contribution of the northern breeding herd to national GHG emissions is not known but, based on animal numbers and feed-based predictions, is estimated be about half of total enteric methane emissions i.e. 4-5% of total GHG. Feeding legumes such as leucaena and desmanthus has been shown to reduce individual animal methane emissions. However, these options for mitigation will be much less effective than the positive effects of improved productive efficiency, including increased weaning rate and reduced cow mortality, on GHG emissions intensity, and, as long as herd sizes do not increase, total emissions.

Environmental stressors affecting the breeding herd include not only heat stress, discussed above, but a range of weed and pest species, including disease agents. Most of these do not specifically target breeding herd performance, with exceptions being the debatable effects of dog predation on calf mortality and the effects of specific arboviruses on early embryo and fetal mortality. Nevertheless, large numbers of breeding animals are negatively affected by toxic plants such as Pimelea and most importantly, diseases caused by cattle tick and buffalo fly ectoparasites.

Pathway to practice

This section addresses the widespread belief among northern beef industry leaders and scientists that adoption and successful implementation of new practices remains a problem.

Extension strategies have been categorised as: (i) top-down technology transfer; (ii) bottom-up participatory approaches; (iii) one-to-one information exchange; and (iv) formal or structured training. Factors that negatively or positively influence adoption are used as the basis for questions in the CSIRO's web-based ADOPT tool.

Most extension providers serving the northern beef industry have, in the past, employed a 'top-down' model, with patchy success. In contrast, the NB2 program, through its Pathway to Practice (P2P) project, proposes to develop a more participatory approach that will enable producers to identify and solve problems specific to their individual enterprises. Once problems have been identified, solutions can be considered and possibly implemented with the aid of expert facilitators and peer coordinators. A recent, successful example of this approach is the RMPP Action Network which serves New Zealand's red meat sector.

Principles outlined above are included in the MLA framework for adoption activities, including awareness, short-term training courses, longer-term training to effect practice change, use of adoption enablers and participatory research.

The rest of the P2P section considers possible solutions to issues raised in the previous sections that may be amenable to various different approaches to increase levels of adoption. This list of topics is neither prescriptive nor comprehensive and is intended to serve simply as an example of items that might be identified and addressed by P2P participants.

Conclusions

It is clear that the urgent, successful adoption of scientific innovation conducted in a focussed and coordinated way is the primary means of improving the productivity of northern beef breeding enterprises. Adoption of existing scientific knowledge and research that can quickly be made adoption-ready is the highest priority. There is still a need to research further innovations and, wherever possible, this should be conducted as participatory research, involving engagement of producers at every step, starting from identification of the problem through to delivery of the solution.

The elements of adoption should include focus on attainable goals such as reducing cow and calf mortality achieved by applying better understanding of feedbase, environment and herd factors. The process should work within the current adoption structure at MLA. This is both efficient and ensures longevity of the program. It also takes advantage of the adoption elements that MLA supports, including training farm consultants with experience in northern Australia. While there are industry-wide targets, NB2 has sensibly decided to focus effort on a subset of 250 producers and apply aspirational targets to these properties.

Coordination is required on at least two levels. First, the NB2 structure provides a system to standardise data collection, refine sources of information such as best practice guides and provide practical decision tools. Second is to bring all of the adoption options to the table so that they can be part of a whole farm plan coupled with financial metrics. Absent from the mix is incorporation of genetics. While genetics has potential to deliver gains it is disconnected from other core management options.

The rate and impact of adoption has been disappointing for many reasons and this calls for a change in approach. Exploring techniques used in marketing and advertising, which also attempt to effect change, is worthwhile. For example, this may help to identify how producers prefer to receive their information, what barriers to change exist, who they listen to or who they take advice from.

Finally, the widespread lack of access to experienced, competent advisors is identified as a critical unmet need of the northern beef industry. It is suggested that NB2 could provide an initial platform to promote the training, regional embedding and career development of new advisors that should continue to be supported by MLA after NB2 .

Recommendations

The following six recommendations are considered as priorities that may vary in importance across regions and between individual enterprises:

1. The NB2 goal of identifying and implementing appropriate and uniform metrics for assessing breeding herd performance is strongly endorsed. 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.
2. Studies on the causes of calf and cow mortality should be continued to better understand the linkages between risk, causation and death, and thus enable the design of interventions to break the linkages. 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, including (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. Involvement in a current project on remote sensing of feed on offer could be a particular opportunity for all producers taking part in the NB2 initiative.
4. Promotion of P supplementation in P-deficient regions/locations should be considered as a high priority 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. Easy P strategy), and (iii) use of appropriate production metrics and economic analysis to demonstrate impacts on herd performance and profitability.

5. Opportunities to broaden levels of adoption of research-proven management practices 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 likelihood of post-partum anoestrous.

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 longer-term priority for the northern breeding industry. However, the path to market and adoption should be better defined, including prerequisite needs for record keeping skills and commitment, and ensuring that levels of animal nutrition and management are sufficient to allow genetic expression of selection traits.

Abbreviations

2,3-DHP	2,3-dihydroxypyridine
3,4-DHP	3,4-dihydroxypyridine
ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ADOPT	Adoption, Diffusion, Outcome, Prediction Tool
AE	Adult equivalent; the standard animal unit measure used in northern Australia, equivalent to a 450 kg steer at maintenance
ATFC	Australian Tropical Forages Collection
BCR	Benefit-cost ratio
BCS	Body condition score
BW	Body weight
C3 plant	A plant in which carbon dioxide is first fixed into a compound containing three carbon atoms before entering the Calvin cycle of photosynthesis
C4 plant	A plant in which carbon dioxide is first fixed into a compound containing four carbon atoms before entering the Calvin cycle of photosynthesis
CF	Central Forest
CL	Corpus luteum
CLEM	CSIRO Crop Livestock Enterprise Model
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAFWA	Department of Agriculture and Food, Western Australia
DM	Dry matter
EBIT	Earnings before interest and tax
EBV	Estimated breeding value
ENSO	El Niño Southern Oscillation
GHG	Greenhouse gas(es)
GPS	Global positioning system
ME	Metabolisable energy
MLA	Meat and Livestock Australia
N	Nitrogen
NABRC	North Australia Beef Research Council
NB2	Northern Breeding Business
ND	Northern Downs
NF	Northern Forest
NLIS	National Livestock Identification System
NPN	Non-protein nitrogen
NRO	Northern rainfall onset
OR	Odds ratio
P	Phosphorus
P2P	Pathway to practice
P4M	Percentage of cows pregnant with four months of calving
PDS	Producer demonstration site(s)
PGS	Profitable Grazing Systems (course)
PiP	Plasma inorganic phosphorus

R&D	Research and development
RD&A	Research, development and adoption
RDC	Research and Development Corporation
RDE&A	Research, development, extension and adoption
RMAC	Red Meat Advisory Council
RMPP	Red Meat Profit Partnership (New Zealand)
ROI	Return on investment
SF	Southern Forest
TCOMP	Tropical composite (cattle)
THI	Temperature-humidity index
TLN	The Leucaena Network
WOW	Walk over weighing

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1 Background

The northern Australian beef industry is located in Queensland, Northern Territory and the Pilbara and Kimberley regions of northern Western Australia. It is comprised of production enterprises that account for about 64% of Australia's national beef herd of approximately 23 million head of 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 approximately $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 management of natural resources across about 60% of the land base of northern Australia, in addition to management of their beef enterprises.

As recently described (Greenwood *et al*. 2018; 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 C4 grasses and few legumes, and widespread P deficiency. This limits cattle growth rates and carrying capacity, necessitating large-scale extensive operations with 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 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.

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 recent 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, these authors also have 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), respectively) (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

These profit drivers were ranked in the following 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 indices 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 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 in Queensland and the Northern Territory for more than 40 years (Figure 1; ABARES 2019). A small upward trend in branding percentages occurred in the late 1980s and early 1990s but the pattern of change has since flattened with a range between 60 and 75%. Year-to-year variation is especially notable.

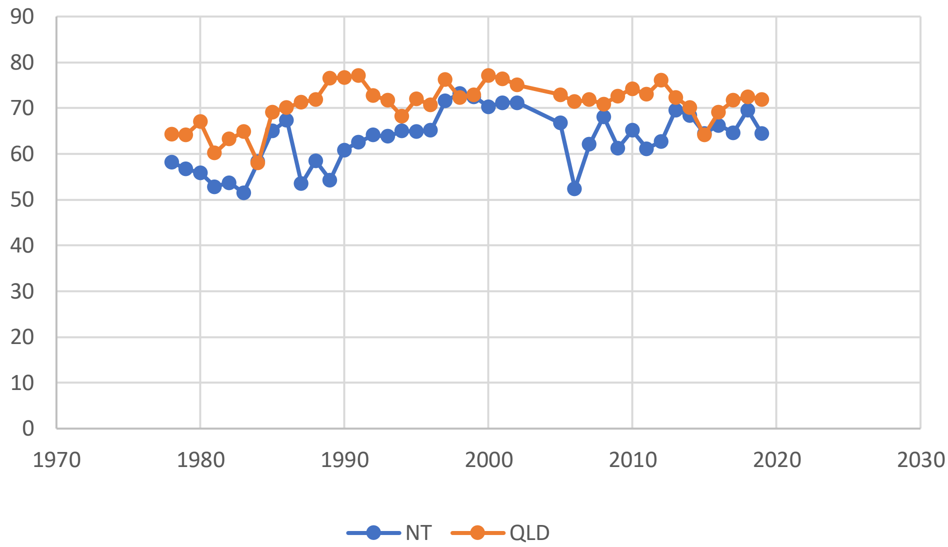

Figure 1. Branding rates in the Northern Territory and Queensland between 1977 and 2019 (adapted from ABARES, 2019).

This report will audit and evaluate 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: breeding herd management; feedbase management; and environmental sustainability. A fourth major section, entitled "pathway to practice", will specifically address barriers to adoption and offer possible avenues to overcome these barriers. The review was conceived as a necessary prelude to commencement of the Northern Breeding Business (NB2) strategic partnership between industry participants and multiple providers of RDE&A for the northern beef sector, sponsored by MLA. The background, vision, objectives and work plan for this initiative are detailed by Fitzpatrick (2020).

Ranking of potential investments and initiatives to improve productivity has not been undertaken in this paper because the basis of any ranking varies over time, location and management. Funding proposals by agencies such as MLA typically contain ex-ante benefit cost ratios (BCR) of the research which is the ratio of investment costs against industry benefits. Such ratios are to support funding decisions and not farming decisions. On-farm implications are not understood until after adoption has occurred and the real inputs and outputs measured. In practice, benefit may be calculated as a Return on Investment (ROI) from trial data collected from commercial farms or from Producer Demonstration Sites (PDS), which are sponsored by MLA, or from controlled trials on research farms. In addition to productivity outcomes, some trials should apply a financial lens to calculate ROI. Results are highly variable because parameters include differences between seasons, pasture quantity and quality, and animal management, as well as infrastructure costs, variable costs and market values. Generalised data of this sort are rare. In the final section of this report a number of adoption examples are described and, where available, the inputs and outputs that contribute to the variability of the ROI are cited from published studies. In addition, we provide details from two longitudinal studies (CashCow and Beef CRC) that quantify industry risk factors for calf loss. This knowledge can be used within NB2 to guide what farm data are important to collect and how they can be applied in farm trials. It follows that the solutions that are appropriate across such a vast and varied industry will be region- and even farm-specific.

2 Breeding 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 appreciation of their ability to survive and produce in challenging tropical environments. However, this initiative became tempered by growing 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*. 2021a). 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 discussed, with a particular focus on R&D needed to understand and reduce causes of calf mortality.

2.1 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 the CSIRO (Bortolussi *et al*. 2005b).

The earliest of these (Holroyd and O'Rourke 1989) was a collation of data from 76 research reports on studies conducted at 146 sites between the early 1960s and late 1980s. Study sites included numerous commercial properties as well as government research stations, in 16 defined regions across Queensland, the Northern Territory and northern Western Australia. These data 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 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 head of cattle. A total of 2,165 usable replies was received, representing 33% of the more than 6,540 properties contacted, and 41% of the cattle numbers reported for northern Australia by the Australian Bureau of Statistics in March 1989. The data provided were analysed on the basis of 14 regions that closely resembled those defined by Holroyd and O'Rourke (1989). The key findings, which are a reflection of the industry at that time, were that on surveyed properties:

- *Bos indicus* genetics were predominant
- Most properties employed year-round mating
- Branding rates were 55-70% (mean 63%)
- Most carried out weaning and half of properties weaned calves down to <6 mo. (150 kg)
- Bull culling rates were low with rates between 10 and 25% being common
- Calving was common in 2-year-olds, but generally delayed in Brahmans
- Most retained <50% heifers, but on extensive properties nearly all were retained
- Culling occurred on temperament, conformation, age, negative pregnancy test or producing a poor calf
- Producers desired technology transfer to improve methods of selective breeding

- While most producers saw value in superior bulls many retained bulls for >5 years and culled based on conformation rather than performance

This survey produced the best snapshot to date of breeding management and other aspects of the northern 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 next survey of northern breeding herd performance and management was conducted in 1996 and 1997 by Bortolussi *et al*. (2005b), and reflected growth in live exports since the previous report. As detailed by Bortolussi *et al*. (2005a), the survey population consisted of 375 properties in 8 regions covering most of the 14 regions defined by O'Rourke *et al*. (1992). However, the Peninsular portion of north Queensland, south-east coastal Queensland and the Darling Downs regions in Queensland were excluded, as were the Alice Springs, Arnhem, Gulf and Tennant Creek districts of the Northern Territory, due to their relatively small cattle numbers or little involvement in live export markets. 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*. (2005a).

Mean branding rates during the 5 years preceding the survey were <65% in the northern regions of Queensland, the Northern Territory and Western Australia. Rates were >70% in all other regions and highest in the more southerly regions of Queensland. Despite harsh seasonal conditions experienced during the survey period, all regions had a trend for higher branding rates than those reported by O'Rourke *et al*. (1992), particularly in the most northerly districts. Reasons suggested for this improvement included: increased vaccination of breeders for botulism and other diseases; increased adoption of ≤4 months as a minimum weaning age; increased use of culling for reproductive performance; high use of pregnancy testing; increased supplementary feeding of N+P during the dry period or year-round; lowering of age at first calving; and increased adoption of controlled mating (Bortolussi *et al*. 2005b).

Another feature of this report was that branding rates of >85% were reported from central and southern Queensland. These data were associated with a high proportion of *Bos taurus* cattle selected for high fertility (O'Neill *et al*. 2000) and again are not representative of the whole industry.

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 northern Australian beef herds was the CashCow study (McGowan *et al*. 2014; McCosker *et al*. 2021a; McCosker *et al*. 2021b). This study reported on ~78,000 cows managed in 142 breeding mobs on 72 commercial properties across four types of country: Southern Forest, Central Forest, Northern Downs and Northern Forest. Measurements were made using a crush-side electronic data capture system over three to four consecutive years during 2008-2011. Key measured variables were: percentage of cows pregnant within four months of calving (P4M); annual pregnancy rate; percentage of fetal/calf mortality; percentage of cows contributing a weaner; and annual percentage of pregnant cows missing (an estimate of mortality rate). For each of these performance measures, the influence of around 83 selected management, environmental, nutritional and infectious disease factors was assessed by univariable screening. Factors having a significant effect on performance were then used to develop candidate multivariable models to evaluate identification and quantification of the major factors influencing reproductive performance. Weaning rates in this study averaged 70%.

The survey data discussed above also have 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 between the studies of O'Rourke *et al*. (1992), Bortolussi *et al*. (2005b), Bunter *et al*. (2014) and McGowan *et al*. (2014). This point is reinforced in a recent meta-analysis of reproductive wastage (Chang *et al*. 2020a), which considered 43 articles on wastage published between 1936 and 2014. The meta-data 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), it is clear that, regardless of historical trends, there is ample room for improvement in most indices of breeder performance across northern Australia.

2.1.1 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 between regions and the extreme of the Northern Forest which is detailed in the following section. The other three regions are each quite similar in rates for 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 % from annual pregnancy rate %). As expected, these estimated values are similar to or slightly less than reported values for weaner contribution and, considering differences between surveys in definition of regions or country type, not markedly different from the values for branding % reported by Bortolussi *et al*. (2005b). Liveweight production per cow is cited here as an enterprise measure of breeding herd productivity.

Table 1. Median values for reproductive performance of all cows by country type. Source: McGowan *et al*. (2014)

Measure	Southern Forest (SF)	Central Forest (CF)	Northern Downs (ND)	Northern Forest (NF)	*Overall*
P4M *(%)	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*

*Pregnant within 4 months of calving

2.1.2 Northern Forest – nature's extreme

The Northern Forest (NF) 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 NF represents the environmental extreme typified by a natural 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 NF is typified by low stocking rates, large properties (top 25% of sampled properties: NF, 11, 000 to 22,000 AE, compared with other regions, 1100 to 6800 AE), 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), NF has the lowest values for: P4M (15%), pregnancy rate (66%), and % of 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 NF at 89 kg per cow retained. While the top 25% of NF properties sampled are superior to the NF median in every metric, each is worse than the median in all other regions. The NF 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 NF. 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. The environment best suits cattle with predominantly Brahman content as other breeds do not thrive. Comparisons in the performance of Brahmans versus Tropical Composites (TCOMP) have not been conducted in NF due to the low number of TCOMP cattle, but in the other three regions the mean P4M difference between cows with <50% and >75% *B. indicus* content was significantly lower by 17.6% points (68.3 and 50.7, respectively). Beef CRC research showed that Brahmans take longer to develop the first corpus luteum (CL) (mean 751 d) compared with TCOMP (mean 651 d). In the second breeding season, Brahman herds, compared with composite herds, had lower pregnancy rates (59% vs 76%), longer lactational anoestrus interval (LAI) (134 vs 84 d) and longer days to calving (363 vs 344 d) compared with TCOMP (Johnston *et al*. 2009). In NF, breed factors predicated by the environment lead to fewer herd pregnancies.

It is assumed the higher rate of median calf loss (12.9%, Table 1) in NF is also associated with the environment and the constraints to management placed on properties under these conditions. In a further example, unlike other regions, in NF herds fetal/calf loss is unaffected by high or low temperature-humidity index (THI) but the effect in increasing calf loss may be because high THI is sustained over time and only falls below 79 for the three winter months each year. The meta-analysis of Chang *et al*. (2020a) calculated a mortality rate of 21.6% (compared with 12.9% in CashCow). Possible reasons for this discrepancy are (i) the CashCow data are a more contemporary assessment since the widespread introduction of Brahman cattle, and (ii) the selection of properties and (necessary) human interventions during conduct of the CashCow trials may have led to improved herd performance.

