The potential of macroalgae for beef production systems in Northern Australia

Article *in* Journal of Applied Phycology · October 2014

DOI: 10.1007/s10811-014-0439-7

Lorenna Machado
James Cook University

Marie Magnusson
The University of Waikato

Rocky de Nys
James Cook University

Nigel Tomkins
Meat & Livestock Australia

J Appl Phycol
DOI 10.1007/s10811-014-0439-7

5TH CONGRESS OF THE INTERNATIONAL SOCIETY FOR APPLIED PHYCOLOGY

The potential of macroalgae for beef production systems in Northern Australia

Lorenna Machado · Robert D. Kinley · Marie Magnusson ·
Rocky de Nys · Nigel W. Tomkins

Received: 29 July 2014 / Revised and accepted: 15 October 2014

Abstract The extensive grazing systems across northern Australia support approximately 50 % of the national beef herd. Livestock productivity is affected by seasonal variation in pasture quality and quantity. Intensifying livestock production in the north is a challenge, but has been recognised as priority for the Australian economy. Macroalgae offer a sustainable and novel dietary supplement for cattle due to its high nutrient value and biomass production, which are generally superior to forages used in ruminant production systems. This paper highlights some of the existing literature associated with the use of macroalgae for beef cattle and discusses the potential of green freshwater (*Cladophora vagabunda*, *Oedogonium* sp., *Spirogyra* sp.) and marine macroalgae (*Cladophora coelothrix*, *Derbesia tenuissima*, *Ulva ohnoi*) as feed supplements in northern Australian livestock production systems. Crude protein content of the six species of green macroalgae discussed here ranged from 75.4 to 339.1 g kg^{-1} dry weight (DW). Dietary mineral limitations in northern livestock production systems include phosphorous (P), sulfur (S) and nitrogen. Four of the six macroalgae species had high P content, ranging from 1.4 to 5 g kg^{-1} DW. Sulfur varied between species, ranging from 2.9 to 57.5 g kg^{-1} DW, with marine macroalgae having a higher sulfur concentration than freshwater macroalgae. This review demonstrates that green macroalgae have considerable potential to supply a high-protein, high-phosphorous feed supplement for northern livestock production systems dependent on extensive unimproved pastures.

Keywords Biomass production · Cattle · Crude protein · Gross energy · Ruminants

Introduction

The Australian beef herd is estimated to be 26.7 million head with approximately 50 % of these animals found in northern regions (McRae and Thomas 2014). The productivity of these regions is characterized by distinct wet season pasture growth followed by dry season pasture senescence resulting in marked seasonal variation in pasture quality and quantity (Tothill and Gillies 1992). These regions are highly heterogeneous and dominated by C4 grasses, which have a lower nutritional value than temperate C3 grasses. Livestock selectively graze these pastures in search of material with higher palatability and nutritional value (Hunt 2008). As a consequence, the viability of beef production systems across northern Australia is strongly influenced by these seasonal conditions which in turn drive animal growth rate and herd fertility.

Growth rates for beef cattle should range between 0.5 and 1 kg day^{-1} for efficient animal productivity (Poppi and McLennan 1995). Consequently, the supplementation of molasses and/or urea, a non-protein nitrogen source to improve energy and N supply of these low quality forages, is commonplace. However, individual animal production is highly variable and maximum growth rates rarely exceed 1 kg day^{-1} during the wet season (Poppi and McLennan 1995). Intensifying rangeland livestock production in northern Australia is a challenge, but has been recognised as a priority for Australian agriculture (Ash and Smith 2003). Macroalgae offer a sustainable and novel dietary supplement for cattle due to their high nutrient value and demonstrated biomass production. Macroalgae can also provide important bioremediation services (de Paula Silva et al. 2012; Cole et al. 2014), and consequently there is the potential to utilise macroalgal

L. Machado (✉) · M. Magnusson · R. de Nys
MACRO–Centre for Macroalgal Resources & Biotechnology, James Cook University, Townsville, QLD 4811, Australia
e-mail: lorenna.machado@my.jcu.edu.au

R. D. Kinley · N. W. Tomkins
CSIRO Agriculture, Australian Tropical Science and Innovation Precinct, James Cook University, Townsville, QLD 4811, Australia

biomass in integrated applications when produced under managed conditions. Macroalgae are predominantly cultured for human nutrition and production of phycocolloids (Paul and Tseng 2012). However, many species have antibacterial, antiviral, antioxidant or anti-inflammatory properties that are used in nutraceutical and health markets and may also be used to manipulate livestock health and productivity (O'Sullivan et al. 2010) and methane emissions (Machado et al. 2014). Species-specific bioactive compounds in marine macroalgae and their characteristics and functions are well described by Holdt and Kraan (2011).

