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Australian Journal of Agricultural Research, 2007, **58**, 185–202

A review of the nutritional value of lupins for dairy cows

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Abstract. Australia is the world's leading source of lupin grain, producing ~1 million tonnes annually, of which 30% is used by the domestic livestock industry and the rest is exported for use in animal diets, including dairy cows. The domestic dairy industry uses ~70 000 tonnes annually, mainly as a supplementary feed source in pasture-based systems. Although much published information exists on the nutritive value of lupins for dairy cows, it tends to be fragmented and, in some important instances, exists only in the form of reports or publications outside the mainstream scientific journals. This paper aims to present a critical assessment of the current knowledge regarding the nutritional value of lupins as a feed for dairy cows, and offers recommendations for future research.

For cows grazing pasture or fed diets based on conserved pasture or cereal hay, the mean fractional response to lupin feeding was 0.53 kg milk/kg DM lupins, with a range of 0–0.97 kg/kg. The mean fractional forage substitution rate was 0.54 kg DM/kg lupins, and this appeared to be independent of the type of basal forage.

In experiments using cows fed iso-nitrogenous and iso-energetic total mixed rations, substituting oilseed protein such as soybean meal with cracked lupin grain had no significant effects on yield of milk, fat, and protein, but it reduced milk protein concentration and had mixed effects on fat concentration. There were no significant differences in milk yield or in fat or protein concentration when lupins were substituted for other pulse grains such as faba beans or peas. Treatment of lupin grain with heat or formaldehyde reduced lupin protein degradability in the rumen, but was not shown to have consistent benefits over untreated lupins in terms of increased milk yield.

Substitution of cereal grains with an equivalent weight of lupins in dairy concentrate rations generally resulted in increased yield of milk, fat, and protein, and a higher fat concentration. The higher yield responses in most cases could be explained on the basis of the higher metabolisable energy content of lupins compared with cereal grains, although the contribution from a potentially lower incidence of rumen lactic acidosis could not be discounted.

Feeding *Lupinus albus* lupins to cows significantly increased the concentration of C18 : 1 in milk and reduced that of C12 : 0–C16 : 0, thus shifting the fatty acid profile of milk towards national dietary guidelines for improved cardiovascular health in human populations.

Although the review lists some recommendations for improving the nutritive value of lupins, current commercially available cultivars possess characteristics that make them attractive as a feedstuff for dairy cows.

Additional keywords: milk, composition, nutritive value, fatty acids, protein, fat.

Introduction

Australia is the world's leading producer and exporter of lupin grains, representing 80–85% of the world's production and 90–95% of the world's exports (J. Craig, Grain Pool Pty Ltd/AgraCorp Pty Ltd, pers. comm.). Their availability as livestock feed is underpinned by the fact that lupins are a valued component of cereal cropping rotations, especially across large areas of Western Australia. In the 2005–06 season, Australia produced ~1 million tonnes (t) of low-alkaloid varieties of lupins, of which 85% was produced in Western Australia. In a normal year, ~300 000 t are consumed in the domestic market for feed and seed, and the remainder is exported to countries including Korea, Japan, The Netherlands, Spain, Thailand, The Philippines, and Indonesia. For the export market, ~40% is used in the dairy and beef sector, 40% in the pig sector, and the remainder spread among sheep, goats, and poultry. For the domestic market, an estimated 60% is used by the sheep industry both on-farm and in the form of pellets for the feedlot and live export industry. The remainder is used mainly in the cattle (beef and dairy) and pig market, with an estimated 70 000 t fed annually to Australia's 2 million dairy cows (Hafi and Rodriguez 2000). Data derived from dairy farm performance surveys conducted by the Western Australian Department of Agriculture suggest that the Western Australian dairy industry is the heaviest user of lupins per cow, feeding 0.6 t/cow.year, totalling 50,000 t annually (S. Gallagher, pers. comm.).

10.1071/AR06109 0004-9409/07/030185

Anecdotal evidence suggests that lupins are valued as a supplementary feed source by dairy farmers because they are generally less expensive than oilseed proteins, they require minimal processing, are easy to store and handle, contain high concentrations of metabolisable energy (ME), true protein, and some minerals, and are considered safe to feed in twice-daily feeding systems at relatively high levels. The introduction of bans on the use of most animal protein sources in ruminant diets in Australia in 1992 further consolidated the role of high-protein grains such as lupins in the diet of dairy cows.

Although much published information exists on the nutritive value of lupins for dairy cows, it tends to be fragmented and, in some important instances, exists only in the form of reports or publications outside the mainstream scientific journals. This paper aims to present a critical assessment of the current knowledge regarding the nutritional value of lupins as a feed for dairy cows, and offers recommendations for future research.

Species, physical and chemical characteristics, and proximate analysis

Most lupins fed to dairy cows in Australia are cultivars of *Lupinus angustifolius*, commonly known as the Australian sweet lupin (van Barneveld 1999; Petterson 2000), although a smaller amount of lupin seed from other species including white lupin (*Lupinus albus*) and yellow lupin (*Lupinus luteus*) is also used. Modern varieties have been bred to contain low concentrations of alkaloids, making them safe for use by monogastric and ruminant animals (Petterson *et al.* 1997). White lupin is the predominant lupin species fed to dairy cows in Europe and the USA (May *et al.* 1993), with much of the Northern Hemisphere literature referring to this species and its use within total mixed rations for high-producing dairy cows. Although the nutritional value of the 2 species appears very similar, there are some differences that warrant identification of the species when comparing data from different experiments. In this review, the term 'lupin' or 'lupins' refers only to the seed or grain component. Weights and concentrations are expressed on a dry matter (DM) basis unless otherwise indicated.

L. angustifolius seeds weigh ~144 mg fresh weight (Petterson and Mackintosh 1994), of which ~250 g/kg is seed coat. The seed has a fresh weight bulk density of 0.78 t/m^3, which is equivalent to that of wheat (0.75 t/m^3) but greater than barley (0.65 t/m^3) and oats (0.50 t/m^3) (DAFWA 2006). On a metabolisable energy per m^3 basis, this amounts to a fractional advantage for lupin storage capacity of 1.1, 1.35, and 2.03-fold, respectively, relative to these cereal grains. *L. albus* seed has a mean weight of 340 mg and has a thinner seed coat than *L. angustifolius*, representing 150 g/kg of total weight. It is also softer than *L. angustifolius* and more readily processed (Petterson *et al.* 1997).

The chemical composition of the seeds of *L. angustifolius* and *L. albus* is shown in Table 1. although values for most constituents vary between cultivars and species, lupins have a consistently high crude protein (CP) content (>300 g/kg) and low starch content (<20 g/kg) compared with those of cereal grains and most other legume grains. Their oil content at 60–100 g/kg is higher than that of most cereal grains (usually 20–40 g/kg) but lower than oilseeds (400 g/kg). *L. angustifolius* contains a lower protein and fat content than *L. albus*, although large variations exist within species (Petterson *et al.* 1997).

Gross energy (GE) and metabolisable energy (ME)

Reported values for the GE of lupins range from 19.6 to 22 MJ/kg dry matter (DM), with ME values for ruminants ranging from 11 to >14 MJ/kg DM, with a mean of 13.3 (Table 1). Values for organic matter digestibility on a dry matter basis (DOMD) of 880 and 920 g/kg have been reported from *in vivo* studies with sheep for *L. albus* and *L. angustifolius* cultivars, respectively (ADAS 1995; White *et al.* 2002), and this high degradability is supported by *in sacco* values for potential fractional dry matter degradability ('a' + 'b') of over 0.95 (Valentine and Bartsch 1988; Singh *et al.* 1995; Rodehutscord *et al.* 1999; White *et al.* 2000, 2002; Aufrere *et al.* 2001; Gonzalez and Andres 2003).

The reason for the wide range in reported ME values is unclear. Petterson *et al.* (1997), in their review of Australian lupins, suggest a value for cattle of 13.3 MJ/kg for *L. angustifolius* and 13.2 MJ/kg for *L. albus*, although the equations used to calculate ME were not given. More recently, White *et al.* (2002) reported values of >14 MJ for *L. angustifolius*, based on sheep studies and calculated using the equation ME = 0.157 × DOMD% (AFRC 1993). Likewise, ADAS (1995) reported ME values from sheep-feeding experiments for *L. albus* of either 14.8 MJ/kg or 16.7 MJ/kg, although the method of calculation was unclear. They reported a DOMD% of 880 g/kg, which gives an ME of 13.8 MJ/kg using 0.157 × DOMD%. AFRC (1993) adopted an ME for lupins of 14.2 MJ ME/kg DM and a rumen-fermentable ME of 10.2 MJ/kg DM based on data of van Straalen and Tamminga (1990). INRA (Sauvant *et al.* 2004) adopted an ME value for ruminants of 14 MJ/kg DM for *L. angustifolius* and 14.9 MJ/kg DM for *L. albus*. It therefore appears that the common value of 13.3 MJ quoted in Australian feed tables for ruminants is perhaps an underestimate, and should be closer to 14 MJ.

Carbohydrates

Although the carbohydrate composition varies between and within species, the main carbohydrate in lupins is complex non-starch polysaccharides (Gdala 1998). This makes lupins distinct from cereals and some other legumes in which starch represents the main storage carbohydrate. Mean values for lignin content in lupin are low (<10 g/kg DM) compared with most other cereal grains [e.g. 17 g/kg in barley, 35–40 g/kg in oats and wheat; (MAFF 1990)], and this may account for the relatively high *in vivo* digestibility values for lupins of >850 g/kg for protein and >770 g/kg for dry matter (MAFF 1990).

The hull and cotyledon of lupins contain different amounts and types of carbohydrates, and hull as a percentage of seed weight can vary widely among species, with literature reports ranging from ~150 to 300 g/kg. For Australian *L. angustifolius* varieties, most hull percentage values are in the range of 200–250 g/kg (Evans *et al.* 1993; Miao *et al.* 1996; Petterson 2000).

