

LUPINS – REFLECTIONS AND FUTURE POSSIBILITIES

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ABSTRACT

The role of lupins in agricultural systems has changed dramatically over the millennia and particularly over the last century since they have been domesticated as a grain crop for modern agriculture. Throughout the history of use of lupins their role as a nitrogen fixer and soil health improver has remained central and their nutritional value as a stockfeed has long been recognised. By contrast, although lupins have been consumed as a human food for centuries, the extent of the health benefits of consuming lupins and their functionality as an ingredient in processed food, is much less known and only recently appreciated. Despite these positive characteristics of lupins, the production of lupins has declined over the last decade in the major producing regions in Europe and Australia. This paper examines some of the reasons for this decline and explores what roles lupins could play in future agriculture and food production.

KEYWORDS

farming systems, food, health, climate change, nitrogen, phosphorus, weed management, GM

INTRODUCTION

The role of lupins in modern agricultural and food systems began in the 20th Century with the well documented domestication of the three Mediterranean species, *Lupinus luteus* and *L. albus* in Europe and *L. angustifolius* in Australia (Cowling *et al.* 1998). The breeding of non-shattering and low alkaloid ('sweet') varieties enabled these species to switch from use as a green-manure and forage to that of a mechanically harvested grain-legume.

The benefit of lupins in crop rotations has long been recognised due largely to the significant quantities of nitrogen fixed (Herridge and Doyle, 1988). The use of inorganic nitrogen (N) fertiliser has contributed enormously to the productivity of 20th Century agriculture, but has also been linked to environmental pollution (Drinkwater *et al.* 1998) and is likely to become increasingly expensive due to the energy intensity of its production. Will higher prices of N fertilisers mean an expanded role for grain legumes as alternative sources of biological nitrogen?

The composition of the lupin grain is quite unique, being high in protein and soluble fibre, with virtually no starch (Pettersen *et al.* 1997). *L. albus*, *L. angustifolius* and *L. luteus* have relatively low oil contents (10%, 6% and 5% respectively) whereas *L. mutabilis* has around 18% oil, making it close in composition to the soybean. The nutritive value of lupins in the diets of monogastric and ruminant animals has been thoroughly determined and reviewed by Australian and European researchers as a protein and energy source (Pettersen, 2000). The absence of starch makes them attractive to ruminant feeders due to their low acidosis risk and rumen fermentation properties (Edwards and van Barneveld, 1998). Lupins also lack anti-nutritional factors such as trypsin inhibitors and saponins. As an energy source they compete with cereals and as a protein source they compete with oilseed meals. It is their capacity to complement other feed components to achieve overall nutrient balance at minimal cost that determines their value (Edwards, 2004). More recently there has been an expansion of lupin as an ingredient for human food uses, particularly in Europe (Schneider *et al.* 2005).

Economic and population growth in China and India has seen these countries nearly triple their meat consumption over the past 30 years, which has stoked demand for grain to feed animals (it takes about 3 kg of grain to produce 1 kg of pork and 8 kg of grain to produce 1 kg of beef). This demand for feed grain remains strong and it supports world grain production that is currently close to being the highest on record. This demand, complemented by a diversion of grains into biofuels, leads many analysts to the view that demand for grain and grain prices will both remain high for sometime to come. Lupins as a feed grain and complementary enterprise for cereal production will benefit from such increased demand.

However, lupins do not have the potential to become a major global crop that can 'feed the world'. Their more minor role is as part of sustainable agricultural systems and they may increasingly contribute to the human diet based on their unique attributes as a protein and dietary fibre source. Certainly centuries ago, when lupins were being de-bittered, they were a subsistence food for the poorer sections of some societies. By contrast, their future role in human nutrition may be for the more affluent sections of some societies who are

plagued by obesity, diabetes and cardiovascular disease and who may particularly benefit from some of the unique properties of lupins.

RECENT PRODUCTION TRENDS

Lupin cultivation expanded across northern Europe and in Australia quite dramatically through the 20th Century but has recently declined almost as dramatically in these same countries (Table 1).

In Western Australia, lupin production has declined since 1999, mostly due to a large reduction in the area sown (Fig. 1). Growers assessed lupins to have lower profitability relative to wheat, especially in seasons with late sowing rains and in the 2000s such seasons were more frequent. The area sown has declined most in the low rainfall regions, where early sowing opportunities are more critical and the cost-price squeeze has affected their profitability the most.

Table 1. Global production of lupin grain (average annual production – metric tons).

