Chapter 25

Land use in Australia for biofuels and bio-energy: opportunities and challenges for livestock industries

Andrew L. Braid
CSIRO Ecosystem Sciences, P.O. Box 6190 O'Connor, ACT 2602 Australia
E-mail for correspondence: jbraid7@bigpond.com

ABSTRACT

Current biofuel production in Australia and the opportunities that the co-products offer for Australia's intensive and grazing livestock production systems are described. Based on the use of grain sorghum and co-products of grain and sugar processing, the current biofuels industry in Australia is small. At present it is not a significant challenge to the availability of feedstocks for the intensive livestock industries and only provides relatively small amounts of co-product for livestock utilization. However, new non-food biomass production systems for biofuel and bio-energy are being researched and developed. These include the use of lignocellulosic feedstocks from agricultural residues and on-farm plantings of short-rotation coppicing eucalypts, as well as new bio-oil feedstocks such as the low-rainfall oilseed crop *Brassica juncea,* the oilseed tree *Pongamia pinnata* and algae. This move towards the production of bio-energy and biofuels from non-food feedstocks raises the question: What will be the likely challenges and opportunities for the Australian livestock industries with land-use change for the production of these feedstocks? To answer this question, those developments that will affect livestock have been considered through an examination of Australian and other research. Factors examined include the diversion of feedstocks currently used by livestock (cereal stubble or straw), the production of co-products potentially useful to livestock (juncea and pongamia meals) and the development of a biomass production system that could be integrated with the livestock production systems in Australia (short-rotation coppicing (SRC) eucalypts). The process as discussed here includes research into the use of these crops. The systems of production of the new lignocellulosic feedstocks are of particular relevance for grazing livestock, both sheep and cattle. Research carried out over many years has been combined to identify the opportunities and challenges for grazing livestock as the new production systems for these feedstocks develop in Australia's agricultural lands.

INTRODUCTION

Australia has a large land area of 7.69 million km^2, a relatively small population of 22.4 million, and an advanced agricultural industry. It is therefore seen by many around the world as potentially a large bio-energy and biofuel provider.

Australia currently has only a small biofuel and bio-energy industry, based on first-generation technologies, as outlined in the next section. Australian ethanol is produced from three feedstocks: grain sorghum; waste wheat starch, a co-product of the extraction of gluten from wheat flour; and C-molasses, a co-product of the sugar industry. Australian biodiesel is produced from tallow and used cooking oil, with some production from juncea mustard seed (*Brassica juncea*), which is a low-rainfall *Brassica* under development as an alternative to canola.

Any major increases in the biofuel industry in Australia will most likely be predicated on new-generation processing technologies and some new types of feedstocks. This is in recognition of the global issues raised by large-scale diversion of starches, sugars, fats and oils from the human and intensive livestock food chains into biofuels. The focus is therefore on non-food feedstocks such as lignocellulose from sources such as cereal stubbles, short-rotation coppicing (SRC) eucalypts and commercial forest residues, and oils from micro-algae or oilseed trees (Farine *et al*., 2012). Australia has significant amounts of lignocellulose from existing production systems in agriculture and forestry, and a strong capacity to produce more (Farine *et al*., 2012). In contrast, the current production base for plant-based oils is very small, and any scaling up of production would rely on new production systems, such as use of brassica, pongamia and algae (Farine *et al*., 2012).

Unlike current processing technologies based on sugar, starch and food-based oilseeds, the new-generation technologies and feedstocks do not necessarily produce