The hull of lupins consists of ~900 g/kg cell wall material comprising mainly cellulose (approx. 500 g/kg DM), pectic polymers (300 g/kg), and hemicellulose (140 g/kg total hull on a DM basis), and with low lignin content (Brillouet and Riochet 1983; Evans *et al.* 1993; Gdala 1998). The hull fibre hydrolysis products are mainly glucose (580 g/kg of total hydrolysis

Table 1. Chemical composition of *Lupinus angustifolius* (Australian sweet lupin, narrow leaf lupin) and *L. albus* (white lupin) seed (dry matter basis)

	L. angustifolius[A]	*L. albus*[A]
Gross nutritional components (g/kg)		
Dry matter (g/kg fresh weight)	911	914
Gross energy (MJ)	20.2	20.5
Metabolisable energy (MJ)	13.3 (14.5)[B]	13.2 (14.8)[C]
Crude protein	351	391 (334)[C]
True protein	n.r.	308[C]
ADIN	n.r.	2[C]
Crude fat	65	103
Ash	30	36
Starch	1.5[D]	14.5[C]
Neutral detergent fibre (NDF)	258	193 (386)[C]
Acid detergent fibre (ADF)	216	160 (290)[C]
Sugar	n.r.	58
Lignin	9.4	7.6 (29)[C]
Alkaloids	0.2	0.1
β-carotene (mg/kg)	3.5[E]	n.r.
α-tocopherol (mg/kg)	3.2[E]	n.r.
Essential amino acids (% crude protein)		
Arginine	11.6	12.3
Histidine	2.6	1.9
Isoleucine	3.9	3.8
Leucine	6.9	6.3
Lysine	4.8	4.3
Methionine	0.7	0.7
Phenylalanine	3.8	3.4
Threonine	3.5	3.3
Tryptophan	1.0	1.0
Valine	3.8	3.7
Non-essential amino acids (g/16 g N)		
Alanine	3.4	2.9
Aspartic acid	9.7	9.0
Cyst(e)ine	1.4	1.3
Glutamic acid	21.6	18.2
Glycine	4.2	3.6

	L. angustifolius[A]	*L. albus*[A]
Proline	4.1	4.0
Serine	5.2	4.6
Tyrosine	3.7	4.3
Macro minerals (g/kg)		
Calcium	2.4	2.2
Magnesium	1.8	1.4
Phosphorus	3.3	4.0
Potassium	8.8	9.7
Sodium	0.4	0.3
Sulfur	2.5	2.7
Micro minerals (mg/kg)		
Copper	5.2	5.6
Iron	75.3	29.8
Manganese	20.9	984.3
Molybdenum	1.8	2.3
Zinc	37.5	33.1
Cobalt	0.086	0.226
Selenium	0.100	0.093
Medium and long chain fatty acids (g/100 g fat)		
Myristic acid (14 : 0)	0.2	0.1
Palmitic acid (16 : 0)	10.3	7.7
Palmitoleic acid (16 : 1)	0.1	0.3
Stearic acid (18 : 0)	4.8	1.1
Oleic acid (18 : 1)	34.0	51.0
Linoleic acid (18 : 2)	37.0	17.3
Linolenic acid (18 : 3)	6.2	11.1
Arachidic acid (20 : 0)	0.7	1.0
Gadoleic acid (20 : 1)	0.3	n.r.
Eicosadienoic acid (20 : 2)	0.4	n.r.
Eicosatrienoic acid (20 : 3)	0.2	n.r.
Arachidonic acid (20 : 4)	<0.01	0.4
Behenic acid (22 : 0)	1.3	3.3
Erucic acid (22 : 1)	<0.01	2.6
Lignoceric acid (24 : 0)	0.1	<0.01

n.r., Not reported.
[A]Australian samples unless otherwise indicated (Petterson *et al.* 1997).
[B]White *et al.* (2002).
[C]UK values (ADAS 1995), $n = 2$.
[D]D. S. Petterson, pers. comm.
[E]Cited by Petterson (2000).

residues), uronic acid, and xylose (each 140 g/kg) (Daveby and Aman 1993; Evans *et al.* 1993). The cotyledon or dehulled component of *L. angustifolius* lupins contains 290–310 g/kg DM non-starch polysaccharides (NSPs), consisting mainly of pectins and a low content of cellulose and lignin; chemical hydrolysis yields galactose (670 g/kg of the fibre residues), arabinose (140 g/kg), and uronic acid (110 g/kg) (Evans *et al.* 1993).

Minerals and vitamins

Lupins are a useful source of most minerals, especially calcium (Ca), phosphorus (P), potassium (K), and sulfur (S) (Table 1). They typically contain 5 times the Ca content of cereal grains, and a similar amount to that reported for canola meal (NRC 2001). In terms of mineral concentrations required to meet lactating cow requirements, *L. angustifolius* lupins supply at least 80% of recommended (NRC 2001) dietary concentrations of Mg, P, and S for a Holstein cow producing 35 kg milk/day, but they don't meet the recommended requirements for Ca (40% of requirements) or sodium (Na) (20%).

The concentrations reported in lupins for Na, selenium (Se), cobalt (Co), copper (Cu), and zinc (Zn) are variable and depend on soil type and source of grain. Depending on where they are grown, they may not meet animal requirements for several trace elements (White *et al.* 1981). *L. albus*, in contrast to *L. angustifolius*, appears to accumulate high levels of manganese (White *et al.* 1981), which can approach toxicity concentrations for some monogastric species but not for ruminants (NRC 1980).

The reported vitamin E content of *L. angustifolius* is well below the requirement level for lactating cows of 30–40 IU/kg [30–40 mg/kg α-tocopherol; (NRC 2001)]. The reported β-carotene level of 3.5 mg/kg (Table 1) is in the normal requirement range of 4000–5000 IU vitamin A [1 mg β-carotene = 1800 IU vitamin A (NRC 2001)].

Oil content and composition

The oil content of lupins generally ranges from 60–100 g/kg, with *L. angustifolius* at the lower end of the range and *L. albus* at the higher end (Table 1). Lupin oils are 75–80% unsaturated, and consist mainly of oleic acid (C18 : 1) and linoleic acid (C18 : 2). While *L. angustifolius* has roughly equal proportions of these 2 acids, *L. albus* has about 3 times more C18 : 1 than C18 : 2. palmitic acid (C16 : 0) and stearic acid (C18 : 0) are also higher in *L. angustifolius*, whereas *L. albus* has a higher proportion of fatty acids (FAs) with C20 + (Table 1).

Antinutritional factors

Commercial varieties of both *L. angustifolius* and *L. albus* grown in Australia have been selected and bred to contain very low levels of antinutritional factors such as alkaloids (<0.2 g/kg DM), tannins (3.2 g/kg DM total tannins), trypsin inhibitor activity (0.14 mg/kg DM) and lectins (Petterson *et al.* 1997). There is no evidence that the presence of these compounds at such levels restricts the amount of lupin that can be fed to dairy cows.

Amino acid composition

About 10% of the N in lupins is considered to be non-protein, which means that the true protein conversion factor is 5.6 (Petterson 2000) rather than the 6.25 typically applied to cereals. Both *L. angustifolius* and *L. albus* have similar concentrations of essential amino acids (EAAs) (Table 1). The respective intercept (*A*) and slope (*B*) values for the relationship between the content of methionine (Met), Met + cysteine (Cys), and lysine (Lys), and the CP in *L. albus* seed (%AA in seed = A + B × %CP) are A = –0.202, B = 0.0138; A = –0.247, B = 0.0303; and A = +0.551, B = 0.0294, respectively (Degussa 1996). For Met and Lys in *L. angustifolius* the respective values are *A* = 0.0004, *B* = 0.007, and *A* = 0.021, *B* = 0.041, respectively (Petterson 2000). The balance of acidic and basic amino acids is such that dissolving lupin protein in water should result in a pH of less than 6 (Weast 1974).

Amino acid content relative to needs of production

Lupin protein has been shown to be deficient in Met and Lys, relative to needs for growth of body tissue and milk protein synthesis in dairy cows (May *et al.* 1993). A comparison between the essential amino acid (EAA) profile of lupins and that of microbial crude protein (MCP) and milk protein indicates that for rumen-undegraded protein (RUP), assuming no difference in the EAA content or availability of RUP-EAA, Met is the first limiting AA for milk production, followed by Lys, tryptophan (Try), and valine (Val) (Table 2). Evidence supporting the primary limiting role of Met in lupin protein is seen by the fact that the addition of rumen-protected Met to the diet of sheep, either as an encapsulated amino acid or via transgenesis, improves the nutritional value of lupins for liveweight gain and wool growth (White *et al.* 2000, 2001, 2002). The transgenic *L. angustifolius* was modified to express in the seed the gene specifying sunflower seed albumin, a protein rich in sulfur amino acids (Molvig *et al.* 2003). Met concentration of the transgenic lupin was almost doubled, and the rumen degradability reduced. It is likely that transgenic lupin seed containing increased protected methionine would be of benefit to dairy cows.

Lupins as a source of rumen-degradable protein (RDP) and rumen-undegradable protein (RUP)

The extent of rumen degradation of dry matter and protein in feedstuffs is commonly described using equations derived from *in sacco* digestion methods. In this review, AFRC (1993) equations are used, whereby degradability (dg) $= a + b(1 - e^{(-ct)})$ and effective degradability (p) $= a + (b \times c)/(c + r)$, where a is fractional solubility in water, b is the insoluble potentially degradable fraction, c is fractional rate of degradation of b, t is time and r is fractional rumen outflow rate.