Country	1961-70	1971-80	1981-90	1991-95	1996-2000	2001-05	2006
Argentina	350	230	80	100	120	130	130
Australia	1,410	57,550	593,620	1,271,450	1,560,410	984,800	174,000
Chile	0	2,070	14,390	30,690	33,240	45,370	70,480
Ecuador	2,800	720	930	1,290	1,330	1,450	1,470
Egypt	7,960	5,820	7,270	6,350	5,230	3,890	2,790
France	0	0	1,810	10,820	14,820	26,770	16,560
Germany	14,580	10,800	12,640	1,110	-	-	-
Greece	3,030	720	270	150	200	460	300
Hungary	4,110	2,960	5,790	880	1,220	320	200
Italy	25,530	8,310	4,740	4,560	4,680	4,790	6,000
Lebanon	0	0	0	1,140	1,150	1,070	1,000
Lithuania	0	0	0	670	1,340	2,400	4,800
Morocco	1,000	1,820	2,690	3,260	11,660	14,000	14,000
Palestine	0	0	0	0	10	0	0
Peru	1,330	2,580	3,510	3,510	7,220	9,540	9,480
Poland	155,900	71,780	99,860	74,200	31,760	15,090	27,990
Portugal	4,190	2,570	830	50	10	10	10
Russia	-	-	-	10,870	15,340	27,810	13,510
South Africa	42,830	6,600	7,100	6,600	11,470	10,230	14,400
Spain	6,350	2,090	1,700	4,630	12,010	9,160	6,900
Syria	20	750	280	100	120	40	10
USSR	449,000	312,500	265,800	116,200	-	-	-
Total	720,390	489,870	1,023,310	1,548,630	1,713,340	1,157,330	364,030

Source information: FAOSTAT (2008).

Australia

Domesticated *L. angustifolius* was first grown in Western Australia in the 1970s. The substantial benefits to the following wheat crop and the high grazing value of the stubbles were readily recognised by farmers, fuelling the rapid expansion of the crop through the 1980s, with production peaking at 1.6 mt in 1999. Production in South Australia, Victoria and southern NSW also expanded over this period and these regions accounted for about 20% of Australian production (ABARE 2007).

There has also been increasing costs and technical difficulties in weed control. Herbicide costs typically account for 40-50% of the variable cost of lupin production. In addition, annual ryegrass resistant to herbicide groups A (fops and dims) and B (sulphonyl ureas), and wild radish with emerging resistance to groups B and C (triazines) increased the complexity of weed management (Gill, 1996). The widespread practice of dry-sowing lupins which gave acceptable results in the 1980s compounded the weed problem through missed opportunities for mechanical and

chemical pre-emergent 'knock-down', and often suboptimal performance from simazine in dry seedbeds. Weed control has become particularly difficult where lupins have been grown on less suitable soil-types where the crop grows less vigorously and competes poorly with weeds. In addition, the first generation anthracnose resistant cultivars had high sensitivity to the post-emergent herbicide metribuzin (Si *et al.* 2006). In response to problematic weed control, growers have begun to apply a wider spectrum of weed control strategies such as collecting weed seeds at harvest and burning header trails. However, many growers now sacrifice some lupin yield to 'set-up' a paddock for the following wheat crop by delaying the sowing of lupins to get a chemical and mechanical knockdown and by 'crop-topping' with a non-selective herbicide to stop weed seed set (Gill, 1996).

The widening of the rotation created some advantages for lupins, reducing the severity of the diseases brown spot, pleiochaeta root rot and phomopsis stem and pod blight. However, anthracnose remains the most important disease threat particularly in the high rainfall Northern Agricultural Region of Western Australia but new resistant *L. angustifolius* varieties and the use of clean seed mean that losses are now low in medium and low rainfall zones (Thomas and Sweetingham, 2004). Bean Yellow Mosaic Virus (BYMV) also remains an important problem in southern environments.

The rate of genetic gain in yield through breeding in *L. angustifolius* (% per annum) matches the rate of genetic gain in cereals over the past 30 years in Australia (Fellowes, 2006). Lupins have been regarded as a crop with a low harvest index particularly in the higher rainfall southern environments. The harvest index of the modern cultivars such as Belara and Mandelup are almost twice that of the first cultivars when grown in suitable environments (Berger *et al.* 2008).

There are some examples of regional adaptation in lupin cultivars. For example, later flowering varieties such as Geebung and Jindalee perform relatively better in parts of South Australia and New South Wales compared to Western Australia. More recently the variety Jenabillup has shown particularly good adaptation to the higher rainfall zone, particularly on the south coast of Western Australia.

L. luteus varieties introduced from Europe in 1960s were more susceptible to insects and inferior in yield to narrow-leafed lupins and so yellow lupin breeding was pursued (Gladstones, 1994). The more recent discovery that *L. luteus* was very resistant to Cucumber Mosaic Virus, root rots and brown spot, together with their tolerance to aluminium toxicity and efficiency of phosphorus uptake, explained their excellent performance in trials on the acidic soils of the eastern wheatbelt (Sweetingham *et al.* 1996). A low alkaloid

variety cv. Wodjil was released in 1997 but proved unpopular due to its extreme susceptibility to aphids.

The higher crude protein of *L. luteus*, which is richer in lysine and sulphur amino acids, offers significant advantages to the intensive livestock industries and particularly to aquaculture. The extent of the advantage is evident with de-hulling as kernel meals at 52% protein exceed the soybean meal 48% benchmark. The high protein requirements of salmonid and prawn diets have been identified as a market niche for yellow lupin. In rainbow trout and red seabream the protein digestibility of yellow lupin kernel meal is better than that of the soybean meal, with a similar overall digestible dietary energy (Glencross, 2005). However, yellow lupin production in Australia remains minimal at present as varieties currently available are based on an ideotype from northern Europe which has proven poorly adapted to local conditions.

