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Reimagining the northern Australian beef industry; review of feedbase opportunities for growth

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ABSTRACT

The current beef industry in northern Australia was established through the adoption of innovative schemes and ideas that transformed the economic viability of the industry in the 20th century. In this paper, we argue that a key driver of beef production, the nutrition of the animal or feedbase, can be sustainably exploited with novel ideas to affect a paradigm shift in the northern beef industry in the 21st century. Although the current economics of beef production limit adoption of 'out-there' ideas, it is nonetheless useful to consider them. It is contended that future global protein shortages for human nutrition may change the economic balance in favour of more creative ideas to utilise the existing and potential, as yet untapped, feedbase. The underlying premise is that the beef industry could better take advantage of the varied feedbase opportunities that exist in the north. In doing so, the industry would shift the balance from a predominantly pastoral system to a mixed model where extensive grazing co-exists with intensive beef production at the regional scale. Concomitant with this change, the long-term productive and environmental conditions of the industry could be improved. For example, intensification in some locations would allow de-intensification in others. In this review, we focus on five potential 'game changers' for the industry, some of which are proven but, for reasons discussed, under-adopted and some of which are more 'blue sky'. These game changers are legumes, silage, irrigation, co-products from the crop and vegetable industries and ligno-cellulosic feedstocks. These are all technically feasible and lend themselves to regionally integrated production systems that take advantage of the opportunities across the north, including land, sunshine, water, people, infrastructure, markets.

Keywords: beef production, co-products, feedbase, legumes, mosaic irrigation, silage, systems, tropical, upcycling.

Introduction

The northern Australian cattle industry is relatively young compared with other pastoral areas of the world, with cattle being introduced by European settlers in the 1800s (Parsonson 1998). The growth of the cattle industry in northern Australia was associated with private initiatives and government schemes to improve cattle genetics, develop the land, control disease and develop infrastructure and new markets, such as the expansion of the live export industry. In particular, replacement of British breeds susceptible to ticks and heat with tropically adapted *Bos indicus* genotypes in the mid-20th century accelerated the growth of the northern beef industry (Bell *et al.* 2011). The brigalow (*Acacia harpophylla*) clearances during the 1960s and 1970s in Queensland, in large measure realised through post-war developments in mechanisation, released approximately 20 million hectares of country, with the majority going into a monoculture of buffel (*Cenchrus ciliaris*) grass pastures for beef production (Thornton and Elledge 2022). During this time the recognition of the importance of adequate phosphorus nutrition further contributed to improvements in the productivity of the industry (Dixon *et al.* 2020). The development of 'the Beef Roads Scheme' across the north was and continues to be a game changer by improving supply chains and allowing mass movement of cattle during drought or to markets and for the movement of hay and supplements (Beef Roads 2024). Another game changer of the 20th century was the eradication of brucellosis through the Brucellosis and Tuberculosis Eradication Campaign (BTEC; Lehane 1996) More intensive management practices such as the establishment of water and fencing infrastructure were also introduced to the less intensively developed parts of the northern beef industry such as Cape York and the Kimberley, at this time (McKeon *et al.* 2004).

These transformative developments from past century transformed the northern cattle industry from a 'frontier' into a well-connected and sophisticated pastoral industry, in at least the parts of northern Australia better endowed with soils, transport infrastructure and access to markets (McDonald 1981). However, this transition was not universal and today many producers are yet to take full advantage of both historic and ongoing industry developments and innovation.

In 1953, there were approximately 7 million cattle in northern Australia (Kelly and Williams 1953) compared with approximately 14.5 million in 2023 (MLA 2023). Fordyce *et al.* (2023) suggested national cattle numbers to be considerably higher (33 million) than survey estimates and recent estimates by the Australian Bureau of Statistics, by using new methods and data sources (ABS 2024), suggest that cattle numbers are likely to be about 20% higher than originally reported. Beef cattle numbers in Australia have reached a plateau at between 20 and 27 (26–33 new method) million head over the past 10 years (Fig. 1; MLA 2023) Of these, approximately 60% are to be found in northern Australia (ABS 2024). This plateau in national production contrasts with the global increase in demand for beef and the growth of emerging markets in China and Southeast Asia (Greenwood *et al.* 2018; Searchinger *et al.* 2019). Several financial analyses of the northern beef industry suggest that profitability is declining owing to lack of operational scale, poor operational efficiency, declining indexed prices for sales and increased input costs (Holmes 2015; Holmes *et al.* 2017; Bowen and Chudleigh 2018; McLean *et al.* 2018; Bowen *et al.* 2019). McLean *et al.* (2023) reported that approximately half of northern businesses carry <800 adult equivalents (AE) and, on average, are unprofitable. Holmes (2015) also concluded that 80% of northern businesses are not economically sustainable long term. However, it should also be noted that high beef prices in 2022 dramatically improved the profitability of the whole beef industry (McLean *et al.* 2023). As a result of these financial realities, total factor productivity of the industry has declined since the late 1990s (ABARES 2023). There is also some evidence that land condition and carrying capacity are in decline across northern Australia (KA Shaw, JW Rolfe, T Beutel, BH English, ND Gobius, DE Jones, unpubl. data).

To reverse these trends the industry needs new game changers to build on those of the mid-20th century. This review considers options aimed at capitalising on existing natural resources of the north and their potential use in the beef industry. The feedbase is the primary driver for both animal growth and reproductive efficiency. Limitations in availability and quality of the feedbase both within and across seasons restricts the ability of northern cattle to reach their genetic potential for reproduction and growth.

To achieve economy of scale, viability at the property level has often been sought through adoption of tried and tested methods and acquisition of more land to keep pace with increasing costs and lower returns. Adoption of improved animal genetics, pasture improvement, precision grazing management and information technology (IT) contribute to incremental change. Although the importance of continual improvement of existing systems is acknowledged, this review focusses on blue sky thinking around shifting the paradigm through the lens of alternative or novel cattle feed resources. Harnessing the unlimited solar radiation and a fickle water supply are key to exploiting areas that can withstand intensification. Many permutations exist. For instance, intensification of land use where practicable also realises the opportunity of selective de-intensification. Overall, changes in how beef production is distributed from within the property to across regional scales can also benefit environmental and biodiversity outcomes. At the property scale, stocking rates

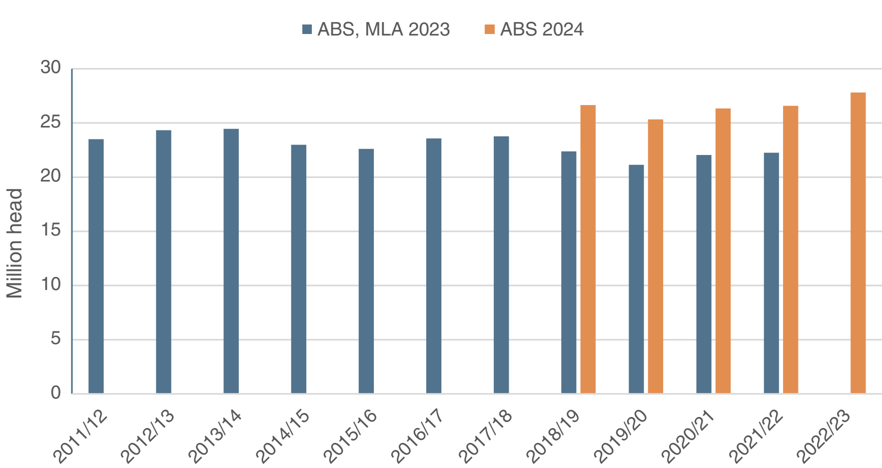

Fig. 1. Beef cattle numbers in Australia (ABS 2024). The blue bars represent data using the former methods of ABS (Source: Australian Bureau of Statistics, Agricultural Commodities, Australia 2021–22 financial year, MLA (2023), the orange bars represent the data using the new ABS methods (ABS 2024).

can be reduced on marginal or degraded land, and carrying capacity can be increased on better soils, with overall stock numbers remaining the same. At a regional scale, high-input beef production can complement more extensive pastoral beef production to increase overall regional returns.

The objective of this review is to explore an alternative model, whereby increased productivity and economic viability are achieved through a mosaic of intensified land uses interspersed within a sustainable pastoral landscape. Consequently, there may arise opportunity to reduce and better manage grazing pressure on vulnerable land, thus potentially benefiting the environment while simultaneously improving whole-of-property herd productivity.

Constraints and future impacts to the northern beef industry

The northern Australia beef situation analysis (Chilcott *et al.* 2020) provided an in-depth review of the current 'state of play' of the northern beef industry and identified constraints to address that lift productivity and profitability. These constraints, including feedbase, the animal and herd structure, climate, geography, and human capital, are intrinsically linked to the dominant production systems utilising low-input–low-output pastoral methods (Table 1).

Any future scoping must be cognisant of future mega-shocks that could affect the industry (Hajkowicz and Eady 2015). For the northern beef sector, climate change and variability, societal concerns around the environment and animal welfare, and land tenure rank as three potential disruptors of the production options proposed here (Table 1). For example, increased temperatures could negatively influence the growth pattern and quality of forages (Henry *et al.* 2012). Public perceptions regarding the production and consumption of beef continue to influence consumer sentiment and the regulatory environment affecting markets and freedom to operate (Chilcott *et al.* 2020). Such issues could have negative impacts on the current scale of the industry and future opportunities for a reimagined beef sector. In future, a more robust and integrated feedbase for the industry is likely to have both positive and negative impacts on consumer sentiment (Moran-Ordonez *et al.* 2017). For example, reducing grazing pressure on sensitive environments will improve ecosystem integrity (Kemp and Michalk 2007; Neilly *et al.* 2018; Runting *et al.* 2024); however, in other areas, diverse grasslands on fertile soils will be replaced by rotational monocultures of crops or forages. Optimising the balance between these two opposing impacts is key to sustained development of the northern beef industry. Irrigation will reduce reliance on uncertain rainfall patterns (Watson *et al.* 2023). Advances in information technology (IT) will have a transformative effect increasing labour efficiency and allowing for custom management options within the herd (Aquilani *et al.* 2022). Similarly, artificial intelligence (AI) technology has potential for enhancing production efficiency and product quality (Wang and Li 2024).

Nutritional options to re-imagine the northern beef industry

Beef production is a multi-faceted endeavour involving the integration of a range of disciplines. Underpinning beef

Table 1. Constraints and future threats of the northern beef industry according to a SWAT analysis in the Northern Beef Situation Analysis.