There is a wide range in published *in sacco* values for lupin protein fractional degradability, with differences in grinding mill sieve size accounting for some of this variation among reports (Fig. 1). However, unexplained differences in reported values remain between laboratories after sieve size is accounted for, with effective degradability ('p') values ranging from 0.53 to 0.96 at a fractional rumen outflow of 0.08/h (Fig. 1). The extreme range of reported '*c*' values for raw *L. albus* [e.g. 0.06/h reported by ADAS (1995) to 0.75/h reported by Aufrere *et al.* (2001)] highlights the uncertainty associated with predictions of RDP and RUP at different rumen outflow rates. AFRC (1993) reports

Table 2. A comparison of the essential amino acid (EAA) profiles of lupins, soybean meal (SBM), microbial crude protein (MCP) and skim milk

	L. angust.[A]	*L. albus*[A]	SBM[B]	Milk[C]	MCP[D]	*L. angust.*	*L. albus*	SBM	MCP
	g AA/100 g EAA					Ratio of AA relative to milk AA			
Arginine	27.8	30.6	16.3	7.0	10.4	4.00	4.37	2.33	1.49
Histidine	5.9	4.5	6.1	5.9	4.1	1.00	0.76	1.49	0.69
Isoleucine	9.2	9.5	10.0	10.6	11.3	0.87	0.90	0.88	1.07
Leucine	16.0	15.4	17.1	20.3	15.6	0.79	0.76	1.10	0.77
Lysine	11.1	10.7	13.7	15.9	18	0.70	0.67	0.76	1.13
Methionine	1.6	1.7	3.2	5.2	4.9	0.31	0.33	0.65	0.94
Phenylalanine	8.9	8.2	11.5	10.1	10.4	0.88	0.81	1.11	1.03
Threonine	8.0	8.0	8.8	9.1	11.1	0.88	0.88	0.79	1.22
Tryptophan	2.4	2.5	2.9	2.8	2.9	0.86	0.89	1.00	1.04
Valine	9.2	9.0	10.4	13.1	11.3	0.70	0.69	0.92	0.86
EAA %CP	42.5	40.2	45.6	48.4	40.7				

[A] Petterson *et al.* (1997).
[B] Degussa 1996.
[C] Skim milk powder (NRC 2001).
[D] Bacterial protein (Orskov 1992).

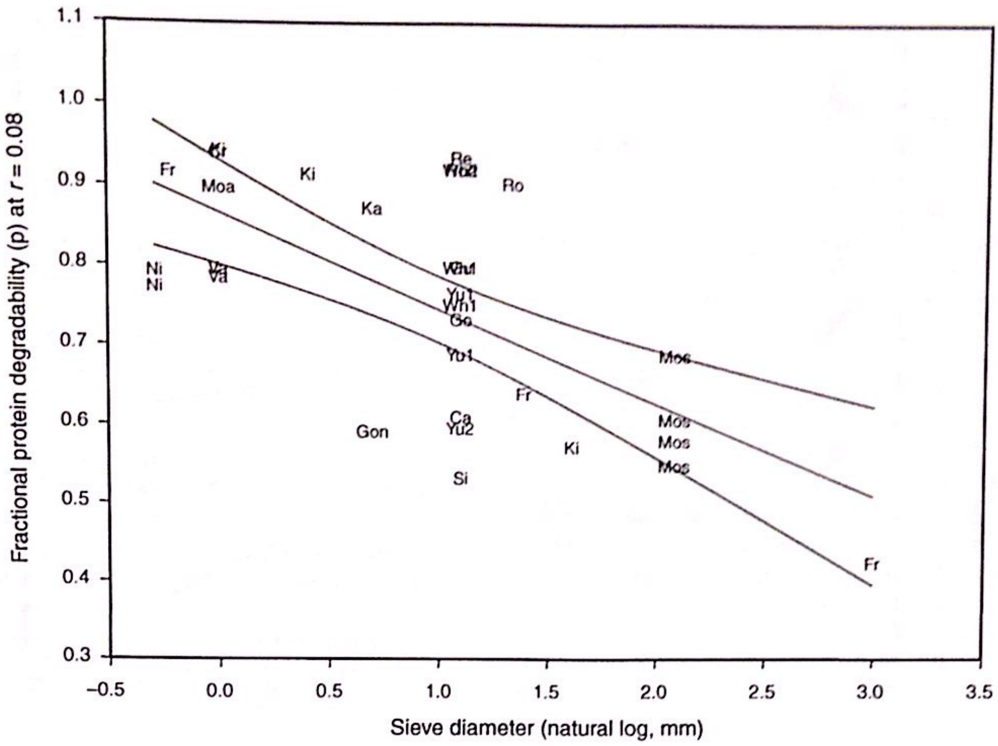

Fig. 1. Effect of grinding sieve size of *L. albus or L. angustifolius* on the *in sacco* fractional degradability of crude protein. Protein degradability (p) was calculated at a fractional rumen outflow rate of 0.08/h. The linear regression equation shown (with 95% confidence limits) is p = 0.87 – 0.12(ln(sieve size)); $R^2 = 0.43$. Symbol labels represent references as follows: Ca (Castrillo *et al.* 1992), Cr (Cros *et al.* 1991), Fr (Freer and Dove 1984), Go (Goelema *et al.* 1998), Gon (Gonzalez and Andres 2003), Gu (Guedes and Da Silva 1996), Ka (Kandylis and Nikokyris 1997), Ki (Kibelolaud *et al.* 1991), Moa (Moate *et al.* 1999), Mos (Moss *et al.* 2001), Ni (Niwinska 2001), Re (Remond *et al.* 2003), Ro (Robinson and McNiven 1993), Rod (Rodehutscord *et al.* 1999), Si (Singh *et al.* 1995), Va (Valentine and Bartsch 1988), Wh1 (White *et al.* 2001), Wh2 (White *et al.* 2002), Yu1 (Yu *et al.* 1999), and Yu2 (Yu *et al.* 2002).

fractional $RDP_{(0.08)}$ values of 0.70 and 0.80 for *L. albus* based on different source data, with a '*c*' value of 0.13/h; which is not too dissimilar from INRA tables (Sauvant *et al.* 2004), which show an $RDP_{(0.08)}$ of 0.83 for *L. albus* with a '*c*' value of 0.13/h, and 0.75 for *L. angustifolius* with a '*c*' value of 0.16/h.

When *in sacco* degradability of protein in an *L. albus* species was compared with *L. angustifolius* in the same experiment, *L. albus* protein had a greater fractional water solubility (0.50 *v.* 0.34) and slightly greater overall degradability (0.80 *v.* 075 at $r = 0.08$/h) than that of *L. angustifolius* (White *et al.* 2000). However, the published between-experiment range of degradability values for *L. angustifolius* is wider than this range, and so it is unclear if these between-species differences are of practical significance.

Effect of heating lupins on in sacco protein degradability and on mobile-bag intestinal amino acid absorption

Roasting under pressure, dry heating, or extruding lupins reduces protein degradability by reducing solubility in water ('*a*') and also rate of degradation ('*c*') such that overall degradability is reduced in a linear fashion as temperature increases (Fig. 2). Roasting at high temperatures (300°C for 1–4 min) also significantly increased acid detergent insoluble nitrogen (ADIN) (Zaman *et al.* 1995). Extruding or heating lupins at lower temperatures (120–195°C) reduced the *in sacco* solubility and rumen degradability of protein (Cros *et al.* 1991), increased intestinal protein flow (Benchaar and Moncoulon 1993), and increased absorption of lupin AAs from the small intestine (Benchaar *et al.* 1991). Schroeder *et al.* (1996) heated lupins for different times and temperatures and correlated ADIN content with intestinal digestibility of lupin (RUP) using mobile bags in cattle. It was not until ADIN levels were above 75 g/kg that intestinal digestion of crude protein was reduced. This was seen at temperatures above 130°C for various times over 10 min. In a report on optimum heating times for lupins, Moss *et al.* (2000) concluded that heating at 120°C for 35 min was the most effective time and temperature treatment in terms of producing their ideal mix of RDP and RUP. The method to determine 'optimum' heat treatment was based on minimum cost to deliver a required amount of RDP and RUP, estimates of which were based on an *in vitro* rumen fluid method combined with post-digestion treatment with pepsin/pancreatin. ADIN levels reached 2.7 g/kg for treated lupins.

Cros *et al.* (1992) reported on the effects of heating on the AA composition of *L. albus* before and after *in sacco* degradation for 16 h, and after intestinal/large bowel exposure of the RUP-AA using mobile bags. Although the AA composition of the RUP from raw or heated lupins differed from the original for most of the AAs, the undegraded AAs represented less than 40 g/kg of the quantity of initial AAs, i.e. fractional degradability of