Europe and North Africa

The area of lupins in the former USSR is estimated to have reached 600,000 ha for grain and up to 2 million ha for green forage and green manure, of which more than 90% was yellow lupin (Takunov *et al.* 1993). The major regions for yellow lupin cultivation are the Belarus, Lithuania, Latvia, the forest-steppe zone of Zhitomir and Chernigov Provinces in Ukraine and the Bryansk Province of European Russia (Kurlovich, 2002). Fusarium wilt spread through the former USSR in the 1960s and caused a decline in lupin area which was not reversed until the introduction of resistant cultivars in the late 1970s.

There has been a steady decline in both *L. luteus* and *L. albus* production in Europe since the 1980s for two main reasons. Firstly, anthracnose which began to spread through Europe in the early 1980s, affected these species more than narrow-leafed lupins. Secondly, the freeing up of imports by East Germany, Poland and Russia in the 1990s has seen greater use of soybean meal for feed and more available nitrogen fertilisers.

An increasing interest in growing lupins in France and the UK occurred in the 1990s in response to a desire by the local animal industries to source a 'home-grown' non-GM source of vegetable protein. In both countries early focus has been on autumn sown French *L. albus* varieties (LISA 2007).

L. angustifolius is becoming more popular in the UK, Germany and Poland due to greater anthracnose resistance compared to the other lupin species.

Only small amounts the 'wild-type' *L. albus* and *L. luteus* are now grown in the Mediterranean countries which were the origin of these species. In Portugal, Spain, Morocco and Tunisia bitter and shattering *L. luteus* landraces have been selected over the centuries for forage. In these regions sheep and goat grazing is practised, and often the lupins are a regenerating cover crop under cork oak plantations (Gladstones, 1998). In

the mid 20th century, *L. luteus* was often cut green for hay or silage but today around 40,000 hectares provide summer forage as 'standing hay' (Abreu, 1993). Relatively little effort has gone in developing sweet, non-shattering yellow lupins in southern Europe because of the practical difficulty of maintaining these characters, due to out-crossing to wild populations. In Portugal, Spain, Italy, Greece and Egypt small quantities of the large seeded bitter *L. albus* ('lupini' or 'tremoco') are grown.

L. nootkatensis, a perennial lupin has for sometime been used for land reclamation in Iceland and has more recently been researched for potential use in agriculture and forestry (Arnalds and Runolfsen, 2002). North America.

In the USA *L. luteus*, *L. angustifolius* and *L. albus* were grown on over one million hectares of the southern Coastal Plain between 1930 and 1950 primarily as a fall sown, winter-spring green manure nitrogen source, prior to cotton and other summer crops (Reeves *et al.* 1990). Occasional severe 'winter freezes' disrupted *L. albus* and *L. angustifolius* plantings in the 1950s and the arrival of cheap nitrogen fertilisers and government programs favoured other crops besides lupins. Furthermore, a seed-borne virus disease (probably BYMV) wiped out *L. luteus*.

There has been experimental *L. albus* cultivation in California, the Pacific north-west, Minnesota, Michigan and in the maritime provinces of Canada but only on a small scale (Clapham *et al.* 1999; Kearney, 1999). The potential use of native lupins such as *L. exaltus* and *L. campestris* has been researched in Mexico with the emphasis on determining their nutritional value as animal feeds both as a fodder or grain (Ruiz and Sotello, 2001) and a source of protein for inclusion in wheat flours and for making milk and yoghurt (Jimenez Martinez *et al.* 2003).

South America

Currently, Chile is the only country in the world where lupin production is increasing with annual production of 70,000 t in 2006 (FAOSTAT, 2008). Most of this production is *L. albus* which is grown in Region IX and has benefited from a strong local breeding effort. However, there is increasing interest in *L. angustifolius* and *L. luteus*. A significant proportion of lupin is being utilised by the large Chilean salmon aquaculture industry.

In the Andean highlands a small quantity of bitter *L. mutabilis* is still cultivated using traditional methods by farmers in Ecuador, Peru and Bolivia. FAO production data indicates production in Peru is consistently in the order of 9,000 t (FAOSTAT, 2008).

Current production in Argentina is insignificant, but trial plots' data matched to climate and soil-type analysis indicate that substantial areas of the Pampas where wheat is currently grown are suitable for *L. albus* production (Ravelo and Planchuelo, 2005).

South Africa

South African lupin production reached 60,000 tonnes in the 1960s (FAOSTAT, 2008). *L. angustifolius* and *L. luteus* have been grown in rotation with wheat in the Western Cape which has a typical Mediterranean winter rainfall climate. *L. albus* has been grown more in the northern summer rainfall zone but weed control has been a major constraint in these areas (Van der Mey, 1996). Disease problems including powdery mildew, phomopsis and more recently anthracnose have limited the expansion of the crop throughout the country (Koch, 1996). Van der Mey (1996) estimated that there were about 80,000 ha of lupins in South Africa at that time, grown for grain, 'standing hay' and silage.