Constraint	Summary
Feedbase	Low-quality, woody vegetation encroachment, overgrazing and climate variability
Genetics	*Bos indicus* dominated with low fertility and meat quality, poor uptake of genetic improvement
Animal	Herd structure limits flexibility and resilience to drought, limited market options
Human capacity	Labour shortages, lack of business acumen, low adoption, older demographics, succession planning
Property	Climate variability challenges, low productivity per head and per hectare, high capital costs and land values
Industry	Limited processing capacity in some areas, live export challenges, indigenous tensions, government restrictions
Northern Australia	Geographically dispersed with limited infrastructure (roads, ports, community, etc.)
Global	Market access, social licence
Future threats	**Summary**
Societal expectations	Loss of markets due to consumer concerns related to animal welfare, greenhouse gases, land degradation, loss of biodiversity, rise of veganism
Climate change	Production impacts owing to increasing mean temperatures, heat waves, droughts, and flooding rainfall
Freedom to farm	Government regulations influenced by biosecurity, societal expectations, land tenure, and environmental protection influences land use in the north

Adapted from Chilcott *et al.* (2020) and Hajkowicz and Eady (2015).

production is the conversion of energy, protein and micronutrients harvested from the environment into a valuable product for human consumption, namely beef. This review investigates the biological potential of novel nutritional pathways for beef production in the north. The underpinning hypothesis is that a multiplicity of approaches can be used to sustainably and more effectively harvest biomass for beef production than the current system that relies predominantly on extensive grazing of native or modified grasslands with supplementation to meet obvious deficiencies. The potential benefit for the industry and the environment is the opportunity to intensify production where resources allow, while reducing grazing pressure in areas better suited to beef production, in combination with environmental, cultural, or other revenue streams.

The primary metric for evaluation in this paper is biological feasibility using known technologies. Although such technologies exist for all the examples provided in this paper, their economic viability in northern Australian rangelands is, at best, questionable under current conditions. However, in the future, current economic constraints may become less important, as global challenges change (Hajkowicz and Eady 2015). For many of the options considered, the economic feasibility is highly dependent on future economic conditions such as capital investments, input costs, beef prices, etc. Robust economic analyses for several similar or related scenarios have been published (e.g. Bowen and Chudleigh 2018, 2019; Bowen *et al.* 2018, 2019). However, the current economic feasibility of options, although a useful metric in the near-term, should not rule out potential future options that could operate under different financial realities.

Five production options were identified, three of which are already well characterised but under-adopted (pasture legumes, silage, mosaic irrigation), and two of which are novel to northern beef production (cropping co-products, lignocellulosic biomass; Table 2). Two of the five options are cross-cutting technologies (irrigation and lignocellulosic biomass) that provide benefits when matched with existing and novel production systems. Although each of these opportunities alone offers potential, it is the creative application of combinations of opportunities into a paradigm shift that could bring the greatest reward for the northern beef industry. For the purposes of this review, northern Australia is defined as all of Queensland and the Northern Territory, plus the Kimberley and Pilbara regions of Western Australia, an area of approximately 4 million km^2 recognised by the Northern Australia Beef Research Council (NABRC) as geographically and commercially relevant to the northern beef industry. The geographic areas likely to be suited to the application of these technologies are given in Figs 2 and 3. Northern Australia is diverse, with rainfall influencing the productive capacity of the landbase. Generally, rainfall declines from east to west and the stocking rates decline accordingly. In high-rainfall areas, stocking rates can be 0.3–0.5 adult equivalents (AE; 1 AE is equivalent to a 450 kg steer)/km^2, but these decline to as little as 0–10 AE/km^2 in the rainfall zones below 400 mm (Fig. 2). Commensurate with the decline in stocking rates, the property size increases from approximately 650 km^2 to almost 1400 km^2 (MLA 2014). Generally, soils are of low fertility and rainfall is highly seasonal, with the majority of rain fall in the monsoonal wet season from approximately December to April. Consequently, pasture quality is variable, being low in nutritive value in the dry season and higher in the wet season. Dry-matter (DM) digestibility of the diet can vary between 40% and 65% and crude protein between 4% and 12% DM (Charmley *et al.* 2023*b*).

Table 2. Production systems considered in this review.

Production system
• While legumes are not considered novel, the opportunity for their more widespread use offers major advantages for existing grazing systems and is considered the 'low hanging fruit' among novel nutritional strategies for the beef industry
• Throughout much of the northern hemisphere, ensilage has long been the solution to providing quality forage outside the growing season. Its relative obscurity in northern Australia is interesting and this conservation technique deserves more attention.
• Small-scale or mosaic irrigation is currently receiving much attention. As a method to bring water to a range of cropping scenarios, it offers a cross-cutting technology that has application for a number of the aforementioned opportunities
• Access to by-products from tropical crops may be regionally specific, but, nevertheless, these offer a potential cost-effective source of nutrients for backgrounding and feedlots.
• Thermal or chemical processing of low-quality biomass from sugarcane and tropical forages offers the potential to convert large volumes of ligno-cellulosic biomass into quality livestock feed.

Under-adoption of proven technologies and production systems remains a perennial problem in northern Australia and has been attributed to a lack of business skills and financial literacy (Holmes 2015) and the need to manage risk and uncertainty (Webb *et al.* (2013). The problem is well known and understood but solutions remain elusive. Marshall *et al.* (2014) surveyed 240 northern cattle producers and found that over 80% of respondents were averse to change. They held strong association with the land and their lifestyle and had low adaptive capacity for change. For these individuals the simple economic imperative was insufficient motivation to enact a change. The annual and decadal cycles in climate and productivity have been managed and mitigated by a cautious approach both to change and to novel ideas, prioritising stability and resilience ahead of innovation. Relying on past experiences has a major influence on future planning. Northern producers have relied on State departments and organisations such as Meat and Livestock Australia (MLA) to provide development and extension services, with a wide range of programs and demonstration sites. Yet, despite clear evidence that new approaches, such as introduction of pasture legumes, for example, are economically viable, a reluctance to change remains for many

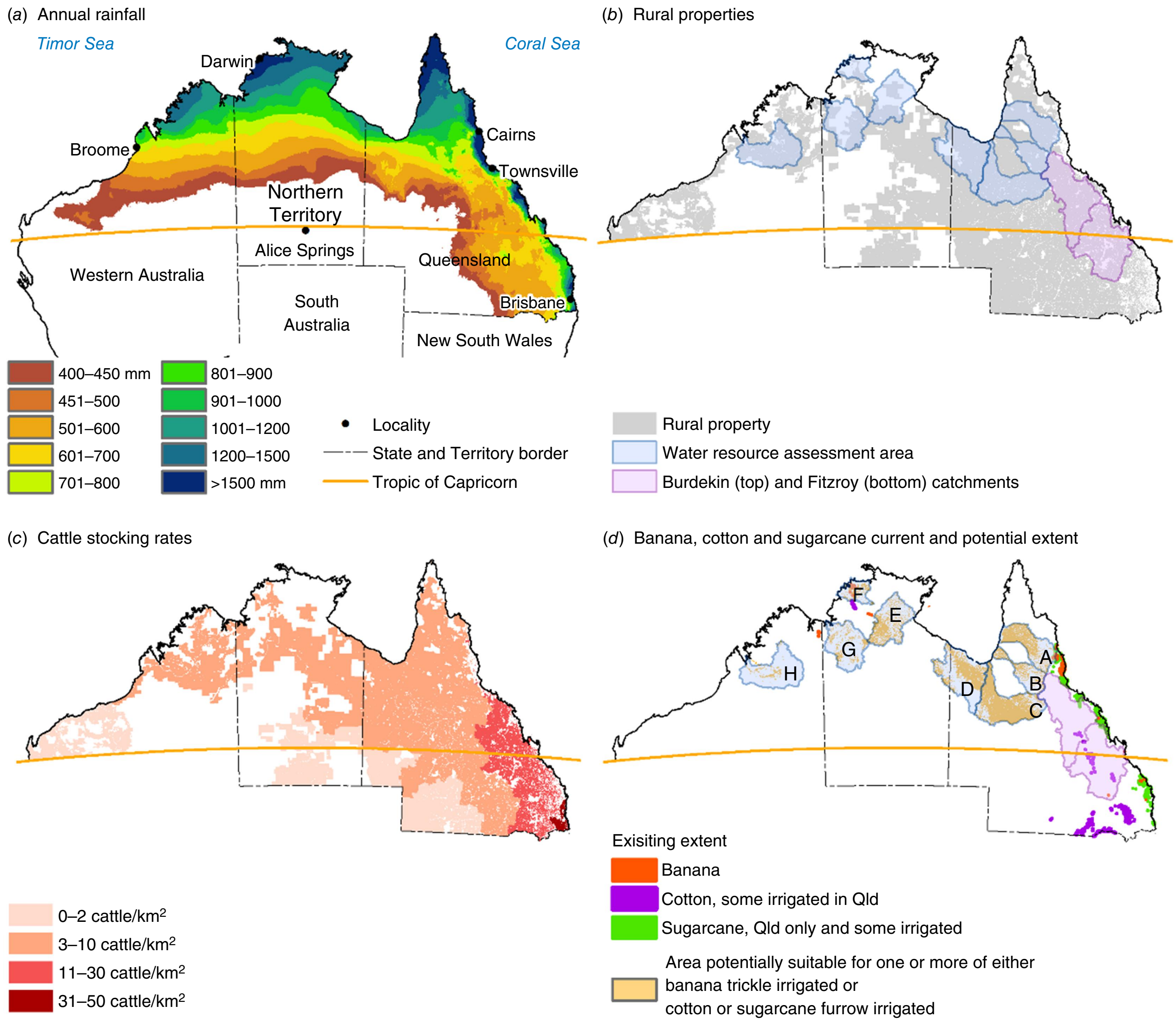

Fig. 2. (*a*) Rainfall map of northern Australia, (*b*) rural properties, also showing the major catchments of northern Australia, (*c*) cattle density map of northern Australia, and (*d*) current production areas of cane, cotton and bananas and potential areas for irrigation that could support various crops and forages for beef production in selected catchments; Mitchell (A), Gilbert (B), Flinders (C), southern gulf (Gregory and Leichardt; D), Roper (E), Darwin area (F), Victoria (G), and Fitzroy (H).

producers. The use and availability of networks in northern Australia is limited and strong diverse networks increase trust in and access to information (Marshall *et al.* 2014). In marked contrast to southern Australia, the use of agricultural consultants is not widespread. The expansive industry and the tyranny of distance makes in-depth, whole-of-enterprise, face-to face consulting difficult and expensive. The agricultural supply industry is also different in the north. In intensive systems sales representatives for feed, seed, chemicals, fertiliser, herbicides and pesticides are in continuous contact with producers providing advice and ideas to embolden producers to make changes. Moreover, such producers are continually observing the ongoing successes and failures of dozens of neighbouring farms as they trial new technologies and enterprise structures. Under more extensive production systems, this network of advice and influence, although still present, is much less pervasive. Without sound holistic advice, the northern producer is left with a myriad of decisions to make regarding adoption and ill-conceived decisions can have a major impact on enterprise viability. In the absence of a de-risked pathway, the safest option is to stick with what one knows.