There is growing interest and evidence of the benefits of using macroalgal biomass in livestock production systems, particularly for ruminants (Arieli et al. 1993; Evans and Critchley 2014). Evans and Critchley (2014) comprehensively discuss the use of seaweeds in animal production with *Ascophyllum nodosum* as a principal example. The use of *A. nodosum* as a supplement in intensive finishing systems for beef cattle was demonstrated as beneficial to carcass characteristics and meat quality (Braden et al. 2007) and, as an additive in molasses blocks, increases ruminal organic matter and total tract crude protein digestibility (Leupp et al. 2005). More recently, the work of Machado et al. (2014) has generated a rich data set based on in vitro incubations with algae at an inclusion rate of 17 % organic matter (OM) basis. This work provides a basis for comparing the nutritional value of macroalgae relative to beef cattle requirements relevant to Australian conditions.

The work presented here provides insight into the comparative nutritional value of macroalgae in beef cattle requirements relevant to Australian conditions and, specifically describes the nutritional value of six species of green macroalgae, three freshwater (*Cladophora vagabunda*, *Oedogonium* sp., *Spirogyra* sp.) and three marine species (*Cladophora coelothrix*, *Derbesia tenuissima*, *Ulva ohnoi*), for the production of ruminant livestock. The potential application of macroalgae as a feed supplement to low quality forage diets in beef production systems of northern Australia is discussed.

Macroalgae production

Macroalgae can be produced in ponds on non-arable land or in existing aquatic environments where biomass production does not compete with existing cropping systems. The potential to culture macroalgae has clear benefits due to higher growth rates per unit area compared with conventional crops. Marine macroalgae have higher biomass productivity than freshwater macroalgae (Neveux et al. 2014a) and among the marine species in this study, *D. tenuissima* and *U. ohnoi* have the greatest potential for integration into livestock production systems with biomass production approaching 70 and 73 t dry weight (DW) ha^{-1} year^{-1}, respectively (Table 1). Of the three species of freshwater macroalgae considered suitable for Australian systems, *Oedogonium* has the highest productivity (Table 1), producing 18 to 55 t DW ha^{-1} year^{-1}. Although dependent on environmental conditions and scale of production (Neveux et al. 2014b; Cole et al. 2014), this level of biomass production is significantly higher than that achievable from conventional grain crops which are used in Australian ruminant production systems (FAO 2014). There is an opportunity to transform existing supplementation practices for cattle given the potential to supply on-farm macroalgal biomass from freshwater macroalgae that are high in lipids, protein and minerals compared with tropical pastures. The use of algae supplementation would also be beneficial to rumen function (Machado et al. 2014) and ultimately livestock productivity.

Matching protein and energy requirements

It is feasible that on-farm production of freshwater macroalgae can be used to fill seasonal gaps in feed availability in northern production systems dependent on native pastures typical of northern Australia. In turn, this may reduce the reliance on protein or non-protein nitrogen and molasses-based supplementation practices to maintain levels of animal productivity. The recommended supplementation of non-protein nitrogen for cattle grazing dry season pastures is typically 15–30 g N day^{-1} per cow (Callaghan et al. 2014). However, non-protein sources supplemented within these levels have little effect on live weight (LW) gain response (Dixon and Coates 2010). Additionally, supplementation of some sources of non-protein nitrogen, such as nitrate, is difficult to manage at a herd scale and toxicity to ruminants may occur (Callaghan et al. 2014).