RECENT TRENDS IN LUPIN UTILISATION

Aquaculture

Of all the animal food producing sectors, aquaculture is the fastest growing in the world, with annual growth rates of 8.8% since 1950 compared to only 1% for beef, 3% for pig meat and 4.9% for chicken meat (Tacon, 2004; Williams, 2007). Demand for seafood is increasing whilst the catch from wild fisheries has plateaued since the 1980s. A major challenge for future aquaculture production is finding sufficient and sustainable feed sources. Of critical significance is the need to replace fishmeal with other sources of protein, as fishmeal is in finite supply. Consequently, soybean meal and plant protein concentrates are increasingly used in compound aquaculture diets.

Lupins have emerged as having exciting potential as an aquaculture feed ingredient. Consistently, lupins have proven to be a source of highly digestible protein and energy, and display few nutritional problems at high (> 20%) inclusion levels in fish diets. In some cases lupin-based diets even surpass the performance of diets based on fishmeal or soybean meal. Other positive 'points of difference' that support the functionality of lupins in extruded diets have been documented by Glencross (2007).

The salmonid and prawn feed markets have been identified as two key markets for lupin kernels. The high protein requirements for these diets reduce formulation flexibility and increase the value per unit protein (Glencross, 2005). Kernel meals of both *L. angustifolius* and *L. luteus* from Western Australia have been included in commercially extruded aquaculture feeds used in Asia, Australia and Europe. *L. albus* kernel meals have also been used in Chile.

The price of fishmeal soared to record heights in 2007 (Fishmeal Information Network, 2008) creating a higher price opportunities for lupins used in aquaculture rather than in other animal feed sectors.

Food trends and health claims

Extensive research has led to a wide range of concept food products containing *L. angustifolius* in Australia over the past 30 years. Lupin food research has explored three main areas (i) whole grain or kernels as a soybean substitutes in traditional fermented Asian foods; (ii) kernel flours in blends with wheat flour; and (iii) protein and fibre fractions. Much of this research has been reviewed by Kyle (1994); Petterson (1998) and Jayasena and Quail (2004). Despite many of these products showing good consumer acceptability, only a very small amount of lupin-containing food products has been commercialised in Australia or in Asia. Commercial production of lupin-containing foods in Australia mostly has been limited to products made with *L. angustifolius* kernel flour, including breads, muffins, pasta and biscuits. At present we estimate the use of lupin kernel flour in Australia to be less than 2000 tonnes per annum. There have also been small commercial consignments of *L. angustifolius* from WA to Indonesia for tempe manufacture and to Japan for fresh lupin sprouts and for shoyu (soy sauce).

In Europe over the last ten years, a much greater level of lupin food commercialisation has taken place, with estimates that the lupin flour and lupin protein ingredients market is in the order of 25,000 tonnes (Schneider *et al.* 2005), based on both locally grown *L. albus* and imported *L. angustifolius* from Western Australia. Lupin-containing products that are commercially available include a wide range of baked goods, milk, icecream and confectionary. Much of the research that underpins this development has been summarised in the Proceedings of the Healthy ProFood Conference (Arnoldi, 2005). There has also been significant research on lupin proteins as food ingredients in Mexico (Jimenez Martinez *et al.* 2003) and a commercial lupin hull fibre product based on *L. albus* has been produced in Chile (www.avelup.cl).

Today, the growing interest in lupins in food products relates to the increasing evidence of its human health benefits and the functional food and nutraceutical opportunities that may flow from lupins' unique protein and fibre profiles and minor constituents of its grain (Table 2).

Table 2. Putative health benefits associated with lupin fractions.

Health indicator	Lupin constituent	Evidence	Reference
Satiety; controlling appetite	whole kernel	Human dietary intervention study	Lee, Y.P. <i>et al.</i> (2006)
	kernel fibre	Human dietary intervention study	Archer, B.J. <i>et al.</i> (2004)
Bowel health (reduced transit time, lower colon pH, prebiotic)	kernel fibre	Human dietary intervention study	Johnson, S.K. <i>et al.</i> (2006); Smith, S.C. <i>et al.</i> (2006)
	lupin protein	Rat feeding study	Pilvi, T.K. <i>et al.</i> (2006)
Hypotensive activity	lupin protein	Human dietary intervention study	Nowicka, G. <i>et al.</i> (2006)
	lupin protein	Rabbit feeding study	Marchesi, M. <i>et al.</i> (2007)
	kernel fibre	Human dietary intervention study	Hall, R.S. <i>et al.</i> (2005)
Hypocholesterolemic activity	lupin protein	Human dietary intervention study	Nowicka <i>et al.</i> (2006)
	lupin protein	Rat feeding study	Spielmann <i>et al.</i> (2007); Rahman, M.H. <i>et al.</i> (1996)
	lupin protein	Pig feeding study	Martins <i>et al.</i> (2007)
Reduced blood glucose and insulin response	whole kernel	Human dietary intervention study	Hall, R.S. <i>et al.</i> (2005)
	gamma conglutin	Rats	Magni <i>et al.</i> (2004)
Enhanced insulin secretion	alkaloids	Mice	García López, P.M. <i>et al.</i> (2004)
Coeliac disease	all lupin fractions	Gluten free	www.naprofood.de
Reduced risk of macular degeneration	lutein, zeaxanthin	Speculative based on generic evidence	Friers, C. <i>et al.</i> (2008)

Note: This is not intended to be an exhaustive list.