Marshall *et al* (2014) concluded that producers were unlikely to respond to traditional sources of information and methods of extension. Yet, these are the producers most likely to benefit. A subsequent survey of northern producers (Jakku *et al.* 2022) highlighted more pragmatic drivers, including assessment of costs and benefits of adoption, increasing

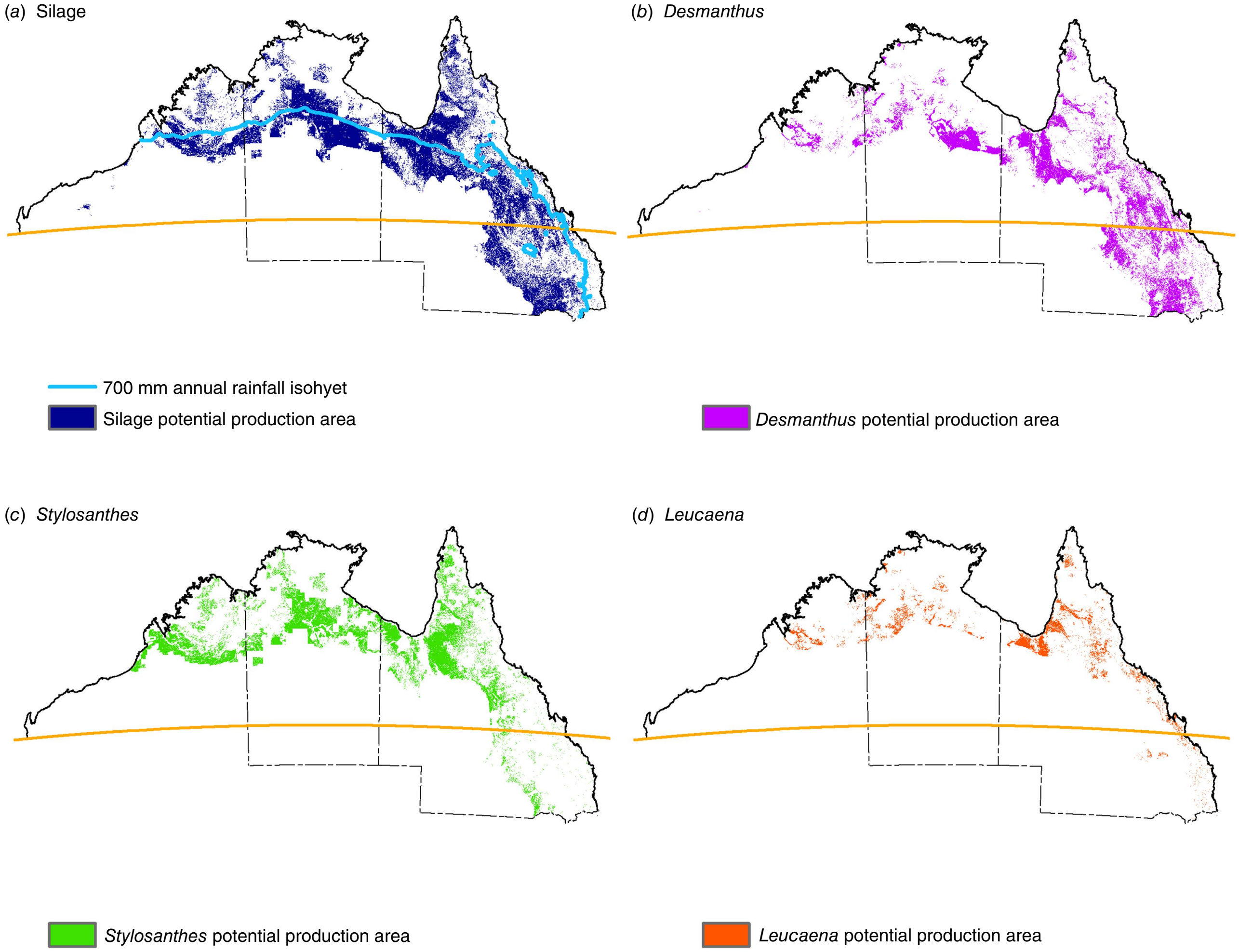

Fig. 3. (*a*) Areas for potential silage and (*b*) legume production in northern Australia: *Desmanthus*, (*c*) *Stylosanthes*, and (*d*) *Leucaena*. For all maps, the area is defined by rainfall plus land type and is restricted to pastoral lands with less than 2% slope. Silage production from forages without irrigation is restricted to >700 mm rainfall and clay to loam soils. Irrigation extends the area to include rainfall between the 400 and 700 mm isohyets. *Desmanthus* is restricted to >400 mm rainfall and vertosols plus sodosols. Stylos are restricted to >500 mm rainfall on lighter soils, apart from *S. seabrana*, which also tolerates vertosols and sodosols. *Leucaena* is restricted to >650 mm rainfall on heavier soils such as vertosols and sodosols.

efficiency and ease with which a change fitted into the existing operation. Taken together, it is clear that producers rely on a myriad of often conflicting factors in decision making and this complexity often favours remaining with the *status quo*. Is it simply that the pain of change is greater than the reward, when business as usual is safe and viable? Future mega-shocks, such as climate variability, may change this paradigm. In the past mega-shocks could be positive and included massive government intervention in roads and animal health, for example. These investments led to wholescale adoption of the benefits. In the future, it is most likely that these positive mega-shocks will come from private investment in the sector, rather than government, leading to increased corporatisation and vertical integration. Whether or not these potential changes will be perceived as positive remains to be seen. Notwithstanding these issues, the purpose of this paper is to highlight possibilities available when the feedbase resources of the north are viewed purely from the perspective of what is biologically possible. In future, these options may become both significantly cheaper and substantially derisked as markets change, regional infrastructure and technical support improves, and significant corporate or government investment is mobilised.

Legumes to improve nutritive value of pastures

The northern rangelands are dominated by C4 grasses noted for their poor nutritive value and decline in quality with advancing maturity (Minson 1981). The introduction of tropically-adapted legumes into these grazed environments simultaneously addresses the problem of low nitrogen (N) status of soils and low dietary protein intake by grazing ruminants (Coates *et al.* 1990; Shelton *et al.* 2005; Ash *et al.* 2015; Peck *et al.* 2022) and has been widely recognised. For example, Peck *et al.* (2017) estimated that establishing legumes in central Queensland was the most cost-effective option to offset productivity decline in the Brigalow belt, a bioregion west of the Dividing Range and extending from approximately Townsville in the north to northern New South Wales in the south and Charleville in the west. However, their widespread adoption has been less than hoped for and limited by the availability of adapted species (Schultze-Kraft *et al.* 2018), establishment failure and costs, and a lack of agronomic understanding by graziers. A range of legumes are adapted to northern Australia varying in growth habit from herbs to trees (Castro-Montoya and Dickhoefer 2020). Australia has a rich diversity of native legumes (Lewis *et al.* 2005) of which only some are described as productive and palatable for livestock, whereas others are of limited significance for grazing because of toxicity limitations (Hacker 1990). Leslie *et al.* (1987) suggested that many of our productive, palatable species declined in abundance after the introduction of domestic livestock into Australia. Little emphasis has been placed on research of our native legumes for grazing and MLA (2011) stated that information on the productivity and quality of native legumes is scant. Hacker (1990) nominated several genera of relevance to northern Australia that warrant further research effort with regard to potential livestock production benefits, including, among others, *Alysicarpus, Desmodium*, *Glycine*, *Rhynchosia*, and *Vigna*. With a changing climate and biosecurity issues around introduced legumes, some of these native species could well be a part of re-imagining the northern feedbase in the future (Whattam *et al.* 2024).

Historically, far greater emphasis has been placed on the introduction, evaluation, and commercialisation of exotic herbaceous legumes for northern Australia, rather than the native species. The majority of exotic species originate from Central and South America. Tropical herbaceous legumes that have been successfully introduced and adopted commercially, depending on region/environment, include the *Arachis*, *Aeschynomene*, *Centrosema*, *Chamaecrista*, *Clitoria*, *Desmanthus*, *Desmodium*, *Dolichos*, *Leucaena*, *Macroptilium*, *Neonotonia*, *Stylosanthes* and *Vigna* genera. Among these, many species and varieties have been released (Cook *et al.* 2020), including most notably several *Desmanthus* (JCU 1–9; Gardiner 2016) and *Stylosanthes* species (Cook *et al.* 2020; Peck *et al.* 2022). The Australian Pasture Gene (APG) Bank holds some 70,000 accessions of tropical and temperate forage accessions. Many are untested and may hold genetic potential for traits such as drought resilience, antimethanogenic activity, anthelmintic properties and other ecosystem benefits as yet undefined (Durmic *et al.* 2017; Tunkala *et al.* 2023).

Plant breeding of pasture legumes with adaptations to northern rangelands is quite limited but offers potential for new and novel crosses including intraspecific, interspecific and even intergeneric crosses, some of which are described by Sturat and Kempe (2017). In addition, Gardiner (2016), Gardiner *et al.* (2017) and Peck *et al.* (2022) have revisited old legume trial sites and selected survivors, resulting in the development of new cultivars of *Desmanthus* and *Stylosanthes*.

Many native browse species are under-exploited and may be considered multipurpose species providing shade, shelter, fodder, N fixation, carbon sequestration, and ecosystem services (Gutteridge and Shelton 1994; Gardiner *et al.* 2025). In times of drought, 'topfeed' or browse species assume the greatest importance (Chippendale and Jephcott 1963; Everist 1985). Among native browse species, mulga (*Acacia aneura*) is the most important fodder tree in Australia, although it is not widespread in the north (Everist 1985).

The following three species relevant to the grazing lands in parts of northern Australia are discussed in greater detail here: *Stylosanthes, Desmanthus*, and *Leucaena*. Of these, the stylos are most widely utilised and distributed, and demonstrate the potential of tropical legumes (Fig. 3). It can be argued that the introduction of legumes from the *Stylosanthes* genus has already revolutionised sown pasture development in northern Australia (Bishop and Hilder 2005). However, for the purposes of this review, we consider that the potential for legumes in northern Australia is yet to be fully realised and is therefore worthy of inclusion as one aspect of the feedbase for consideration. If the current estimated areas of established stylos, *Desmanthus* and *Leucaena*, are combined with approximate stocking rates, then it is estimated that only approximately 300,000–350,000 of the 14.5–16 million beef cattle in northern Australia are grazing pastures with substantial legume biomass (Table 3). The genus *Stylosanthes* includes a number of species that are widely adapted to northern Australia, including *S. scabra* (e.g. cv. Seca), *S. hamata* (e.g. cv. Verano), and *S. seabrana* (e.g. cv. Unica). They are adapted to sandy loam soils (with the exception of *S. seabrana*, which prefers clay soils) and the higher-rainfall (>600 mm) areas of northern Queensland (Walker *et al.* 2022) and sporadically in the Northern Territory and the Kimberley region of Western Australia (Fig. 3). It has been reported that, in 2000, there were approximately 1 million hectares of pastures in northern Australia where stylos have been introduced (Noble *et al.* 2000). Since then, the area has increased, and stylos represent the most common of tropical legumes in northern Australia, found across approximately 1.5 million hectares, approximately 0.4% of the north as defined in this review (Table 3).

Desmanthus is one of the few legume genera adapted to clay (vertosols) soils prevalent in western Queensland (Gardiner *et al.* 2013; Gardiner *et al.* 2017), but is also found across the Northern Territory and in Western Australia (Fig. 3). Uptake by the industry is relatively recent, and it is estimated that in 2023 *Desmanthus* had been introduced to more than 100,000 ha of pastures. However, there is potential for more widespread establishment across 35 million hectares of suitable edaphic and climatic zones (Fig. 3).

Table 3. Potential biophysical area for legume establishment in northern Australia and estimated areas of *Stylosanthes*, *Desmanthus*, and *Leucaena*.