The NF environment clearly constrains production. However, despite the challenges of cattle production in the harsh NF environment, a business comparison across the northern Industry concluded that the financial performance of properties in this area follow the broader industry pattern (Holme*s et al*. 2017). For example, mean earnings before interest and tax (EBIT) of the top 25% properties in the NF (4 to 8.6 $/AE) were in the same range as those in other areas of the north (3.6 to 9.7 $/AE).

2.2 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 NB2, the major focus is on the breeding females in the herd and their calves. Examples include herd data (numbers, weights, BCS of each sex and age class) at particular times (weaning, branding, weaning, 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) was largely addressed in the CashCow project (McGowan *et al*. 2014; McCosker *et al*. 2021a). The ABARES data collection framework is also standardised.

Table 2 gives examples of the most commonly used physical measurements that can 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 report. It is worthwhile noting that weaning (or branding) % is the most useful single variable for 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.

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

Type and name	Definition	Purpose
Physical data		
Body mass	Liveweight in kg. Individual or presented as herd x type average	Weight gain, target weight for breeding. Measure with scales, girth tape.
Body condition score	5 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)	% herd pregnant.
Lactation	Udder full at branding or weaning	Equates to % 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 to 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		
Annual weaner live wt	kg	Individual or herd basis.
Weaner production	kg/cow/year	Live weight 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 of cattle	
P4M	% pregnant within 4 months of calving	Used as denominator of calf loss % (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 (EBV)		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.

Data capture should be practical to the situation, collected in a timely fashion, recorded and, as appropriate, acted upon. 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 coupled to weigh bars. Results such as pregnancy diagnosis and BCS should also be entered into a data system. Subsequent analysis is achieved through downloading records and processing through management software. The use of remote data capture is becoming feasible for some data and these developments are covered below under 'Remote Systems'.

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

- Bull semen and soundness evaluations to ensure successful mating by bulls.
- Measuring plasma inorganic phosphorus (PiP) to assess 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, purchase of bulls with known EBVs chosen to meet productivity goals.

2.3 Challenges and opportunities for genetic improvement of reproductive performance

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. Also, 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 breeds (Schatz *et al*. 2010), as has the practical experience of astute and well-informed producers (e.g. Anon 2011). Recently, the genetic bases for these outcomes have become much better understood through research conducted by the Cooperative Research Centre (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*. (2009a; 2009b) and Johnston *et al*. (2009). Briefly, genetic evaluations of reproductive performance were based on data collected from 1020 Brahman and 1117 TCOMP females that were generated over 4 years at eight cooperating properties. At weaning, heifers were allocated to one of four Queensland research stations that represented a range of northern Australia breeding environments. There they were initially mated in natural service multiple-sire groups to calve at 3 years of age, remaining in the study until calves from their sixth pregnancy were weaned, except for the culling of cows for consecutive weaning failure, poor temperament or acquired physical conditions. In addition to the rigorous collection of data on reproductive outcomes, regular ultrasonic scanning of cows' ovaries was performed from the start of mating until calving commenced, to determine the presence and size of CL and follicular dimensions.

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 TCOMP, respectively (Table 3; Johnston *et al*. 2014a). However, component traits of early reproductive performance had moderate to high heritabilities, especially in Brahmans. These included age at puberty as determined by age at first observation of a CL (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*. 2014a). Importantly, genetic correlations between early-in-life measures and lifetime traits were moderate to high, particularly that between post-partum anoestrous interval and lifetime annual weaning rate (Table 3; Johnston *et al*. 2014a). These results highlight an important opportunity to genetically improve 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 TCOMP 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*. 2014b). Semen quality traits were genetically correlated with 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 indices may indirectly help improve female reproduction in tropical breeds.

Table 3. Heritabilities 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 (estimated values ± approximate standard errors).

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

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 research stations, respectively located in central and northern Queensland, and the Northern Territory. 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 so far have focussed 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 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 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 more than 3,300 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 CL (Engle *et al*. 2019).

2.4 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 reproductive inefficiencies that 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 %) not having changed in northern Australia during the last 30 years (Figure 1; ABARES 2019).

Fertilisation failure can only be assessed through analysis of oestrus cycle components, but 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 be 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) are in the range 2-8%.

In commercial herds, fertility and embryo/fetal losses are difficult to measure, but 1 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 10% is the minimum effect, a level which is common internationally (Burns *et al*. 2010).

Opportunities for improvement are through puberty management, nutrition (rising plane to initiate ovulation), genetic selection and disease management. In many cases these factors are fixed or slow to change, so the more immediate gains on offer are to reduce 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 there is the opportunity to improve animal welfare. An additional source of wasted productivity is cow mortality which runs at around 10%.

As an example of the financial benefits, Holmes *et al*. (2017) have assessed the relative impact costs of three proposed improvements. For the stated improvements the equivalent benefit is estimated:

- 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 1kg 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 compensate their growth and return to oestrus sooner than otherwise because they are not producing milk. Dead cows and calves not only cost the enterprise inputs but provide no return. Like the biological analysis, the financial analysis indicates that reducing both cow and calf mortality are where the major benefits will be achieved. Cow mortality and calf mortality are discussed in turn below.

2.4.1 Cow mortality

Estimating cow mortality is difficult. In enterprises that systematically collect data, failure of pregnant cows to appear at muster is one measure (Table 1). Percent mortality rates vary between regions, seasons and properties, but accounting for other factors a mean of about 9% is a conservative estimate (Fordyce *et al*. 2021). Current cattle numbers in northern Australia are estimated to be ~14 million and assuming half of those are cows, more than 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 y.o., 27.5%; 3-7 y.o., 2.8-8.9%; 8 y.o., 11.9%; 9 y.o., 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 to 18.1%. The major determinants of loss appear to be location and nutrition:

- harsh compared with milder conditions (eg Nf vs ND) can account for 9.2% points
- mortality is highest in first calf heifers and cows >7 y.o.
- the difference between a BCS of 1 and a score of 5 accounts for 7.8 % points
- low dry season biomass of <2000 kg/ha compared with >2000 kg/ha accounts for 5.4% points
- Time to follow-up rain >30 d at the start of the wet accounts for 4% points.

The gaps between the median and 25th percentile (see Table 4) show that there is an opportunity for gains across the industry in the order of 5% points. To address heifer mortality, separate management of this cohort that improves nutrition and BCS is essential, as is providing the best possible conditions for calving. Opportunities to reduce mortality of aged cows are in providing nutrition to increase BCS and culling for age (>7 years), bottle teats and failure to raise a calf. Alternatives are to remove the pressure of pregnancy on older cows by sterilising them and finishing for sale.

2.4.2 Calf mortality

Data from successive surveys suggest that rates of calf loss in northern beef herds have been similar for several decades. While 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 Brigalow (7-18%) and regions of the NT (several regions >20% with others 3.4 to 14%). Perinatal loss (within 48 h of birth) accounts for 2 to 12% points and postnatal mortality (between 48 h and weaning) contributes 0.3% to 15% points. Holroyd (1987) considered that 12% would be an acceptable level of loss, comprised of 5% prenatal, 4% perinatal and 3% postnatal losses. CRC data reported 9.5% losses across five Queensland research stations sampled in the Beef CRC trials (Bunter *et al*. 2014) which may underestimate losses on commercial properties.

2.4.2.1 Risks for calf loss

Two studies separately published in 2014 drew conclusions from analyses of large data sets (Table 4). While 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 across five Queensland research stations over 9 years with 9296 calves from Brahman and TCOMP breeds. The sites of the research stations ranged from Brian Pastures (25.39'S) to Swans Lagoon (20.05'S) across a diversity of country types. 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 2-fold. A factor that had no effect in that analysis was 'calving outside the season'. 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). 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 likely due to them being standard procedures (castration) or where data are fragmentary (e.g. cow spaying).

The CashCow study ran over 3-4 consecutive years and collected data from 142 breeding mobs across four regions (McGowan *et al*. 2014). The work was performed mainly on commercial properties. The animal data inputs were: pregnancy status, weight, BCS, sex, horn status, lactation status, hip height, age, *B. indicus* content, udder structure, disease prevalence (serology), and weaner numbers and weights. Property data were: land condition, pasture analysis, rainfall, environmental temperature and humidity, faecal near infrared spectroscopy (NIRS), property size, distance to water and cull rates. Property level management data collected by the survey included: supplementation, vaccination, mustering dates, wild dog control, genetic selection, joining dates and weaning practices. 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.

Table 4. Odds Ratio (OR) of a factor affecting calf mortality or estimated impact (% points of calf mortality). Note that country type is not included, because, while it is a major component, it cannot be changed.

CRC QLD (Bunter *et al*. 2014)			
Risk	Attributed quantum	Regions	Actionable response
Calf sex	Female calves 2x more likely to die (OR ~ 2)		No
Low calf body weight (BW)	<32kg increase cf >39 kg (OR 1.5 to 2.8)		Nutrition, genetics
Cow breeding status	Higher loss in heifers cf. 4-7 y.o. (OR 2.6 to 5.6). No calf in previous year (OR 2.5).		Nutrition, genetics Cull cows >4 y.o. 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 x BW	Interaction with small calves born to cows <4 yrs old (OR 1.8-5.6)		
Breed	Mortality higher in Brahmans (10.5%) than TCOMP (8.6%) (OR 1.5)	Toorak, Belmont comparison	Cull, genetics/breed
Horned vs. polled	Higher risk if horned (OR 8.4)	Post branding	Use polled genetics, analgesia with procedures

		dehorning 1.5% mortality	
Cashcow (McGowan *et al*. (2014)			
Risk	Increase in mortality % points mortality		Actionable response
Low BCS	lower pregnancy rates for 2nd lactation heifers and low birth BW (8%)		Herd segregation and feeding, genetic selection for low birth weight
P deficiency	P:ME ratio <500 (1-10%)	Especially CF NF	Diagnose and supplement
Low crude protein	Lowers BCS (up to 4%)		Nutrition, supplements
THI	>79 for >15 d. (4-6%)	SF CF ND	Shading, calving facilities
Mustering	<90% effective (9%) within 2 mo. of calving (1st lactation cows) (9%)	May impact when calving is year-round	Tighter mating period and planned muster dates
Hip height	>140 cm (3.7%)		More common in older cows, so cull as required
Mother's age	Overall 'heifer gap' is 3-4% compared with other ages (also see Table 5)	All	Yes – heifer management, genetics
No calf in previous year	(3.6%)	Commonly related to teat and udder problems	No calf in sequential seasons - cull.
Disease	Only with recent infection, Pestivirus (8%), Vibrio (7%). Akabane was not tested	All	Vaccinate when at risk
Presence of wild dogs	Unsubstantiated, but estimated (6-11%)	All	Bait

From these data, a ranking of effects, conflated with likely source across the industry, is:

1. Nutrition, which also affects BCS
2. Heifer management issues
3. Risks resolved by culling cows
4. Temperature/humidity
5. Aspects amenable to genetic control

2.4.2.2 Causation

Causal webs of calf loss have been generated by McGowan *et al*. (2014; 2017). The webs are complex and a multitude of factors, including those examined in CashCow, are involved. While this is helpful in understanding possible impacts, those acting at property level may differ in importance. Despite these and earlier investigations, the causes of calf mortality remain poorly understood. Part of the problem is that the extensive nature of the industry means mothers cannot be observed around the time of calving. Fetuses as well as dead or weakened calves are rarely found, let alone made available for investigation of the cause of death. Even when observations are possible, it is estimated that about half of the deaths have an unknown cause. 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.

Prenatal loss of a fetus is especially difficult to identify. Some infectious agents cause reproductive wastage including abortions. Agents known to cause infertility or early abortions include *Campylobacter foetus*, *Neospora caninum*, *Tritrichomonas foetus*, Akabane virus, Bovine Herpes Virus, Bovine Pestivirus and Bovine Ephemeral fever (see summary in Burns *et al*. (2010)). Diseases that tend to affect older fetuses, including abortions in later term, are *Leptospira* spp., *Neospora caninum* and Akabane virus. In addition to abortions, Akabane virus can cause premature birth and stillbirths. Serology may be useful in ruling in or ruling out losses caused by these agents. Disease events were sporadic in the CashCow study and could be considered as a property level issue and, overall, a lower ranked risk factor.

The majority of deaths are perinatal, occurring during or within 48 h of birth. It has been estimated that 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 postnatal period, between 48 h and weaning, death may occur through predation and wound infection following branding and dehorning. However, rates of predation in this period are unknown. The magnitude of losses to wild dogs is equivocal. While anecdotal reports of mauled calves suggest that such predation may contribute to calf loss, survey observations suggest otherwise (Allen *et al*. 2021).

It is clear that there is a major gap in direct evidence of causation. The types of studies that need to be performed are those that monitor herds during the breeding season, can mother up cows and calves, can find calves and fetuses and then diagnose their conditions to categorise causes. That all needs to be done over several seasons and ideally in several regions. A further challenge is that research methods should minimise disruption of cow-calf bonds while collecting data. The aim of this work is to link causation to risk factors and use that information to develop and evaluate interventions to improve 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.

2.4.2.3 Remote surveillance – opening opportunities to understand causation

Remote surveillance of cattle is a developing technology. The discussion below covers a number of techniques categorised into fixed and mobile data collection systems. The main focus is the use of technology in a research environment to study causation. 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 understood examples are walk over weighing (WOW) systems. The principle is to weigh cows as they enter or leave watering points. The animal weights linked to ear tag numbers over time can be used to estimate weights, growth rates, mothering up and potential calving events (Menzies *et al*. 2018a; 2018b). The advantage of these systems is that they are 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 aspects of the herd.

Mobile systems move with the cow and 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. Electronic tags and/or collars have been used for 'virtual fencing' where animals receive a signal when leaving a prescribed area. Ear tags incorporating accelerometers can inform on additional activities such as calving behaviours (Chang *et al*. 2020b). Several proprietary accelerometer-based ear tags are commercially available for dairy cattle, in particular. An additional mobile system is the intravaginal device, Calf Alert, that is ejected at birth (Stephen and Norman 2021). It can signal time of birth and location can be estimated from triangulation of signals or the cow's ear tag GPS signal, 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 examined by laboratory post mortem. Stationary GPS signals can also indicate cow death (or lost tags).

Even with the best resourced research programs, measuring causes of calf loss remains a challenge. The aim is to mimic typical production systems. Some challenges are physical (e.g. internet coverage, frequency of reporting, loss of tags), others are human (e.g. night time coverage, rugged terrain), or due to the animal (e.g. 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 over 5% can be measured with any 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 space with the Calf Watch project (Future Beef 2020) which is building upon the earlier trialling of WOW, accelerometer use and intravaginal devices to identify causation especially in the perinatal period.

2.4.2.4 Potential gains in addressing calf loss - benchmarking the top 25%

Property data aggregated regional data and longitudinal data collected from the cattle industry are highly variable. Because calf loss data sets 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 farms in the top 25%. These were: (i) higher reproductive rate, (ii) lower mortality rate and (iii) 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: (i) % of cows pregnant, (ii) % fetal/calf loss (or weight of weaned calves), (iii) liveweight change in cows/heifers and (iv) % herd mortality. Some examples of the 75th percentile target (25th percentile for mortality) are shown in Table 5.

Table 5. 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. Source: McGowan *et al*. (2014)

	SF	CF	ND	NF	Overall
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)

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 % and OR of the risks in Table 5 are industry trends which may not be translated to a particular farm where some risks may be more important or more readily mitigated than others. Nevertheless, the set of aspirational benefits are:

- 6% in heifers across all regions (the 'heifer effect')
- 3.2% for 2nd lactation cows in SF, CF and NF and opportunities to improve return to in calf is the priority in all regions
- Benefits of 2.4 to 4.1% for older cows in all regions.

It has been claimed (Holmes *et al*. 2017) that half of the production comes from properties already at or above the 25th percentile level but 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% overall reduction in calf loss.

2.4.2.5 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 mortality were obtained, including birth weight (0.48), udder score (0.49) and teat score (0.38). Therefore, the authors recommended selection for the maternal contribution to birth weight, while avoiding very high birthweights that may predispose to dystocia. The genetically correlated measurement of weaning weight is considered to be an acceptable proxy when birth weight 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).

3 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*. (2005c). 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 pasture quality are especially important influences. 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.

3.1 Grazing management

3.1.1 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 of this concept is central to best practice in all types of grazing systems. However, its importance is absolutely critical to the sustainable management and long-term productivity of perennial native grasses in northern Australia that are especially sensitive to overgrazing (Hunt 2008).

Almost all studies to date 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 has been funded by MLA to determine levels of pasture utilisation required for optimal breeding herd performance in northern Australia as judged by pregnancy rate, lactating cows pregnant within 4 months of calving, calf mortality and weaning percentage (Cowley *et al*. 2019). This project aims to relate cow performance datasets from 28 commercial properties across the 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 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 their 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 is high resolution satellite imagery, initially developed by the CSIRO and DAFWA (Edirisinghe *et al*. 2011), and since refined and commercialised by Cibo Labs Pty Ltd https://www.cibolabs.com.au/. A recent study conducted under extensive commercial conditions in the Victoria River Downs region of the

Northern Territory found significant positive relations between various indices 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, Julian calendar date and rainfall.

3.1.2 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*. (Table 6; 2014). 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 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 the 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 which simulated a hypothetical property in the Charters Towers district (MacLeod *et al*. 2004). However, unlike the Wambiana trial, economic assessment in this study was based on breeding herd performance as well as steer growth rates.

An ongoing, long-term grazing strategies trial has been underway 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 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.

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 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, and for longer if the initial condition is less than B.
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 2,000 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 head 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.

Technical guides to best-management practices for grazing management to optimise land condition, animal production and profitability in the Barkly Tablelands (Walsh and Cowley 2014a), Victoria River Downs (Walsh and Cowley 2014b) and Alice Springs (Walsh *et al*. 2014) regions of the Northern Territory are generally aligned with the recommendations of Hunt *et al*. (2014). These publications additionally identified 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, recently have been summarised in practical terms (Walsh and Paton 2020).

Despite the clarity and consistency of advice its widespread communication to northern beef producers, and well-documented examples of the successful adoption of advice to commercial enterprises (Walsh and Cowley 2016), overgrazing continues to be a major concern. Ongoing rangeland degradation and declining profitability of beef enterprises are demonstrated 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 increased understanding of the impacts of grazing pressure has occurred, 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. The focus of many producers (and some advisors) on production per hectare rather than production per animal exacerbates this problem (D. Walsh, personal communication).