Unfortunately the potential health benefits of lupins have been complicated by the fact that a small percentage of the human population is allergic to ingesting or inhaling lupin protein. The understanding of this risk has increased in recent years. Exposure to trace quantities of lupin in some individuals can result in a severe anaphylactic response (Moneret-Vautrin *et al.* 1999; Smith *et al.* 2004). There have been differing reports on the incidence of people cross reactive to both lupin and peanut. Smith *et al.* (2008) report that about 5% of people known to exhibit clinical symptoms of peanut allergy also show clinical symptoms when exposed to lupin. In their study other individuals were either lupin-only or peanut-only sensitive.

EMERGING ISSUES

Supply and demand for plant protein and energy

Global soybean production is projected to reach 240 mt in 2008/09 as areas sown to soybean in the US and South America increase in response to strong price signals. Balancing this is an underlying increase in demand for vegetable protein. For example, meat consumption in China and India has nearly tripled over the past 30 years, fuelling their demand for grain to feed animals. Consequently many analysts are suggesting that grain and vegetable protein prices will remain relatively high for the rest of this decade, particularly if fertiliser prices remain high.

Escalating production costs

There has been a rapid rise in the price of N fertiliser in 2008. This has been primarily caused by (i) an increasing cost of production linked to the rise in the cost of energy, (ii) an increased demand from agricultural producers, (iii) a constrained manufacturing capacity and (iv) increased costs of transport. Moreover, recently some large producing countries such as China have imposed additional taxes on the export of fertiliser to shore up local supply.

About 90% of the cost of manufacture of ammonia via the Haber-Bosch process is the cost of energy, usually natural gas. To make 1 tonne of urea fertiliser about 35 gigajoules of energy is consumed. So the N fertiliser price is strongly linked with the supply and price of fossil fuels. The recent increasing demand for N fertiliser has come from an unprecedented global demand lifting the price of grain. Farmers have responded by planting more cereals and maize. One ingredient influencing the demand side has been the US government policy to support ethanol production from maize which has diverted a lot of maize from animal feed that has to be replaced with other grain.

Clearly the nitrogen fixing ability of legumes, including lupins, must be more highly valued in agricultural systems in the current an emerging environment. Reeves *et al.* (1990) estimated that if lupins were to replace a quarter of the wheat acreage in

the south-eastern USA it could replace about 90,000 tonnes of N fertiliser worth \$60m per year (in 1990 dollar terms). In 2008, Western Australia planted its smallest lupin crop for many years at about 400,000 ha, but even at this level it can be estimated that the crop will fix \$120m worth of N at current prices (J. Howieson pers. comm.).

In another blow for farmers, world prices for rock phosphate have spiked about 8 fold in the past 12 months because of sustained demand and because inexpensive reserves are being rapidly depleted. This is translating into substantial price hikes for superphosphate, DAP and MAP fertiliser for farmers throughout the world. Whilst it is likely that the current prices may ease somewhat it is important to recognise that phosphorus (P) is a finite mineral resource.

Crop yield on 40% of the world's arable land is limited by P availability and it is the most common limiting nutrient for lupin production in Western Australia despite large applications of superphosphate to agricultural soils for many years. Most of the water-soluble P from superphosphate is rapidly adsorbed to form insoluble complexes with cations and organic fractions in the soil. Typically less than 20% of applied P is removed in the first year of crop growth. Vance (2001) promoted the need to develop agronomic systems that enhance N and P acquisition and increased efficiency of conversion of N and P to plant products. There is evidence that lupins' roots release organic acids which can solubilise inorganic P and acid phosphatases to release organically bound P from phytate. The proteoid roots of *L. albus* and the more abundant branching system of *L. luteus* appear likely to contribute to this ability to 'mine' the insoluble P in the soil to a greater extent than *L. angustifolius* (Bolland *et al.* 2000). In four field experiments, each on a different soil type, at least twice as much P was required to produce the maximum yield in *L. angustifolius* compared to that required by *L. luteus* (Bolland *et al.* 2000, 2001).

The value of lupins in farming systems

We have used MIDAS (Model of an Integrated Dryland Agricultural System) (Kingwell and Pannell, 1987; Schilizzi and Kingwell, 1999; Gibson *et al.* (in press)) to look the impact of recent higher prices of inputs (Fig. 2) on the profitability and enterprise mix for a typical central wheatbelt and a typical northern wheatbelt sandplain farm in Western Australia. Since mid 2006 grain prices have risen dramatically causing farmers to increase the proportion of their farm in crop and to reduce their livestock numbers. However, model runs, based on average climatic conditions, indicate that the large increases in the cost of fertiliser and fuel and slightly higher herbicide costs, combined with less favourable grain prices will greatly erode the profitability of cropping in 2009.