Item	Suitable area for establishment (million ha)	Estimated area established (thousand ha)	Estimated stocking rate (ha/AE[A])	Estimated AE
Northern Australia	400			
Stylosanthes	50	1500	5	300.000
Desmanthus	35	100	7.5	13,000
Leucaena	13	130	2.5	50,000

[A]AE, adult equivalent, equates to a 450 kg steer.

Table 4. Typical range in nutritive value of tropical legumes and grasses (% of dry matter unless otherwise stated).

Item	Tropical legumes (*n* ~ 100)[A]			Tropical grasses (*n* ~ 100)[B]		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Crude protein (% DM)	17.4	6.13	30.9	10.9	2.11	21.1
Neutral detergent fibre	49.5	19.7	79.5	67.3	50.9	79.8
Acid detergent fibre	38.4	11.4	66.2	38.8	24.7	57.4
Lignin	10.0	2.7	25.5	5.69	2.83	8.20
Condensed tannins	44.5	0	254	–	–	–
Digestibility	56.6	15.8	–	56.0	30.2	70.1
Metabolisable energy (MJ/kg DM)	8.95	4.37	11.9	7.41	3.50	9.75

[A]After Castro-Montoya and Dickhoefer (2020).
[B]After Jayasinghe *et al.* (2022).

Leucaena was first bred for northern Australia in the 1960s and 1970s, but uptake by the industry has been less than expected. It offers potential in the frost-free higher-rainfall (>650 mm) coastal zone or under irrigation on well drained, neutral to alkaline deep soils (Shelton and Dalzell 2007). Recent estimates of planted *Leucaena* range from 123,500 ha in Queensland (Beutel *et al.* 2018) to 130,000 ha across all of northern Australia (Buck *et al.* 2019). However, Shelton and Dalzell (2007) considered that there was potential for 13 million hectares (Fig. 3, Table 3). Poor adoption is possibly related to the challenges and expense of establishing a row crop in pastoral landscapes because of a lack of farm infrastructure and expertise and regional support services, or can be simply due to a lack of seed for new cultivars. The interspecific breeding of *Leucaena* has recently developed the psyllid tolerant cultivar Redlands and it is expected that this will see the expansion of *Leucaena* into coastal areas (Dalzell 2019; Shelton *et al.* 2020), with an additional 1.2 million hectares of suitable land (Shelton and Dalzell 2007). *Leucaena* has weedy traits, including the abundant production of hard seeds, which has led to it being a declared weed in some regions (QDAF 2024). In Western Australia, *Leucaena* is classified as a high or very high weed risk assessment (Department of Primary Industries and Regional Development, Western Australia 2022) and its cultivation is highly restricted. The production of sterile (seedless) *Leucaena* has the potential to alleviate the weediness issue (McMillan *et al.* 2019; Real *et al.* 2023), although the requirement for vegetative propagation may slow adoption. *Leucaena* also contains mimosine, which together with its breakdown products are toxic to ruminants (Dalzell *et al.* 2012). Toxicity can be avoided by inoculation either through dosing or passive inoculation from the environment with *Synergistes jonesii*, a bacterium capable of degrading the toxic compounds (Halliday *et al.* 2014).

Nutritive value of tropical legumes

Data from two international reviews of tropical legumes (Castro-Montoya and Dickhoefer 2020) and grasses (Jayasinghe *et al.* 2022) are summarised in Table 4. Overall, tropical legumes are higher in crude protein (CP) and lower in neutral detergent fibre (NDF) than are grasses, but also contain more lignin, levels of which are negatively correlated with digestibility, resulting in legumes being less digestible than grasses at equal NDF content (Archimède *et al.* 2011). Phenolic compounds (including condensed tannins) are more prevalent in legumes than grasses and can reduce availability of CP in the rumen (Barry and McNabb 1999). However, at moderate concentrations, tannins may also improve N utilisation (Panjaitan *et al.* 2010) and reduce methane production in the rumen of grazing animals (Archimède *et al.* 2016). International reviews have found that digestibility and metabolisable energy (ME) were similar for tropical legumes and grasses (Castro-Montoya and Dickhoefer 2020; Jayasinghe *et al.* 2022). However, in a study comparing tropical grass and legume species commonly grown in northern Australia, Kennedy and Charmley (2012) found that legumes contained more CP (15.9% versus 6.1% DM) and lignin (8.1% versus 5.6% DM), but less NDF (47% versus 69% DM). The concentrations of acid detergent fibre (ADF) and NDF-N were similar. The differences in nutritive value between grasses and legumes reflect different morphologies, with legumes relying more on lignin and less on NDF (cellulose and hemicellulose) for physical rigidity. However, these differences also affect the feed value of tropical legumes. For example, physical breakdown of legume material in the rumen is faster than for grasses, allowing for increase rate of passage of legumes from the rumen, leading to potentially increased rate of feed intake (Charmley *et al.* 2023*b*). Archimède *et al.* (2011) found that in spite of the lower digestibility of the legumes (48% versus 62% for grasses), organic-matter (OM) intake was similar for both groups (1.8% and 1.9% LW for grasses and legumes respectively). Kennedy and Charmley (2012) compared the intake response to four tropical legumes and found, on average, a 13% increase in dry-matter (DM) intake as the legume content increased from 0% to 40% of the diet DM.

Changes in nutritive value with advancing maturity are less pronounced in legumes than in grasses. Diniz *et al.* (2023) investigated four *Stylosanthes* species and showed little change in NDF or ADF content when cutting frequency was increased from 56 to 98 days. Mwangi *et al.* (2022) studied the change in nutritive value of three *Desmanthus* species when the regrowth period was increased from 11 to 103 days. Whereas CP of leaves declined with increasing regrowth days, there was no consistent maturity effect on NDF or ADF in leaves. The situation is much the same for *Leucaena*. Figueredo *et al.* (2019) observed a decline in CP of *Leucaena* leaves and petioles with advancing maturity, whereas Charmley *et al.* (2023*a*) observed variable changes in CP content of leucaena over a 24-week grazing period, which probably reflected repeated leaf harvesting and regrowth during grazing. From these studies, it can be concluded that the main effect on nutritive value of tropical legumes is related to the leaf:stem ratio. However, under grazing conditions, cattle will preferentially select leaves over stem, thus maintaining the nutritive value of the ingested portion of the legumes (Coates 1996)

Animal performance from tropical legumes

Ash *et al.* (2015) used bio-economic modelling to simulate the inclusion of legumes in three northern regions of Australia. It was estimated that including legumes in pasture increased beef turn-off by 17% and gross margin by 28%. Inclusion of these high-quality tropical legumes had a consistent positive effect on animal performance through a combined effect of increased individual animal growth and increased carrying capacity of the pasture (Ash *et al.* 2015). Table 5 summarises several Australian grazing studies and the response to legume inclusion. In almost all cases, the presence of legumes in the pasture had marked positive effects on productivity. Variations in response can be attributed to the proportion of legume in the pasture, the particular legume species, the location of the study as well as the trial design. Across seven comparisons, including stylos in the pasture doubled production. Although there were fewer studies with *Desmanthus*, the average response was 14% in favour of the *Desmanthus*. For example, Godson *et al.* (2024) compared weight gains of cattle grazing buffel grass or buffel grass/*Desmanthus* pastures and observed an increase in liveweight (LW) gain of 0.2 kg/day. Pen studies have observed greater responses to *Desmanthus* inclusion (Marsetyo *et al.* 2017; Aoetpah *et al.* 2018). Regarding *Leucaena*, Bowen *et al.* (2018) compared six forage types in central Queensland and showed annual LW gain to be 198 kg/ha for grass/*Leucaena* pastures, which exceeded LW gain from other forages evaluated in the study. Harrison *et al.* (2015) presented data comparing cattle grazing Rhodes grass pastures with and without *Leucaena* and showed a 50% increase in LW gain over a 14-month period when *Leucaena* was included in the pasture.

Anecdotally, graziers expect a 10–20% improvement in LW gain per hectare through a combination of increased individual animal performance and increased carrying capacity (MLA 2024). This level of response should be sufficient to encourage greater uptake of legumes by graziers, but this has not been the case, and reasons are given later. Legume inclusion may also reduce enteric methane emissions (Suybeng *et al.* 2020; Stifkens *et al.* 2022) and contribute to soil carbon (Conrad *et al.* 2017). With carbon trading becoming an increasing reality for graziers, revenue from sequestered carbon and avoided emissions should further encourage the adoption of legumes. However, increased adoption continues to be limited.

Reasons for failure to adopt

The case for widespread adoption of legumes is clear, yet this has not happened. Economic reasons exist (e.g. Bowen *et al.* 2018), but less so than for the other scenarios discussed. From an agronomic perspective, generally speaking, as one moves further west into drier and more variable rainfall zones, the risks of failed seasons, and thus establishment failure, increase. The suite of suitably adapted legume cultivars also diminishes in these regions. There is also a lack of improved cultivars of perennial legumes for tropical regions (Schultze-Kraft *et al.* 2018). Access to reliable agronomic advice, equipment and inputs is also more constrained with an increasing distance from the south-eastern corner of the study region. Newman *et al* (2022) surveyed 267 graziers in the Brigalow region and found that poor legume establishment was the most common reason for legumes failing and stated that the adoption of better agronomic practices regarding establishment is

Table 5. Animal performance proportional response to including tropical legume and tropical grass pastures.

Author	Legume	Grass	Animal response Legume versus Control	Proportional response (legume/control)
Bowen and Rickert (1979)	Stylos	Native pasture	167 *versus* 62 kg/year	2.7
			1.47 *versus* 0.62 head/ha	2.4
Gardener *et al.* (1993)	Stylos	*Heteropogon contortus* dominant	138 *versus* 109 kg/year	1.3
Noble *et al.* (2000)	Stylos	Native pasture	147 *versus* 90 kg/year	1.6
			157 *versus* 120 kg/year	1.3
Hill *et al.* (2009)	Stylos	*Bothriochloa insculpta Dichanthium sericeum, Panicum maximum*	240 *versus* 159 kg/year	1.5
			192 *versus* 50 kg/year	3.8
Collins *et al* (2016)	*Desmanthus*	*Cenchrus ciliaris*	330 *versus* 300 kg LW at turnoff	1.1
Gardiner and Parker (2012)	*Desmanthus*	*Cenchrus ciliaris*	400 *versus* 370 kg LW at turnoff	1.1
Mwangi *et al.* (2021)	*Desmanthus*	*Cenchrus ciliaris*	0.75 kg/day *versus* 0.74 kg LW/day	1.0
			43 *versus* 37 kg/ha	1.2
Godson *et al.* (2024)	*Desmanthus*	*Cenchrus ciliaris*	0.86 *versus* 0.68 kg/day	1.3
Bowen *et al.* (2018)	*Leucaena*	Native grass	198 *versus* 76 kg LWG/year	2.6
Harrison *et al.* (2015)	*Leucaena*	*Chloris gayana*	1.5 *versus* 1.1 kg/day	1.4
			0.7 *versus* 0.4 kg/day	1.7
			0.6 *versus* 0.4 kg/day	1.5

likely to improve productivity and adoption. The new MLA/DPI Queensland Pasture Resilience Program has a major focus on demonstrating the merits of legumes and their establishment (FutureBeef 2024). Setting aside economics, what else is holding producers back? If, as argued by Marshall *et al.* (2014), the industry is dominated by a conservative attitude to change, and business as usual is not threatened, then implementing change has to be relatively easy. Having all the necessary information and infrastructure to successfully establish legumes into perennial pastures may simply be too difficult, particularly, as reasoned by Holmes (2015), because the majority of producers lack appropriate levels of business and financial skills.