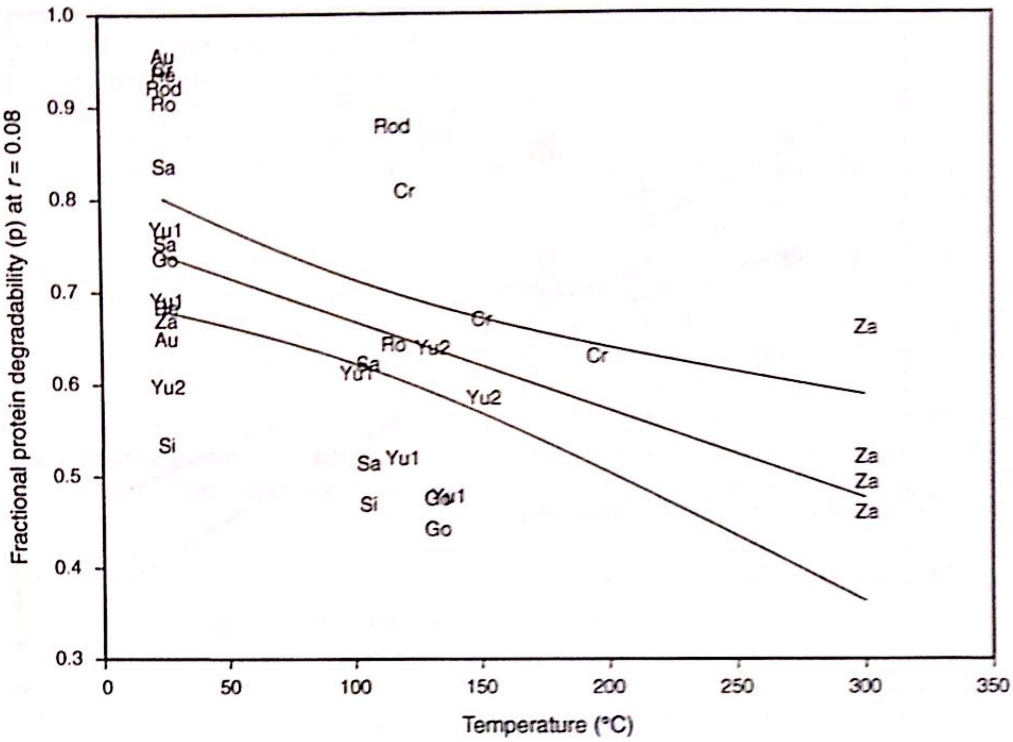

Fig. 2. Effect of heating extrusion of *L. albus* or *L. angustifolius* on fractional protein degradability ('p': Fig. 2). The line of best fit is shown with 95% confidence limits: p = 0.76 − 0.0010 (°C), adjusted r^2 = 0.29, P (slope) = 0.001. Symbols represent the following references: Au (Aufrere *et al.* 2001), Cr (Cros *et al.* 1991), Go (Goelema *et al.* 1998), Re (Remond *et al.* 2003), Ro (Robinson and McNiven 1993), Rod (Rodehutscord *et al.* 1999), Sa (Sauvant *et al.* 2004), Si (Singh *et al.* 1995), Yu1 (Yu *et al.* 1999), Yu2 (Yu *et al.* 2002), Za (Zaman *et al.* 1995). Raw untreated grain was assigned 25°C.

unheated lupins ranged from 0.97 to 0.99. Heating the seeds to 120 or 150°C significantly reduced RDP (10% drop for each increase in temperature), but had no significant effect on the intestinal/large bowel availability of the RUP-AA, which remained high (>90%). For RUP from raw lupins, Cros *et al.* (1992) calculated that Met was first limiting for milk production, followed by Val, Lys, and Leu. For RUP-EAA, they estimated that the limiting AAs would rank (in decreasing order) Met, Val, Phe plus Tyr, and Thr.

Thus, although proteins in raw lupin RUP may have a different EAA profile from those that are readily degraded, these differences represent small contributions to total intestinal supply of metabolisable protein because of the extent of rumen degradation of raw lupins.

In vivo responses to lupins

Effects of milling

Several studies have shown that feeding whole lupin grain to dairy cows leads to relatively large losses in digestible energy and protein compared with cracked or hammer-milled grain. For example, Valentine and Bartsch (1986) examined the effects on apparent DM and CP digestibility in dairy cows of feeding either hammer-milled or whole *L. angustifolius* grains. The basal diets consisted of oaten hay or oaten pasture. They reported an increase in apparent *in vivo* DM digestibility of 11% (670–780 g/kg DMD) and 18% (620–800 g/kg DMD) due to hammermilling for the oaten hay and oaten pasture diets, respectively. The fraction of whole grain appearing in the faeces was 36% for the oaten hay diet and 24% for oaten pasture, with 27% of the whole grain dry matter disappearing as it passed through the cow. May *et al.* (1993) reported that cows fed ground *L. albus* grain at 3.5 kg/day produced 2 kg/day more milk than cows fed whole grain; a result similar to that of Hough (1991), with no significant differences in milk fat or protein content. Milling lupin grain requires more energy than cereal grain because of the harder seed coat, and the size difference between cereal and lupin grains can create problems for processing grain mixtures on-farm where a single mill setting is used. Pre-soaking whole grain lupins in water for 24 h before feeding did not improve *in vitro* digestibility over untreated whole seeds (Hough and Jacobs 1994).

Effects of formaldehyde or heat treatment

Treating lupins with formaldehyde to reduce RDP does not appear to increase the value of lupins to dairy cows. Hough (1991) found no significant differences in milk yield or composition when cows grazing pasture were supplemented with raw milled lupins (1.5 kg/day), formaldehyde-treated (HCHO) milled lupins (0.7 g formaldehyde/100 g protein), or HCHO milled lupins with added protected methionine (30 g Mepron/day). This result is similar to that for sheep, where neither liveweight gain nor wool growth was improved by treating lupins with HCHO (Fortune *et al.* 1980; Hynd and Allden 1986; Hough 1991; Rodehutscord *et al.* 1999).

Although there is clear evidence that heating lupins will reduce RDP, there is little experimental evidence to support its cost-effectiveness in practical diets. Robinson and McNiven (1993) found no benefits from heating lupins in an experiment comparing milk production and composition in high-producing cows fed diets containing 1.6 kg soybean meal (SBM) or ~2.3 kg DM of raw or roasted lupins. They reported that roasting milled lupins to 115°C (time unspecified) increased lupin *in sacco* RUP from 70 g/kg CP to 330 g/kg CP, but there was no difference in the yield of milk or protein between the 2 sources of lupins, nor was there any difference between lupins and SBM apart from a reduced milk protein concentration with lupins.

The only published study in which heating provided a production benefit over raw lupins was that of Singh *et al.* (1995). Treatments consisted of unspecified amounts (estimated at less than 2 kg/day) of SBM, raw or roasted lupins (105°C for 60 s), fed to moderate-yielding dairy cows (25 kg milk/day). This process increased *in sacco* RUP from 380 to 450 g/kg CP, resulting in increased yields of milk, fat, protein, and lactose compared with feeding with ground raw lupins.

Moss *et al.* (2000) compared heat-treated lupins (120°C for 35 min) with SBM as a source of protein for high-producing (38 kg milk/day) dairy cows fed a basal diet of grass silage. Cows fed heat-treated lupins had reduced DMI and milk protein concentration compared with the SBM group, but there were no differences in the yield of milk, protein, fat, or lactose. In this experiment, the basal diet contained grass silage with wheat (200 g/kg) and sugarbeet (100 g/kg) as concentrates. Unfortunately, there was no raw lupin treatment as a control, and so any potential benefits of heating lupins were not demonstrated.

The weight of evidence does not support the heating or treating of lupins with formaldehyde as a cost-effective measure for dairy cows. This lack of a consistent effect can perhaps be explained in terms of Met supply, whereby modelling the effect of reducing lupin RDP on amino acid flow using the program AminoCow (V3.03; Degussa 1996) shows that the supply of Lys and Leu is significantly improved but that of Met is not. Results from experiments with sheep support the limiting role of Met when lupin protein is protected against degradation by heat or formaldehyde (Rodehutscord *et al.* 1999). There is also evidence from laboratory animal studies, which shows that heating lupin protein reduces its effectiveness for growth. Rozan *et al.* (1997) have shown that the protein efficiency ratio (PER; bodyweight gain per unit of protein) of purified freeze-dried *L. albus* protein was 0.8, which was not significantly different from soy protein (0.9) but less than rape protein (PER of 1.9). Drying the purified lupin protein by heating at 50°C for 16 h reduced the PER to 0.3 compared with a value of 0.7 for heated SBM and 1.8 for heated rapeseed meal (RSM) given the same treatment. This raises questions about the susceptibility to heat of some amino acids in lupin protein, and suggests that the cost-effectiveness of applying heat to protect lupin protein against ruminal degradation requires further examination.

Steam flaking of lupins is not generally practiced in Australia, and so it is not known if this confers any cost-benefit advantage. Petterson (2000) reported that feed companies in Japan and the Republic of Korea steam flake rolled lupins for use in beef and dairy cattle diets, and have been doing so for 10 years.

Production and milk-component responses to feeding with lupins

Dose-responses to lupin supplements

Australian dairy farmers often feed lupins to cows in early lactation as a combined energy and protein supplement because lupins have a higher ME concentration than most cereal grains and they are considered relatively safe to use in high amounts in the dairy during twice-daily milking. Table 3 summarises data from dose-response experiments conducted in Western Australia (Hough 1991) and South Australia (Bartsch *et al.* 1985; Valentine and Bartsch 1989), in which lactating Holstein/Friesian cows in early lactation were fed various amounts of milled lupin grain twice daily during milking. The Western Australian data of Hough (1991) for cows in early lactation show a mean response slope of 0.66 kg milk/kg DM lupins, with a slope of 0.023 kg for milk fat and 0.024 kg for protein. For the experiments in which cows were fed lupins for the entire lactation, the response slopes for milk, fat, and protein, respectively, were 0.74, 0.033 and 0.028 kg/kg. In these experiments there appeared to be no clear effect of base feed (pasture, silage or hay) or level of lupin supplement (1.4–9 kg DM/day) on the response slopes, although data are insufficient to make any firm conclusions about this. Similarly, the base level of milk production did not appear to influence the protein yield response to lupins. These responses are within the range reported for immediate responses to cereal grains for cows in early lactation (Kellaway and Harrington 2004).

Despite the mostly consistent nature of the response data from the experiments of Hough (1991) the slopes for the milk yield responses to lupin feed in the 2 South Australian experiments (Bartsch *et al.* 1985; Valentine and Bartsch 1989) were not significantly different from zero. If data from all experiments in Table 3 involving early lactation cows are included, the mean response slopes for yield (kg) of milk, fat, and protein to 1 kg of lupin (DM basis) are 0.53, 0.022, and 0.019, respectively. The reason for the difference in responses between the Western Australian and South Australian experiments are not apparent.

Substitution effects

There are few data on the effects of feeding with supplementary lupins on intake of the base forage. The results of 5 experiments of Hough (1991) show a substitution value (kg reduction in DMI of forage per kg DM lupin fed) of 0.54 kg/kg (range 0.3–0.6 kg/kg), with no clear relationship between substitution value and type of base forage (Table 4). In a supplementation experiment undertaken with cows strip-grazing irrigated pastures over 3 seasons (spring, summer and autumn), Stockdale (1999) reported a non-significant difference between mean substitution values for cows fed a concentrate mix containing 50% lupins (0.24 kg/kg) and one containing 100% cereal grains (0.31 kg/kg). These values are within the range of 0–0.95 kg/kg substitution reported by Stockdale (2000) where pasture allowance is varied from low to high.