Another beneficial feature of macroalgae is their nutritional plasticity, such that the content of mineral, protein and lipids can be manipulated to yield a biomass with the desired characteristics for specific ruminant feed supplements (Angell et al. 2014; Neveux et al. 2014b). The main constraint in extensive ruminant production systems, particularly in the dry season, is maintaining the supply of protein and energy throughout an animal's growth and reproductive cycles. Supplementation of low quality forages with concentrates rich in protein and energy can markedly increase LW gain (Poppi and McLennan 1995) and decorticated cottonseed meal (DCM), a by-product of the cotton industry, is a highly valued protein supplement (Table 1) when available. Machado et al. (2014) demonstrated that the inclusion of macroalgae with a typical northern grass diet resulted in similar or higher volatile fatty acid (VFA) production compared to cottonseed meal. This shows that the addition of some species of macroalgae to low quality forage-based diets improve production of end

Table 1 Nutritional content and production yields of freshwater and marine green macroalgae compared to decorticated cottonseed meal (DCM)

	Freshwater macroalgae			Marine macroalgae			DCM
	Cladophora vagabunda	*Oedogonium* sp.	*Spirogyra* sp.	*Cladophora coelothrix*	*Derbesia tenuissima*	*Ulva ohnoi*	
CP[h] (g kg^{-1} DW)	268–278[a, b]	167–288[a, b, c]	75.4[a]	178–269[a, b]	216–339.1[a, b, d]	163–220.6[a, b]	497.5[a]
TAA	268[b]	225[b]	ND	178[b]	216[b]	163[b]	ND
EAA	101[b]	97[b]	ND	71[b]	91[b]	64[b]	128.3[e]
GE (MJ kg^{-1} DW)	16–16.5[a, b]	15.8–19.4[a]	15.2[a]	12.7–15.3[a, b]	12.4–20.1[a, b]	11.7–12[a, b]	18.6[a]
TL (g kg^{-1} DW)	53–97[a, b]	79–94[a]	52.09[a]	46–50[a]	104–130[a, b, d]	19–24.6[a, b]	47.2[a]
Phosphorous (g kg^{-1} DW)	1.4[a]	5.0[a, c]	<0.5[a, b]	2.3[a]	2.3[a]	<0.5[a, b]	12.7[a]
Sulfur (g kg^{-1} DW)	11.2–18[a, b]	2.9–4[a, b]	3.1[a]	21–23[a, b]	12.3–28[a, b]	50–57.5[a, b]	3.1[a]
Production yield (t DW ha^{-1} year^{-1})	12[b]	18–56[b, c]	ND	31.5[f]	43–70[b, d]	42–73[b]	3.1[g]

DW dry weight, *CP* crude protein, *TAA* total amino acids, *EAA* essential amino acids, *GE* gross energy, *TL* total lipids, *ND* not determined

[a] Machado et al. 2014

[b] Neveux et al. 2014a

[c] Cole et al. 2014

[d] Magnusson et al. 2014

[e] Lyman et al. 1956

[f] de Paula Silva et al. 2012

[g] http://cottonaustralia.com.au/cotton-library/statistics

[h] crude protein calculated using nitrogen factors of 5.13 for macroalgae and 6.25 for cottonseed (Machado et al. 2014)

products essential to ruminant productivity and do not negatively affect in vitro fermentation parameters.

The content of crude protein (CP) varied substantially among the tested macroalgae used, ranging from a low of 75.4 g kg^{-1} dry weight (DW) for the freshwater *Spirogyra* up to a maximum of 339.1 g kg^{-1} DW for the marine *D. tenuissima* (Table 1). However, while macroalgae have lower CP than DCM, the CP content is up to 12 times higher than the native grasses typical of northern Australia (Kennedy and Charmley 2012; Machado et al. 2014). A steer of approximately 400 kg LW requires 675 g day^{-1} of crude protein (assuming a metabolizability [q_m] of 0.55) to achieve a LW gain of 0.75 kg day^{-1} (McDonald et al. 2011). This would be challenging under extensive grazing conditions; however, a supplement of 2.0 kg DW day^{-1} of *D. tenuissima* or 2.4 kg DW day^{-1} of *Oedogonium* could meet this requirement. The amino acid (threonine, lysine, tryptophan, cysteine and methionine) profiles of macroalgae have been perceived as limiting, although in species such as *Ulva* up to 75 % of the crude protein is in the form of true protein and the amino acid profile is characterized by high lysine and sulfur containing amino acids (Arieli et al. 1993). In general, amino acid levels in macroalgae are higher than those found in terrestrial plants (Galland-Irmouli et al. 1999) making them a rich source of limiting amino acids for livestock production. Five species of macroalgae assessed here contained the six amino acids (methionine, lysine, histidine, arginine, threonine and cysteine) generally associated with LW gain in cattle (Poppi and McLennan 1995), with *Oedogonium* and *D. tenuissima* containing the highest amounts of these amino acids (Neveux et al. 2014a).