Another key practical issue is the tendency of many graziers to retain stock for too long during a drought event before being forced to sell or agist cattle (Landsberg *et al*. 1998). The lead author of the latter 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 time. 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 cattle grazing selectivity 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 northeast 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 state to one more desirable for sustainable production and rangeland condition. Results of other studies of the effects of resting have been more equivocal but, in some cases, 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.

3.1.3 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. about 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 head (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, these 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, paddocks of 20 km^2 with two water points were recommended to optimise grazing distribution (Table 6).

The principles established by Hunt *et al*. (2014) are being applied in a current MLA-funded project which aims to assess the influence of paddock area and distance to water on the 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, almost thirty 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).

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, recently was evaluated in an MLA-funded project conducted at Kidman Springs in the Northern Territory (Revell 2019). Positive outcomes included the attraction of cattle into previously under-grazed 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 was conducted on breeders 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.

3.2 Review of production and utilisation of native and naturalised forages

Most native grasses in northern Australia are tropically-adapted C4 species that, compared to temperate C3 grasses, feature more efficient photosynthetic processes and relatively high biomass production during the growing season. However, the feeding value of these grasses is poorer due 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). The great diversity of native grasses used for northern beef production has been systematically organised into functional groupings to allow comparisons among plant communities and explain their different responses to management interventions (Ash *et al*. 1994). This and other aspects of the botanical nature and management of native pastures, including growth patterns and seasonal variation, roles and values of rangeland grasses, responses to and management of grazing, and effects of fire and fire management have been recently reviewed (Chilcott *et al*. 2020).

To a 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. Notable early examples include buffel grass (*Cenchrus ciliaris*) which is believed to have been accidently introduced to north-west Australia by Afghan cameleers during the 1870s, and the tropical legume, Townsville stylo (*Stylosanthes humilis*), first noted on the Townsville common in 1903 (Clements and Henzell 2010). The nutritious tree legume, leucaena (*Leucaena leucocephala*), also was first recorded in Australia in the late 19th century but was not used as a forage plant until the 1940s (Gray 1968).

These and related species can, in more favoured 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)	Liveweight gain/yr (kg/head)	Av. age at 600 kg LW (mo)
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

3.2.1 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 weight 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 of >$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 million ha and 'common' on a further 25.9 million ha in Queensland, mostly in central and southern regions.

3.2.2 Tropical legumes

The most widespread tropical legumes in northern Australia are the *Stylothanthes* 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 million ha of native pastures (Noble *et al.* 2000). Both of these cultivars are adapted to the 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 that 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 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 50 kg/head per year more than steers grazing native grasses alone 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).

In contrast to the relatively widespread use of stylo legumes by northern Australian beef producers, adoption of the highly nutritious and productive tree legume, leucaena, 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 about 130,000 ha, mostly in central and southern Queensland (Buck *et al*. 2019b). This is miniscule compared to a conservative estimate that, in Queensland alone, more than 8 million ha 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; 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*. 2019a; 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).

Strategies to increase producer awareness of the benefits of leucaena and requirements for establishment and management will be considered later as a case study in the section on pathway to practice. The breeding and evaluation of psyllid-resistant cultivars are discussed in the next sub-section on new and improved pasture species, as are genetic approaches to preventing the escape of leucaena from managed plantations.

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). Recently, doubts have been raised about the efficacy of the inoculum (Halliday *et al*. 2019) and 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.

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, e.g. 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 dry matter production and grazing tolerance of several accessions of *Desmanthus 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 to 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. Recent trials have indicated that new cultivars of hard-seeded desmanthus, such as Progardes™ , respond well to faecal seeding through dispersal by cattle and horses (see http://progardes.com.au/establishment).

3.3 New and improved pasture species for northern Australia

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 5,000 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, Cook *et al*. (2005) developed an online interactive tool, Tropical Forages (see www.tropicalforages.info), that allows access to information on 180 tropical and sub-tropical forage species, their adaptation and potential. More recently, this resource was extended by a comprehensive stocktake and analysis of legume evaluations for tropical pastures in Australia that 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, located 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. Their approach involved both re-evaluation of previous work, including re-visiting abandoned pasture evaluation trial sites, as well as identification of opportunities to develop new, elite cultivars. These 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*.

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 Pty Ltd. By 2019, some 35,000 ha had been sown to Progardes™, mostly across Queensland but also in northern New South Wales and the 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).

Re-examination of old plant evaluation sites 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.

The destruction of *S. humilis* and *S. guianensis* cultivars by anthracnose caused by *C. gloeosporioides* 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. Recently, however, a range of genetic lines of *S. seabrana* and *S. scabra* have been 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 to be considerably more resistant than the other new lines and commercially available cultivars.

Past and present research on leucaena breeding in Australia, and possible future opportunities, have been recently reviewed (Dalzell 2019). This 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.

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 the Redlands cultivar in terms of psyllid resistance and cattle growth is currently 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 lease-hold land in Western Australia and the Northern Territory, establishment of commercial plantations of leucaena is restricted due to a perceived environmental weed risk. In others, such as parts of the 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). It has been suggested that, 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).

While most recent R&D on new pasture species and cultivars for the tropics and subtropics has focussed 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).

3.4 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 to significantly increase 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).

Therefore, 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 ROI 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 more recent economic evaluation of various management strategies for beef enterprises in different regions of central and northern Queensland and the Northern Territory (Bowen and Chudleigh 2021). This modelling study found that neither genetic nor nutritional strategies, including irrigation, to improve breeding herd performance were likely to significantly improve enterprise profitability due to the high costs and timing of implementation.

3.5 Supplementation strategies

Use of nutritional supplements has long been advocated and, to a 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 (NPN), 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 to supplement P (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).

3.5.1 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. 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. This author 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 supplementation. Rather, it was recommended the less risky option of 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. However, this advice was not supported by results a recent modelling study, using current cattle prices and supplement costs, for a breeding enterprise in the Victoria River District of the Northern Territory. This study predicted that protein supplementation of weaners to achieve growth rates of 0.3 kg/d during the first dry season increased gross margins and net present value across the entire breeder herd, with a break-even threshold of $770/t of supplement when steer prices are $3.50/kg liveweight (Niethe *et al*. 2022).

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*. 2017a) and older (10-12 or 33-36 months) (McLennan *et al*. 2017b) Brahman x 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 that are grazing mature dry season grasses and clearly demonstrated the biological efficacy of protein supplementation. The response curves obtained by McLennan *et al*. (2017a) 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, as recently modelled by Niethe *et al*. (2022).

The supplements used in the above studies included cottonseed meal or fishmeal for N, and molasses, sorghum 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, 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 NPN 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). These authors suggested that the most feasible source of microalgae as supplements would be 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.

As discussed 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 body weight 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 others (Siebert *et al*. 1976; Fordyce *et al*. 1996, 1997; Dixon *et al*. 1997a, 1997b). Failure to respond in the latter cases usually was associated with a lack of effect of supplementation on pre-partum liveweight of heifers due to 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, these were much less than effects of early weaning in the same experiments on second-lactation Droughtmaster cows at Swans Lagoon (Dixon *et al*. 2011b; 2011c). 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, but these effects were not maintained when the cows subsequently grazed high-quality grass-stylo pasture during lactation (Dixon and Mayer 2021).

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, in a study in the Victoria River District of the Northern Territory (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 carefully evaluate 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 to energy supplementation of rapidly growing young cattle grazing leucaena-grass pastures in the Ord River Irrigation Area have been observed (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/d in unsupplemented controls to 1.1 kg/d in animals fed 2.5 kg/head.d 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, 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).

3.5.2 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 P 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 (Niethe 2019).

The management of P nutrition of beef cattle in northern Australia recently 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. The rest of 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 problem is exacerbated by the tendency of P-deficient cattle to select plant material with higher P concentration (Coates and Le Feuvre 1998) and 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 overcome this limitation (Forkuor *et al*. 2017).

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 at slaughter (Dixon *et al*. 2020). Each of these has limitations, especially for the diagnosis of less severe or subclinical P deficiency. For example, while 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; Niethe 2019). 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 and Coates, 2019; Dixon *et al*. 2020). Substantial individual variation of PiP in breeding herds of mixed age and reproductive history presents an additional challenge (Dixon *et al*. 2019).

During the dry season, growth responses to P supplementation of cattle grazing pastures on P-deficient soils may be muted because the first-limiting nutritional factor 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 northern Australian rangelands and the demonstrated efficacy of P supplementation in numerous controlled experiments, adoption of the practice has been relatively low (Dixon *et al*. 2011a; 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. To address these issues, a study of the effects of P supplementation on growth and reproductive performance of Brahman heifers grazing acutely P-deficient pastures was conducted over three successive seasons (2017-2019) in a demonstration trial at the Victoria River Research Station at Kidman Springs in the Northern Territory (Schatz et al. 2022). Results are summarised in Table 8.

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*. 2022).

Year	**2017**		**2018**		**2019**	
Treatment	**+P**	**-P**	**+P**	**-P**	**+P**	**-P**
Cow PiP (mmol/L)[a,b]	1.81	0.71***	1.23	0.66***	1.73	0.65***
Liveweight (kg)[b]	380	262***	426	357***	430	324***
Pregnancy rate (%)[b]	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)[c]	8,634	5,564	7,949	5,145	12,936	6,912

[a]Plasma inorganic phosphorus concentration.
[b]Data are for lactating animals at the May muster.
[c]Assumes both treatments started with 100 heifers; not subjected to statistical analysis.
Mean values for -P group are significantly lower than those for +P group (***, $P<0.001$; *, $P<0.05$)

Treatments were applied after the heifers were weaned in June 2014. During the dry periods (May to October) in 2014 and 2015, there was no effect of P supplementation on heifer growth rate but the supplemented group grew significantly faster during the wet seasons of 2014/15 and 2015/16. Thus, at first mating in in May 2016, mean weight of the supplemented heifers was 65 kg heavier 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 compared to 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 over 30% of the unsupplemented cows.

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 the 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 region of Central Queensland were modelled. These predictions of the profitability of P supplementation, together with the empirical findings of Schatz (unpublished), summarised above, highlight the need for more effective translation of research findings into feasible management practices (see section on Pathway to Practice).

3.6 Forage conservation

In contrast to dairy and beef farms in southern Australia, forage conservation is not normally part of the annual production cycle on most extensively managed northern beef properties. Thus, while 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 the 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 sub-tropical conditions have been prepared by relevant state agencies and RDCs. While these are useful technical aids, an economic case for greater and more strategic use of conserved forages by the northern beef industry has yet to be made. Specific questions may 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 e.g. 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 to substantially increase 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?

4 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 in the section on Breeding Herd Management, including alternatives to aversive practices such as surgical dehorning and spaying, and reducing the incidence of calf and cow mortality. Opportunities to reduce the negative effects of poor nutrition and heat stress are discussed in the section on Feedbase Management and the present section, respectively. The profitability of northern beef enterprises is clearly an important aspect of sustainability that recently has been assessed by experts in farm business management and northern beef production (McLean *et al*. 2020).

The northern Australian beef industry is challenged by a natural environment that is characterised by a highly variable and unpredictable climate, nutrient-deficient soils, animal pests, and 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 increase these natural environmental challenges. The built or managed environment includes the further challenges of long distances to markets and necessary services, and lack of supply chain infrastructure. This section will focus on 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 will be 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).

4.1 Managing climate variability for northern pastoral systems

Predicted changes in the northern Australian climate will accentuate the existing 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 are predicted to change with increased incidence of extreme rainfall events, interspersed with prolonged and severe droughts.

4.1.1 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 that 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 C4 grasses which 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 C4 versus C3 pasture species in tropical pastures. Early studies indicated that the ability of C4 plants to increase rates of photosynthesis in response to elevated CO_2 is much less than that of C3 plants (Ehleringer *et al*. 1997). However, these experiments were short-term and more recent studies conducted over 20 years have observed 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 C4 grasses was attributed to increased rates of mineralisation of soil N by C4 but not C3 plants. Thus, there is evidence that long-term effects of climate change on northern pasture communities may change the present balance between C4 and C3 plants to further favour C4 grasses. This has implications for biomass production (likely positive), forage quality (likely negative) and the successful establishment and maintenance of C3 legumes (likely negative).

4.1.2 Heat stress and breeding herd performance

4.1.2.1 Effects on reproductive physiology

The most significant non-nutritional environmental stressor affecting the productivity of breeding herds in northern Australia is undoubtedly 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 (Abdelatty *et al*. 2018; Hansen 2009; 2013), although such effects appear to be less pronounced in *B. indicus* than in *B. taurus* breeds (Rocha *et al*. 1998). Heat exposure during the first half of pregnancy also can impair placental growth and functional development (Tao and Dahl 2013), with consequences for later fetal growth, birth weight and calf survival. 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 (Tao *et al*. 2018). Finally, while 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 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).

4.1.2.2 Genetic selection for heat tolerance

There is considerable genetic variance in heat tolerance between and within cattle breeds. The substantially greater tolerance of *B. indicus* compared to *B. taurus* breeds is well known (Beatty *et al*. 2006; Gaughan *et al*. 2010b) and, together with tick resistance, was a major reason for the introduction of Brahmans to northern Australia in the middle of the 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 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 (C. J. O'Neill, personal communication).

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 x Hereford x Shorthorn, O'Neill and Frisch 1998; Senepol – N'Dama x Red Poll, O'Neill *et al*. 2010), and the Tuli, a pure African Sanga breed. These 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). 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*. 2012). 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.

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 the 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 negatively affect heat tolerance or other tropically adaptive traits (Prayaga *et al*. 2009).

4.1.2.3 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 focussed mainly on intensively managed dairy and feedlot beef systems (Blackshaw and Blackshaw 1994; Gaughan *et al*. 2010a). 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, 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*. 2008a; Gonzales-Rivas *et al*. 2018) are infeasible for extensively managed northern beef operations.

4.2 Reducing the impact of beef production on the rangeland environment

4.2.1 Optimising stocking rates for long-term productivity and sustainability

As discussed in the section on 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. While 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 underway which aims 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).

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 which is likely to be exacerbated by emerging climate change (Cobon *et al*. 2020b). 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 total precipitation because the latter is dominated by extreme events when most rainfall is lost as run-off (Brown *et al*. 2019). The latter 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*. 2020a).

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 northern Australian climate. As discussed by Niethe and Holmes (2020), the key elements of a sound drought management plan should be preservation of native pastures and land condition.

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

The contribution of the northern breeding herd to emissions of greenhouse gases (GHG) and possible strategies to mitigate this likely contribution to global warming also need to be addressed. According to the latest Australian National Greenhouse Accounts (Australian Government 2020), enteric methane, mostly emitted by cattle and sheep, accounts for about 68% of agricultural GHG emissions and just under 10% 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% national) and the fact that cattle grazing low-quality tropical grasses produce relatively large volumes of methane per kg dry matter (DM) consumed (Kennedy and Charmley 2012). Confidence in the predictability of methane emissions by Australian cattle has been boosted by the derivation of a universal equation relating methane production to dry matter intake in dairy and beef cattle fed temperate forages and 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 to that of GHGs derived from the combustion of fossil fuels (Ridoutt 2021).

A range of nutritional, pharmacological and immunological strategies to mitigate ruminal methane production have been investigated in recent decades (Black *et al*. 2021). While some of these may be applicable to intensively managed dairy and lot-fed beef cattle, their application for use in extensive northern beef production systems is unlikely, with the possible exception of pastoral systems including certain tropical legumes. The latter include leucaena (Kennedy and Charmley 2012; Tomkins *et al*. 2019) and *Desmanthus* spp (Suybeng *et al*. 2020), both of which appear to reduce methane production per kg DM intake in Brahman and Droughtmaster cattle. However, despite additional benefits such as increased plant and soil carbon sequestration (Radrizzani *et al*. 2011), the impact of these findings on the carbon footprint of the northern breeding herd is likely to be modest in comparison to the demonstrated benefits of increased reproductive efficiency and turnoff rates for reducing GHG emissions intensity. For example, detailed analysis of the records of a leading breeder enterprise in the Barkly region of the Northern Territory has shown that increases in weaning rate (46%) and annual liveweight turnoff (71%) and an 82% decrease in breeder mortality, 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%. The outcomes of this commercial case study are entirely consistent with the results of a comprehensive life cycle analysis of factors influencing changes in GHG intensity of Australian beef production between 1981 and 2010 (Wiedemann *et al*. 2015).

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 2020) 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 also should be able to benefit from the development of new methods to measure increases in soil carbon content over space and time (Australian Government 2016).

4.3 Management and amelioration of environmental stressors

4.3.1 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 indices for intensively managed dairy (Lees *et al*. 2018) and lot-fed beef cattle (Gaughan *et al*. 2008b). However, in their present form, these methods are inapplicable to free-ranging cattle in extensive pastoral systems. There is a clear need for the development of techniques to remotely monitor 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).

4.3.2 Weeds and Pests

Breeder 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 loss of grazing land, gully erosion and silting waterways. A second is the potential for predation of calves by dogs.

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 due to 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 with grass, thorny plants are a particular problem when they grow in dense thickets and the scrub becomes impenetrable. Toxic plants such as Pimelea can cause production losses 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 (*Rhipecephalus australis*) and buffalo fly (*Haematobia exigua*), together causing $250M of losses per annum. Ticks are endemic north of a line near the Tropic and extending down the coastal regions of Queensland into northern NSWand transmit tick fever which is 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 more of those animals are at risk and need to be monitored for infection and treated. It has been reported that during years of heavy infestation ticks may contribute to a 30% decline in conception rate of cows and 24 kg average decrease in calf weaning weight (Holroyd *et al*. 1988). Ticks are currently controlled by dipping with acaricide and enforcement of 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 due, respectively, to emergence of acaricide resistance and climate change that is allowing ticks to survive south of the quarantine lines. Compared with ticks, buffalo flies are endemic over a wider range and both the range and intensity of infection increases in rainy years. Quarantine is of little use to restrain a flying insect and so insecticidal treatments are a common practical method of control.

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 in that it creates a trade barrier where animals in a variable range of northern Australia are banned from live export to disease-free areas such as northern China.