Responses to lupins compared with cereal grains

Although lupins are considered primarily as a source of protein in feed formulating, they are also a valuable energy source for ruminants because of their high metabolisable energy value and

Table 3. Responses in milk yield and components to feeding milled lupins to Holstein cows

Data apply to the first third of lactation unless otherwise indicated. The response equations are of the form $Y = A + BX$, where X is kg of lupins on a dry matter basis, A is the intercept, and B is the response slope (kg/kg)

References	Range (kg DM/day)	Base feed	Base milk (kg/day)	Milk yield response (kg/kg) Intercept	Slope	Points[B]	r^2	Prob.	Fat yield response (kg/kg) Intercept	Slope	r^2	Prob.	Protein yield response (kg/kg) Intercept	Slope	r^2	Prob.
Bartsch *et al.* (1985)	6–12[A]	Cereal hay	28.0	26.5	0.12	3	0.01	0.85	0.88	0.017	0.50	0.32	0.84	−0.001	0.01	0.88
Hough 1991–2[C]	0–5.8	Pasture	22.3	22.8	0.79	5	0.92	0.01	0.86	0.030	0.92	0.01	0.69	0.027	0.88	0.01
Hough 1991–3	1.8–9.0	Pasture hay	22.6	21.1	0.70	5	0.89	0.01	0.76	0.029	0.74	0.05	0.58	0.025	0.92	0.01
Hough 1991–4*a* (early lactation)	0–5.4	Pasture	19.9	20.0	0.63	3	0.99	0.04	0.76	0.024	0.99	0.04	0.60	0.023	0.99	0.01
Hough 1991–4*b* (entire lactation)	0–5.4	Pasture	15.2	15.5	0.63	3	0.87	0.16	0.62	0.030	0.95	0.10	0.50	0.021	0.93	0.12
Hough 1991–5	1.4–5.8	Pasture	22.5	22.7	0.36	4	0.00	0.50	0.94	0.005	0.00	0.78	0.71	0.018	0.25	0.29
Hough 1991–6*a* (early lactation)	0–3.6	Pasture	17.0	17.0	0.95	2			0.63	0.038			0.50	0.028	0	
Hough 1991–6*b* (entire lactation)	0–3.6	Pasture	15.4	15.4	0.97	2			0.59	0.042			0.49	0.031		
Hough 1991–7a (early lactation)	0–3.6	Pasture	23.1	23.1	0.70	2			0.91	0.026			0.68	0.030		
Hough 1991–7*b* (entire lactation)	0–3.6	Pasture	18.0	18.0	0.69	2			0.73	0.028			0.56	0.033		
Hough 1991–7	3.6–7.2	Pasture silage	25.7	23.7	0.50	2			0.86	0.025			0.64	0.018	0	
Valentine and Bartsch (1989)	3.5–7.0	Pasture	20.6	21.7	−0.28	2			0.82	−0.003			0.58	−0.003		
Weighted mean[D]				21.0	0.57				0.79	0.024			0.63	0.021		

[A]This is the range of amount of lupin supplement in DM, assuming lupins were 90% DM.

[B]This is the number of mean value points used in the regression.

[C]The report by Hough (1991) contains a description of 8 separate experiments conducted over several years. The numbers against this reference in the table refer to the experiment number listed in the report.

[D]Weighted using the number of data points contributing to the mean for early lactation cows only.

Table 4. Substitution effects of lupin feeding for cows grazing pasture or fed conserved forage

Regression equations are $DMI_{(base\ forage)} = A + B \times DMI_{(lupins)}$. Cows were Holstein/Friesians in early lactation. Units are kg/day

References	Base feed	Data points	Slope (B)	Intercept (A)	r^2	$P_{(slope)}$
Hough 1991–2[A]	Irrigated summer pasture[B]	5	–0.59	16.9	0.95	0.003
Hough 1991–3	Pasture hay[C]	5	–0.56	16.7	0.98	0.001
Hough 1991–6*a*	Irrigated summer pasture[D]	2	–0.57	19.9		
Hough 1991–7	Irrigated summer pasture[D]	2	–0.32	15.5		
Hough 1991–8	Pasture silage[E]	2	–0.6	15.5		
Weighted mean and s.d.			–0.54 ± 0.17	16.9 ± 2.6		

[A]The report by Hough (1991) contains a description of a series of separate experiments conducted over several years. The numbers against this reference in the table refer to the experiments in the order listed in the report.
[B]Irrigated summer pastures are ryegrass/white clover and kikuyu. For the summer pastures when pasture intakes were assessed, ME was 9.9 MJ/kg DM and CP was 149 g/kg DM.
[C]Pasture hay comprised capeweed, ryegrass, lotus and subterannean clover; ME 8.1 MJ/kg DM and CP 108 g/kg DM.
[D]Irrigated summer pasture of ryegrass/white clover; ME 9.0 MJ/kg DM and CP 157 g/kg DM.
[E]Ryegrass pasture and subterannean clover silage; ME 8.9 MJ/kg DM and CP 123 g/kg DM.

low risk of acidosis. Most experiments in which lupin grain is compared with cereal grains on a weight basis show that cows fed lupins have higher yields of milk, fat and protein, regardless of stage of lactation (Table 5). All experiments in Table 5 involved twice daily feeding with grain in the milking parlour. For cows grazing annual or perennial pastures, the mean milk response to an equivalent weight substitution of lupins for barley or oats was 0.21 kg milk/kg DM grain with a range of –0.53 to + 0.70 kg/kg. Because of the small number of experiments and the large variation between them it is not possible to separate advantages of lupins over oats compared with barley. In the grazing experiments there was no evidence that CP content of pasture was limiting milk production because pasture CP values were generally over 150 g/kg DM and levels of milk production were 21–27 kg/day. For the few studies in which cows were fed grain with a basal diet of conserved forage as either pasture silage or cereal hay, the relative responses to lupin substitution compared with cereal grain were all positive. For experiments in which the basal ration was not deficient in protein (i.e. excluding Bartsch and Wickes 1984; Moate *et al.* 2002), the mean response to lupin substitution was 0.31 kg extra milk/kg lupins. Although it is difficult to be precise about the difference in ME values between grain batches, these positive responses fall within the expected range based on relative ME concentration. For example, using INRA tables for the ME concentration of grains (Sauvant *et al.* 2004), *L. angustifolius* at 14 MJ ME/kg DM provides an additional 1.6, 3.6, 1.0 and 1.1 MJ more ME/kg DM than barley, oats, wheat, or triticale, respectively. The relative advantage of lupins is less if MAFF (1990) values for cereal grain are used. The MAFF tables do not list lupins, but taking an ME value of 14 MJ/kg DM, this would provide an additional 0.5, 1.5, 0.3, and 0.2 MJ ME/kg DM than the values they list for barley, oats, wheat, and triticale, respectively. Based on these INRA and MAFF values, for milk with an ME requirement of 5 MJ/kg, the expected increase in milk yield from substituting 1 kg DM lupins for 1 kg DM barley should be somewhere between 0.1 and 0.3 kg/day, which fits the mean observed data shown in Table 6, and supports the (lower) INRA estimates of cereal grain ME concentrations.

Despite a wide range in responses, cows fed lupins had higher mean milk fat content (+ 0.33 g/kg per kg DM lupin substitution) than those fed cereal grain (Table 5), suggesting that lupin may have less of a milk fat depressing effect than cereal grain. The positive responses to lupins were mainly seen in experiments involving early lactation cows fed cereal grain and grazing highly digestible pastures, conditions that are often associated with milk fat depression (e.g. Hough 1991, Table 5). Data on mechanisms are lacking, but may include a more stable rumen pH with lupins than with cereal grain, and less of a shift towards propionate production at the expense of acetate when lupins are fed to cows at high levels. The fat content of lupins (60–100 g/kg DM) is also higher than that of most cereal grains (typically 20–40 g/kg DM; MAFF 1990), and although increased intakes of some forms of unsaturated fat can suppress milk fat content (Baumgard *et al.* 2001), it does not appear to be a problem at the levels of lupins typically used.

For effects on protein concentration, Table 5 shows that milk protein concentration tended to decrease with lupin substitution of cereal grain by 0.3 g/kg per kg DM lupins in cows grazing pasture of adequate protein content. Milk protein responses to lupin for cows fed a basal diet of conserved forage showed a wide range in values, partly because of the fact that in some cases the basal diets were protein deficient (e.g. Bartsch and Wickes 1984; Moate *et al.* 2002) and so the response to lupins included overcoming a protein deficiency. The milk protein depressing effect of lupins compared with cereal grains was also reported by Kefford (1995) who conducted a series of experiments investigating effects of diet on the quality of milk for cheese manufacture. Wheat in the concentrate mix (6 kg DM total) was replaced with varying proportions of lupins in the diet of late-lactation cows fed a basal diet of pasture hay and silage. At a ratio of 5 : 1 wheat : lupin in the concentrate mix, milk yield was unaffected compared with a ratio of 2 : 4 wheat : lupin, but milk protein concentration was lower (33.9 *v.* 35.7 g/kg) with the high-lupin diet. Fat concentration was not significantly different.