The gross energy (GE) and total lipid content of macroalgae can vary within and between species (Table 1). This variability within species is explained by differences in the cultivation and processing of biomass (Magnusson et al. 2014; Cole et al. 2014). Processing practices have the potential to increase the OM content of biomass resulting in increases in GE and the concentration of lipids. Rinsing the biomass of *Oedogonium* and *D. tenuissima*, for instance, can reduce ash content of the biomass and concomitantly increase GE and the concentration of lipids (Neveux et al. 2014b). Post-harvesting drying techniques can also affect the concentration and quality of the fatty acid profile of the biomass (Magnusson et al. 2014). This demonstrates that the initial processing of the algae biomass can directly influence its nutritive value. There is also the potential to combine macroalgal biomass as a supplement to other fodder crops to manipulate protein and energy content of the diet. For example, *U. ohnoi* does not have a high inherent GE content; however, CP is at least 50 % higher than most tropical pastures found in northern Australia (Kennedy and

Charmley 2012). Therefore, *Ulva* could be characterized as a low-energy high-protein feed and may be combined with cereal grains (Arieli et al. 1993), or other macroalgae with higher GE to provide a suitable livestock feed supplement when dietary CP and energy are limited.

Matching mineral requirements

Whilst nitrogen is the primary limiting nutrient in the diet selected by cattle grazing tropical pastures, these forages also contain low concentrations of the essential minerals phosphorus and sulfur. Phosphorus and sulfur are usually the first limiting elements to livestock growth (Hamlyn-Hill 2012), and supplementation of phosphorus throughout the year is a major cost for the northern beef industry. Phosphorus is an important macro-mineral, and cattle grazing low P pastures actively mobilise P from bone, decrease food intake, experience a decrease in gastrointestinal microbial activity and ultimately experience lower levels of productivity compared to supplemented animals (Ternouth 1990). A 300-kg steer can accumulate approximately 2 kg of P, which is primarily stored in bones (Ternouth 1990) and dedicated supplementation programmes are required to avoid P deficiency. The recommended intake of P for the maintenance of a steer weighing 400 kg LW is 7 g day^{-1} and increases to 22 g day^{-1}, or 0.9 to 1.5 g kg^{-1} DW, to achieve a LW gain of 1.2 kg day^{-1} (Jackson et al. 2012). Achieving this dietary level of P may be challenging in most grazing situations throughout the year; however, four of the green macroalgae assessed contained P at levels from 1.4 to 5 g kg^{-1} DW. *Oedogonium* had the highest P content among the macroalgae described (Table 1). Based on this data, it can be estimated that a supplement of 20 % (DW basis) of *Oedogonium* (with a CP content of 250 g kg^{-1} DW) to low quality forage could increase dietary P to 1 g kg^{-1} DW and sustain live weight gains.

Sulfur may also limit cattle production, particularly when urea or other non-protein sources of nitrogen are added to the diet of animals and/or during the wet season (NRC 1996; Hamlyn-Hill 2012). Sulfur plays an important role in the metabolism of protein, fat and carbohydrates, such that S deficiency can decrease digestive microbial population density and activity (NRC 1996). Since the daily requirement of sulfur for beef cattle is 1.5 g kg^{-1} DW, any of the six green macroalgae described here could be used as a source of dietary sulfur for cattle (Table 1).

On farm

Implementing animal husbandry practices that reduce the environmental impact of livestock, but maintain a viable level of productivity in northern Australia is challenging. The ability to grow macroalgal biomass under controlled conditions to yield a product high in crude protein and lipids on farm is particularly attractive for an industry that spends up to AU $30 per head annually on nitrogen supplementation (Callaghan, pers. comm.) which at best only maintains the live weight of cattle.