5 Pathway to practice

Despite considerable RD&E devoted to northern issues and problems for more than half a century, adoption and successful implementation of new practices remains a central problem (e.g. McLean *et al*. 2018; Chilcott *et al*. 2020). Certainly, there are clear examples to the contrary, such as the introduction and widespread uptake of Brahmans and other *B. indicus* genotypes, feeding of NPN supplements and use of hormonal growth promotants (although the latter has declined recently because of market issues). This section provides examples of R&D that have not had the expected industry impact and discusses possible reasons for past failures and opportunities for future improvement, focussing on issues that have been deemed important by industry. While each of these has specific aspects requiring different approaches to research translation, technology transfer, dissemination of advice and on-farm implementation, a common theme is the role of producers in defining and addressing issues rather than top-down prescriptive advice from scientists to practitioners. Discussion of these examples is preceded by a brief sub-section that considers extension and adoption models and their applicability to the northern beef industry.

5.1 Extension and adoption models

In a review of extension theory and practice, Black (2000) classified extension strategies into four major categories: (i) linear 'top-down' transfer of technology by scientists to producers; (ii) participatory 'bottom-up' approaches (also termed 'group empowerment') in which producers take a primary role in identifying problems and formulating solutions; (iii) one-to-one advice or information exchange, increasingly involving private farm management consultants as well as informal exchanges between producers; and (iv) formal or structured education and training involving tertiary education coursework as well as learning programs provided by the RDCs and other industry bodies. Black (2000) further conceptualised 'top-down' technology transfer and 'bottom-up' participatory methodologies as two ends of a spectrum of extension strategies, as illustrated in Figure 2. This diagram is intended to depict that, as situations become more complex, increasing emphasis should be given to the empowerment of individuals and groups to engage in on-going, self-directed processes of experimentation, learning and human development. However, after consideration of the strengths and limitations of these various extension models, it was concluded that no single model is likely to be sufficient by itself.

Any organised attempt to increase the adoption of new technologies or practices should consider barriers to adoption. A simple summary of individual and group factors, as well as the distinction between perception and reality, are illustrated as a quadrant in the so-called 'Republic of everyone'. Individual factors highlighted the importance of providing evidence and inspiration ('Give me a reason') for change, as well as the need for demonstration of outcomes ('Show me how'). Group factors focussed on the experiences of others in the individual's peer group ('Show me others doing it'), and on the importance of simplification of the process of adoption through changes to policy and infrastructure ('Make it easy'). This approach inherently recognises the complexity of beef businesses and the need for simple messaging.

Using a different approach, the CSIRO's web-based ADOPT (Adoption, Diffusion, Outcome, Prediction, Tool) tool (CSIRO 2020) includes questions about factors that negatively or positively affect adoption. Negative factors are: impact on other farm income; skill required for implementation; time to implement as affected by need for training and new development; business risk if adopted; and time post adoption to realise full benefits. Positive factors are: opportunity to avoid risk; perceived benefits; and feel good factor e.g. environmental protection. The ADOPT questionnaire attempts to assess producers' propensity for adoption of a given practice based on factors such as profit orientation, environmental orientation, risk appetite, enterprise scale, management horizon and short-term financial constraints (Kuehne *et al*. 2017). The importance of enterprise scale has been emphasised by Holmes *et al*. (2017) who concluded that smaller beef herds (<800 head) are less likely to gain economic benefits from innovation (apart from increasing scale) than larger enterprises (>1,600 head).

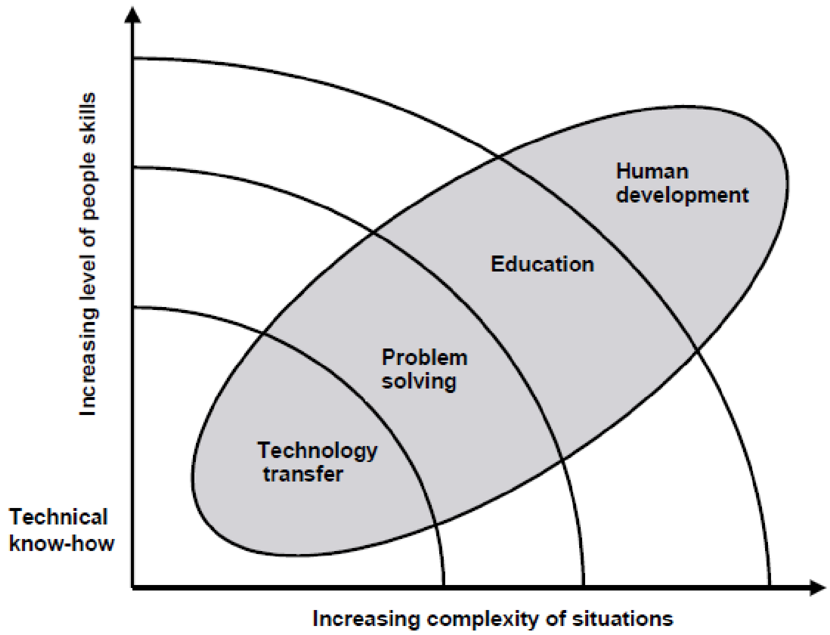

Figure 2. The extension spectrum. Reproduced from Black (2000), with permission from CSIRO Publishing.

Traditionally, most extension providers serving the northern beef industry have employed a 'top-down' model of information transfer and industry engagement, the success of which has been described by knowledgeable providers and recipients as patchy at best. The Northern Breeding Business (NB2), through its Pathway to Practice (P2P) project, proposes to develop more participatory 'bottom-up' approaches that will enable beef producers to identify and solve problems specific to their individual enterprises. Once problems have been identified, various technical and other solutions can be considered with the aid of facilitators. A recent, apparently successful example of facilitated small group learning that is directly relevant to the NB2 program is the Red Meat Profit Partnership (RMPP) Action Network that was developed specifically to serve New Zealand's red meat sector (Patchett *et al*. 2020). This program was launched in 2017 by the RMPP to address a lack of adoption support and follow-up and enable farmers to develop the confidence to take action and be accountable for making changes in their businesses. Independent research to evaluate the economic benefits of the RMPP Action Network found that the investment of NZD14.4 million into the Network has generated benefits with a present value of NZD381 million i.e., a return on investment of 26:1 (Scarlatti Limited 2020).

Principles cited above are included in the MLA framework for adoption activities including awareness, short-term training courses, long-term training aimed a practice change, use of adoption enablers and engagement of producers in research. Involvement of producers in research projects from inception is especially important to ensure the relevance and practicality of research findings which are features of the Producer Demonstration Sites co-sponsored by MLA, individual producers and/or regional industry groups.

A particular challenge is to synergise top-down and bottom-up approaches. Conceptually that could include a set of adoption plans that are compelling in their own right and that are well understood in terms of deployment and benefits. These could act as triggers for producers who have been through a process of participatory data collection and business analysis and wish to identify innovations that suit the needs of their individual enterprises.

The rest of this section is devoted to the consideration of possible solutions to problems and issues identified in the preceding sections on breeding herd management, feedbase management and environmental issues and management. The list of topics is by no means comprehensive and is intended to serve as an example of items that might be identified and addressed by participants in the Pathway to Practice project.

5.2 Opportunities to improve adoption and business performance

5.2.1 Breeding management

Many of the potential gains in metrics such as pregnancy rates and mortality could be influenced by improvement in feedbase management . Research has shown that improving pregnancy rates can be tackled through breed selection and genetic improvement, especially in 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 developing for Droughtmaster. Rapid and effective deployment of superior genetics through bull selection is urgent and a plan needs to be promulgated. In addition, there is a direct genetic effect of low birth weight, large teats and small udders on calf growth and survival (Bunter *et al*. 2014). Progress towards these as selection goals in cows is expected to be rapid due to the high heritabilities for birthweight (0.48) and weaning weight (0.39), udder score (0.49) and teat score (0.38). The recommendations are to select for calf body weight, although weaning weight may be more accessible (these characters are highly correlated (r = 0.63) along with larger udder scores and smaller teat scores). It is noted that very high birth weights should be avoided so as to reduce the risk of dystocia (Bunter *et al*. 2014). 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 traits.

Mitigation of calf loss can leverage the knowledge that is now available on risks. Studies on causation are underway as described and will, hopefully, close the knowledge gap. Together, they will point to areas where improvement through reducing risks and removing causes can occur. The major 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 a number of 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, 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 % across a region and possibly more on a single farm. A gap in research is in demonstrating the return on investment (ROI) 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. Heat impacts may also be reduced by smaller paddock size or shorter distance to water.
- Herd management and especially a focus on heifer management but also managing cow cohorts
- Reducing the mating period to optimise feed utilisation and clustering 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. The quantity, quality and timing are important aspects and, where financially viable, feeding supplements. A rising plane of nutrition, can also be used to induce ovulation. For some properties the management of breeding is around the 'green date' when significant rain leads to a build-up of feed after onset of the wet season.

5.2.2 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 amount of effort 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, personal communications). The authors of this review 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 solutions to this challenge should be amenable to the facilitated small group learning approach proposed for use by the NB2 program, particularly if groups include respected producers who have had long-term success with adoption (Landsberg *et al*. 1998). To assist this process, 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 ground cover percentage, identify key pasture species and other key skills related to feedbase and grazing management (Walsh 2021).

It is generally agreed that the opportunities to greatly improve the performance of breeding and growing cattle in northern Australia by including tropically adapted perennial legumes in native or sown grass pastures have 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 have been discussed in the section on feedbase management (Buck *et al*. 2019a; b), principal of which are inadequate knowledge of the environmental and agronomic requirements for, and cost of, successful establishment and long-term maintenance of leucaena . 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 and Livestock Australia 2020). However, exposure to these positive examples should be accompanied by financial literacy training and technical support to ensure that producers have (i) a clear view of financial risks and benefits and (ii) access to appropriate agronomic expertise. While some of the required tools and sources of advice are already publicly available, 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 northern Australia, the level of adoption of wet season supplementation remains unsatisfactory (Niethe 2019). 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 (Jackson *et al*. 2012) and regionally relevant modelling of long-term business productivity and profitability (Bowen *et al*. 2020). The NB2 approach to identifying 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 (Viscarra Rossel and Bui 2016) and animal P status, preferably by blood collection and laboratory measurement of PiP levels (Niethe 2019), followed by expert advice on supplementation strategy and assessment of responses. The latter data should then be used in BCR analyses for the enterprise . A specific practical issue that may require further technical development is devising effective strategies for feeding 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 2021b).

5.2.3 Environmental issues and management

It has been convenient to separately discuss R&D needs and gaps for the herd, feedbase and sustainability pillars of NB2. 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. The need to match stocking rates to appropriately estimated long-term carrying capacity of native and naturalised pastures, discussed in the section on Feedbase Management, 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. 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 environmental impacts on breeding herd performance include (i) technologies for remote assessment of effects of environmental stressors, especially heat, on animal physiology and production under extensive pastoral conditions, and (ii) meteorological tools to predict climatic variation, including the occurrence of extreme weather events and the timing of wet season onset. The first of these are still under development but producers should be made aware of the benefits of being able to gauge the status of their cattle during extreme heat and other climatic events. Regarding the second opportunity, 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 training in their operation could be considered as an example of low-hanging fruit for the P2P project.

5.3 Adoption

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 in identifying practices where research has shown potential for a significant quantum of improvement, are practical in their application and offer an attractive ROI. The process of adoption should be underpinned through knowledge exchange, skills development, demonstration in the region, and the application of metrics and tools to demonstrate benefits, for example, on calf survival rates.

The north presents many challenges to success in adoption. This section first mentions some innovations that have been adopted. Second it lists research projects that have provided underpinning data and knowledge on which further research and adoption has been based. Third, we consider specific examples that have contributed or continue to contribute to adoption. These examples profile a range of adoption approaches that are in use. They serve as examples and are not comprehensive.

Successful adoption has been taken up 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 efforts of pioneering producers. Examples are helicopter mustering, yard feeding of weaners and growing steers for live export.

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

- The Wambiana Grazing Trial has been running for more than 25 years and has provided valuable data on stocking rates and land condition across seasons including three droughts and economic analysis of the enterprise. A major insight has been that excessive stocking rates lead to lower productivity and profitability over time and land condition also suffers.
- CashCow and the Beef CRC benchmarked breeder productivity metrics and also 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.
- Technologies to improve feedbase utilisation have been developed and have future promise. Virtual fencing using GPS collars that deliver auditory or electrical cues can be used to keep animals within grazing zones. This technology was developed through CSIRO research and has been licensed for field use. Self-herding is an initiative that uses animal behaviour cues to move animals across a landscape. Both approaches lend themselves to extensive conditions and provide potential savings on fencing infrastructure. As noted in a recent review, adoption of these and other technologies for remote feedbase management will require ongoing, active consultation and technical support of end users by developers and providers (Masters 2021). In October 2021, Cibo Labs and MLA announced their partnership to provide red meat levy payers access to high resolution satellite imagery for remote sensing and monitoring of pasture biomass and ground cover (https://www.beefcentral.com/news/major-mla-project-plans-to-accelerate-farm-mapping-and-feed-budgeting/). This offers an opportunity for all producers taking part in the NB2 initiative to trial a novel and potentially valuable technology for feed budgeting under extensive rangeland conditions, at little cost.

Data for the adoption examples in Table 9 were obtained from MLA project reports, Centre for International Economics (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 BCRs are included.

Table 9. Examples of adoption activities in the northern Australian beef industry.

Topic	Enhanced nutrition through planting *Leucaena*, a deep-rooted tree legume with high productivity in areas >800mm p.a. rainfall.
The research	To reduce psyllid attack, the Redlands (Plant Breeding Rights registered) variety was developed. Rumen inoculation to reduce impact of mimosine toxin was also developed. Production characteristics were trialled on 2 sites in NQ-demonstrating up to 30% improved live weight gain. In order to mitigate issues of its 'weed' status in some jurisdictions, research to develop sterile (non-seeding) varieties is underway.
The aims and potential (incl pre ROI)	To stimulate enhanced planting of Redlands leucaena. Overcome limitations of plant establishment (up to 30 % failure rate) through methods development and skills training. Demonstration trials on establishment and productivity including calculating BCR on farms based on an ex-ante estimate of 3.0-4.7.
The plan and execution of adoption (refer to methodologies)	Assumptions are that a maximum benefit of 150 kg LW/ha is possible, although a range establishment costs that are cited ($85 to $400 /ha) will impact benefit ratios. A total area of 1.5M ha is amenable to planting and adoption of the Redlands variety on 10% of this area would lead to a benefit of $59M between 2021 and 2030. The Leucaena Network (TLN) used a participatory approach to bring producers and extension people together to provide education and agronomy advice. TLN developed and published manuals on establishment and management, ran conferences and formed international links. Trial planting sites including Pinnarendi and those involved in the Redlands4regions producer innovation fast track program were also used for farm demonstrations. Producers of proprietary seeds were contracted.
Success or lack of ways to measure (post BCR)	2021 is the first year of expected benefits. Scale up of seed production was a limiting factor in deployment with just two commercial seed suppliers holding PBR. No independent ex-post BCR is available. Uncertainly in the success rate of establishment remains an impediment. This issue is in common with other legumes proposed for use in the north.
Comments including barriers to adoption and other options	TLN was successful in fostering, coordinating and lobbying, providing producer input, advice and structured training including demonstration. Leucaena is rated the most successful of the tropical legumes that have been researched and Redlands obviates a major pest issue. While it has not yet met its potential, systems are in place to support further development. A remaining need is more certainty about establishment. Sterile varieties could expand geographic range and impact.

Topic	P supplementation in the wet season
The research	P deficiency in northern cattle has a long history of research. Soils in marginal areas are P-deficient and P status in cattle reflects soil levels to an extent. Recent research has demonstrated benefits in breeding females of using wet season supplementation with P compared with standard mineral supplementation. BCR of 5 to 8 have been reported. Deficiency is associated with: soil, <5 mg P/ kg; faecal, P (from unsupplemented animals during the wet season), <100 mg P/kg (growing) or <200 mg P/kg (lactating). Plasma levels of inorganic P (PiP) <30 mg/L is a further indication of deficiency.
The aim and potential (incl pre BCR)	Reduce losses in the northern industry due to cow mortality, low weaning rates and low carrying capacity. Expected net benefit of $40 per animal per season following use of loose blocks or water-based medication in the wet season for breeding females. About 3M cattle are deficient and adoption of P supplementation in the wet in 60% of these cattle could achieve a BCR of 5. While the benefits are well known, the practice has inconsistent adoption and so the message needs to be simple. The ROI had also not been demonstrated in a range of locations and this work is required. The logistics of delivery of P in the wet season is also relevant.
The plan and execution of adoption (refer to methodologies)	As one example, in 2012 MLA produced a Handbook 'Phosphorus management of beef cattle in northern Australia' with several case studies. Its impact on adoption is not recorded. Amongst other initiatives the 'P Challenge' ran in 2019 which engaged 100 producers in faecal P testing. The 'Easy P' project has recently been launched with MLA funding through the Producer Demonstration Site scheme. The approach is to enrol 6 farms in northern Australia and demonstrate an 'easy' system that deploys P blocks at the beginning of the wet.
Success or lack of ways to measure (post BCR)	Herd performance will be measured in the 'Easy P' project which aims to demonstrate a ROI of >5 fold (weaner weight ROI =5; Cow weight ROI = 7.7).
Comments including Barriers to adoption and other options	P supplementation is considered the best investment available in terms of returns and is expected to lift the productivity of breeding herds by 1%. The 'Easy P' project contains many positive adoption elements including simplicity of deployment, access to training tools, demonstration and an attractive ROI.

Topic	Remote feedbase budgeting
The research	Satellite imaging became available in the 1980s and CSIRO used a single band, two-weekly image collection to develop and NDVI-based system of estimating biomass. The product 'Pastures from Space' was not widely adopted. An approach using more recent technology including multispectral imaging, 5-day satellite sampling, fast computing power linked with machine learning has been developed by Cibo Labs Pty Ltd www.cibolabs.com.au. Calibrated against ground sampling, this system can predict pasture dry matter across a wide range of land and pasture types. The accuracy of dry matter is estimated at ±300 kg/ha.
The aims and potential (incl pre ROI)	Deliver timely paddock-level estimates of dry matter to assist grazing decisions, including carrying capacity, over time. Provide land condition scores for long term planning. Capacity to estimate different foliage and fodder types as well as stages of growth and senescence. BCR was not determined as this was a commercial initiative where costs are recovered through income from a user subscription model. The technology is relevant to all properties with a notional uptake target being 10% of northern grazing land.
The plan and execution of adoption (refer to methodologies)	Cibo Labs developed technology to produce a commercial product (PastureKey®). This product continues to develop through AI-based refinement as new data are collected. Initial and ongoing ground-based data collection/calibration (via phone app.) is conducted by extension staff and advisors. Demonstration to potential users was undertaken during MLA engagement activities. Next steps are to involve more extension and advisory personnel.
Success or lack of ways to measure (post BCR)	Large land holders such as northern corporate beef companies are initial clients and 50M ha, mainly in northern Australia, is currently 'managed'. Such properties use the data for dry matter assessment in 'near real time' to optimise future grazing strategies. Advisors can manage farms remotely in most cases and so save resources and costs. This initiative is a good example of a digital technology where the outputs are understandable and provides a good basis to enhance decision making.
Comments including barriers to adoption and other options	Future developments include feed quality assessment and integration with animal location tag data. Achieving market penetration will require availability of case studies and ROI for enterprises of different size and type. Providing a linked solution is a feature. For example, Cibo Labs has an API to aggregate data from their MyFarmMapper® into herd management software such as Agriweb® and thus streamline farm management tools. Tools can be readily used by advisors and should be incorporated in courses such as Nutrition, Grazing land management EDGE and PGS.