The reason for the negative effect of lupins compared with cereals on protein content may be due to the fact that lupin substitution usually results in a reduction in dietary starch intake and increasing levels of dietary starch have been shown to be associated with increased milk protein concentration (Reynolds *et al.* 1997; Beever *et al.* 2001) through mechanisms that are poorly understood. The lower starch levels in the lupin-

Table 5. A comparison of lupins *v.* cereal grains: summary of effects on production and composition of milk from dairy cows grazing pasture or fed conserved forage

Stage of lactation	Supplement (kg DM/day)		Milk yield (kg/day)			Fat conc. (g/kg)			Protein conc. (g/kg)		
	Lupin	Cereal	Lupin	Cereal	Diff./kg DM	Lupin	Cereal	Diff./kg DM	Lupin	Cereal	Diff./kg DM
Vegetative pasture											
Hough 1991–5 – lupin v. barley											
Early	1.4	1.4	22.5	22.4	0.07	41	37	2.78	32	33	−0.69
Early	2.9	2.8	25.6	23.9	0.59	40	37	1.04	32	31	0.35
Early	4.3	4.2	23.2	25.5	−0.53	40	36	0.93	33	33	0.00
Early	5.8	5.6	25.2	25.1	0.02	39	37	0.35	33	32	0.17
Hough 1991–6a – lupin v. barley											
Early	3.6	3.6	20.8	18.8	0.56	39	39	0.00	30	32	−0.56
All lactation	3.5	3.5	18.9	17.8	0.31	40	42	−0.56	33	35	−0.56
Hough 1991–6b – lupin v. barley											
Early	3.6	3.5	25.9	25.6	0.08	39	39	0.00	30	32	−0.56
All lactation	3.6	3.5	20.5	20.7	−0.06	40	42	−0.56	33	35	−0.56
Moate et al. (1984) – lupin (heated) v. oats											
n.r.	2.0	2.2	17.2	17.2	0.00	39.6	39.2	0.20	29.9	31.5	−0.80
Moate et al. (1999) – lupin v. barley											
Mid	2.0	2.0	19.7	18.3	0.70	43.8	45.4	−0.80	30.3	31.7	−0.70
Stockdale (1999) – lupin v. barley											
n.r.	2.5	2.5	24	22.9	0.44	42.1	42.2	−0.04	32.1	32.6	−0.20
Valentine and Bartsch (1989) – lupin v. oats											
Early	3.1	3.2	23.9	23	0.29	36.9	37.8	−0.29	30.4	31.3	−0.29
Early	6.3	6.4	23.1	21.5	0.25	34.2	34.4	−0.03	29.8	32.2	−0.38
Mean	3.4	3.4	22.3	21.7	0.21	39.6	39.1	0.23	31.4	32.5	−0.37
s.d.			2.7	3.0	0.33	2.3	3.1	0.93	1.4	1.3	0.36
Conserved forage											
Bartsch and Wickes (1984)–1 (oaten hay) – lupin v. barley											
Early	4.5	4.4	22.6	16.9	1.27	37.7	36.5	0.27	29.6	28.6	0.22
Bartsch and Wickes (1984) –2 (oaten hay) – lupin v. barley											
Early	4.5	4.4	24.2	16	1.82	40.8	38	0.62	29.8	28.7	0.24
Hough (1991)–7 (pasture silage) – lupin v. barley											
Early	3.6	3.5	25.7	24.4	0.36	38	37	0.28	28	27	0.28
Early	7.2	7.0	27.7	26.8	0.13	38	38	0.00	28	29	−0.14
Moate et al. (2002) – lupin v. barley											
Mid	1.0	1.0	20.7	20.2	0.50	44.2	44.1	0.10	32.0	32.2	−0.20
Valentine and Bartsch (1990) (oaten hay) – lupin v. barley											
Early	4.7	4.6	20.6	18.5	0.45	40.8	40.3	0.11	28.4	29.1	−0.15
Mean[A]	5.2	5.1	24.7	23.2	0.31	38.9	38.4	0.13	28.1	28.4	0.00
s.d.	1.8	1.8	3.7	4.3	0.17	1.6	1.5	0.14	0.2	1.2	0.24
Overall mean[A]	3.8	3.8	22.8	22.0	0.23	39.5	39.0	0.21	30.8	31.7	−0.30

n.r., Not reported.
[A]Mean values do not include the results of Bartsch and Wickes (1984) or (Moate *et al.* 2002) because the basal diets were low in CP and part of the response may have been to overcoming a protein deficiency.

supplemented diets may also explain why the fat content of milk is usually unchanged with lupin feed compared with that observed when high levels of cereal grain-based concentrate mixes are used (Kellaway and Harrington 2004). However, lupin supplements did not always reduce milk protein concentration compared with cereal grains (e.g. Hough 1991, experiments 5 and 8; Table 5), and so factors in addition to starch level are likely to be involved.

Responses to lupins compared with alternative protein sources

In experiments using iso-nitrogenous and iso-energetic diets, substituting SBM with lupins had no significant effects on yield of milk, fat, and protein, but consistently reduced milk protein concentration and had mixed effects on fat concentration (Table 6). Similar effects were seen when lupins were compared with protected canola meal (CM) (White *et al.* 2004). When

Table 6. A comparison of lupins *v.* alternative protein sources: summary of effects on production and composition of milk from dairy cows fed conserved forages

Diets were designed to meet energy and protein requirements

References	Supplement	Stage of lactation	Kg DM/day		Milk yield (kg/day)			Fat (g/kg)			Protein (g/kg)			Fat (kg/day)			Protein (kg/day)		
			Lupin	Other	Lupin	Other	Diff./kg lupin protein^A	Lupin	Other	Diff.^A	Lupin	Other	Diff.^A	Lupin	Other	Diff.^A	Lupin	Other	Diff.^A
								Soy products											
Bayourthe *et al.* (1998)	Lupin *v.* SMB	Mid	3.6	2.2	36.0	32.6	0.33	29.7	34.5	−0.47	28.0	30.0	−0.19	1.07	1.12	0.00	1.00	0.98	0.00
Froidmont and Bartiaux-Thill (2004)	1. Lupin *v.* SBM (wt for wt)	Mid	3.2	3.2	33.5	33.5	0.00	32.3	30.0	0.3	30.4	30.7	−0.03	1.06	0.99	0.01	1.01	1.02	0.00
	2. Lupin *v.* SBM (CP for CP)	Mid	6.1	4.0	35.7	34.2	0.09	32.1	35.2	−0.2	31.6	31.8	−0.01	1.12	1.19	0.00	1.12	1.08	0.00
Guillaume *et al.* (1987)	Lupin *v.* SBM	Early	2.6	2.0	23.9	25.7	−0.24	35.8	35.9	−0.01	31.6	34.1	−0.34	0.82	0.92	−0.01	0.76	0.88	−0.02
May *et al.* (1993)	1. Ground lupin *v.* SBM (CP for CP)	Mid	5.3	2.5	28.3	27.2	0.07	37.5	36.7	0.05	29.1	30.1	−0.07	1.02	0.97	0.00	0.82	0.82	0.00
	2. Whole lupin *v.* whole soybean (CP for CP)	Mid	3.3	2.4	25.2	25.3	−0.01	40.0	37.4	0.28	31.5	32.4	−0.10	1.02	0.93	0.01	0.80	0.81	0.00
Moss *et al.* (2000)	Lupin *v.* FM/SBM	Early/mid	2.5	1.2	33.9	33.0	0.13	42.1	45.5	−0.48	30.6	32.3	−0.24	1.40	1.48	−0.01	1.00	1.06	−0.01
Robinson and McNiven (1993)	1. Lupin *v.* SBM	Early	2.3	1.6	37.7	37.9	−0.03	35.6	34.8	0.12	29.7	30.9	−0.18	1.34	1.31	0.00	1.12	1.17	−0.01
	2. Roasted lupin *v.* SBM	Early	2.4	1.6	37.1	37.9	−0.12	35.9	34.8	0.16	29.7	30.9	−0.18	1.32	1.31	0.00	1.10	1.17	−0.01
Singh *et al.* (1995)	1. Lupin *v.* SBM	Mid/late	2.0	1.3	24.7	25.7	−0.18	39.6	39.6	0.00	32.7	33.6	−0.16	0.98	1.03	−0.01	0.81	0.87	−0.01
	2. Roasted lupin *v.* SBM	Mid/late	2.0	1.3	26.7	25.7	0.18	38.8	39.6	−0.14	32.4	33.6	−0.21	1.05	1.03	0.00	0.87	0.87	0.00
Mean			3.21	2.12	31.1	30.8	0.02	36.3	36.7	−0.04	30.7	31.9	−0.15	1.11	1.12	0.00	0.95	0.98	0.00
s.d.			1.35	0.88	5.41	4.99	0.16	3.79	3.93	0.26	1.45	1.46	0.10	0.17	0.18	0.01	0.14	0.13	0.01

(Continued next page)

Table 6. (continued)