Silage

Ensiling offers the possibility of conserving tropical forages at optimum nutritive value for livestock production. Nutritive value can be optimised by selecting the desired growth stage for a particular class of livestock or ration formulation. Silage fermentation can be controlled by the use of inoculants and wilting and feed-out losses can be controlled by good silo management and an appropriate inoculant. Silage making is a high-input technology requiring significant capital investment and labour and should be considered as a component of an intensive beef production system. However, bale silage offers a lower cost alternative that can have application for small-scale production.

Ensiling is an ancient conservation method for lower-DM vegetation relying on the production of acids by anaerobic microflora to conserve the nutrients in the biomass. Various techniques have been developed suited to all scales of production, but all rely on the exclusion of air (oxygen) from the ensiled mass (McDonald *et al.* 1991; Wilkinson *et al.* 2003). In northern Australia, the seasonal pattern of summer rainfall followed by an extended dry season produces a short but intense growing season for forages, and silage is ideally suited for such seasonal growth patterns. Ensiling is practised only to a limited degree in northern Australia and is primarily associated with large-scale backgrounding and finishing operations using ensiled maize or sorghum stored in bunker or pit silos. Ensiling tropical forages is more common in Brazil where grasses such as *Megathyrsus maximus*, *Urochloa decumbens*, *Urochloa brizantha*, and *Cenchrus clandestinus* are used (Da Silva *et al.* 2019). In northern Australia, there is potential for ensiling a range of crops as well as ensiling of co-products from the cane, citrus and horticultural industries. However, scale and consistency of supply currently limit these options. The preferred method of ensiling is precision-chop harvesting of material wilted to between 35% and 45% DM, depending on the crop and storage method. To control feed-out losses, storage in bunker or pit silos is preferred, with the face designed to ensure the exposure of the silage surface is limited to 2–3 days. Bale silage (square or round) is an option for small-scale opportunistic forage conservation (Piltz *et al.* 2022).

Ensiling offers a method whereby forages can be harvested at optimum yield and quality and stored for use either during feed gaps or fed out to specific high-producing livestock within the herd. Compared with grazing, ensiling allows for timed harvests to optimise yield with quality, and benefits the physiology of the grass through appropriate regrowth periods (Da Silva *et al.* 2015). In practice, harvesting at optimum periods may not be possible because of weather events and growth patterns of grasses and may be interrupted by lack of rainfall. Nevertheless, the role for an intensive silage system using adapted perennial tropical grasses under irrigation could provide a reliable source of high-quality feed for beef operations. Although the nutritive value of silages is closely related to that of the original forage, it is typically somewhat reduced following fermentation (McDonald *et al.* 1991).

Unlike hay, silage is difficult and costly to transport. Silage lends itself to production at or close to the feeding site. It therefore necessitates the cost and capability to establish infrastructure and equipment on the farm. Whereas the use of dedicated contractors can defray the operational costs, availability of contractors in the north remains a constraint. Nevertheless, systems exist for all scales of operation and offer an option for high-quality, on-farm fodder production.

Estimating the current and potential quantity of silage production in northern Australia is difficult. According to ABS (2024) there were 459,000 ha of sorghum and 22,000 ha of maize grown in Queensland in 2021/22. Assuming a yield of 10 Mg DM/ha and 5% of the area being devoted to silage, the total quantity of annual crop silage would be about 225,000 Mg of DM. Hay and silage production from-pastureland in northern Australia accounts for approximately 600,000 Mg/annum (ABS 2024). A conservative estimate would suggest that the north currently produces only about 0.75 million megagrams (annual and perennial crops combined) of hay/silage annually (DM basis). The challenge in a future scenario would be to increase the production of high-quality silage from annuals such as maize and sorghum and also encourage the use of perennial crops for silage, possibly with the increased use of irrigation (see section on irrigation). The area used for hay/silage production in northern Australia is relatively small. ABS statistics for Queensland and the Northern Territory estimate an area of only 74,266 ha. Yet modelling based on rainfall and soil type suggests that large areas are theoretically suitable (Fig. 3) either as rainfed or irrigated production. A 10-fold increase in the area devoted to silage production could readily be accomplished and yet still only account for less than a million hectares of just under 400 million hectares in the area covered in this review.

Tropical perennial grasses

Biomass accumulation rates of tropical grasses are very high following the break of season and grasses exhibit a sigmoidal growth pattern (Brougham 1955). Tropical grasses produce a higher proportion of stem during the vegetative stage of growth than do temperate forages (Da Silva *et al.* 2015), which results in a more rapid decline in digestibility and CP than with temperate grasses. Nevertheless, an optimum yield of digestible nutrients can be achieved by harvesting during the linear increase in biomass after 3–4 weeks regrowth at 95% light interception (Da Silva *et al.* 2019). Research with *Megathyrsus maximus* has demonstrated biomass yield of approximately 5 Mg/ha from a single harvest, with *in vitro* organic matter digestibility of 58%, and CP of 11% (Da Silva *et al.* 2019). Under optimum conditions of soil fertility and irrigation in the tropics, multiple harvests per year can be expected. Fig. 4 shows a stylised pattern of crop growth and nutritive value for intensive silage production with perennial grasses. Harvesting before the yield asymptote will increase individual animal performance at

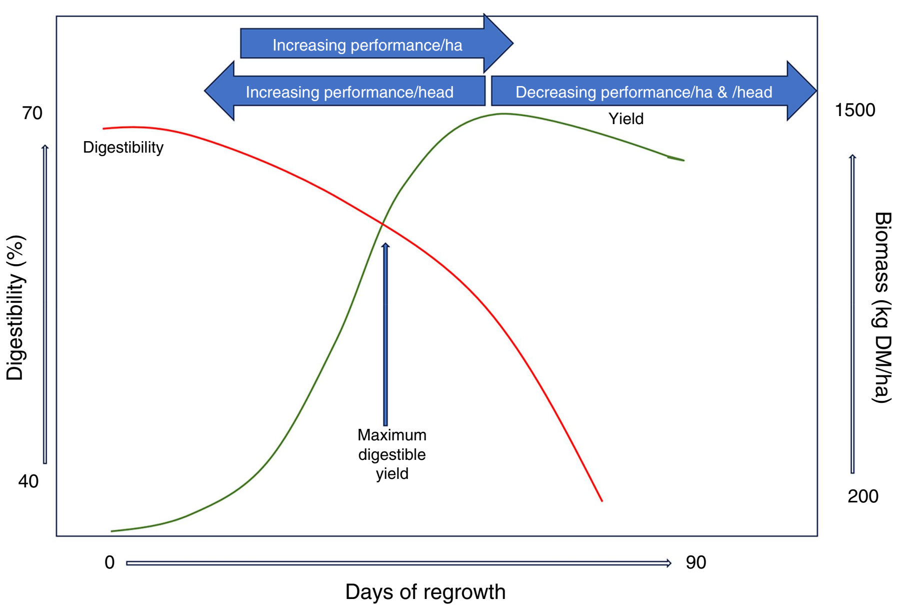

Fig. 4. Generalised relationship between quality (digestibility) and quantity (yield) of a tropical grass, showing the optimum harvest date for yield of digestible nutrients.

the expense of performance per hectare. Harvesting after the point of maximum digestible yield will reduce both individual animal performance and performance per hectare. Harvesting at the point of maximum digestible yield optimises both gain per head and per hectare.

Tropical grasses are generally considered more difficult to ensile than are temperate grasses (Parvin *et al.* 2010; Bernardes *et al.* 2018), being lower in water-soluble carbohydrate (WSC), the substrate for microbial growth during ensiling (Bernardes *et al.* 2018; Piltz *et al.* 2022). Furthermore, higher ambient temperatures at ensiling favour the less effective heterolactic over homolactic fermentations (Bernardes *et al.* 2018). Piltz *et al.* (2022) showed that increasing WSC concentration by wilting to increase DM content improved silage fermentation by favouring homolactic bacteria over spoilage organisms such as *Clostridia,* and heterolactic bacteria. The results also showed the importance of a silage inoculant on the extent and quality of fermentation (Table 5).

Typically, heterolactic fermentations contain less lactic acid and increased concentrations of acetic and other volatile fatty acids and are generally considered to be of lower nutritive value for livestock because of reduced feed intake (McDonald *et al.* 1991). However, higher concentrations of acetic and butyric acids can impart greater aerobic stability during feeding of silage (Arriola *et al.* 2021). This is particularly beneficial under the higher ambient temperatures experienced in northern Australia (Piltz *et al.* 2022). Under tropical conditions use of a microbial inoculant is recommended to improve fermentation and aerobic stability (Parvin *et al.* 2010; Arriola *et al.* 2021; Piltz *et al.* 2022). Recently, the silage inoculant containing *Lactobacillus buchneri* has shown promise in improving aerobic stability of silages. *L. buchneri* converts lactate to acetate and 1,2 propanediol, two compounds that inhibit aerobic deterioration of silages by yeasts and moulds (Arriola *et al.* 2021).

Annual crops

Maize and sorghum are two annual crops well adapted to dryland and irrigated farming opertions in northern Australia. Both grain and forage sorghuims can be ensiled. When grown in warmer climates, nutritive value of maize silage is less than when it is grown in cooler environments because of lower starch and higher cell wall contents (Adesogan 2010). Maize and sorghum are well suited to large-scale production and conservation in bunker silos or pits. The high yield and acceptable nutritive value of both crops offer solutions for use in large-scale feedlots. Sorghum is similar to maize but slightly lower in nutritive value (Bernardes *et al.* 2018). Nevertheless, both crops are a reliable source of high-energy forage and can be successfully ensiled (Parvin *et al.* 2010). These silages typically have an ME of between 10 and 11 MJ/kg DM, owing to the silage comprising both leaf and stem, and grain. Ensiling maize at the optimum dry matter of ~35% is critical when the milk line is about half way down the kernel (Francis *et al.* 2023). Kernel processing at harvest is highly recommended to reduce the proportion of whole kernels passing out in faeces (Francis *et al.* 2023). Maize and sorghum silages should be finely chopped and well packed in the silo and the silo properly sealed to reduce aerobic deterioration (Bernardes *et al.* 2021).

Legumes

All legumes are considered difficult to ensile because of high buffering capacity and low WSC content (McDonald *et al.* 1991), and this is true for tropical legumes (Castro-Montoya and Dickhoefer 2020). Nevertheless, they can be successfully ensiled, particularly when combined with a grass and treated with an inoculant. Castro-Montoya and Dickhoefer (2018) reviewed 33 studies with cattle fed ensiled tropical legumes in combination with non-legume forages. They concluded that DM intake was decreased as the proportion of legume in the silage increased and a 30–40% inclusion rate was recommended. Despite the negative impact on intake, feed conversion was improved and LW gain maximised at 20% and 40% legume content in the diet.