Although macroalgae productivity will vary throughout the year, it is feasible to achieve an average weekly supply of approximately 1.1 t ha^{-1}. The freshwater macroalgae *Oedogonium* has been cultured with a mean annual productivity of 16 g DW m^{-2} day^{-1} or 56 t DW ha^{-1} year^{-1} (Cole et al. 2014). Crop growth models indicate that intensive farming of feeds such as forage sorghum using irrigation would achieve a peak production of up to 5 t DW ha^{-1}; however, these crops are planted annually and are grown over a 9-month period (Hunt et al. 2014). Considering this production and an average daily intake of 7–8 kg DW, a hectare of *Oedogonium* production could supply 112 steers per week with a supplement of 20 % algae. Similarly, the marine macroalgae *D. tenuissima* could be employed in coastal regions where marine water is available for cultivation. This macroalgae has a potential productivity of 20 g DW m^{-2} day^{-1} or 70 t DW ha^{-1} year^{-1} (Magnusson et al. 2014). If used as a feed supplement equivalent to 20 % of the diet on a daily basis, *D. tenuissima* could support 116 to 142 steers with potential to increase animal productivity. To provide a 20 % feed supplement for the whole northern beef cattle herd, a maximum area of 149×10^3 ha would be required for *Oedogonium* and/or a maximum area of 126×10^3 ha for *D. tenuissima*. In each case, this corresponds to a quarter of the land area currently used for sorghum production in Australia (FAO 2014). With the proposed development of northern agricultural systems in Australia, an opportunity now exists to deliver this biomass as an integrated process on farm using decentralised small- to medium-scale production systems, or in centralised purpose-built large-scale production sites that would satisfy industry requirements.

Conclusion

Green macroalgae are highly nutritious, with protein, energy, lipids and mineral contents higher than most forage typical of northern Australia. Current in vitro studies for a number of macroalgae suitable for intensive culture across Australia have demonstrated potential benefits associated with feeding biomass to ruminants. Algal biomass is already produced and processed for food and nutraceutical purposes. The identification of specific species of macroalgae with high biomass production and nutrient content can be used to determine the economic viability of this novel feed sources to supplement existing animal feed formulations. However, factors including palatability, delivery, appropriate levels of inclusion and potential milk or meat taint may limit the adoption of macroalgae in livestock production systems. Translating in vitro relationships to animal production systems is a significant challenge. Nevertheless, it has been demonstrated in vitro that the addition of macroalgae to low quality forages typical of northern Australia improves the production of fermentation end products and a similar effect could be expected in vivo. This supports the potential to use macroalgal biomass as a sustainable functional feed for beef cattle, acknowledging that in vivo trials are required to quantify palatability and effects on animal productivity.

Acknowledgments This research is part of the MBD Energy Research and Development program for Biological Carbon Capture and Storage. This work was co-funded by the National Livestock Methane Program, through funding from the Australian Government Department of Agriculture, Carbon Farming Futures Filling the Research Gap Program and Meat and Livestock Australia; the Australian Renewable Energy Agency, and the Advanced Manufacturing Cooperative Research Centre.

References

Angell AR, Mata L, de Nys R, Paul NA (2014) Variation in amino acid content and its relationship to nitrogen content and growth rate in *Ulva ohnoi* (Chlorophyta). J Phycol 50:216–226

Arieli A, Sklan D, Kissil G (1993) A note on the nutritive value of *Ulva lactuca* for ruminants. J Anim Sci 57:329–331

Ash A, Smith MS (2003) Pastoralism in tropical rangelands: seizing the opportunity to change. Range J 25:113–127

Braden KW, Blanton JR, Montgomery JL, van Santen E, Allen VG, Miller MF (2007) Tasco supplementation: effects on carcass characteristics, sensory attributes, and retail display shelf-life. J Anim Sci 85:754–768

Callaghan M, Tomkins N, Benu I, Parker A (2014) How feasible is it to replace urea with nitrates to mitigate greenhouse gas emissions from extensively managed beef cattle? J Anim Sci 54:1300–1304

Cole AJ, de Nys R, Paul NA (2014) Removing constraints on the biomass production of freshwater macroalgae by manipulating water exchange to manage nutrient flux. PLoS One 9(7):e101284

de Paula Silva PH, de Nys R, Paul NA (2012) Seasonal growth dynamics and resilience of the green tide alga *Cladophora coelothrix* in high-nutrient tropical aquaculture. Aqua Environ Inter 2:253–266

Dixon R, Coates D (2010) Diet quality estimated with faecal near infrared reflectance spectroscopy and responses to N supplementation by cattle grazing buffel grass pastures. Anim Feed Sci Tech 158:115–125

Evans FD, Critchley AT (2014) Seaweeds for animal production use. J Appl Phycol 26:891–899