It was hypothesised that the increase in N fertiliser price would lead to an increase in the proportion of lupin (*L. angustifolius*) sown on farm. This was not the

case for the central wheatbelt farm because in spite of lupins being a biological source of nitrogen, the lower profitability of cropping resulted in a switch to pasture and sheep production. Crop production was less favoured on the lesser fertile soils that typically required higher rates of N and P fertilisers. On some of these soils, lupin-based rotations were replaced by pasture phases that supported additional livestock production.

For the northern wheatbelt sandplain farm with a higher proportion of soils more suited to lupins more supported the initial hypothesis with a larger area of the farm being allocated to lupins under the 2009 price and cost conditions. Canola that was selected as part of optimal rotations under 2008 price and cost conditions was largely displaced by additional lupins and pasture (Fig. 3). In 2008 the optimal resource allocation involved all the farm being in crop, whilst for 2009 under 90% of the farm was in crop. Hence, it appears that in the traditional lupin-growing regions of Western Australia, the profitable selection of lupins, at least given average seasonal conditions, are a profitable and robust part of optimal farm plans.

According to Prine and Chambliss (2004) lupins have 'enormous potential' in Florida provided consistently cold-tolerant cultivars can be developed. Recent research and breeding into *L. albus* for the southern US has seen renewed interest in Alabama and has also been shown to have potential in the mid-Atlantic region on fine sandy loam soils (Bhardwaj *et al.* 2004). Experimental plot yields up to 4.8 t/ha of non-determinant French *L. albus* cv. Lunoble has been recorded. Van der May (1996) reported more opportunities for *L. albus* cultivation in South Africa, Angola and Zimbabwe based on climatic analysis but soil-type suitability was not assessed. In all these situations the extent of adoption of lupins will ultimately be determined by their relative profitability and systems' benefits compared to other crops.

Low alkaloid varieties of *L. mutabilis* have been developed in Chile (von Baer and von Baer, 1988) and in Australia (Clements *et al.* 2005) but none are currently in commercial production. This specie offers significant potential advantage because the inherent value of its seed is substantially higher than that of other lupin species due to its high oil and protein content. However, there are likely to be significant local adaptation problems to overcome before this crop can achieve commercially attractive yields and disease resistance. It is very unlikely that low alkaloid varieties of *L. mutabilis* would be adopted in the Ecuador, Peru or Bolivia because of the high risk of out-crossing to wild bitter populations.

Climate change

There is now general acceptance in the scientific and broader community that elevated levels of greenhouse gases such as carbon dioxide and nitrous oxide can trigger global warming. What is less certain is the rate

of change of temperature, rainfall and other climatic factors; particularly how these factors may change on a regional or local level. Broadly, the mid-latitudes are expected to experience the largest drying trends (Intergovernmental Panel on Climate Change 2007). In south Western Australia it is predicted that growing season temperatures will rise and rainfall will decline quite significantly by mid century making lupin and cereal cropping more risky in the north-eastern agricultural region. However, crop yields in the high rainfall parts of the south-west could be higher where a decrease in rainfall leads to less winter waterlogging. Modelling by Farre and Foster (2008) indicates that heavier textured clay soils are more vulnerable to climate change in Western Australia than sandier soils. Thus lupin production may less affected overall than as they are not grown on the heavier soils. Irrespective of this, plant breeding and agronomic developments should compensate for some of the adverse impacts of a changing climate.

We have not attempted to review the detailed climatic models of all lupin growing regions in the world but can draw attention to the maps drawn by the Hadley Centre for Climate Prediction and Research (www.metoffice.gov.uk). These maps indicate that growing season rainfall will decline by mid century in current lupin production zones in Australia, Chile, South Africa, and the countries in the Mediterranean Basin. This will tend to be a negative for lupin production in these regions, as growing season length which dictates potential yield is already moisture limited. In contrast, rainfall should increase in the growing season in northern Germany, Poland and Russia and warmer temperatures should extend growing seasons and support lupin production. Winter temperatures are predicted to become warmer in the southern and mid Atlantic USA which will mitigate against the current frost risk for lupins.

Genetically modified (GM) lupins

The adoption of GM soybean, particularly Round Up Ready® soybean has been rapid in the US and South America over the past decade. Similar adoption of GM herbicide resistant corn and canola has occurred in the US and Canada. It has undeniably led to simpler and effective weed management which has been of great benefit to growers. The situation in Europe has been in stark contrast where strong anti-GM consumer sentiment has stopped widespread production of GM crops and resulted in a reluctance to import GM food products. The non-GM status of lupins has clearly provided much of the impetus to develop and differentiate lupin-based foods from soybean-based foods in Europe.

There is currently a moratorium on the commercial production of any GM crops in Western Australia. A similar moratorium was lifted in New South Wales and Victoria in 2008 which will see the production of GM

canola with herbicide tolerance such as Round-Up Ready® canola and Liberty Link® canola production commencing in those states.