In northern Australia, herbaceous legumes such as *Arachis*, *Centrosema*, *Clitoria* (butterfly pea), *Desmodium*, *Macroptilium* (siratro), and *Vigna* (cow pea) can be grown as monoculture or in mixtures. Although these species are of good nutritive value, they are difficult to ensile and low yielding. Grass–legume mixtures (e.g. sorghum and lablab (*Lablab purpureus*)) offer the benefit of higher biomass, and easier ensiling, combined with higher CP content of the silage (Bernardes *et al.* (2021).

Reasons for failure to adopt

In contrast to legumes, adoption of silage as a high-quality, year-round feedstuff is a much more significant challenge. Greater adoption of silage will likely follow a potential industry shift towards more intensification and possibly corporatisation, where investment in capital infrastructure and machinery is less of an impediment. Nevertheless, the option for family-owned adoption is possible, particularly if access to silage contractors and nutritional consultants were more widespread. The expected expansion of the cotton industry in the north may provide the necessary impetus for more widespread adoption of on-farm feedlots.

Mosaic irrigation for livestock feed

Northern Australia receives between 8 and 10 sunshine hours per day for plant photosynthesis (Bureau of Meteorology 2023). However, water is often lacking, with much of the grazing areas receiving less than 600 mm rainfall per year, with most of this occurring in the wet season between approximately December and April (Bureau of Meteorology 2023).

This constrains the production potential of the landbase and particularly the better-quality soils.

Growing crops on-property for forage, hay or silage in the extensive grazing areas of northern Australia (particularly north of the Tropic of Capricorn) is a concept that has strong support in principle but is rarely practised (Grice *et al.* 2013; MacLeod *et al.* 2018; Moore *et al.* 2021). The high capital costs of irrigation schemes at all scales have generally ruled out the production of forages for beef production in favour of higher-value crops such as vegetables, cotton and pulse crops (Ambiel *et al.* 2019). We acknowledge that despite the biophysical possibilities for mosaic agriculture, there are a large number of constraints including economic, regulatory, socio-political and cultural, which have so far precluded mosaic agriculture on most cattle enterprises in the extensive cattle-producing (predominantly Crown leasehold) areas of northern Australia.

Theoretically, the use of on-farm irrigated crops for forage or silage production would allow producers greater options for marketing cattle, such as meeting market LW specifications for cattle at a younger age, meeting the specifications required for markets different from those typically targeted by cattle enterprises in the region, providing cattle that meet market specification at a different time of the year, and for supplementary feeding during drought. Forages or silage may also allow graziers to implement management strategies, such as early weaning, weaner feeding or drought feeding, which should lead to flow-on benefits throughout the herd, including increased reproductive rates. Some of these management strategies are already being practised within the extensive cattle growing areas of northern Australia but are reliant on hay or other supplements purchased on the open market. By growing crops on-property, the scale of these management interventions might be increased, at reduced net cost. Furthermore, the addition of irrigated crops may also allow graziers to increase the total number of cattle that can be sustainably carried on the property, while maintaining the same (or lower) utilisation rates of native pasture.

Soil and water

While there are a number of constraints to the implementation of mosaic irrigation on-property, there can be no question that the region possesses the biophysical elements required. A series of agricultural and water resource assessments at catchment scale across northern Australia (Petheram *et al.* 2013*a*, 2013*b*, 2018*a*, 2018*b*, 2018*c*, 2024; Watson *et al.* 2023, 2024) have assessed land suitability for a range of crops and the water resources, which might be deployed to grow them across a combined area of close to 62 million hectares. Fig. 2 shows the catchments studied and the proportion of these catchments where irrigation for the production of crops and forages for beef cattle could be grown. The land suitability results show that about 52% of the total aggregated land area assessed would be suitable for overhead spray-irrigated Rhodes grass and about 42% for annual crops such as irrigated, dry-season forage sorghum. Although much of the north was not included in these study areas, notably the Burdekin and Fitzroy catchments in Queensland, these values are likely indicative for cattle properties outside the studied catchments.

The water resources which might be applied to irrigation are also substantial. From a biophysical perspective alone, there is sufficient water in several rivers in northern Australia to grow tens of millions of megagrams of irrigated forage as hay or silage. Using the Fitzroy River catchment (9.4 million hectares) in the west Kimberley region of Western Australia as an example, Petheram *et al.* (2018*a*) calculated that it was 'physically possible' (although practically unlikely) to pump 1700 GL of surface water during high-flow events (at 85% reliability) into 425 four-GL above-ground storages (ring tanks). The term 'physically possible' should be understood in terms of (a) the potential water licensing and allocation rules, which might be applied to such extraction and (b) a realistic assessment of how much water could be pumped economically, given that 79% of total streamflow in the Fitzroy River is discharged in the highest 10% of days. Producers' ability to use surface water would depend on the proximity of their properties to the river. However, a networked regional beef production system could use the excess from properties close to the river to feed cattle on less well-endowed properties, or in regional feedlots.

Exactly what could be grown with that amount of water would depend on the farming system but, after considering evaporation and seepage losses, it might irrigate about 150,000 ha of forage sorghum, or 60,000 ha of Rhodes grass, producing nearly 2.6 million megagrams (fresh weight) of forage sorghum or 1.9 million megagrams (fresh weight) of Rhodes grass, in 85% of years.

Petheram *et al.* (2018*a*) suggested that in addition to surface water, it might be possible to supply an additional 120–170 GL of groundwater across the Fitzroy catchment in Western Australia. Using a case study approach, Petheram *et al.* (2018*b*) suggested that it could be used to potentially irrigate 12,000 ha of wet-season cotton as part of a cotton–mung bean–forage sorghum rotation. Incorporating cotton seed and the silage generated from 1000 ha of forage sorghum grown on-property into an existing beef enterprise of 23,000 head of cattle was found to generate an additional A$3.1 million in revenue from cattle sales.

Water can also be moved to where it is in short supply. In 1938, John Bradfield first proposed a scheme whereby water from eastward-flowing catchments in northern Queensland fed by high rainfall, could be turned inland into the drier parts of Queensland. There have been a number of variants proposed to the original 'Bradfield Scheme', considered nation-building by many, and political interest to develop all or parts of the scheme remains today. Petheram *et al.* (2021) considered a number of these variants, as well as their own modifications. While there is no single answer to how much water might be available, they suggest that an average of 2270 GL/year might be released, along a channel which would traverse more than 1000 km of northern Australia, before flowing into the Murray–Darling Basin in southern Australia. Clearly, such a source of readily available water might provide opportunities for livestock enterprises along the channel to grow crops to feed their stock. However, the cost of the scheme (estimated at between $15 and $30 billion) suggests that high-value crops such as horticulture and cotton would need to be grown, rather than crops for livestock. Nevertheless, the opportunities for the livestock industry to benefit from co-products, such as break crops and cotton seed, still exist.

Potential crops

As well as a range of forages, grains, oilseeds and pulse crops, which could be successfully grown in northern Australia and could be incorporated into a networked regional beef production system, there is also a significant opportunity to utilise off-specification fruits and vegetables and co-products from crops grown under irrigation and these can be ensiled often with higher DM roughage such as hay, to prolong storage (Nicholson 1981). The level of control afforded by irrigation allows for optimisation of water and nutrients to maximise the production of biomass at the desired quality to achieve appropriate production levels in livestock. For example, in more intensive systems, irrigated *Leucaena* can produce in excess of 1000 kg animal gain/ha annually (Taylor *et al.* 2016). High-frequency cutting of improved grasses and legumes for ensiling can produce high quality and quantity of forages through year-round production. de Jesus *et al.* (2021) demonstrated that over 60 Mg DM/ha (comprising 50 Mg leaf DM/ha) of guinea grass (*Megathyrsus maximus*) could be produced under irrigation in tropical Brazil, although N fertiliser use was excessive. It has been estimated that under irrigation in northern Australia, Rhodes grass (*Chloris gayana*) could yield between 20 and 35 Mg/ha (O'Gara 2010; Moore *et al.* 2021). Annual forages such as maize and forage sorghum also respond well under irrigation with high yields (10–20 Mg/ha of high nutritive value crops for ensiling (Moore *et al.* 2021).

Earlier turn-off of cattle with mosaic agriculture

Despite its inherent attractiveness, there is little mosaic agriculture practised on cattle properties in the more extensive parts of northern Australia and very little commercial-scale data are available where it has been tried. However, insights on the impact on cattle turn-off through feeding forages or hay can be gained through bio-economic modelling.

In the following example, the bioeconomic model CLEM (Crop Livestock Enterprise Model) was used to represent a beef cattle enterprise in the Victoria River catchment of the Northern Territory (Webster *et al.* 2024) and has been adapted here to suit the purposes of this review. The Victoria

Table 6. Fermentation characteristics of tropical silages adapted from Piltz *et al.* (2022).

Item	Moderate wilt		High wilt	
	Control	Inoculant	Control	Inoculant
Dry matter (%)	31.7	34.0	45.0	42.2
CP (% DM)	14.5	14.1	13.6	13.3
pH	5.40	4.35	5.90	4.30
NH_3-N (g/kg DM)	8.30	4.65	5.00	4.00
Fermentation acids (g/kg DM)				
Lactic	17.5	52.0	5.10	47.5
Acetic	6.10	8.55	1.30	4.35
Iso-butyric	0.016	0.006	0.008	0.004
Total	6.30	9.05	1.40	4.15
Lactic/acetic	2.87	6.28	3.92	12.3

catchment is approximately 8.2 million ha, of which about 62% is used for extensive cattle production. There is virtually no irrigation in the catchment and live cattle export is the primary market.

In the model, irrigation was used to grow forage sorghum, lablab or Rhodes grass. Lablab was grazed while forage sorghum and Rhodes grass were conserved as hay. A baseline enterprise was included in the model. Cattle were mustered twice per year in May or September. All weaned males, below the age of 24 months were put onto irrigated forage or fed hay between June and September (for the shorter growing-season lablab) or October (forage sorghum and Rhodes grass). Cattle given hay also had access to native pasture. Steers were sold at a minimum sale weight of 280 kg in May, September (baseline or lablab) or October (forage sorghum or Rhodes grass) (Table 6).

The most obvious biophysical impact of the various feeding strategies was the increase in LW, compared with the base-enterprise (Fig. 5). This allowed a greater proportion of the castrated males to be sold earlier, at the minimum sale weight of 280 kg. For example, for the two hay options, nearly 79% of the cohort was sold as '1-year old' cattle (i.e. 8–12 months old) in October, whereas no animals under the base-enterprise option met the minimum weight at that time (Table 7). For the baseline cohort, no cattle were sold as '1-year olds' in their first September and 100% were carried over the following wet season, 78% then being sold at the May sale as '1.5-year olds' (i.e. 15–19 months old). The remainder of the baseline cohort were sold the following September (9%) or held over the next wet season and sold in the following May sale (13%). By contrast, for the two hay options, 99% were sold as '1.5-year olds' or younger. On average, cattle fed irrigated forages or hay were sold earlier, at younger ages, than were cattle on the baseline scenario. Irrigation offers management options such as lowering grazing pressure on native pastures, running higher livestock numbers, or retaining cattle on feed to slaughter weights, depending on market opportunities.