FAO (2014) Food and Agricultural Organization of United Nations: Economic and social department: The statistical division. http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor. Updated 7 February 2014; verified 4 March 2014

Galland-Irmouli AV, Fleurence J, Lamghari R, Lucon M, Rouxel C, Barbaroux O, Bronowicki JP, VillaumeC GJL (1999) Nutritional value of proteins from edible seaweed *Palmaria palmata* (dulse). J Nutr Biochem 10:353–359

Hamlyn-Hill F (2012) Mineral and vitamins [Online]. In: Future beef. Available at http://futurebeef.com.au/topics/nutrition/minerals-and-vitamins/. Posted 8 May 2012; verified 4 March 2014

Holdt SL, Kraan S (2011) Bioactive compounds in seaweed: functional food applications and legislation. J Appl Phycol 23:543–597

Hunt LP (2008) Safe pasture utilisation rates as a grazing management tool in extensively grazed tropical savannas of northern Australia. Range J 30:305–315

Hunt L, Ash A, MacLeod N, McDonald C, Scanlan J, Bell L, Cowley R, Watson I, McIvor J (2014) Research opportunities for sustainable productivity improvement in the northern beef industry: a scoping study. Final report. Meat & Livestock Australia Ltd, Sydney

Jackson D, Rolfe J, English B, Holmes B, Matthews R, Dixon R, Smith P, MacDonald N (2012) In: Partridge I (ed) Phosphorus management of beef cattle in northern Australia. Meat & Livestock Australia Ltd, Sydney

Kennedy P, Charmley E (2012) Methane yields from Brahman cattle fed tropical grasses and legumes. Anim Prod Sci 52:225–239

Leupp JL, Caton JS, Soto-Navarro SA, Lardy GP (2005) Effects of cooked molasses blocks and fermentation extract or brown seaweed meal inclusion on intake, digestion, and microbial efficiency in steers fed low-quality hay. J Anim Sci 83:2938–2945

Lyman CM, Kuiken K, Hale F (1956) Amino acids in feedstuffs, essential amino acid content of farm feeds. J Agric Food Chem 4:1008–1013

Machado L, Magnusson M, Paul NA, de Nys R, Tomkins N (2014) Effects of marine and freshwater macroalgae on *in vitro* total gas and methane production. PloS One 9:e85289

Magnusson M, Mata L, de Nys R, Paul NA (2014) Biomass, lipid and fatty acid production in large-scale cultures of the marine macroalga *Derbesia tenuissima* (Chlorophyta). Mar Biotechnol 16:456–464

McDonald P, Edwards R, Greenhalgh J, Morgan C, Sinclair L, Wilkinson R (2011) Evaluation of foods: protein. In 'Animal Nutrition'. Pearson Education Ltd, Essex, pp 303–339

McRae T, Thomas B (2014) Australian cattle industry projections. Mid-year update. Meat & Livestock Australia Ltd, Sydney

Neveux N, Magnusson M, Maschmeyer T, de Nys R, Paul NA (2014a) Comparing the potential production and value of high-energy liquid fuels and protein from marine and freshwater macroalgae. GCB Bioenergy. doi:10.1111/gcbb.12171

Neveux N, Yuen A, Jazrawi C, He Y, Magnusson M, Haynes B, Masters A, Montoya A, Paul N, Maschmeyer T, de Nys R (2014b) Pre- and post-harvest treatment of macroalgae to improve the quality of feedstock for hydrothermal liquefaction. Algal Res 6:22–31

NRC (1996) National research council. Nutrient requirements of beef cattle. National Academy Press, Washington

O'Sullivan L, Murphy B, McLoughlin P, Duggan P, Lawlor PG, Hughes H, Gardiner GE (2010) Prebiotics from marine macroalgae for human and animal health applications. Mar Drugs 8:2038–2064

Paul NA, Tseng C (2012) Seaweed. In: Lucas JS, Southgate PC (eds) Aquaculture: farming aquatic animals and plants. Blackwell Publishing Ltd, Oxford, pp 268–284

Poppi DP, McLennan SR (1995) Protein and energy-utilization by ruminants at pasture. J Anim Sci 73:278–290

Ternouth J (1990) Phosphorus and beef production in northern Australia. 3. Phosphorus in cattle—a review. Trop Grassl 24:159–169

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