Agrobacterium mediated transformation protocols for making GM lupins are well developed and numerous experimental transgenic *L. angustifolius* lines have been generated including ones with improved seed quality (Molvig *et al.* 1997).

With the increasing cost and complexity of managing weeds in Western Australian farming systems there are many advocates for the introduction of GM lupins with glyphosate resistance. Economic modelling suggests there would be significant economic benefits from doing so (R. Fellowes unpublished data; A. Diggle and C. Peek unpublished data).

GM lupins could readily find markets that currently use GM soybean meal for animal feeds. In addition, the lack of cross-pollination within and between *Lupinus* species and the nature of seed dispersal provides the opportunity for non-GM lupins to co-exist with GM lupins with very low risk of genetic contamination. Supplying non-GM lupins for sensitive food markets would not be too problematic.

In relation to glyphosate tolerance, the Western Australia grains industry would demand a strong stewardship approach to protect against the risk of accelerating the selection of glyphosate resistance in weeds such as annual ryegrass and wild radish. An effective method to extend the life of glyphosate would be to stack a second type of herbicide resistance together with glyphosate resistance in lupins. This technique is being employed belatedly in parts of the world where glyphosate is already beginning to fail. If stacked resistance was introduced in lupins from the start, it could be a world-leading example of responsible herbicide husbandry (Diggle *et al.* 2008).

Future opportunity for the GM route to provide other important benefits must also not be overlooked, the opportunity for enhanced pest and disease resistance being obvious examples. Work on transgenic legumes to boost root organic acid excretion to improve P accumulation is advocated (Vance, 2001).

Lupin food futures

Use of lupins by mainstream food companies in Europe and Australia is limited for various reasons including:

1. concern over the continuity of supply of lupin ingredients and consistency of quality;
2. limited access to knowledge on how to process and utilise the grain, including issues of flavour stability;
3. risks surrounding lupin allergy;
4. unclear advantages or 'points of difference' compared to soybean;
5. image as an animal feed not a food (in some markets).

There is no reason why these issues cannot be resolved or managed. The supply and processing issues are complicated by the fact that there are 3 species, and possibly a fourth nearing commercial production. As Australia recovers from consecutive years of very severe drought in lupin producing regions, supply risk can be reduced by appropriate price signals and product specifications through the supply chain. The 'point of difference' may be found in the mounting evidence for lupin ingredients beneficial role in promoting consumers' health and wellness. However, a key limitation in using lupins in some situations is the allergenic properties of some lupin proteins. The opportunity to remove or denature these proteins through genetic means or through processing would be extremely valuable. Nonetheless, based on the evidence to date this appears to be a significant challenge but well worth ongoing consideration as genomic knowledge expands and food processing technologies evolve. Genetic solutions to other grain quality issues are potentially available through non-GM and GM routes.

The incidence of food allergy appears to be increasing in the developed world and is creating challenges to the food industry and government authorities in terms of food labelling issues. However, empirical evidence suggests that there should be a much lower risk of lupin allergy in Asia, as is the case with peanut, and this may be a more appropriate market for lupin food products. Hence, an Asian market focus rather than a Western economy focus may be a more appropriate food product development strategy.

Other end-uses

We should not ignore opportunities for the industrial use of lupin ingredients, as is the case with soybean. One example is lupin (*L. albus*) oil fractions that are currently being incorporated into cosmetics by companies such as Clarins (www.lupins.org).

Global food security

About 10,000 plant species have been used as human food throughout history but modern agriculture has left us with a diet based on about 150 species of which, just 12 species provide 75% of the world's food (FAO 2007; FAONewsroom; www.fao.org/newsroom). A sobering 50% of the world's plant derived food energy comes from just 3 crops: rice, wheat and maize. This staggering lack of species diversity has been further concentrated by modern plant breeding, resulting in a relatively narrow genetic base of cultivars within these species. This probably leaves the world more vulnerable than perhaps it should be to the consequences of widespread plant disease or pest epidemics or even large scale weather events such as drought or frost.

As mentioned before, lupins will not rise to challenge the scale of these 'mega-crops' mainly due to lupins suitability to a limited range of soil types. Nonetheless lupins can make an important contribution

to the diversity and stability of crop rotations. Luckily lupin genetic resources appear relatively well conserved at present to provide a rich source of genes for plant breeders to further enhance the crop. But we should remain vigilant that this remains the case.

The Green Revolution of the second half of the 20th Century was fuelled by a dramatic increase fertiliser N and P inputs. The prices of these inputs are related to the cost of energy which may be increasingly expensive. Moreover, excessive use of N fertilisers exacerbates N₂O (greenhouse gas) emissions and nitrate and leaching and run-off into drinking water create environmental problems. A search for cheaper, less polluting sources of N may support greater interest in growing grain legumes including lupins in the 21st Century, supporting the profitability, diversification and stability of farming systems.