Topic	Selection of polled cattle for breeding
The research	A molecular test for the poll phenotype, which aims to increase the % of polled animals, was developed. The justification is that horned animals injure other animals and dehorning is a major factor in calf loss between branding and weaning which stands at 2% points due to infection of dehorning wounds. Dehorning is an aversive animal welfare practice that the industry plans to discontinue. The older test has been displaced by the Optimised Poll Test which is claimed to be>99% accurate in identifying the P gene, a significant gain over previous versions. Bulls that are homozygous (PP) in the test will always pass the gene on to calves.
The aim and potential of adoption (incl pre ROI)	Produce and market a test that allows bull producers across breeds to reliably identify poll animals for breeding in northern Australia. Aim for 80% adoption by 2030 so that the large majority of bulls sold are polled. In 2015 there was an expectation that 19,500 calf deaths would be avoided (value of benefit $6M annually). In addition, reduced cost of production (dehorning, operator risk) at $10 per animal is cited.
The plan and execution of adoption (refer to methodologies)	Provision of a commercial test offered either separately or alongside other genomic testing. Cost of a test is $20-30 and available through providers (eg. Neogen Australasia Pty Ltd ('HP Test') and Zoetis ('HORNPOLL')). Approximately 20% of bulls in BREEDPLAN are currently homozygous (PP) in the poll test.
Success or lack of ways to measure (post BCR)	In 2015, 12,780 (older) tests had been purchased. The Optimised Test has been available since 2020 so penetration of this test into the market is yet to be reported.
Comments including Barriers to adoption and other options	One barrier to adoption is the perception that polled bulls have poorer reproductive potential. This was largely disproved by analysis of BREEDPLAN records (Randhawa *et al*. 2021). There is a weak association with smaller calves in Brahmans and there are small negative correlations for production traits in Droughtmaster. It is unclear if the 80% adoption target cited above is 80% of bulls tested or 80% of bulls in BREEDPLAN having poll genes.

Topic	Mitigation of environmental impacts on fertility and mortality
The research	Impacts take several forms and there are several approaches to mitigation. • Provision of shade has been well researched in feedlots and live export where high temperature/humidity, clear skies and low air movements are risks of heat stress. Analysis of the importance of shade and sheltering in breeding cattle is being conducted. • Distance to water is linked to how far cattle travel each day, which is also a risk factor. Observations on breed factors show that a white coat, slick hair coat (including having the *slick* gene) can reduce body temperature by about 1°C. Brahman cattle and smaller animals are also better able to control body temperature when exposed to heat. While there are EBVs for southern breeds, genetics research in this space is critical to understand adaptation to climate variability in northern cattle.
The aim and potential (incl pre ROI)	Enhanced shade and water access is expected to provide benefits, however optimising design aspects of shade structures and BCR are required. Tree cover is another factor with potential shade, shelter and land use benefits.
The plan and execution of adoption (refer to methodologies)	Two projects are underway to develop protocols for shade provision (immediate proximity to the water point, observations on sheltering opportunities, impact on mortality,) and distance to water (Paddock Power) where 3 km^2 and 5 km^2 water ranges are being compared. Both projects include economic assessment, engaging commercial producers and field demonstrations.
Success or lack of ways to measure (post BCR)	Shade structures of various designs have been constructed on many farms. The driver for this appears to be that shade in a hot climate is an obvious need, a known mortality risk and a welfare issue. Infrastructure has been developed on many properties to reduce distance to water. While improved feedbase utilisation is a common reason for these developments, reducing walking is also important. These studies, together with attractive BCRs and an effective adoption plan are required to drive adoption.
Comments including Barriers to adoption and other options	Environmental extremes are a well-known problem and producers have commenced their own mitigation based on 'feel-good' attraction due to perceived positive animal welfare outcomes and superior land use. Both work areas involve participatory work, demonstration and will produce training and decision support materials to improve uptake. Research into climate adaptation in cattle is an urgent need.

6 Conclusions

6.1 Research, development and adoption

The goal of further research on northern breeding herd productivity is to generate adoption-ready knowledge. Opportunities for participatory research, especially engagement of producers at every step, starting from identifying the problem through to delivering the solution, should be central to the RD&A process. New projects should be partnerships between researchers and producers. The MLA-badged processes of Producer Demonstration Sites and Profitable Grazing Systems are well placed to entrench this type of thinking. Digital technology is well positioned as a means of data collection in research projects. However, the uptake of digital technology into commercial breeding herds remains a longer-term goal. Some technologies, such as remote pasture sensing and water monitoring, are already in use but with variable rates of uptake. Methods for monitoring animals or herds such as walk-over weighing are commercially available but have low penetration. Future uptake will require significant improvements in ease of use, integration, data access and economic value and should not be a high priority for public funding.

Increasing adoption of existing research outputs is the highest priority and has the potential to deliver the quickest gains. The Centre for International Economics (2016) indicates that 'MLA's adoption strategy needs more focus, particular for the northern beef industry, (where public sector capacity has declined significantly and there is less private sector takeup)'. The need for a jump in adoption success is also emphasised in the Red Meat 2030 report (Red Meat Advisory Council 2019) where an increase in funding for adoption over research is mandated. Further, the gap left by publicly funded agencies will need to be filled by private investment. However, meeting the challenge of improved adoption is not trivial. The nature of the industry makes it difficult to develop solutions that can be adopted across the industry and support change. Long distances and variable environments add to the challenge. The time for adoption to achieve impact is long, and so initiating successful adoption programs is an urgent need. The call for better focus may be best served by coordination through a single entity and bringing this activity under initiatives such as NB2 is a good start. Blending the top-down solutions with bottom-up producer-driven identification of problems and demand for solutions is a practical way forward.

6.2 MLA adoption categories

Over many years MLA has invested in adoption activities. Most of the activity has been in the south and enterprises in those regions have been the major beneficiaries of RDE&A. The disadvantage of working in the north is reflected in the lower number of events and engagements. Taking a broad view of previous adoption events compared with the number of livestock reveals that about 80% of activity occurred in the southern regions while approximately 66% of cattle production occurs in northern Australia. Nevertheless, approaches tested in the south have helped to initiate adoption efforts in the north. One example is Bred Well Fed Well in which MLA has a range of offerings that (across northern and southern regions) have engaged managers of 4.4M cattle and those attendees gave a satisfaction rating of 86.5%. Further, 82% of attendees stated an intention to make change in their enterprises. An external review of the Communication and Research Adoption Program of MLA's northern beef program was undertaken in 2009 (Chudleigh and Simpson 2009). This review found that the program had substantially achieved its goals and had met a large proportion of the performance criteria set for the three-year period. The investment in the program over the three years of $1.24 million (present value of costs in 2008/09 terms using a discount rate of 5%) was estimated to have produced a benefit cost ratio of 2.6 to 1 and a net present value of $2 million. Most of the key framework of the 2009 program remains largely intact today, including Beef Up

Forums, Producer Demonstration Sites (PDS) and EDGE Network. In the past, adoption training was fully sponsored by MLA and there were also in-kind contributions from various government extension agencies, whereas now it is largely user pays. While data such as calculations of RoI, attendance figures at events and personal intent in adopting practices have helped to improve general understanding of the impact of northern cattle adoption outcomes, actual efforts on farm are impossible to measure. The variability of geography, enterprise types, markets and weather generate too much 'noise' to see local and incremental changes.

Over time, MLA has invested in adoption and in the process has developed a framework. The adoption initiatives at MLA are comprised of five elements, four demonstrating a sequential increase in levels of producer engagement and sophistication. The fifth is an enabling initiative. These provide a range of service delivery options that can be tailored to personal preference and needs. Unsurprisingly, participation in more passive areas such as use of resource materials is highest and participatory activities which require considerable time and expense have the least engagement. The programs and their elements are:

1. Resource materials such as printed guides, websites, decision tools, 'Tips and Tools' and many are focussed on beef productivity. More than 30 'publications' are available as well as web-based material especially on the Queensland government managed FutureBeef website.
2. Awareness activities such as BeefUp Forums, unique to northern Australia, which are also used to direct producers towards adoption opportunities. The Forums commenced in 2007 and numbers of participants annually approach 1,000. BeefUp Forums supplement the resource materials, provide locally relevant information and act as a conduit for those wishing to step up to EDGE courses. Numbers of producers attending courses vary and the COVID pandemic has curtailed much of the recent activity.
3. Short term skills training offerings such as the EDGE network which commenced in 2000. These courses communicate R&D outcomes and their practical application face to face. Topics include many relevant to beef productivity such as Nutrition EDGE, Breeding EDGE, Business EDGE and Grazing Land Management. Between 2016 and 2021, 163 courses were held with 939 businesses represented nationwide.
4. Participatory projects and mentoring including PDS and Profitable Grazing Systems (PGS) courses which are designed to lead producers to change practices on farm. The PDS program is designed to support trialling of new ideas from producer groups. They focus on peer-to-peer interactions and are generally coordinated by a researcher or paid officer. As suggested by the name, multisite on-farm trials are central to each PDS project along with demonstration to an audience outside the immediate group. The topics are wide ranging and MLA maintains a database of projects. At the time of writing, 12 PDS programs had been funded in northern Australia. The PGS program is still ramping up and the focus is to engage more providers to cover the territory although in 2021 more than 600 producers attended. While its reach is small, the impact on attendees is expected to be large. The NB2 adoption plan resembles PGS in some ways including use of mentors. These approaches benefit from groups of producers working together.

In addition to the above four aspects, a fifth important initiative is to enhance livestock advisory capacity through sponsoring of Future Livestock Consultants, advisor updates, Livestock Advisors Network, future consultant sponsorship and mentoring by experienced operators. For example, the Future Livestock Consultants enrolees enter a 2-year mentoring agreement and also perform a research project. Retention in the cattle industry is high so far, but the north is still underserved, with the great majority of graduates working in southern regions.

Other initiatives that complement the framework remain in place. The Tropical Beef Technical Services supports the northern beef genetics adoption especially with seedstock producers.

However, its reach and impact are not clear. An initiative to create a Northern Beef Hub in Townsville included a proposal to offer formal credentialed training for the northern industry (Gatenby and Anderson 2018). Unfortunately, this initiative has not progressed.

6.3 NB2 structure and plan

In recent years, RD&A investment by MLA for the northern beef industry has been prioritised by producer input through NABRC and funds distributed through selection of projects from a pool of applications to an open call process. Much of the underpinning science relevant to breeding herds has been performed under this and previous schemes. In contrast, NB2 brings the stakeholders of RD&A together in one place. The division of work is across three R&D pillars (feedbase, sustainability, herd) and is brought together in an adoption node (pathway to practice) which is also tasked with trialling candidate interventions and practices to be adoption-ready. The structure lends itself to better coordination and alignment of research and development with adoption. The name 'Northern Breeding Business' emphasises the financial imperative of the initiative.

The aim is to focus on 250 properties in four regionally diverse clusters and, over 7 years, produce an extra 10 kg sale weight per head, a 5% increase in weaning rates and 1% decrease in herd (cow) mortality on these properties. The three key drivers cited are to: address calf wastage, improve adoption and improve financial sustainability. Apart from setting achievable targets, other hallmarks are embedding producers in research, a business-oriented approach and a facilitated group process to match problems with solutions. This matching process is not clearly articulated. Pinpointing the cause of a problem, such as a low weaning rate compared with peers, is not simple without further investigation. Equally, identifying solutions will rely on not only R&D evidence of a productivity gain but also on trials to establish the geographic applicability, methods of practical application and economic benefits.

Alignment with MLA adoption elements cited above are evident in the plan and this ensures that adoption initiatives can be embedded in existing and continuing programs. Nevertheless, an ongoing challenge will be to maintain programs that are self-funding. The program also has a strong evidential basis including standardised metrics and benchmarking. The types of measurements would include breeder performance (e.g. pregnancy rate, weaning rate) and growth (e.g. annual liveweight production) and economic performance. A shortcoming, however, is that annual variation may disguise longer term trends, so collection of data in a longitudinal fashion will be required and may delay the identification of problem areas.

A stated aim under the herd pillar is the 'rapid dissemination of superior genetics'. In particular, increased use of bulls with superior EBVs to improve genetic traits such as female reproductive efficiency and tick resistance has great potential to deliver productivity gains. However, we were unable to find a target for genetic gain or a plan for adoption in either publicly available sites or NB2 plans. This is a serious deficiency that requires attention.

6.4 Potential role of marketing techniques

Given the renewed effort on adoption in NB2, it is timely to look for other viewpoints on adoption and assess the value of alternative approaches. This is asking what can we do differently? It is worth reflecting on how marketing approaches can be used to drive practice change and if any of those insights can be usefully applied to beef breeding herds. Promoting change is a social science and, while not covered in detail here, some ideas are suggested.

Aspects that seem appropriate are profiling producers, matching profiles to preferred communication methods, understanding work routines and using techniques to promote change. Surveys have been used to segment Australian beef producers based on business and lifestyle aspirations, but this knowledge has not been specifically applied. This notion is included in the NB2 plan but it needs to be further articulated. One benefit of understanding profiles is in determining how individual producers prefer to receive information and training. For example, some may prefer passive means such as printed media or websites while others may show a preference for interactive webinars, on-line meetings or face-to-face learning. Providing material to producers in a preferred medium and on a relevant topic may be more successful that random activity in this space. Understanding individual work routines also can help to assess 'default bias' which is a tendency to resist change. This knowledge can help in designing new practices that can be accommodated into a work routine or business plan. Infrastructure improvements also need to overcome 'default bias' that reinforces the status quo. Other aspects include what approaches experts can take in mentoring and coaching, how other producers can be effective peer-to-peer influencers, belief in innovation as a way to achieve goals and how marketing techniques such as 'nudging' may be used. These approaches that leverage social science are not obvious in the P2P planning and deserve examination and testing.

6.5 Coordinated adoption

While the elements of adoption exist, bringing them into focus to deliver results remains a challenge. There appears to be a lack of coordination of this effort.

The needs and preferences of producers vary widely and match the range of MLA adoption elements that are available. MLA has tailored its offerings to deliver an industry-wide remit but NB2 has chosen to influence a subset of the industry by focussing on 250 producers. Not only are these producers more likely to be amenable to change, the likelihood of success will be enhanced by their being coached through the process. A further strength is in aligning this with the MLA elements. The production targets for the enrolled properties are ambitious but achievable, and the support offered to each producer group, as well as the producer-driven ethos, has been well thought out. The unstated benefit is that these 250 properties will be exemplars for the rest of the industry and will provide case studies with evidence-based productivity and economic records. This will provide powerful leverage to promote further adoption.

Coordination of effort is essential. The system of adoption needs to cater for the idiosyncrasies of each property and manager, and provide a customised approach offering the full range of adoption choices. These include options in all of the NB2 work areas. If an individual producer wants to set worthy goals and introduce proven innovations, then they will need a single source of information and access to appropriate experts to interpret, contextualise, direct them to resources and examples, advise and mentor them. Economic goals and plans are also central to this.

The likely benefits of a multipronged, coordinated approach have been demonstrated by simulation modelling (Ash *et al*. 2015). This study modelled the impact of a number of scenarios on herd productivity parameters across three sites in northern Australia. Just the predicted weaning rates for northern Queensland are quoted here to illustrate the point. The predicted weaning rates (%) for each scenario were: baseline rate, 58; improved reproduction through genetic gain, 63; improved growth genetics, 61; improved rumen function, 64; improved pastures, 69; cheap protein supplement, 69. When the technologies were combined a weaning rate of 76% was predicted. While this was theoretical exercise, the model suggests that gains can be made using initiatives in concert.

A producer needs to be able to choose which innovation or combination would best suit their situation, so all options need to be on the table.

6.6 Low hanging fruit

Rapid uptake of existing research findings is important because there are long lead times in achieving the benefits of adoption and the time horizon for NB2 is short. A number of research-based innovations are already backed by good value propositions or are developing compelling arguments for adoption and should be actively promoted. Examples such as remote feedbase monitoring and genetic gain have broad industry application but need clearer pathways to improve uptake and increase breeding herd productivity. Benefits from P supplementation are likely be economically rewarding in areas where P is deficient.

6.7 Meeting a critical need

Perhaps the most critical unmet need to facilitate adoption in the northern beef industry is the widespread lack of access to experienced and competent advisors. While we endorse the broad scope of the MLA framework for adoption, a mechanism is needed to ramp up support for adoption in the north to a level that approaches that achieved in southern regions. This would require decisions to be made on both the focus of desired adoption outcomes and the approaches to be used. The focus for adoption and adoption targets can be drawn from the Recommendations in this report, listed below. The approach must include the training and regional embedding of advisors who can lead and mentor. Timing will also be critical as the skills of the currently active cohort of advisors may soon be lost due to retirement or resignation and dwindling financial support. This need could be met by establishing a northern beef adoption entity to drive appropriate training and ongoing support. NB2 could be an appropriate early platform for such an initiative to bring forward younger trainee advisors. NB2 can also set specific adoption goals, establish a data management system and identify the desired skill sets of future advisors. Once NB2 concludes , MLA will be better placed to use the learnings to establish and support a northern hub that not only trains advisors but acts as a point of integration of ideas, manages data including electronic communications, and promotes adoption in the northern beef industry.

7 Recommendations

The following list of recommendations to advance the northern beef breeding industry are taken from the text and related to conclusions drawn in the previous section. These are not intended to be prescriptive or all-encompassing, but to provide guidance by identifying elements of NB2 that appear to be appropriately aligned with industry objectives and highlighting areas of work that need attention.

7.1 Priority recommendations

The following six recommendations are intended to address priority needs, some of which could have short-term impact while 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 NB2 goal of identifying and implementing appropriate and uniform metrics for assessing breeding herd performance is strongly endorsed. 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. A tenet is producer engagement in this activity and in other trials and research work within NB2.