Reasons for failure to adopt

The production benefits of irrigation are well documented. As with ensiling, irrigation provides year-round supply of high-quality feeds and the two technologies share many synergies such as equipment use and agronomic expertise and knowledge. However, crops other than livestock feeds compete for irrigated water. High-value crops such as cotton and horticulture generate greater returns under current economic conditions. However, economics aside, irrigated livestock feeds have a role within an integrated beef industry where regional on-farm backgrounding and finishing becomes a viable alternative to live export or centralised finishing close to markets. A future mega-shock, such as the end of the live export trade, could shift the balance in favour of irrigation for the beef industry.

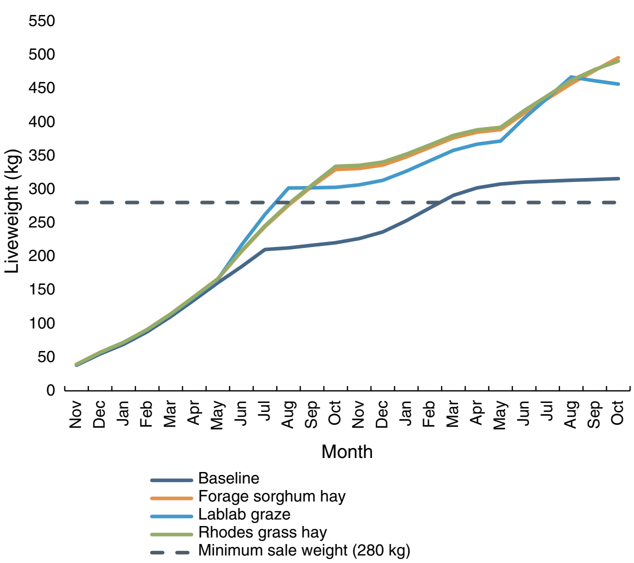

Fig. 5. Monthly mean liveweights for each scenario for male animals born at the end of November. For the purposes of this graph, all sales were switched off in the model, so as to show growth rates over the full period of feeding, without the removal of sale animals having an impact on the mean weights of the remainder of the cohort.

Co-products from other production sectors

Irrigation and rainfed agriculture along the eastern coastal areas of the subtropical and tropical north is focussed on sugarcane, bananas and a range of horticulture crops. All of these produce co-products that potentially have value as feedstock for cattle, particularly for feedlot backgrounding and finishing. In Australia, the adoption of co-products for ruminant feeds has been limited for a variety of reasons listed below:

- absence of an established feedlot industry in the north,
- lack of guaranteed supply at scale and across the season,
- transportation costs,
- low nutritive value of some co-products,
- high moisture content,
- spoilage during storage.

However, with the increasing costs of feed ingredients, improved infrastructure in northern Australia and cattle processing capacity in the region, the potential to increase use of co-products in beef diets could be realised.

Sugarcane

Sugarcane is grown along the eastern coast of Australia from northern New South Wales to far-northern Queensland (Fig. 2). Sugarcane is grown on approximately 380,000 ha and the industry produces between 30 and 35 million megagrams of sugarcane *per annum* (Queensland Farmers' Federation 2024). As a high-volume crop, sugarcane produces large quantities of co-product biomass than can provide valuable feed resources for cattle. These include molasses, bagasse, and cane tops. Bagasse is discussed in the section on improving nutritive value of ligno-cellulosic biomass.

Molasses yield can vary between 3% and 7% of fresh sugarcane, which equates potentially to an annual production in Australia of 1-2 million megagrams. As feed for ruminants, it is low in protein but very high in energy (14.7 MJ/kg DM). In northern Australia, it is commonly used to supplement dry-season pasture and offered alone or with urea. However, given its high ME value, it could be included in finishing rations for cattle. Hunter (2012) demonstrated the potential of high-molasses diets for intensive beef production. Diets

Table 7. Influence of different irrigated forage and beef production scenarios on percentage of cattle sold by age on reaching 280 kg liveweight for a modelled property in the Victoria River catchment (NT).

Item	Base-enterprise	Grazed lablab	Sorghum hay	Rhodes grass hay
'1-year-olds' sold September or October	0	63	79	79
'1.5-year olds' sold May	78	27	20	20
'2-year olds' sold September or October	9	10	1	1
'2.5-year olds' sold May	13	0	0	0

Adapted from Webster *et al.* (2024). The second sale of each year was either September (baseline or lablab) or October (sorghum hay and Rhodes grass hay).

were formulated with between 30% and 72.5% molasses. Feed intake averaged 2.4% of LW and LW gain averaged 1.5 kg/day when molasses was included at 60% of the diet DM. Currently most molasses is exported and not available for domestic inclusion into feedlot diets because of high demand and strong export prices (Indexbox 2025).

Cane tops are typically removed from the cane at harvest and blown back onto the ground as mulch. However, they can be harvested and used as a low-quality fibre source in mixed rations for growing/finishing cattle. Nutritionally, they are equivalent to dry-season tropical grasses with approximately 5% CP and an ME of 8 MJ/kg DM (Harrison 2016).

Whole sugarcane as a feed source is a high-yielding forage of potentially good nutritive value (Sousa *et al.* 2019). Recently in the Americas, interest in making sugarcane silage has increased with the development of new silage inoculants that control aerobic deterioration (Rabelo *et al.* 2019). With DM yields of up to 35 Mg/ha and high soluble sugar content (30–60% DM), sugarcane is primarily an energy feedstuff. The CP is low (<5% DM), NDF is high (60% DM) and the ME is typically ~9 MJ/kg DM. If fed in combination with protein-rich ingredients, it can be used to formulate diets for growing cattle at up to 30% inclusion (Sousa *et al.* 2019).

Cotton

Recent interest for growing cotton in the north is leading to the establishment of regional cotton gins to support growth of both irrigated and opportunistic rain-fed cotton production. Areas highlighted for growing cotton include the Ord Irrigation Scheme, Katherine area of the Northern Territory and north-west Queensland (Fig. 2). There is potential for approximately 80,000 ha of irrigated cotton and a further 10,000 ha rain-fed cotton with a potential cottonseed yield of 340,000 Mg/year (S. Yeates, pers. comm.). Cottonseed is a valuable protein source for livestock, either in the raw form as whole cottonseed or processed into cottonseed meal (CSM).

Whole cottonseed is an excellent source of protein (CP, 21% DM) and energy (ME, 12 MJ/kg DM) for cattle (Coppock *et al.* 1987). The protein is highly soluble in the rumen, leading to a rapid release of amino acids for microbial protein synthesis. Whole cottonseed contains relatively high levels of lipid (~20% DM). Thus, cottonseed can be used in diets for growing/fattening cattle to increase both the protein and energy content of the diet. As a supplement, cottonseed should be fed at less than 20% of the diet to avoid the negative effects of high fat in the diet, which reduces rumen fermentation. Additionally, the effect of the anti-nutritional compounds, tannins and gossypol, can be successfully controlled by limiting cottonseed intake. One positive attribute of cottonseed is the ability to reduce methane production in the rumen because of the presence of lipid and/or tannins (Grainger *et al.* 2010).

Cottonseed meal is a high-protein co-product of cottonseed following the extraction of the oil (Coppock *et al.* 1987). Depending on the proportion of oil remaining and whether the seed has been de-hulled, the CP content of CSM can vary from 40% to 50% DM and is therefore similar to soybean meal. The protein is much less soluble in the rumen than whole cottonseed because of processing and is therefore a better source of undegraded rumen protein. The absence of processing mills restricts the availability of cottonseed meal in northern Australia, although new mills in Katherine and Kununurra currently under construction or recently commissioned will ameliorate this (Cotton Australia 2025).

Other tropical crops

Fruit and vegetable production for human consumption inevitably produces co-product that often can be fed to ruminants. However, this practice is not widespread in northern Australia due to the dispersed and seasonal nature of production, high moisture content, spoilage during storage and transport costs. It has been estimated that losses from tropical crops (not including bananas) amount to between 50 and 110,000 Mg/year, mainly from melons/watermelons, sweet potatoes, pineapples and potatoes (Ambiel *et al.* 2019). These losses and potential co-products are typically high in digestible energy and can successfully be incorporated into feedlot rations as a partial replacement for cereals. Sources include off-specification fruit and vegetables (Charmley *et al.* 2006), peel (Bampidis and Robinson 2006), vines (Ali *et al.* 2019), and secondary by-products after extraction of higher-value co-product (Amini *et al* (2022). They may be fed fresh (Charmley *et al.* 2006) or ensiled, often with cellulosic materials to increase DM content (Nicholson 1981).

Banana production is an important crop in areas of northern Queensland with high rainfall and produces large amounts of potential co-product (Fig. 2). It is estimated that Queensland banana production is over 350,000 Mg annually across approximately 13,000 ha (Plant Health Australia 2024). Co-products from banana production include leaves, stems, peel and off-specification bananas and can amount to 13 t DM/ha (Rusdy 2019). Much of the waste is the pseudo-stem and leaves (75%), with the remainder being peel and off-specification bananas. All parts of the banana plant can be fed to ruminants. Atypically the pseudo-stem has higher digestibility than do the leaves, but is low in DM (9.8%), CP (2.8% DM) and NDF (35% DM), but is a good source of ME (Wang *et al.* 2016). Banana waste can be ensiled when mixed with higher-DM materials such as wheat straw and urea (Elahi *et al.* 2019). There are little data on feeding banana co-product to cattle and this represents an area of research deserving more attention. In developing countries banana waste has been fed to cattle with modest results of 0.3–0.5 kg/day liveweight gain (e.g. Xue *et al.* 2020). Banana waste is difficult to process owing to low DM, high biomass and lends itself to industrial-scale transformation and blending into balanced mixed diets with a protein supplement and higher DM content ingredients.

Opportunity for incorporating crop co-products into beef diets exists where co-products are abundant and preferably available year-round. As with all vegetable co-products, there are issues with consistency of quality, nutritive value and supply. The ability to blend co-products with other ingredients and store as ensiled material overcomes some of these limitations and potentially offers an untapped opportunity for vegetable waste up-cycling.

Reasons for failure to adopt

In other parts of the World, upcycling (or recycling) in agriculture is seen as a better way to benefit from finite resources (Dougherty *et al.* 2023). The abundant supply of residues from crops such as bananas, sugarcane, cotton and vegetables represent underutilised resources. Seasonality of production, distance from production to point of use, nutritional variability and low nutritive value are all valid reasons why upcycling has not been adopted by the beef industry that is dominated by smaller-scale family-owned operations. As with silage and irrigation, widespread adoption of coproducts is better suited to a more industrialised form of beef production than pastoralism. There is opportunity for the two systems to co-exist with pastoral breeder operations benefiting from the demand for feeder cattle from a regionalised finishing sector.

Improving nutritive value of low-quality biomass

In northern Australia, there are ample resources of ligno-cellulosic materials that with remediation could be a major source of digestible energy for ruminants. Techniques to break down the lignocellulosic bonds in fibrous biomass continue to be developed in both efficiency and sophistication. Two opportunities will be discussed below.