Communication

The first International Lupin Conference was held in Peru in 1980. It was sponsored by GTZ (German Organisation for Technical Co-operation) who were working in South America at that time to assist the development of 'low input' agricultural and food systems based on *L. albus* and *L. mutabilis*. The Proceedings of the International Lupin Conferences have provided a rich and concentrated source of scientific data, much of which has not been published elsewhere.

As a small crop with a modest commercial and R&D footprint in the global context we need to make to a greater effort to disseminate information on the potential of lupins to benefit growers and end-users of the grain. The soybean industry provides a substantial amount of quality information on the internet. The website www.lupins.org was established with the aim of becoming an information portal that could connect to a host of reputable sources of lupin information, both scientific and commercial, for both producers and consumers. But to succeed it needs to gain international ownership with diverse contributions, if it is to deliver to its potential.

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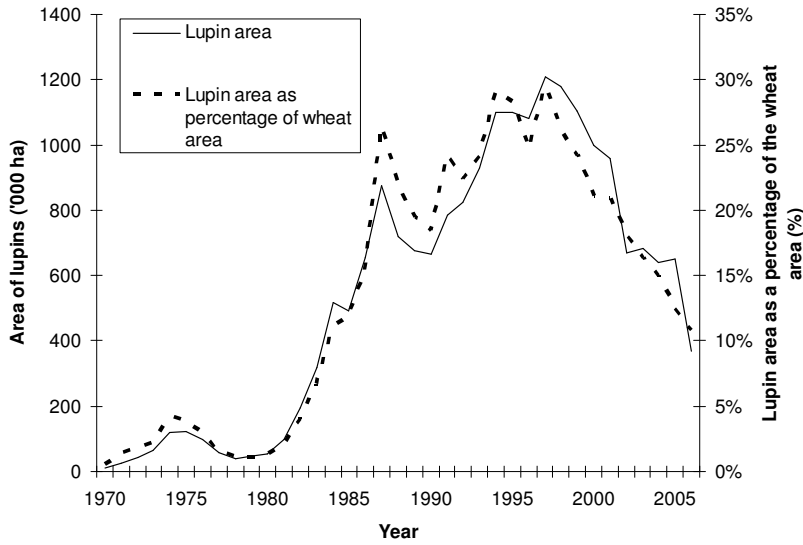


Fig. 1. The area sown to lupins in Western Australia: 1970-2006.

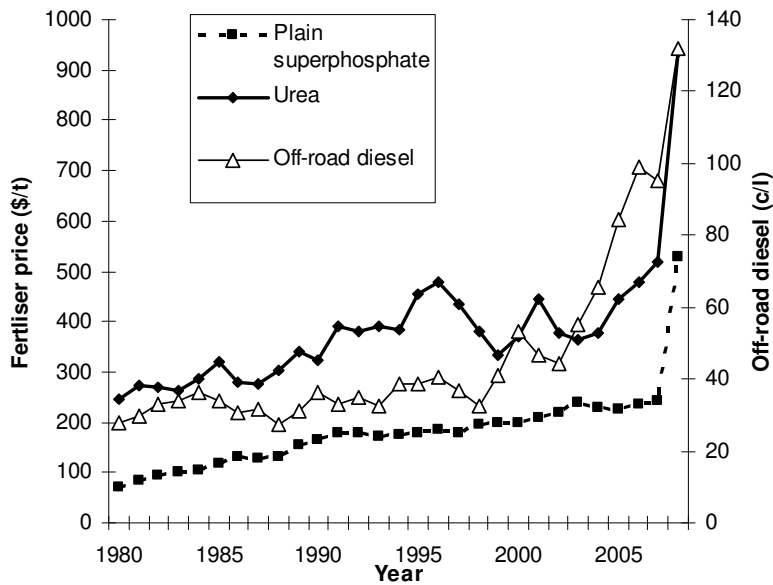


Fig. 2. Prices of plain superphosphate, urea and off-road diesel in Western Australia: 1980-2008.

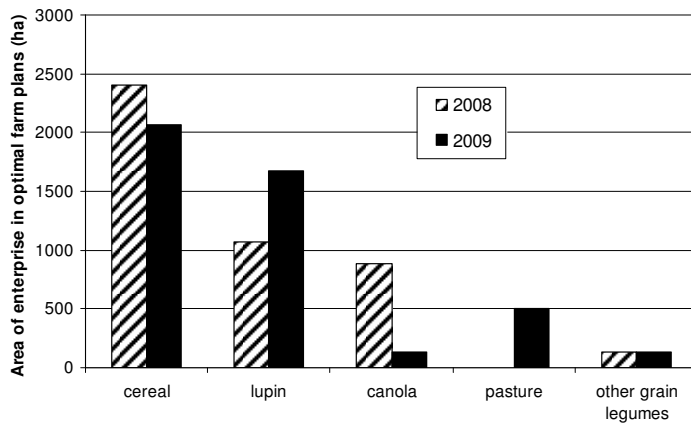


Fig. 3. Optimal area of each key enterprise for a northern region sandplain farm in Western Australia (total area 4,500 ha) given price and cost conditions for 2008 and 2009 respectively.