2. Studies on the causes of calf and cow mortality should be continued to better understand 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, estimate pasture biomass and other key variables as elaborated in the NB2 Feedbase Learning Program. 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. ‘Sweet Spot’ project. Involvement in a current project on remote sensing of feed on offer could be a particular opportunity for all producers taking part in the NB2 initiative.

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. 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 likelihood of post-partum anoestrous.

   Advertisement 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 adequately feed 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 should 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.

7.2 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 for drought management and decision-making, and promoting 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. Research and development 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, leucaena stands out, at least in regions with appropriate soil types and adequate rainfall. Efforts to fulfil leucaena's undoubted potential should include increasing producer awareness of both its productive benefits and potential challenges to its 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. New research on mitigation of methane emissions of individual animals is not recommended. However, 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.

8 Bibliography

ABARES (2019) Beef farms. Available at: https://www.agriculture.gov.au/abares/research-topics/surveys/beef#table-9 [Verified 26 July 2020]

Abdelatty AM, Iwaniuk ME, Potts SB, Gad A (2018) Influence of maternal nutrition and heat stress on bovine oocyte and embryo development. *International Journal of Veterinary Science and Medicine* **6**, S1-S5.

Allen LR, Barnes TS, Fordyce G, McCosker KD, McGowan MR (2021) Reproductive performance of northern Australia beef herds. 8. Impact of rainfall and wild dog control on percentage fetal and calf loss. *Animal Production Science*. doi:10.1071/AN19430

Alvarez-Hess PS, Thomson AL, Karunaretne SB, Douglas ML, Wright MM, Heard JW, Jacobs JL, Mores-McNabb EM, Wales WJ, Auldist MJ (2021) Using multispectral data from an unmanned aerial system to estimate pasture depletion during grazing. *Animal Feed Science and Technology* **275**, 114880.

Anon (2011) Case study: Brahman reproduction at Gundaroo. Beef Bulletin Quarter 4. http://www.beefcrc.com/documents/products/case-studies/Alf_Collins.pdf [Verified 05 September 2020]

Ash A, Hunt L, McDonald C, Scanlan J, Bell L, Cowley R, Watson I, McIvor J, MacLeod N (2015) Boosting the productivity and profitability of northern Australian beef enterprises: Exploring innovation options using simulation modelling and systems analysis. *Agricultural Systems* **139**, 50-65.

Ash AJ, Bellamy JA, Stockwell TGH (1994) State and transition models for rangelands. 4. Application of state and transition models to rangelands in northern Australia. *Tropical Grasslands* **28**, 223-228.

Ash AJ, Corfield JP, McIvor JG, Ksiksi TS (2011) Grazing management in tropical savannas: utilization and rest strategies to manipulate rangeland condition. *Rangeland Ecology and Management* **64**, 223-239.

Ash AJ, McIvor JG (1998) How season of grazing and herbivore selectivity influence monsoon tall-grass communities of northern Australia. *Journal of Vegetation Science* **9**, 123-132.

Australian Government (2016) Boosting farm productivity – improved soils and reduced greenhouse gas emissions. Department of Agriculture and Water Resources, Canberra. https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/climate-change/carbon-farming/boosting-farm-productivity.pdf [Verified 18 April 2021)

Australian Government (2020) National inventory report: 2018 Volume 1. Commonwealth of Australia, Canberra. https://www.industry.gov.au/sites/default/files/2020-05/nga-national-inventory-report-2018-volume-1.pdf [Verified 11 April 2021]

Barwick SA, Wolcott ML, Johnston DJ, Burrow HM, Sullivan M (2009a) Genetics of steer daily feed intake and residual feed intake in tropical beef genotypes and relations among intake, body composition, growth and other post weaning measures. *Animal Production Science* **49**, 351-366.

Barwick SA, Johnston DJ, Burrow HM, Holroyd RG, Fordyce G, Wolcott ML, Sim W, Sullivan M (2009b) Genetics of heifer performance in 'wet' and 'dry' seasons and their relationships with steer performance in two tropical beef genotypes. *Animal Production Science* **49**, 367-382.

Baumgard LH, Rhoads RP Jr (2013) Effects of heat stress on postabsorptive metabolism and energetics. *Annual Review of Animal Biosciences* **1**, 311-337.

Beatty DT, Barnes A, Taylor E, Pethick D, McCarthy M, Maloney SK (2006) Physiological responses of *Bos taurus* and *Bos indicus* cattle to prolonged, continuous heat and humidity. *Journal of Animal Science* **84**, 972-985.

Bell L, Fainges J, Darnell R, Cox K, Peck G, Hall T, Silcock R, Cameron A, Pengelly B, Cook B, Clem B, Lloyd D (2016) Stocktake and analysis of legume evaluation for tropical pastures in Australia. Final Report of Project B.NBP.0765. Meat and Livestock Australia, North Sydney NSW.

Bertram JD, Fordyce G, McGowan MR, Jayawardhana GA, Fitzpatrick LA, Doogan VJ, De Faveri J, Holroyd RG (2002) Bull selection and use in northern Australia 3. Serving capacity tests. *Animal Reproduction Science* **71**, 51-66.

Black AW (2000) Extension theory and practice: a review. *Australian Journal of Experimental Agriculture* **40**, 493-502.

Black JL, Davison TM, Box I (2021) Methane emissions from ruminants in Australia: mitigation potential and applicability of mitigation strategies. *Animals* **11**, 951.

Blackshaw JK, Blackshaw AW (1994) Heat stress in cattle and the effect of shade on production and behaviour: a review. *Australian Journal of Experimental Agriculture* **34**, 285-295.

Bortolussi G, McIvor JG, Hodgkinson JJ, Coffey SG, Holmes CR (2005a) The 1996-97 CSIRO northern Australian beef industry survey: methods and data classification. Australian Journal of Experimental Agriculture Accessory Publication.

Bortolussi G, McIvor JG, Hodgkinson JJ, Coffey SG, Holmes CR (2005b) The northern Australian beef industry, a snapshot. 2. Breeding herd performance and management. *Australian Journal of Experimental Agriculture* **45**, 1093-1108.

Bortolussi G, McIvor JG, Hodgkinson JJ, Coffey SG, Holmes CR (2005c) The northern Australian beef industry, a snapshot. 3. Annual liveweight gains from pasture based systems. *Australian Journal of Experimental Agriculture* **45**, 1075-1091.

Bowen MK, Chudleigh F (2021) An economic framework to evaluate alternative management strategies for beef enterprises in northern Australia. *Animal Production Science* **61**, 271-281.

Bowen MK, Chudleigh F, Buck S, Hopkins K (2018) Productivity and profitability of forage options for beef production in the subtropics of northern Australia. *Animal Production Science* **58**, 332-342.

Bowen MK, Chudleigh F, Dixon RM, Sullivan MT, Schatz T, Oxley T (2020) The economics of phosphorus supplementation of beef cattle grazing northern Australian rangelands. *Animal Production Science* **60**, 683-693.

Briske DD, Derner JD, Brown JR, Fuhlendorf SD, Teague WR, Havstad KM, Gillen RL, Ash AJ, Willms WD (2008) Rotational grazing on rangelands: reconciliation of perception and experimental evidence. *Rangeland Ecology and Management* **61**, 3-17.

Brown JN, Ash A, Macleod N, McIntosh P. (2019) Diagnosing the weather and climate features that influence pasture growth in Northern Australia. *Climate Risk Management* **24**, 1-12.

Buck S, Rolfe J, Lemin C, English B (2019a) Establishment of leucaena in Australia. *Tropical Grasslands-Forrajes Tropicales* **7**, 104-111.

Buck S, Rolfe J, Lemin C, English B (2019b) Adoption, profitability and future of leucaena feeding systems in Australia. *Tropical Grasslands-Forrajes Tropicales* **7**, 303-314.

Bunter KL, Johnston DJ, Wolcott ML, Fordyce G (2014) Factors associated with calf mortality in tropically adapted beef breeds managed in extensive Australian production systems. *Animal Production Science* **51**, 25-36. doi:10.1071/AN12421

Bunter KL, Johnston DJ (2014) Genetic parameters for calf mortality and correlated cow and calf traits in tropically adapted beef breeds managed in extensive Australian production systems. *Animal Production Science* **54**, 50-59. doi:10.1071/AN12422

Burns BM, Fordyce G, Holroyd RG (2010) A review of factors that impact on the capacity of beef females to conceive, maintain a pregnancy and wean a calf – Implications for reproductive efficiency in northern Australia. *Animal Reproduction Science* **122**, 1-22.

Burrow HM (2001) Variances and covariances between productive and adaptive traits and temperament in a composite breed of tropical beef cattle. *Livestock Production Science* **70**, 213-233.

Burrow HM (2012) Importance of adaptation and genotype x environment interactions in tropical breeding systems. *Animal* **6**, 729-740.

Burrow HM, Griffith GR, Barwick SA, Holmes WE (2012) Economic value of crossbreeding and grain-finishing tropically adapted cattle. Outcomes of past investments in Beef CRC (1993-2005). Appendix 6 – Northern crossbreeding. http://www.beefcrc.com/products/outcomes-of-past-investments-in-beef-crc.html [Verified 15 March 2021]

Burrows WH, Orr DM, Hendricksen RE, Rutherford MT, Myles DJ, Back PV, Gowen R (2010) Impacts of grazing management options on pasture and animal productivity in a *Heteropogon contortus* (black speargrass) pasture in central Queensland. 4. Animal production. *Animal Production Science* **50**, 284-292.

Cameron DF, Edye LA, Chakraborty S, Manners JM, Liu CJ, Date RA, Boland RM (1996) An integrated program to improve anthracnose resistance in Stylosanthes – a review. Proceedings of the 8th Australian Society of Agronomy Conference, 30 January – 2 February, Toowoomba, Australia.

Campbell S, Vogler W, Brazier D, Vitelli J, Brooks S (2019) Weed leucaena and its significance, implications and control. *Tropical Grasslands-Forrajes Tropicales* **7**, 280-289.

Chakraborty S (2004) Anthracnose disease of *Stylosanthes*. In 'High-yielding anthracnose-resistant *Stylosanthes* for agricultural systems.' (Ed. S Chakraborty) pp. 113-124 (ACIAR Monograph No. 111: Canberra)

Chang AZ, Swain DL, Trotter MG (2020a) Calf loss in northern Australia: a systematic review. *The Rangeland Journal* **42**, 9-26. doi.10.1071/RJ19049

Chang AZ, Swain DL, Trotter MG (2020b) Towards sensor-based calving detection in the rangelands: a systematic review of credible behavioral and physiological indicators. *Translational Animal Science* **4**, 1-18. doi:10.1093/tas/txaa155

Charmley E, Williams SRO, Moate PJ, Hegarty RS, Herd RM, Oddy VH, Reyenga P, Staunton KM, Anderson A, Hannah MC (2016) A universal equation to predict methane production of forage-fed cattle in Australia. *Animal Production Science* **56**, 169-180.

Chilcott C, Ash A, Lehnert S, Stokes C, Charmley E, Collins K, Pavey C, Macintosh A, Simpson A, Berglas R, White E, Amity M (2020) Northern Australia beef situation analysis. A report to the Cooperative Research Centre for Developing Northern Australia.

Chudleigh P, Simpson S (2009) External review of MLA northern beef communications and research adoption program. Final Report of Project B.NBP.0513. Meat and Livestock Australia, North Sydney NSW.

Clements RJ, Henzell EF (2010) Pasture research and development in northern Australia: an ongoing scientific adventure. *Tropical Grasslands* **44**, 221-230.

Coates DB, Dixon RM, Mayer RJ (2019) Between-year variation in the effects of phosphorus deficiency in breeder cows grazing tropical pastures. *Tropical Grasslands-Forrajes Tropicales* **7**, 223-233.

Coates DB, Le Feuvre RP (1998) Diet composition of cattle grazing *Stylosanthes*-grass pastures in the seasonally dry tropics: the effect of phosphorus as fertiliser or supplement. *Australian Journal of Experimental Agriculture* **38**, 7-15.

Coates DB, Miller CP, Hendricksen RE, Jones RJ (1997) Stability and productivity of *Stylosanthes* pastures in Australia. II. Animal production from *Stylosanthes* pastures. *Tropical Grasslands* **31**, 494-502.

Cobon DH, Darbyshire R, Crean J, Kodur S, Simpson M, Jarvis C. (2020a) Valuing seasonal climate forecasts in the northern Australia beef industry. *Weather, Climate, and Society* **12**, 3-14.

Cobon DH, Stone G, Carter J, McKeon G, Zhang B, Heidemann H (2020b) Native pastures and beef cattle show a spatially variable response to a changing climate in Queensland, Australia. *European Journal of Agronomy* **114** (126), 002.

Collins J, Gardiner CP, Kempe N, Hannah I (2016) Successful pasture development at Cungelella: a grazier, a researcher and a seed company's perspective. Proceedings of the Northern Beef Research Update Conference, Rockhampton 15-18 August 2016, pp 67-72.

Cook BG, Pengelly BC, Brown SD, Donnelly JL, Eagles DA, Franco MA, Hanson J, Mullen BF, Partridge IJ, Peters M, Schultze-Kraft R (2005) Tropical Forages: an interactive selection tool. CSIRO, DPI&F (Qld), CIAT and ILRI, Brisbane, Australia. www.tropicalforages.info [Verified 29 September 2020]

Corbet NJ, Burns BM, Johnston DJ, Wolcott ML, Corbet DH, Venus BK, Li Y, McGowan MR, Holroyd RG (2013) Male traits and herd reproductive capability in tropical beef cattle. 2. Genetic parameters of bull traits. *Animal Production Science* **53**, 101-113.

Costa DFA, Quigley SP, Isherwood P, McLennan SR, Poppi DP (2016) Supplementation of cattle fed tropical grasses with mocroalgae increases microbial protein production and average daily gain. *Journal of Animal Science* **94**, 2047-2058.

Cowan T, Stone R, Wheeler MC, Griffiths M (2020) Improving the seasonal prediction of Northern Australian rainfall onset to help with grazing management decisions. *Climate Services* **19**, 100182.

Cowley R, McCosker K, Pahl L, Smith D, Whish G, Wooderson M, Fordyce G, Holloway C, Jenner D, Materne C (2019) Finding the 'Sweet Spot' for reproductive performance in north Australian beef herds. Proceedings of the Northern Beef Research Update Conference, Brisbane 19-22 August 2019, p 94.

Cowley R, Walsh D, Collier C, Jenner D, Hearnden M (2020) Forage utilisation and consumption patterns with distance from water. Northern Territory Government, Australia. Technical Bulletin No. 359.

Cox KG (2016) Recent development and commercial adoption of legumes for heavy clay soils in Queensland. In 'Tropical forage legumes: harnessing the potential of *Desmanthus* and other genera for heavy clay soils' (Eds. JR Lazier, N Ahmed) pp. 254-282.

Cox K, Dayes S, Lemin C, Keating M, Bambling L (2019) Seed production of some promising new grasses for seasonally dry areas of northern and central Queensland. Proceedings of the Northern Beef Research Update Conference, Brisbane 19-22 August 2019, p 127.

CSIRO (2020) ADOPT: Adoption Diffusion Outcome Prediction Tool. https://www.csiro.au/en/research/technology-space/it/adopt [Verified 5 June 2021]

Dalzell SA (2019) Leucaena cultivars – current releases and future opportunities. *Tropical Grasslands-Forrajes Tropicales* **7**, 56-64.

Davis GP, Corbet NJ, Mackinnon MJ, Hetzel DJS, Entwistle KW, Dixon R (1993) Response in female fertility and calf growth to selection for pregnancy rate in tropical beef cattle. *Australian Journal of Agricultural Research* **44**, 1509-1521.

Dixon RM (1998) Improving cost-effectiveness of supplementation systems for breeder herds in northern Australia. Final Report of Project DAQ.098. Meat and Livestock Australia, North Sydney NSW.

Dixon RM, Anderson ST, Kidd LJ, Fletcher MT (2020) Management of phosphorus nutrition of beef cattle grazing seasonally dry rangelands: a review. *Animal Production Science* **60**, 863-879.

Dixon RM, Coates D (2019) Blood phosphorus concentration depends on the reproductive status of breeder cows. Proceedings of the Northern Beef Research Update Conference, Brisbane 19-22 August 2019, p 95.

Dixon RM, Coates D, Holmes B, English B, Rolfe J (2011a) Phosphorus nutrition and management – overcoming constraints to wider adoption. Proceedings of the Northern Beef Research Update Conference, Darwin 3-4 August 2011, pp 102-109.

Dixon RM, Coates DB, Reid DJ (2018) The effects of supplementary P in the diet on the concentration of P in faeces. *Animal Production Science* **58**, 2600.

Dixon RM, Mayer B (2021) Effects of a nitrogen-based supplement on intake, live weight and body energy reserves in breeding *Bos indicus* cross cows. *Tropical Grasslands* **9**, 70-80.

Dixon RM, Muller J, Mayer B (2019) Blood phosphorus concentration may be highly variable in mixed age breeder herds. Proceedings of the Northern Beef Research Update Conference, Brisbane 19-22 August 2019, p 96.

Dixon RM, Playford C, Coates DB (2011b) Nutrition of beef breeder cows in the dry tropics 1. Effects of nitrogen supplementation and weaning on breeder performance. *Animal Production Science* **51**, 515-528.

Dixon RM, Playford C, Coates DB (2011c) Nutrition of beef breeder cows in the dry tropics 2. Effects of time of weaning and diet quality on breeder performance. *Animal Production Science* **51**, 529-540.

Dixon RM, Porch IK, D'Occhio MD, Fordyce G (1996) Effects of dry season and wet season supplementation on fertility of *Bos indicus* cross cows. *Proceedings of the Australian Society of Animal Production* **21**, 441.

Dixon RM, White A, Fry P, Fordyce G, D'Occhio M (1997a) Effect of dry season licks containing dried molasses or cottonseed meal for first-calf heifers. *Swans Lagoon Annual Report* 1997, 18-22.

Dixon RM, White A, Fry P, Fordyce G, D'Occhio M (1997b) Effect of dry lick supplements fed during the early and/or late dry season on productivity of Bos indicus X Shorthorn cross breeder cows. *Swans Lagoon Annual Report* 1997, 23-30.

Dyer RM, Cafe L, Cobiac M, Cowley R (2003) Developing sustainable grazing management systems for the semi-arid tropics. Final Report of Project NAP3.211. Meat and Livestock Australia, North Sydney NSW.

Edirisinghe A, Hill MJ, Donald GE, Hyder M (2011) Quantitative mapping of pasture biomass using satellite imagery. *International Journal of Remote Sensing* **32**, 2699-2724.