Bagasse

Bagasse is the residual fibre in sugarcane after the juice has been extracted. It is highly fibrous and of low nutritive value for ruminants, with less than 2% CP and over 80% NDF (MLA 1997). However, due to the large quantities that are produced, improvements of the nutritive value with chemical, thermo-chemical, or thermal processing represent an option to improve nutritive value (Harrison 2016). Alkali treatment with sodium hydroxide or ammonia can increase apparent digestibility to over 60%, depending on the nature of the untreated fraction and the level of alkali addition (Harrison 2016). Gunun *et al.* (2016) successfully treated bagasse with ammonia and calcium hydroxide to increase intake and digestibility in beef cattle. Ammonia also has the added advantage of adding N to a low-N feed. Oxidative conditioning with or without alkali treatment has also been investigated and effectively increased the digestibility of bagasse (Harrison 2016). Chemical treatment has health and safety risks for both the processor and animal. An alternative approach is to use heat and pressure to render the carbohydrates more accessible for rumen digestion (Chen *et al.* 2019). Steam explosion uses a combination of heat and pressure to convert moisture in the bagasse to steam. The process breaks the ligno-cellulosic bonds in the bagasse, resulting in increased digestibility (de Castro and Machado 1990). The method does not rely on chemicals and is seen as environmentally friendly.

Although large amounts of bagasse are produced in the refining of sugar, and there are proven methods to increase its nutritive value, opportunities for inclusion in cattle diets are becoming more restricted as alternative uses for bagasse are explored. About half of all bagasse is used in sugar mills as an energy source in sugar production or on-sold to other electricity users. It is also being developed as a source for biofuel production (Dias *et al.* 2012). More recently, interest has grown in the use of sugarcane co-products as the feed source for biodigestion to produce high-value products such as alcohols, sugars and enzymes, rather than animal feed (Amini *et al.* 2022). Nevertheless, it remains a missed opportunity that, given the large cattle population in proximity to a large and reliable feedstock, the industry has not developed an integrated production system with the sugar industry.

High-biomass grasses

Rapid maturation of tropical grasses results in large amounts of high-biomass, low-quality forages. Currently, these are burned, grazed, or left to decay *in situ*, but could be used as livestock feed following treatment to increase digestibility. In particular, wet-season growth of a range of forages in the monsoonal north can produce large amounts of biomass per hectare. Some of these species, for example, gamba grass (*Andropogon gayanus*), are highly invasive and strictly controlled. Nevertheless, under intensive rotational grazing, these grasses can be maintained in the vegetative stage and produce gains of 0.5–0.8 kg/day in growing cattle (Schatz 2023) where gamba grass is already present in the sward.

An alternative option involves maximising biomass production and harvesting at scale outside the wet season in a manner similar to that used in the production of biofuels from grasses (Herr *et al.* 2012; Uden *et al.* 2013). This avoids the damage caused by grazing or mechanical harvesting in the wet season.

However, to render the feedstock suitable for animal production, secondary processing would be required to increase nutritive value of these grasses. As gamba grass and hymenachne (*Hymenachne amplexicaulis*) are both listed as weeds of national significance (Weeds Australia 2024), utilising these species for fodder production is not permitted but high-pressure thermal treatment could be envisaged as an eradication or control measure. Processing options include those already discussed for bagasse such as high-pressure thermal treatment, ammonisation, and alkali treatment to increase digestibility and energy value of the biomass (Harrison 2016).

Grasses that potentially could be grown on flood plains or under irrigation include para grass (*Urochloa mutica*), hymenachne (*Hymenachne acutigluma* and *H. amplexicaulis*), Amity aleman grass (*Echinochloa polystachya*), and forage sorghum (NTgov.au 2024). Yields of over 10 t DM/ha are possible with the use of N fertiliser and can be maximised by delaying harvest to the dry season when machinery can access the crop (NTgov.au 2024). Other grasses with potential for very high DM yields (10–35 Mg/ha) in fertile high-rainfall regions include elephant grass or Napier grass (*Cenchrus purpureus*), pearl millet (*C. americanus*) and their hybrids (Cook *et al.* 2020)

Currently, the sugar industry produces approximately 5 million megagrams of bagasse DM per year that is available after mill requirements for thermal power are fulfilled (Queensland Government 2022). Potential biomass production from grasses in the monsoonal north is unknown and a thorough analysis of this potential would be required. However, utilisation of this resource may prove difficult because of the smaller scale of production relative to bagasse, and environmental concerns around weediness and damage to native ecosystems.

Reasons for failure to adopt

Of all the scenarios discussed, this is the least likely to see adoption. It is a highly industrialised process and as such requires large amounts of feedstock to achieve economy of scale. Although this cannot be envisaged in the high-rainfall areas of the Northern Territory in the medium term, the sugarcane industry does generate the amounts of feedstock required. However, competition for higher-value uses, such as energy and fermentation products, would restrict the quantities needed for nutritionally enhanced bagasse. However, given the uncertainty regarding future geopolitical and environmental conditions, this is a technology awaiting an opportunity.

Opportunities in perspective

The options to source alternative feeds for the northern cattle industry each carry pros and cons regarding their potential use. Fig. 6 classifies these options according to their technical challenge and likelihood, and opportunity. Legumes and silage are both shown to be technically feasible and the opportunity for increased adoption is large because there is ample suitable land base for expansion. A seven-fold increase in the proportion of pastures with legumes would be needed to fully utilise the suitable landbase and a 10-fold increase in silage production is technically realistic (Fig. 3). Although these adoption rates are unlikely to be ever achieved, they highlight the unfulfilled potential. Silage conservation is a proven method and offers real opportunity to produce quality livestock feed from annual and perennial forages and vegetable waste. Yet, adoption remains very low, particularly when compared with other countries including Brazil (Bernardes and Do Rêgo 2014) and the United States

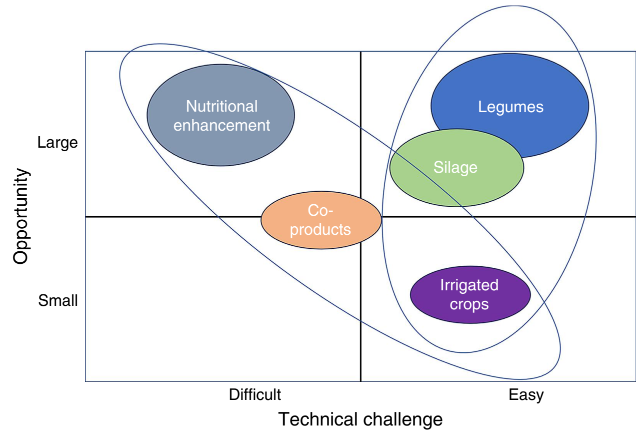

Fig. 6. Schematic showing the opportunity relative to the technical challenge of the five technologies. The size of the coloured ovals represent the potential impact for the industry, and the open ovals demonstrate potential synergies among technologies.

(Bernardes *et al.* 2018). Currently, irrigation is used primarily for the production of high-value horticultural and related crops. However, smaller-scale irrigation projects that are integrated closely with beef enterprises would facilitate silage production. Globally, there is increased interest in up-cycling, i.e. diverting waste co-product form agricultural enterprises into valuable commodities. Northern Australia produces crop and vegetable waste at scale in close proximity to a large and expanding beef industry. Novel processes can increase digestibility and nutritive value of co-products at scale to produce energy feedstock for lot-feeding. Expansion of the cotton industry in the north could produce over 300,000 Mg/year cottonseed plus protein break crops (e.g. mung beans), both being quality protein sources to complement high-energy silage, thermally treated bagasse and vegetable waste (ABARES 2024).

All the above options are technically feasible. Taken individually, each technology offers improvements in animal productivity through the provision of feeds of higher nutritive value. This could be achieved by improving production on farm, for example, by growing crops for silage, or by accessing feed resources such as vegetable co-product off farm. However, the combination of complementary technologies can lead to synergies that amount to more than a simple additive effect. Simple combinations such as irrigation with silage result in less variability in production and the potential for seasonal or year-round feeding of a high-quality forage. Nutritional enhancement of co-products such as bagasse or vegetable waste increases the nutritive value of two underutilised, widespread feed resources in the north. However, the major benefits of these alternative feed sources become more apparent when they are woven into integrated regional production systems. For example, introducing a suitably adapted legume into native pasture could increase carrying capacity by up to 20%. The producer is then faced with options such as increasing the herd size, developing irrigation-fed forage production for an on-farm feedlot or releasing land for environmental co-benefits. Alternatively, integrating feedlot enterprises within a cane-growing region or irrigation schemes could generate income from co-products and break crops while reducing feed costs for the feedlot. In a truly circular economy, manure would then be returned to the intensive cropping enterprise.

In reality there will always be barriers that limit opportunities. Although financial barriers are paramount, even if these are set aside, challenges remain. These include the following:

- dispersed production; cattle and crops are grown across large areas and transport logistics can limit opportunities,
- lack of adaptive capacity for the majority of beef producers,
- socio-economic vulnerability; a predominance of small-scale enterprises operating under tight financial constraints, including overcapitalisation and debt limiting their ability to adopt,
- poor infrastructure; lack of roads and rail for transport and limited investment in industrial plant for up-cycling,
- technical know-how and slow rates of adoption; novel production systems require novel thinking,
- climate and weather; long-term decline in land condition and short-term effects of flooding, drought, fires on production and logistics,
- competition from other industries and land use; increasing demand for biofuel from bagasse, land for cultural and environmental use,
- consistency of supply and quality of feedstuffs and pasture; opportunities for blending ingredients constrained by availability and seasonality of production, seasonal extremes in pasture production and quality.

However, there are opportunities too. Through optimisation of the potential feed resources available, the northern beef industry could expand in a sustainable manner, always under the assumption that systems are economically viable. Under the current economic and financial conditions, most of the discussed technologies are not viable. However, the purpose of this paper is to highlight what could be achieved either through external investment in creation of novel industries, or increased demand and value of beef, or through a combination of both. Today's beef industry would not be what it is without past investment and entrepreneurship in developing the north. The future industry will depend on creative means of better utilising the north's resources while maintaining its natural assets. We also recognise that the future of the northern cattle industry will remain contested with the ongoing need to balance environmental outcomes with agricultural production as well as acknowledging the multiple perspectives on how this might be achieved (e.g. Morán-Ordóñez *et al*. 2017; Runting *et al.* 2024).

Although all five production options are technically possible, current economic realities of the northern beef industry preclude their wider adoption. However, in other parts of the world, practices such as irrigation, and use of alternative feedstocks in beef production are more prevalent. A key difference between domestic and overseas beef production is the greater intensification of the beef sector in other developed countries, often supported by subsidies. Intensification is associated with higher animal performance and a greater reliance on formulated rations. Such a shift in intensification is occurring in Australia, but at a slower pace. Australian feedlot capacity continues to increase and in 2024 was 1.65 million head (https://www.mla.com.au/news-and-events/industry-news/data-shows-australian-grain-fed-beef-sector-continues-to-grow/). In many overseas countries there is segmentation of breeder and finishing operations, with breeder operations being small, part-time and typically only accounting for a small proportion of the family income. In the USA, for example, average cow--calf herd size is 47 head (USDA 2025), whereas in Canada it is 63 head (Canada Beef 2025). In Australia, breeder operations are commercially more viable, large scale with the herd size in northern Australia ranging from 220 to 44,000 head (MLA 2014). Such pasture-based breeder operations could remain viable in co-existence with an intensive beef finishing sector.

This review has highlighted some alternative feeding practices for the northern beef industry. The intent is not to question the *status quo* but to demonstrate that there are alternatives that in the future may or may not become economically viable.

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