References	Supplement	Stage of lactation	Kg DM/day Lupin	Kg DM/day Other	Milk yield (kg/day) Lupin	Milk yield (kg/day) Other	Milk yield (kg/day) Diff./kg lupin protein[A]	Fat (g/kg) Lupin	Fat (g/kg) Other	Fat (g/kg) Diff.[A]	Protein (g/kg) Lupin	Protein (g/kg) Other	Protein (g/kg) Diff.[A]	Fat (kg/day) Lupin	Fat (kg/day) Other	Fat (kg/day) Diff.[A]	Protein (kg/day) Lupin	Protein (kg/day) Other	Protein (kg/day) Diff.[A]
							Other protein feeds sources												
Froidmont and Bartiaux-Thill (2004)	Lupin *v.* peas	Mid	3.2	3.2	33.5	30.6	0.32	32.3	28.5	0.42	30.4	30.3	0.01	1.06	0.87	0.02	1.01	0.92	0.01
Kefford (1995)	1. Lupin *v.* canola meal	Mid	2.5	2.5	17.2	18.3	–0.15	39.6	41.0	–0.20	28.6	28.9	–0.04	0.68	0.75	–0.01	0.49	0.53	–0.01
	2. Lupin *v.* CSM	Mid	2.5	2.5	17.2	17.0	0.03	39.6	40.3	–0.10	28.6	29.2	–0.08	0.68	0.69	0.00	0.49	0.50	0.00
Moate *et al.* (1999)	Lupin *v.* CSM	Mid	2.0	2.0	17.4	18.1	–0.12	46.8	44.2	0.45	30.9	29.9	0.18	0.79	0.76	0.01	0.52	0.54	0.00
Moss *et al.* (2000)	1. Lupin *v.* CM	Early/mid	2.5	2.5	33.9	32.9	0.14	42.1	44.9	–0.39	30.6	32.1	–0.21	1.40	1.50	–0.01	1.00	1.04	–0.01
	2. Lupin *v.* faba bean	Early/mid	2.5	3.5	33.9	33.4	0.07	42.1	42.2	–0.01	30.6	31.6	–0.14	1.40	1.38	0.00	1.00	1.05	–0.01
Strzetelski *et al.* (2001)	Lupin *v.* feathermeal	Early	2.1[B]	0.8	34.7	32.8	0.37	40.3	40.8	–0.10	31.7	31.3	0.08	1.40	1.34	0.01	1.10	1.03	0.01
Valentine and Bartsch (1990)	1. Lupin *v.* barley + urea	Early	5.2	5.2	20.6	18.3	0.15	40.8	41.8	–0.07	28.4	29.5	–0.07	0.81	0.73	0.01	0.57	0.51	0.00
	2. Lupin *v.* faba beans	Early	5.2	5.2	20.6	19.5	0.07	40.8	41.9	–0.07	28.4	29.4	–0.07	0.81	0.79	0.00	0.57	0.55	0.00
	3. Lupin *v.* peas	Early	5.2	5.2	20.6	19.5	0.07	40.8	42.8	–0.13	28.4	30.1	–0.11	0.81	0.80	0.00	0.57	0.56	0.00
Valentine and Bartsch (1996*a*)	Lupin *v.* vetch	Early	4.0	4.0	30.3	27.7	0.23	43.1	44.8	–0.15	30.5	31.6	–0.10	1.30	1.23	0.01	0.92	0.87	0.00
Valentine and Bartsch (1996*b*)	1. 50 : 50 lupin : barley *v.* lupin : barley : blood meal	Early	2.3	1.6	29.7	28.4	0.20	40.8	40.8	0.00	28.6	28.3	0.05	1.16	1.13	0.00	0.82	0.78	0.01
	2. 50 : 50 lupin : barley *v.* lupin : barley : blood meal	Early	2.1	1.9	31.7	31.7	0.00	39.3	39.7	–0.07	28.6	28.6	0.00	1.20	1.22	0.00	0.87	0.88	0.00
White *et al.* (2004)	Lupin *v.* HCHO-CM	Early/mid	2.2	2.2	22.5	22.5	0.00	40.0	40.0	0.00	29.5	30.5	–0.16	0.90	0.90	0.00	0.66	0.69	0.00
Mean			3.09	3.02	26.0	25.1	0.09	40.6	41.0	–0.03	29.6	30.1	–0.05	1.03	1.01	0.00	0.76	0.75	0.00
s.d.			1.27	1.42	7.0	6.6	0.12	3.1	4.0	0.22	1.17	1.2	0.10	0.28	0.28	0.01	0.22	0.22	0.01
Overall mean			3.01	2.54	27.7	27.0	0.07	39.3	39.7	–0.04	30.0	30.8	–0.10	1.06	1.05	0.00	0.82	0.83	0.00

[A]Difference due to lupins, expressed as kg/kg lupin protein, assuming 350 g CP/kg.
[B]Assuming the concentrate was fed at 400 g/kg of the diet, protein supplement supplied as iso-nitrogenous.

lupins were substituted for other pulse grains such as faba beans or peas, milk yield generally increased, albeit non-significantly (Table 6).

The reduction in milk protein concentration that occurs when lupin is substituted for oilseed protein, against a background of constant protein and lactose yield, suggests that the mechanism involves more than just differences in EAA supply. If EAA deficiency or imbalance was the cause then protein yield would be expected to decline. If glucose supply was impaired with lupin feed then lactose and milk yield should also decline. Whatever the mechanism, it is important to understand and deal with this because lupins are used extensively in some dairy regions where milk price penalties apply if milk protein falls below a critical concentration.

Effect of lupin feed on milk processing quality

There are limited data on effects of lupin feed on milk quality for cheese making. Kefford (1995) conducted a series of experiments on Holstein-Friesian cows in Victoria and showed that for cows fed silage and hay, cheese yield (kg/kg milk) was unaffected by substituting 2.5 kg DM lupins/day for an equivalent amount of cottonseed meal or canola meal. When lupin replaced wheat in the concentrate mix (6 kg DM total), cheese yield was increased. However, the work of Christian *et al.* (1999*a*, 1999*b*) in Victoria showed that there were no significant differences in casein fractions or cheese-making characterisics of milk from cows fed a basal diet of pasture hay and silage and offered concentrate mixes containing lupin as a substitute for oilseed meals or wheat. Reports from the Northern Hemisphere indirectly suggest that lupin feed may lead to reduced cheese yield in cases where lupins replace high quality protein sources in the diet of cows fed mixed rations. For example, Moss *et al.* (2000) observed that the reduction in crude protein content of milk in cows fed lupins compared with SBM was associated with a significant decline in the casein fraction of milk but not in whey protein content or in casein number. Likewise, May *et al.* (1993) compared whole lupins with whole soybeans in mid-lactation cows and reported a non-significant fall in milk protein content (32.4 *v.* 31.5 g/kg) and casein (40 *v.* 38 g/kg), with a significant increase in milk non-protein nitrogen (NPN) (0.31 *v.* 0.34 g/kg milk) and a non-significant increase in whey protein content. These effects would be expected to influence cheese yield since the processing quality of milk for cheese making is generally increased as milk casein content increases and also as the ratio of casein to CP or casein to whey protein increases (Dalgleish 1997). Despite this possibility, current data show that feeding with lupins has no detrimental effects on milk quality for cheese making, and in fact may improve it under some circumstances.

Effect of lupin feed on the fatty acid (FA) profiles of milk

There were no reports of effects of feeding with lupins on the FA profile of milk from cows grazing pasture, but for cows fed conserved forage plus concentrates the replacement of solvent-extracted SBM or feathermeal with *L. albus* resulted in a decrease in medium-chain saturated fats (C12 : 0–C16 : 0) in milk and an increase in longer chain saturated (C18 : 0) and unsaturated fats (C18 : 1–C18 : 3) (Table 7). These changes were consistent with the high C18 : 1 and C18 : 2 FA profile of lupins (Table 1), indicating that a proportion of these fats was escaping ruminal hydrogenation and being incorporated directly into milk fat. The increase in milk C18 : 0 was also consistent with an increased concentration and hydrogenation of C18 : 1 in the rumen to form C18 : 0. Robinson and McNiven (1993) showed that roasting lupins to an exit temperature of 115°C increased the amount of C18 : 1 and C18 : 2 in milk of early lactation cows compared with those fed raw lupins, suggesting that heating protected the unsaturated fat in lupin against rumen biohydrogenation. However, Singh *et al.* (1995) reported no difference in C18 : 1 or 18 : 2 in milk in mid–late lactation cows fed *L. albus* roasted for 60 s at 105°C compared with raw lupins, and so it remains unclear if roasting confers protection.

The effects of lupin feed on reducing the concentration of medium-chain fats while increasing that of longer chain mono- and polyunsaturated fats are consistent with current Australian National Health and Medical Research Council (NHMRC) dietary guidelines for reducing cardiovascular risk in humans (Truswell 2003). It remains to be seen, however, if or to what extent *L. angustifolius*, which is lower in fat than *L. albus*, also alters milk FA profile, or whether effects are seen in cows grazing pasture.

Potential problems associated with lupin feed

Lupinosis

Lupinosis is a liver disease of livestock associated with the consumption of lupin seeds or stems contaminated with the *Phomopsis* fungus (Allen *et al.* 1979). Under certain humid weather conditions or poor storage conditions, *Phomopsis* contamination of lupins can occur. Although there is evidence that lupinosis can be of practical significance in sheep enterprises where the stubble is used, there is none to indicate that *Phomopsis* is an issue of practical importance for dairy cattle, at least under Australian conditions (Hough and Allen 1993).

Rumen acidosis

Acidosis is a disease associated with the rapid or excessive consumption of rapidly fermented carbohydrate (Laven 2003). The mechanism is thought to be related to lactic acid accumulation in the rumen, leading to rumenitis. Although the low starch and high NDF content of lupins make them generally safe to feed *ad libitum* to ruminants, acidosis has been reported in sheep and beef cattle when animals were on a falling plane of nutrition and offered lupins *ad libitum* (Allen *et al.* 1998). Under experimental conditions, acidosis did not occur if sheep were on a normal plane of nutrition and fed high levels of lupins via ruminal fistula (Allen *et al.* 1998). The authors are not aware of any cases of acidosis in dairy cattle caused by lupin feed.

Bloat

The only report of lupins causing bloat in dairy cows is that of Bartsch *et al.* (1985). They reported a total of 4 cases: 3/9 cows fed *ad libitum* levels of hammer-milled lupins with 3 kg of oaten hay, and 1/9 cows fed 12 kg lupins with 3 kg hay. Only one of the affected cows had to be removed from the experiment.