Edye LA (1997) Commercial development of *Stylosanthes* pastures in northern Australia. I. Cultivar development within *Stylosanthes* in Australia. *Tropical Grasslands* **31**, 503-508.

Ehleringer JR, Cerling TE, Helliker BR (1997) C_4 photosynthesis, atmospheric CO_2, and climate. *Oecologia* **112**, 285-299.

Engle BN, Corbet NJ, Allen JM, Laing AR, Fordyce G, McGowan MR, Burns BM, Lyons RE, Hayes BJ (2019) Multivariate genomic predictions for age at puberty in tropically adapted beef heifers. *Journal of Animal Science* **97**, 90-100.

Fisher A (2001) Biogeography and conservation of Mitchell grasslands in northern Australia. PhD Thesis, Charles Darwin University, Darwin, Australia.

Fitzpatrick LA (2020) Northern Breeding Business: NB2 Strategic Partnership Development. Final Report of Project L.NAB.1903. Meat and Livestock Australia, North Sydney NSW.

Fitzpatrick LA, Fordyce G, McGowan MR, Bertram JD, Doogan VJ, De Faveri J, Miller RG, Holroyd RG (2002) Bull selection and use in northern Australia 2. Semen traits. *Animal Reproduction Science* **71**, 39-49.

Fordyce G, Cooper NJ, Kendall IE, O'Leary BM, de Faveri C (1996) Creep feeding and prepartum supplementation effects on growth and fertility of Brahman cross cattle in the dry tropics. *Australian Journal of Experimental Agriculture* **36**, 389-395.

Fordyce G, Fitzpatrick LA, Mullins TJ, Cooper NJ, Reid DJ, Entwistle KW (1997) Prepartum supplementation effects on growth and fertility in *Bos indicus*-cross cows. *Australian Journal of Experimental Agriculture* **37**, 141-149.

Fordyce G, McCosker K, Smith D, Perkins N, O'Rourke P, McGowan M (2021) Reproductive performance of northern Australia beef herds. 7. Risk factors affecting mortality rates of pregnant cows. *Animal Production Science*, in press.

Forkuor G, Hounkpatin OKL, Welp G, Thiel M (2017) High resolution mapping of soil properties using remote sensing variables in south-western Burkina Faso: a comparison of machine learning and multiple linear regression models. *PloS ONE* **12**: e0170478.

Frisch JE (1981) Changes occurring in cattle as a consequence of selection for growth rate in a stressful environment. *Journal of Agricultural Science, Cambridge* **96**, 23-38.

FutureBeef (2020) CalfWatch – developing a system to remotely monitor calving in northern Australia. https://futurebeef.com.au/knowledge-centre/calfwatch-developing-a-system-to-remotely-monitor-calving-in-northern-australia/ [Verified 12 August 2021]

FutureBeef (2021a) Quality Graze – so much more than a rotational grazing project. https://futurebeef.com.au/projects/quality-graze/ https://futurebeef.com.au/projects/quality-graze/ [Verified 2 April 2021]

FutureBeef (2021b) Phosphorus supplementation of cattle in Northern Australia. https://futurebeef.com.au/knowledge-centre/phosphorus-supplementation-of-cattle-in-northern-australia/#managing%20intake [Verified 19 May 2021]

Gardiner CP (2016) Developing and commercialising new pasture legumes for clay soils in the semiarid rangelands of northern Australia: The new *Desmanthus* cultivars JCU 1-5 and the Progardes story. In 'Tropical forage legumes: harnessing the potential of *Desmanthus* and other genera for heavy clay soils' (Eds. JR Lazier, N Ahmed) pp. 283-304. (CABI: Wallingford, UK)

Gardiner C, Kempe C, Kempe N, Campbell G, Fleury H, Malau-Aduli AEO, Walker G, Suybeng B, Mwangi F (2019) Progardes Desmanthus – an update. Proceedings of the Northern Beef Research Update Conference, Brisbane 19-22 August 2019, p. 46.

Gardiner CP, Parker A (2012) Steer liveweight gains on Progardes™/buffel pastures in Qld. Proceedings of the 2nd Australian and New Zealand Societies of Animal Production Joint Conference, Lincoln University, Christchurch 2-5 July 2012, pp.

Gatenby A, Anderson A (2018) Scoping the viability, feasibility and capacity for a Northern beef centre of excellence. Final Report of Project B.GBP.0033. Meat and Livestock Australia, North Sydney NSW.

Gaughan JB, Bonner S, Loxton I, Mader TL, Lisle A, Lawrence R (2010a) Effect of shade on body temperature and performance of feedlot steers. *Journal of Animal Science* **88**, 4056-4067.

Gaughan JB, Mader TL, Holt SM (2008a) Cooling and feeding strategies to reduce heat load of grain-fed beef cattle in intensive housing. *Livestock Science* **113**, 226-233.

Gaughan JB, Mader TL, Holt SM, Lisle A (2008b) A new heat load index for feedlot cattle. *Journal of Animal Science* **86**, 226-234.

Gaughan JB, Mader TL, Holt SM, Sullivan ML, Hahn GL (2010b) Assessing the heat tolerance of 17 beef cattle genotypes. *International Journal of Biometeorology* **54**, 617-627.

Gonzales-Rivas PA, Sullivan M, Cottrell JJ, Leury BJ, Gaughan JB, Dunshea FR (2018) Effect of feeding slowly fermentable grains on productive variables and amelioration of heat stress in lactating dairy cows in a sub-tropical summer. *Tropical Animal Health and Production* **50**, 1763-1769.

Gorman J, Cox K, Peck G (2019) Tolerance of new stylosanthes lines to leaf and stem diseases. Proceedings of the Northern Beef Research Update Conference, Brisbane 19-22 August 2019, p. 125.

Gray S (1968) A review of research on *Leucaena leucocephala*. *Tropical Grasslands* **2**, 19-30.

Greenwood PL, Gardner GE, Ferguson DM (2018) Current situation and future prospects for the Australian beef industry – a review. *Asian-Australasian Journal of Animal Sciences* **31**, 992-1006.

Grice AC, Watson I, Stone P (Eds.) (2013) 'Mosaic irrigation for the Northern Australian beef industry. An assessment of sustainability and potential.' Technical Report. (CSIRO Sustainable Agriculture Flagship: Brisbane).

Hacker JB (1997) Priorities and activities of the Australian Tropical Forages Genetic Resource Centre. *Tropical Grasslands* **31**, 243-250.

Hall TJ, McIvor JG, Jones P, Smith DR, Mayer DG (2016) Comparison of stocking methods for beef production in northern Australia: seasonal diet quality and composition. *The Rangeland Journal* **38**, 553-567.

Hall TJ, McIvor JG, Reid DJ, Jones P, MacLeod ND, McDonald CK, Smith DR (2014) A comparison of stocking methods for beef production in northern Australia: pasture and soil surface condition responses. *The Rangeland Journal* **36**, 161-174.

Hall TJ, Walker RW (2005) Pasture legume adaptation to six environments of the seasonally dry tropics of north Queensland. *Tropical Grasslands* **39**, 182-196.

Halliday MJ, Giles HE, Padmanabha J, McSweeney CS, Dalzell SA, Shelton HM (2019) The efficacy of a cultured *Synergistes jonesii* inoculum to control hydroxypyridone toxicity in *Bos indicus* steers fed leucaena/grass diets. *Animal Production Science* **59**, 696-708.

Hansen PJ (2009) Effects of heat stress on mammalian reproduction. *Philosophical Transactions of the Royal Society B* **364**, 3341-3350.

Hansen PJ (2013) Cellular and molecular therapies to ameliorate effects of heat stress on embryonic development in cattle. *Animal Reproduction* **10**, 322-333.

Harper K, Quigley SP, Antari R, Anuddin D, Panjaitan TS, Marsetyo M, Poppi DP (2019) Energy supplements for leucaena. *Tropical Grasslands-Forrajes Tropicales* **7**, 182-188.

Hasker P (2000) Beef cattle performance in northern Australia: a summary of recent research. Department of Primary Industries, Brisbane QLD.

Hawkins H (2016) Does holistic planned grazing work in rangelands? A global meta-analysis. In 'The future management of grazing and wild lands in a high-tech world. Proceedings of the 10th International Rangeland Congress'. 16-22 Jul 2016, Saskatoon, Canada. (Eds A. Iwaasa, HA Lardner, M Schellenberg, W Willms, K Larson) pp. 933-934.

Heatley D (2019) Irrigated leucaena in the Burdekin catchment produces high quality cattle for premium markets. *Tropical Grasslands-Forrajes Tropicales* **7**, 345-347.

Henry B, Charmley E, Eckard R, Gaughan JB, Hegarty R (2012) Livestock production in a changing climate: adaptation and mitigation research in Australia. *Crop and Pasture Science* **63**, 191-202.

Holmes P, McLean I, Banks R (2017) The Australian Beef Report. Bush Agribusiness Pty Ltd, Toowoomba QLD.

Holroyd RG (1987) Foetal and calf wastage in *Bos indicus* cross beef genotypes. *Australian Veterinary Journal* **64**, 133-137.

Holroyd RG, Dunster, O'Rourke PK (1988) Effect of cattle tick (*Boophilus microplus*) infestation on performance of *Bos indicus* cross cows and their progeny. *Australian Journal of Experimental Agriculture* **28**, 1-9.

Holroyd RG, O'Rourke PK (1989) Collation of basic biological data on beef cattle production in north Australia. The Australian Meat and Livestock Research and Development Corporation, Sydney NSW.

Holroyd RG, O'Rourke PK, Allan PJ (1979) Reproductive performance of Shorthorn and Brahman cross cows in the dry tropics of north Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry* **19**, 276-282.

Hughes S, Smith R, Cox K, Humphries A, McClements D, Harris C, Rogers M-J (2017) The Australian Pastures Genebank – A short history and update of progress. Proceedings of the 18th Australian Society of Agronomy Conference, 24-28 September 2017, Ballarat, Australia.

Hunt LP (2008) Safe pasture utilisation rates as a grazing management tool in extensively grazed tropical savannas of northern Australia. *The Rangeland Journal* **30**, 305-315.

Hunt LP, McIvor JG, Grice AC, Bray SG (2014) Principles and guidelines for managing cattle grazing in the grazing lands of northern Australia: stocking rates, pasture resting, prescribed fire, paddock size and water points – a review. *The Rangeland Journal* **36**, 105-119.

Hunt LP, Petty S, Cowley R, Fisher A, Ash AJ, MacDonald N (2007) Factors affecting the management of cattle grazing distribution in northern Australia: preliminary observations on the effect of paddock size and water points. *The Rangeland Journal* **29**, 169-179.

Hunt LP, Petty S, Cowley R, Fisher A, White A, MacDonald N, Pryor M, Ash A, McCosker K, McIvor J, MacLeod N (2013) Sustainable development of Victoria River District (VRD) grazing lands. Meat and Livestock Australia, North Sydney NSW.

Jackson D, Rolfe J, English B, Holmes B, Matthews R, Dixon R, Smith P, MacDonald N (2012) Phosphorus management of beef cattle in northern Australia. Meat and Livestock Australia, North Sydney NSW.

Johnston DJ (2013) Genetic keys to progress: improving female reproduction in tropical beef breeds. Proceedings of the Northern Beef Research Update Conference, Cairns 12-15 August 2013, pp 67-72.

Johnston DJ, Barwick SA, Corbet NJ, Fordyce G, Holroyd RG, Williams PJ, Burrow HM (2009) Genetics of heifer puberty in two tropical beef genotypes in northern Australia and associations with heifer- and steer-production traits. *Animal Production Science* **49**, 399-412.

Johnston DJ, Barwick SA, Fordyce G, Holroyd RG, Williams PJ, Corbet NJ, Grant T (2014a) Genetics of early and lifetime annual reproductive performance in cows of two tropical beef genotypes in northern Australia. *Animal Production Science* **54**, 1-15.

Johnston DJ, Corbet NJ, Barwick SA, Wolcott ML, Holroyd RG (2014b) Genetic correlations of young bull reproductive traits and heifer puberty traits with female reproductive performance in two tropical beef genotypes in northern Australia. *Animal Production Science* **54**, 74-78.

Johnston DJ, Grant TP, Schatz TJ, Burns BM, Fordyce G, Lyons RE (2017) The *Repronomics* project – enabling genetic improvement in northern Australia. *Proceedings of the Association for Advancement of Animal Breeding and Genetics* **22**, 385-388.

Johnston DJ, Moore KL (2019) Genetic correlation between days to calving and other male and female reproduction traits in Brahman cattle. *Proceedings of the Association for Advancement of Animal Breeding and Genetics* **23**, 354-357.

Johnston D, Moore K, Cook J, Grant T (2019) Enabling genetic improvement of reproduction in tropical beef cattle. Final Report of Project B.NBP.0759. Meat and Livestock Australia, North Sydney NSW.

Jones RJ, McGarrity RG (1986) Successful transfer of DHP-degrading bacteria from Hawaiian goats to Australian ruminants to overcome the toxicity of Leucaena. *Australian Veterinary Journal* **63**, 259-262.

Jones RM, Brandon NJ (1998) Persistence and productivity of eight accessions of *Desmanthus virgatus* under a range of grazing pressures in subtropical Queensland. *Tropical Grasslands* **32**, 145-152.

Jones RM, McDonald CK, Clements RJ, Bunch GA (2000) Sown pastures in subcoastal south-eastern Queensland: pasture composition, legume persistence and cattle liveweight gain over 10 years. *Tropical Grasslands* **34**, 21-37.

Kennedy PM, Charmley E (2012) Methane yields from Brahman cattle fed tropical grasses and legumes. *Animal Production Science* **52**, 225-239.

Kimberley Pilbara Cattlemen's Association (2020) Irrigated fodder and grazing animal production systems analysis for the northern beef industry. Department of Primary Industries and Regional Development, WA, August 2020.

Klieve AV, Ouwerkerk D, Turner A, Robertson R (2002) The production and storage of a fermentor-grown bacterial culture containing *Synergistes jonesii*, for protecting cattle against mimosine and 3-hydroxy-4(1H)-pyridone toxicity from feeding on *Leucaena leucocephala*. *Australian Journal of Agricultural Research* **53**, 1-5.

Kuehne G, Llewellyn R, Pannell DJ, Wilkinson R, Dolling P, Ouzman J, Ewing M (2017) Predicting farmer uptake of new agricultural practices: A tool for research, extension and policy. *Agricultural Systems* **156**, 115-125.

Landsberg RG, Ash AJ, Shepherd RK, McKeon GM (1998) Learning from history to survive in the future: management evolution on Trafalgar Station, north-east Queensland. *The Rangeland Journal* **20**, 104-118.

Lean IJ, Rabiee AR, Golder HM, Lloyd J (2011) Analysis of the potential to manipulate the rumen of northern beef cattle to improve performance. Final Report of Project B.NBP.0623. Meat & Livestock Australia: North Sydney.

Lees JC, Lees AM, Gaughan JB (2018) Developing a heat load index for lactating dairy cows. *Animal Production Science* **58**, 1387-1391.

Lemin C, Rolfe J, English B, Caird R, Black E, Dayes S, Cox K, Perry L, Brown G, Atkinson R, Atkinson N (2019) Comparing the grazing productivity of 'Redland' and 'Wondergraze' leucaena varieties. *Tropical Grasslands-Forrajes Tropicales* **7**, 96-99.

Leng RA (1990) Factors affecting the utilization of 'poor-quality' forages by ruminants particularly under tropical conditions. *Nutrition Research Reviews* **3**, 277-303.

Lewis Baida, BE, Swinbourne AM, Barwick J, Leu ST, van Wettere WHEJ (2021) Technologies for the automated collection of heat stress data in sheep. *Animal Biotelemetry* **9**, 4.

McCaskill MR, McIvor JG (1993) Herbage and animal production from native pastures oversown with *Stylosanthes hamata* 2. Modelling studies. *Australian Journal of Experimental Agriculture* **33**, 571-579.

McCosker KD, Jephcott S, Burns BM, Smith DR, Fordyce G, O'Rourke PK, McGowan MR (2021a) Reproductive performance of northern Australia beef herds. 1. Survey of nutritional, breeding and herd health management practices and of the environment. *Animal Production Science*. doi:10.1071/AN17494

McCosker KD, Fordyce G, O'Rourke PK, McGowan MR (2021b) Reproductive performance of northern Australia beef herds. 2. Descriptive analysis of monitored reproductive performance. *Animal Production Science.* doi:10.1071/AN17495

McGowan MR, Bertram JD, Fordyce G, Fitzpatrick LA, Miller RG, Jayawardhana GA, Doogan VJ, De Faveri J, Holroyd RG (2002) Bull selection and use in northern Australia 1. Physical traits. *Animal Reproduction Science* **71**, 25-37.

McGowan M, Fordyce G, O'Rourke P, Barnes T, Morton J, Menzies D, Jephcott S, McCosker K, Smith D, Perkins N, Marquart L, Newsome T, Burns B (2014) Northern Australian beef fertility project: CashCow. Final Report of Project B.NBP.0382. Meat & Livestock Australia: North Sydney.

McGowan M, Fordyce G, Smith D, McCosker K, Barnes T, Hegarty R, Mc Neil D, Perkins N, Miller J, Schooley K, Brodie W, Comiskey R, Lynch D, Murrell G, McClymont A (2017) Development of candidate management interventions to reduce calf wastage in beef herds in northern Australia. Final Report of Project B.GBP.0001. Meat and Livestock Australia, North Sydney NSW.

McLean I, Holmes P (2015) Improving the performance of northern beef enterprises (2nd ed). Meat and Livestock Australia, North Sydney NSW.

McLean I, Holmes P, Wellington M, Herley J, Medway M (2018) Pastoral Company Benchmarking Project 2012-2017. Final Report of Project P.PSH.0718. Meat and Livestock Australia, North Sydney NSW.

McLean IA, Holmes PR, Wellington MJ, Walsh DJ, Paton CJ, Freebairn RJ (2020) The Australian Beef Report: 2020 Vision. Bush Agribusiness Pty Ltd, Toowoomba QLD.

McLennan SR (2014) Optimising growth paths of beef cattle in northern Australia for increased profitability. Final Report of Project B.NBP.0391. Meat and Livestock Australia, North Sydney NSW.

McLennan SR, Bolam MJ, Kidd JF, Chandra KA, Poppi DP (2017a) Responses to various protein and energy supplements by steers fed low-quality tropical hay. 1. Comparison of response surfaces for young steers. *Animal Production Science* **57**, 473-488.

McLennan SR, Campbell JM, Pham CH, Chandra KA, Quigley SP, Poppi DP (2017b) Responses to various protein and energy supplements by steers fed low-quality tropical hay. 2. Effect of stage of maturity of steers. *Animal Production Science* **57**, 489-504.

McLennan SR, Dunster PJ, O'Rourke PK, Murphy GM (1981) Comparison of dry season urea supplements containing salt, sulfur or molasses for steers grazing native pasture in the dry tropics of northern Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry* **21**, 457-463.

McLennan SR, Poppi DP, Gulbranson B (1995) Supplementation to increase growth rates of cattle in the tropics. In 'Recent advances in animal nutrition in Australia 1995'. (Eds JB Rowe, JV Nolan) pp. 89-96. (University of New England Press: Armidale)

MacLeod ND, Ash AJ, McIvor JG (2004) An economic assessment of the impact of grazing land condition on livestock performance in tropical woodlands. *The Rangeland Journal* **26**, 49-71.

MacLeod ND, Mayberry DE, Revell C, Bell LW, Prestwidge DB (2018) An exploratory analysis of the scope for dispersed small-scale irrigation developments to enhance the productivity of northern beef cattle enterprises. *The Rangeland Journal* **40**, 381-399.

McMillan HE, Liu G, Shelton HM, Dalzell SA, Godwin ID, Gamage H, Sharman C, Lambrides CJ (2019) Sterile leucaena becomes a reality? *Tropical Grasslands-Forrajes Tropicales* **7**, 74-79.

Martin P (2009) The Australian fodder industry – An overview of production, use and trade. Rural Industries Research and Development Corporation publication no. 09/001, July 2009.

Masters DG (2021) Lost in translation – the use of remote and on-animal sensing for extensive livestock systems. *Animal Frontiers* **11**, 59-62.

Meat & Livestock Australia (2020) Leucaena for the long run. 13 May 2020. https://www.mla.com.au/news-and-events/industry-news/leucaena-for-the-long-run/ [Verified 7 May 2021]

Meier E, Prestwidge D, Liedloff A, Verrall S, Traill S, Stower M (2019) Crop Livestock Enterprise Model (CLEM) – a tool to support decision-making at the whole-farm scale. Proceedings of the 19th Australian Agronomy Conference, 25-29 August, Wagga Wagga, Australia.

Menzies D, Patison KP, Corbet NJ, Swain DL (2018a) Using temporal associations to determine maternal parentage in extensive beef herds. *Animal Production Science* **58**, 943–949. doi:10.1071/AN16450

Menzies D, Patison KP, Corbet NJ, Swain DL (2018b). Using Walk-over-Weighing technology for parturition date determination in beef cattle. *Animal Production Science* **58**, 1743–1750. doi:10.1071/AN16694

Meyer K, Hammond K, Parnell PF, Mackinnon MJ, Sivarajajasingam S (1990) Estimates of heritability and repeatability for reproductive traits in Australian beef cattle. *Livestock Production Science* **25**, 15-30.

Middleton CH, Murphy KJ, Blight GW, Hansen VL (1993) Large-scale property demonstrations of the effect of Seca stylo and phosphorus on beef cattle growth in central Queensland, Australia. Proceedings of the XVII International Grasslands Congress, Palmerston North and Rockhampton pp. 1994-1996.

Moore KL, Girard CJ, Grant TP, Johnston DJ (2019) Increases in accuracy of female reproduction genetic evaluations for beef breeds in northern Australia. *Proceedings of the Association for Advancement of Animal Breeding and Genetics* **23**, 366-369.

Myers RJK, Robbins GB (1991) Sustaining productive pastures in the tropics 5. Maintaining productive sown grass pastures. *Tropical Grasslands* **25**, 104-110.

Nicholson C, Long J, England D, Long B, Creelman Z, Mudge B, Cornish D (2015) Farm decision making: the interaction of personality, farm business and risk to make more informed decisions. Grains Research and Development Corporation, June 2015.

Niethe GE (2011) New R&D for better herd health and productivity. Proceedings of the Northern Beef Research Update Conference, Darwin 3-4 August 2011, pp 34-40.

Niethe GE (2019) Update on latest findings in phosphorus research in beef cattle. *The Australian Cattle Veterinarian* March 2019, vol. 20.

Niethe G, Holmes P (2020) The last 50 years of pastoralism: what impact drought strategies? *Proceedings of the Royal Society of Queensland* **127**, 99-104. https://www.royalsocietyqld.org/proceedings-127/

Niethe G, Holmes PR, Callaghan MJ, Poppi DP, Schatz T, McLennan SR, Quigley SP (2022) Protein supplementation of weaners – reassessing the role in northern Australian breeder cattle herds. *Animal Production Science* (submitted for publication).

Noble AD, Orr DM, Middleton CH, Rogers LG (2000) Legumes in native pasture – asset or liability? A case history with stylo. *Tropical Grasslands* **34**, 199-206.

North Australian Agribusiness Management (2016) Douglas Daly agricultural zone economic analysis. Report for Regional Development Australia NT, June 2016.

O'Neill CJ, Frisch JE (1998) Consequence of selection in two *Bos taurus* breeds in the tropics. Proceedings of the 6th World Congress on Genetics Applied to Livestock Production **25**, 223-226.

O'Neill CJ, Reid DJ, Kelly MJ, Hill RA (2000) Variation in calving success in a Brahman herd in northern Australia. *Asian-Australasian Journal of Animal Sciences* **13**, 150. Supplement July 2000 B.

O'Neill CJ, Swain DL, Kadarmideen HN (2010) Evolutionary process of *Bos taurus* cattle in favourable versus unfavourable environments and its implications for genetic selection. *Evolutionary Applications* **3**, 422-433.

O'Neill CJ, Weldon GJ, Hill RA, Thomas JE (1998) Adaptaur Association of Australia; a breed association based on the performance of Adaptaur cattle. Animal Production in Australia **22**, 229-232.

O'Reagain P, Bushell J, Pahl L, Scanlan J (2018) Wambiana grazing trial phase 3: stocking strategies for improving carrying capacity, land condition and biodiversity outcomes. Final Report of Project B.ERM.0107. Meat and Livestock Australia, North Sydney NSW.

O'Reagain PJ, Turner JR (1992) An evaluation of the empirical basis for grazing management recommendations for rangeland in South Africa. *Journal of the Grassland Society of South Africa* **9**, 38-49.

O'Rourke PK, Winks L, Kelly AM (1992) North Australia Beef Producer Survey 1990. Meat & Livestock Australia Limited, North Sydney.

Orr DM, Paton CJ (1997) Using fire to manage species composition of *Heteropogon contortus* (black speargrass) pastures 2. Enhancing the effect of fire with grazing management. *Australian Journal of Agricultural Research* **48**, 803-810.

Panjaitan T, Quigley SP, McLennan SR, Swain AJ, Poppi DP (2015) Spirulina (*Spirulina platensis*) algae supplementation increases microbial protein production and feed intake and decreases retention time of digesta in the rumen of cattle. *Animal Production Science* **55**, 535-543.

Patchett B, Bewsell D, Grigg J (2020) RMPP Action Network Final Report, September 2020. https://www.actionnetwork.co.nz/site_files/16853/upload_files/ActionNetworkFinalReport-web.pdf?dl=1 [Verified 2 May 2021]

Pearson C, Filippi P, González LA (2021) The relationship between satellite-derived vegetation indices and live weight changes of beef cattle in extensive grazing conditions. *Remote Sensing* **13**, 4132.

Peck G, Buck S, Hofman A, Holloway C, Johnson B, Lawrence B, Paton C (2011) Review of productivity decline in sown grass pastures. Final Report of Project B.NBP.0624. Meat and Livestock Australia, North Sydney NSW.

Petty SR, Poppi DP (2012) The liveweight gain response of heifers to supplements of molasses or maize while grazing irrigated *Leucaena leucocephala/Digitaria eriantha* pastures in north-west Australia. *Animal Production Science* 52, 619-623.

Petty SR, Poppi DP, Triglone TR (1998) Effect of maize supplementation, seasonal temperature and humidity on the live weight gain of steers grazing irrigated *Leucaena leucocephala/Digitaria eriantha* pastures in north-west Australia. *Journal of Agricultural Science, Cambridge* **130**, 95-105.

Poppi DP, McLennan SR (1995) Protein and energy utilization by ruminants at pasture. *Journal of Animal Science* **73**, 278-290.

Porto-Neto LR, Reverter A, Prayaga KC, Chan EKF, Johnston DJ, Hawken RJ, Fordyce G, Garcia JF, Sonstegard TS, Bolormaa S, Goddard ME, Burrow HM, Henshall HM, Lehnert SA, Barendse W (2014) The genetic architecture of climatic adaptation of tropical cattle. *PLoS ONE* **9** (11): e113284.

Post DA, Bartley R, Corfield J, Nelson B, Kinsey-Henderson A, Hawdon A, Gordon I, Abbott B, Berthelsen S, Hodgen M, Keen R, Kemei J, Vleeshouwer J, MacLeod N, Webb M (2006) Sustainable grazing for a healthy Burdekin catchment. Final Report of Project NBP.314. Meat and Livestock Australia, North Sydney NSW.

Prayaga KC, Corbet NJ, Johnston DJ, Wolcott ML, Fordyce G, Burrow HM (2009) Genetic analyses of heifer adaptive traits and their relation to growth, pubertal and carcass traits in two tropical beef cattle genotypes. *Animal Production Science* **49**, 413-425.

Quigley S, Poppi D, Schatz T (2015) Validation and demonstration of a diagnostic tool for phosphorus status of beef cattle. Final Report of Project B.NBP.0537. Meat and Livestock Australia, North Sydney NSW.

Radrizzani A, Shelton HM, Dalzell SA, Kirchhof G (2011) Soil organic carbon and total nitrogen under *Leucaena leucocephala* pastures in Queensland. *Crop and Pasture Science* **62**, 337-345.

Randhawa IAS, McGowan MR, Porto-Neto LR, Hayes BJ, Lyons RE (2021) Comparison of genetic merit for weight and meat traits between the polled and horned cattle in multiple beef breeds. *Animals* **11**, 870 doi.org/10.3390/ani11030870

Real D, Han Y, Bailey CD, Vasan S, Li C, Castello M, Abair A, Crouch S, Revell C (2019) Strategies to breed sterile leucaena for Western Australia. *Tropical Grasslands-Forrajes Tropicales* **7**, 80-86.

Red Meat Advisory Council (2019) Red Meat 2030. http://rmac.com.au/misp2030-staging/wp-content/uploads/2019/10/RedMeat2030.pdf [Verified 27 March 2021]

Red Meat Advisory Council (2021) Australian Beef Sustainability Framework Annual Update 2021. https://www.sustainableaustralianbeef.com.au/globalassets/beef-sustainability/documents/bh02_annual-update_v18.pdf [Verified 17 October 2021]

Reich PB, Hobbie SE, Lee TD, Pastore MA (2018) Unexpected reversal of C_3 versus C_4 grass response to elevated CO_2 during a 20-year field experiment. *Science* **360**, 317-320.

Revell C, Moore G, Real D, Crouch S (2019) Environmental adaptation of leucaena in Western Australia – challenges and opportunities. *Tropical Grasslands-Forrajes Tropicales* **7**, 112-119.

Revell D (2019) Grazing with self herding. Final Report of Project B.GBP.0025. Meat and Livestock Australia, North Sydney NSW.

Ridoutt BG (2021) Climate neutral livestock production – a radiative forcing-based climate footprint approach. *Journal of Cleaner Production* **291**, 125260.

Rocha A, Randel RD, Broussard JR, Lim JM, Blair RM, Roussel JD, Godke RA, Hansel W (1998) High environmental temperature and humidity decrease oocyte quality in *Bos taurus* but not in *Bos indicus* cows. *Theriogenology* **49**, 657-665.

Scarlatti Limited (2020) Evaluation of the impact of the Red Meat Profit Partnership, June 2020 (not available online)

Schatz TJ (2015) Pre-partum supplementation increases first-lactation heifer re-conception rates in the Victoria River District, NT. *Animal Production Science* **55**, 180-184.

Schatz T (2019) Intensive rotational grazing of improved pasture in the NT – update. Proceedings of the Northern Beef Research Update Conference, Brisbane 19-22 August 2019, p. 64.

Schatz TJ, Jayawardhana GA, Golding R, Hearnden MN (2010) Selection for fertility traits in Brahmans increases heifer pregnancy rates from yearling mating. *Animal Production Science* **50**, 345-348.

Schatz TJ, McCosker KD, Heeb C (2022) The effect of phosphorus supplementation on the growth and reproductive performance of Brahman females grazing phosphorus deficient pastures in the Victoria River District, NT. *Animal Production Science* (under review).

Seebeck RM (1973) Sources of variation in the fertility of a herd of zebu, British, and zebu x British cattle in Northern Australia. *Journal of Agricultural Science, Cambridge* **81**, 253-262.

Shelton HM (2019) International Leucaena Conference 2018: Highlights and priorities. *Tropical Grasslands-Forrajes Tropicales* **7**, 469-478.

Shelton HM, Kerven G, Dalzell SA (2019) An update on leucaena toxicity: Is inoculation with *Synergistes jonesii* necessary? *Tropical Grasslands-Forrajes Tropicales* **7**, 146-153.

Siebert BD, Playne MJ, Edye LA (1976) The effects of climate and nutrient supplementation on the fertility of heifers in north Queensland. Proceedings of the Australian Society of Animal Production **11**, 249-252.

Stafford Smith DM, McKeon GM, Watson IW, Henry BK, Stone GS, Hall WB, Howden SM (2007) Learning from episodes of degradation and recovery in variable Australian rangelands. *Proceedings of The National Academy of Sciences of the United States of America* **104**, 20690-20695.

Stephen CP, Norman ST (2021) Design and development of a biological implant for long term intravaginal retention in cattle. *Australian Veterinary Journal* **99**, 326-333.

Stockwell TGH, Smith PC, Stafford Smith DM, Hirst DJ (1991) Sustaining productive pastures in the tropics 9. Managing cattle. *Tropical Grasslands* **25**, 137-144.

Stuart PN, Kempe N (2017) Intraspecific and interspecific crossing of Desmanthus yields new and novel plants. Proceedings of the 18th Australian Society of Agronomy Conference. 24-28 September 2017, Ballarat, Australia.

Suybeng B, Charmley E, Gardiner CP, Malau-Aduli BS, Malau-Aduli, AEO (2020) Supplementing northern Australian beef cattle with *Desmanthus* tropical legume reduces in-vivo methane emissions. *Animals* **10**, 2097.

Tao S, Dahl GE (2013) Heat stress effects during late gestation on dry cows and their calves. *Journal of Dairy Science* **96**, 4079-4093.

Tao S, Oreliana RM, Weng X, Marins TN, Dahl GE, Bernard JK (2018) The influences of heat stress on bovine mammary function. *Journal of Dairy Science* **101**, 5642-5654.

The Centre for International Economics, AgStrat Associates Pty Ltd and ISJ Investments Pty Ltd (2016) Impact Assessment of MLA Expenditure 2010-11 to 2014-15 Economic quantification of benefits. Final Report of Project F.EVA.1601. Meat and Livestock Australia, North Sydney NSW.

Tomkins N, Harrison M, McSweeney CS, Denman S, Charmley E, Lambrides CJ, Dalal R (2019) Greenhouse gas implications of leucaena-based pastures. Can we develop an emissions reduction methodology for the beef industry? *Tropical Grasslands-Forrajes Tropicales* **7**, 267-272.

Tothill JC, Gillies C (1992) The pasture lands of northern Australia: their condition, productivity and sustainability. Tropical Grassland Society Occasional Publication No. 5. Tropical Grassland Society Inc., Brisbane.

Turner HG (1982) Genetic variation in rectal temperature in cows and its relationship to fertility. *Animal Production* **35**, 401-412.

Van Soest PJ (1994) 'Nutritional Ecology of the Ruminant.' 2nd edn. (Cornell University Press: Ithaca NY)

Viscarra Rossel RA, Bui EN (2016) A new detailed map of total phosphorus stocks in Australian soil. *Science of the Total Environment* **542**, Part B, 1040-1049.

Wadsworth JC, McLean RW, Coates DB, Winter WH (1990) Phosphorus and beef production in northern Australia. 5. Animal phosphorus status and diagnosis. *Tropical Grasslands* **24**, 185-196.

Walsh D (2021) Feedbase learning program & templates for Pathways to Practice pilot.

Walsh D, Cowley RA (2014a) Best-bet practices for managing grazing lands in the Barkly Tableland District of the Northern Territory. Northern Territory Government, Australia. Technical Bulletin No. 350.

Walsh D, Cowley RA (2014b) Best-bet practices for managing grazing lands in the Victoria River District of the Northern Territory. Northern Territory Government, Australia. Technical Bulletin No. 352.

Walsh D, Cowley R (2016) Optimising beef business performance in northern Australia: what can 30 years of commercial innovation teach us? *The Rangeland Journal* **38**, 291-305.

Walsh D, Kain A, Cowley RA (2014) Best-bet practices for managing grazing lands in the Alice Springs District of the Northern Territory. Northern Territory Government, Australia. Technical Bulletin No. 351.

Walsh D, McCosker K (2019) "Paddock Power": unlocking the secrets to sustainable and profitable intensification. Proceedings of the Northern Beef Research Update Conference, Brisbane 19-22 August 2019, p. 77.

Walsh DL, Paton CJ (2020) The effective utilisation and preservation of the natural resource base. In: McLean IA, Holmes PR, Wellington MJ, Walsh DL, Paton CJ, Freebairn RD (2020) The Australian Beef Report: 2020 Vision. Bush Agribusiness Pty Ltd, Toowoomba, Queensland.

Wiedemann SG, Henry BK, McGahan EJ, Grant T, Murphy CM, Niethe G (2015) Resource use and greenhouse gas intensity of Australian beef production: 1981-2010. *Agricultural Systems* **133**, 109-118.

Wilson JR, Hacker JB (1987) Comparative digestibility and anatomy of some sympatric C_3 and C_4 arid zone grasses. *Australian Journal of Agricultural Research* **38**, 287-295.

Winks L (1990) Phosphorus and beef production in northern Australia. 2. Responses to phosphorus by ruminants – a review. *Tropical Grasslands* **24**, 140-158.

Winks L, Laing AR, Wright GS, Stokoe J (1976) Effects of nitrogen, phosphorus and molasses on the performance of weaner cattle during the dry season in north Queensland. *Journal of the Australian Institute of Agricultural Science* **42**, 246-251.

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