Table 7. A comparison of effects of lupins *v.* alternative protein sources on milk fatty acid composition in cows fed conserved forage

Means within columns within reference sources followed by the same letter are not different at $P < 0.05$

References	Base feed	Stage of lactation	Supplement	DMI (kg/day)	Lupin fat intake (kg/day)	Milk yield (kg/day)	Fat (g/kg milk)	Milk fatty acids (g/100 g fat) C10:0	C12:0	C14:0	C14:1	C15:0	C16:0	C16:1	C18:0	C18:1	C18:2	C18:3	Unsat. % total fat (w/w)
Froidmont and Bartiaux-Thill (2004)	Maize and grass silage	Mid	SBM @ 3.2 kg	22.1a[A]	0.0	33.5a	30.0a	3.4	4.0	11.7			31.4ab	1.3	9.9ab	22.04	3.2	0.35	29
			Lupin @ 3.2 kg	21.9ab	0.3	33.5a	32.3b	2.6	3.0	10.4			28.2b	1.2	11.9a	26.32	3.4	0.41	33.6
			Pea @ 3.2 kg	21.4b	0.0	30.6b	28.5a	3.1	3.7	12.1			33.9a	1.4	8.1b	20.65	3.5	0.35	28.2
			Lupin/pea @ 3.2 kg	22.1a	0.2	32.2c	28.0a	3.3	3.9	12.2			32.4ab	1.2	9.5b	20.8	3.3	0.38	28.1
Robinson and McNiven (1993)	Lucerne silage + concentrate	Early	SBM @ 1.6 kg	23.8a	0	37.9	34.8	3.3a	3.8a	13.7a	0.9	2.0a	34.7a	2.2	9.2b	19.1c	2.4ab	0.5b	25.1c
			Lupins @ 2.3 kg	22.4b	0.2	37.7	35.6	3.0ab	3.3b	12.6b	0.8	1.7ab	31.2b	1.9	11.4a	21.9b	2.1b	1.3a	28.0b
			Roasted lupins @ 2.4 kg	22.2b	0.3	37.1	35.9	2.8b	3.1b	12.1b	0.8	1.0b	29.7c	2	11.4a	24.0a	2.6a	1.1a	30.5a
Singh *et al.* (1995)	Lucerne/ timothy silage + concentrate	Mid–late	SBM @ 1.3 kg	23.6	0	25.7ab	39.6	3.2a	3.9a	12.3a	1.1a	1.65a	35.6a	3.8	9.8b	20.5b	2.6a	1.1b	29.1b
			Lupins @ 2 kg	23.9	0.2	24.7b	39.6	2.9b	3.3b	11.4b	1.0b	1.54ab	33.1b	3.3	12.1a	22.8a	2.2b	1.9a	31.2a
			Roasted lupins @ 2 kg	22.7	0.2	26.7a	38.8	2.9b	3.3b	11.5b	0.9b	1.46b	32.7b	3	11.7a	23.8a	2.5ab	2.0a	32.2a
Strzetelski *et al.* (2001)	Mixed silage + concentrate	Early	Lupins @ 2.2 kg	23.9	0.1	34.7a	4.03	3.0	3.7	11.6a	1.2a	1.3	30.7a	2.0	8.9a	20.1a	2.5	0.32	29.7
			Feathermeal @ 1.0 kg	23.7	0	32.8b	4.08	2.9	3.7	12.0b	1.4b	1.3	31.8b	2.1	7.7b	18.8b	2.2	0.27	28.6

Infertility

Lupin protein is rapidly degraded in the rumen, and when ingested at high levels can lead to increased concentrations of rumen ammonia and plasma urea. Although there are reports of an inverse correlation between plasma urea concentration and fertility in dairy cows (Butler *et al.* 1996; Laven and Drew 1999; McCormick *et al.* 1999), the mechanisms and level at which effects are seen are unclear to the extent that no recommendations can be made about what constitutes a 'safe' level of RDP or plasma urea (e.g. see Dawuda *et al.* 2004 and Laven *et al.* 2004). Recently, Rhoads *et al.* (2006) showed that embryos from cows fed high RDP diets (plasma urea nitrogen concentration of 244 mg/L) had lower survival when transferred to heifers than embryos from cows fed a moderate RDP diet (plasma urea N of 155 mg/L), but that there was no effect of RDP on embryo survival when applied to the heifer acceptor animal. High levels of plasma urea have been recorded in sheep fed lupins; Banchero *et al.* (2004) reported plasma urea-N levels of up to 340 mg/L in sheep fed 1.1 kg lupins per day before parturition *v.* 140 in sheep fed 750 g maize per day, and this was associated with a reduction in colostrum at parturition, although not at subsequent sampling times. There was also a reduction in lactose content of peri-parturient colostrum in lupin-fed sheep and the authors suggested that the high plasma urea from lupins may be interfering with glucose uptake. White *et al.* (2002) reported plasma urea-N concentrations of 399 mg/L for sheep fed diets containing 70% lupins *v.* 220 mg/L for those fed a diet of 35% lupins. Unfortunately, there are no data on blood urea levels in dairy cattle fed high levels of lupins as a single supplement. Valentine *et al.* (2000) fed cows grazing temperate pastures increasing levels of concentrate (7–14 kg/day) containing 74% barley and 25% lupin and reported no significant effect of level of concentrate on plasma urea, with a mean value of 202 mg urea-N/L. In the only lupin-feeding experiments in which fertility was recorded, Hough (1991) reported no effects of lupins (up to 9 kg DM/day) on pregnancy rates in 8 experiments involving both grazing and silage-fed cows.

In summary, while there is no evidence that feeding with high levels of lupins will reduce fertility, it may be prudent to investigate the potential reproductive consequences of feeding high levels of lupins to dairy cows that are already receiving high levels of soluble nitrogen in the diet, from ryegrass for example.

Low milk protein concentration

Replacing cereal grains or oilseed meals with lupins in the diet of dairy cows has been shown to reduce milk protein concentration without necessarily reducing protein yield (Tables 5 and 6). Although not a pathology as such, it can have economic consequences for milk producers in circumstances where price penalties apply for failing to meet protein content standards.

Conclusions and possible lupin breeding objectives to improve nutritive value

Lupins provide a practical source of energy and soluble protein for dairy cows, especially under conditions where cows are required to consume their daily concentrate mix in the dairy while being milked. The higher energy and protein concentration of lupins and low concentration of starch relative to cereal grains make them a popular grain to feed to early lactation cows, especially when pasture quality or quantity is seasonally limiting, and where the energy and protein content of silage or pasture hay is insufficient to meet the milk demands for high-producing cows.

Results from a limited number of dose-response experiments show that there is a linear response in milk production to increased lupin grain up to at least 9 kg DM lupin/day. The response appears to be independent of type of base forage (conserved forage or grazed pasture) and stage of lactation or level of milk production. The mean response slope from all experiments was 0.53 kg/kg for milk, and ~0.02 kg/kg for both milk protein and milk fat. However, the range for milk yield response was wide at 0.00–0.95 kg/kg, the reasons for which remain unclear. The mean estimate of forage substitution was 0.54 kg/kg DM lupins, also independent of the base forage type.

Results from experiments in which lupins were substituted for cereal grains on a weight/weight basis showed that mean fractional milk yield was increased by 0.21 kg milk/kg DM lupin for cows grazing pasture, or 0.31 kg/kg for cows fed conserved forage, with an overall mean of 0.23 kg/kg. Overall mean fat content of milk increased by 0.21 g/kg per kg DM lupin when lupins replaced cereals, but mean protein content decreased by 0.30 g/kg per kg DM lupin. If the basal diet was deficient in protein, then substituting cereal with lupins gave a much larger milk yield response. Although the size of the increase in milk yield could be explained by differences in the ME content of the grains, there was evidence that lupins were less likely to cause milk fat depression than cereal grains, but were more likely to reduce protein content while not reducing protein yield. The reasons behind the reduction in milk protein concentration are unclear, but could be due to a deficiency in essential amino acids, increased fat intakes, or reduced starch intakes, all factors known to be associated with reduced protein concentration of milk.

Results from experiments in which lupins were substituted for SBM in iso-energetic and iso-nitrogenous diets showed that yield of milk, fat, and protein was relatively unaffected, but that protein content declined by 0.15 g/kg.kg DM lupin. A similar trend was seen when lupins were substituted for other oilseed meals. Modelling EAA flows suggest that this lower protein content may be associated with a reduced supply of Met and Lys from lupins than from oilseed meals.

Replacing SBM with *L. albus* lupins resulted in changes in the FA profile of milk commensurate with the FA profile of the lupin oil. The main changes were increased concentrations of C18 : 0–C18 : 3 and reduced concentrations of C12 : 0–C16 : 0 in milk. These alterations in milk FA profiles in cows fed lupins are in the same direction as current NHMRC dietary guidelines for reducing cardiovascular risk in humans.

Cows fed whole lupins produced less milk than those fed cracked or hammer-milled lupins, due to lower whole-tract DMD. Apart from milling, processing of lupins (e.g. heating, extrusion, or treating with formaldehyde) resulted in inconsistent responses in milk yield and composition compared with raw lupins, with no overall advantages shown from processing. Further work is needed to understand circumstances under which benefits are derived from protecting lupin protein or carbohydrates from ruminal degradation.

In terms of important knowledge gaps, we currently don't know:

- the consequences of feeding high levels of raw lupin grains to cows in terms of the possible effect of a high soluble N load on embryo survival and on net energy requirements;
- the practical benefits, if any, to dairy cows of processing lupins using heat, steam flaking, or chemical treatment. This is important from the point of view of adding value to raw lupin grains, especially for the export market.

In terms of possible breeding objectives relating to improving the feeding value of lupin grains, especially *L. angustifolius*, for dairy cows, the following priorities are suggested:

1. Improving the protein quality by reducing ruminal degradability by 15–20% together with increasing the content of rumen-protected methionine by 100%. These changes must not compromise the metabolisable energy content nor reduce intestinal absorption of essential amino acids.
2. Reducing NDF content of the seed and reducing processing costs by reducing the seed-coat thickness of *L. angustifolius* as a fraction of total seed weight from 250 g/kg to 150 g/kg.
3. Increasing available starch content from its current low value (<10 g/kg) to at least 100 g/kg at the expense of non-starch polysaccharides.
4. Increasing the oil content of *L. angustifolius* from its current level of 60 g/kg to 100 g/kg DM.

In conclusion, lupin seeds provide a safe and practical source of metabolisable energy and soluble protein for dairy cows. They possess a high bulk density and a carbohydrate, fat and protein composition that makes them especially suited to in-dairy feeding systems. Although there is evidence of a decrease in milk protein concentration associated with lupin feed under some situations, milk yield and milk fat concentration are usually equivalent to or increased compared with other feed grains.

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Manuscript received 6 April 2006, accepted 4 December 2006