MAIN MESSAGES

- **The current small biofuels industry in Australia, based largely on the use of co-products of grain and sugar industry, is not a significant challenge to the availability of feedstocks for the intensive livestock industries and only provides a relatively small amount of co-product for livestock feed. An expansion of the current first generation biofuels industry would increase direct competition for grain, but would also increase the availability of protein feedstuffs – DDGS and oilseed meals, which could provide a useful source of supplementary protein for livestock grazing low-protein, dry summer pastures. DDGS is particularly suitable for this role in ruminants.**
- **New, non-food biomass production systems for biofuel and bio-energy are being researched and developed in Australia. These include the use of lignocellulosic feedstocks from agricultural residues and on-farm plantings of short-rotation coppicing eucalypts; and new bio-oil feedstocks, such as the low-rainfall oilseed crop *Brassica juncea,* the oilseed tree *Pongamia pinnata,* and algae. Much work remains yet to be done to fully design, test and implement the production systems.**
- **The harvesting of stubble for bio-energy should have little impact on grazing livestock in mixed grazing-cropping farming systems. There is little of nutritional value in stubble for grazing livestock. When modelled as part of a whole farm system, the value for livestock of grazing stubble is variable, often marginal or negative. The use of long-phase perennial pasture rotations in the cropping-livestock system is the most beneficial practice in the long-term maintenance of cropping soils and will always provide the major opportunity for livestock within the system, whether stubble is harvested for bio-energy or grazed.**
- **The re-introduction of trees for bio-energy and biofuels into cleared agricultural lands in Australia, will provide direct benefits in livestock productivity and animal welfare through the provision of shade and shelter as well as long-term benefits through land conservation for the grazing livestock industries. The integration of biomass production in the form of SRC eucalypts with pasture and livestock grazing may provide a benefit in improved resilience and land conservation while maintaining economic productivity of the land.**
- **Integration of cropping, grazing and bio-energy production presents a complex set of biophysical, social and economic interactions that will need to be well understood to ensure sustainable development of such land use. While some recent research at landscape scale has been reported here, there is need to continue this at a range of scales, including sociological, to better understand the likely land use changes in Australia associated with developing bio-energy industries.**

processing co-products that can be used as livestock feed. However, the biomass production systems themselves can either compete with, or be complementary to, animal production systems. In this sense, animal production can be viewed as a legitimate co-product of biofuel production, albeit in a different part of the value chain than usually assumed.

The co-products produced from the current biofuels industry and the value of these for the Australian livestock industries are outlined as they are available and are being utilized now. However, the potential move towards the production of bio-energy and biofuels from non-food feedstocks raises the question: "What will be the likely challenges and opportunities for the Australian livestock industries associated with land use change for the production of these feedstocks for bio-energy and biofuels?"

CURRENT BIOFUEL PRODUCTION IN AUSTRALIA

The amount of biofuels currently being produced in Australia is small in comparison with global activities. In 2009, as a percentage of the world's total, Australia's ethanol production was 0.15 percent, biodiesel was 0.4 percent (F.O. Licht, 2009), and, over all, biofuels represented only about 0.5 percent of Australia's transport fuel consumption. Over the past decade there have been numerous proposals for the development of first-generation biofuel production facilities in Australia, not all of which have proceeded. Of those that have, some are not currently in production due to changes in feedstock costs and other economic issues. In 2008–09 actual production of biofuels was approximately 50 percent of the stated production capacity (ABARE, 2010a; Geoscience Australia and ABARE, 2010). As a consequence the amount of co-product available for livestock is relatively small.

An estimate has been made of the amount of co-products, i.e. wet or dried distillers grain and protein meals, based on the stated capacities of the small number of bio-ethanol and biodiesel plants currently in production (Table 1). These are potentially available to the Australian livestock industries if the plants are operating at full capacity, and in the absence of imported biofuel co-products.

TABLE 1
Fuel ethanol production facilities in Australia, 2009

Facility	Capacity ($\times 10^6$ L/yr)	Feedstock	Co-products
Manildra Group, Nowra, NSW	180	Waste wheat starch, low-grade wheat and sorghum grain	175 000 t/yr DDGS
Dalby Biorefinery, Dalby, Qld	90	Grain sorghum	134 000 t/yr WDG 38 500 t/yr syrup
CSR Distilleries, Sarina, Qld	60	C-molasses	225 000 t/yr C-molasses converted to ethanol
Total fuel ethanol capacity	330		

Notes: NSW = New South Wales; Qld = Queensland.

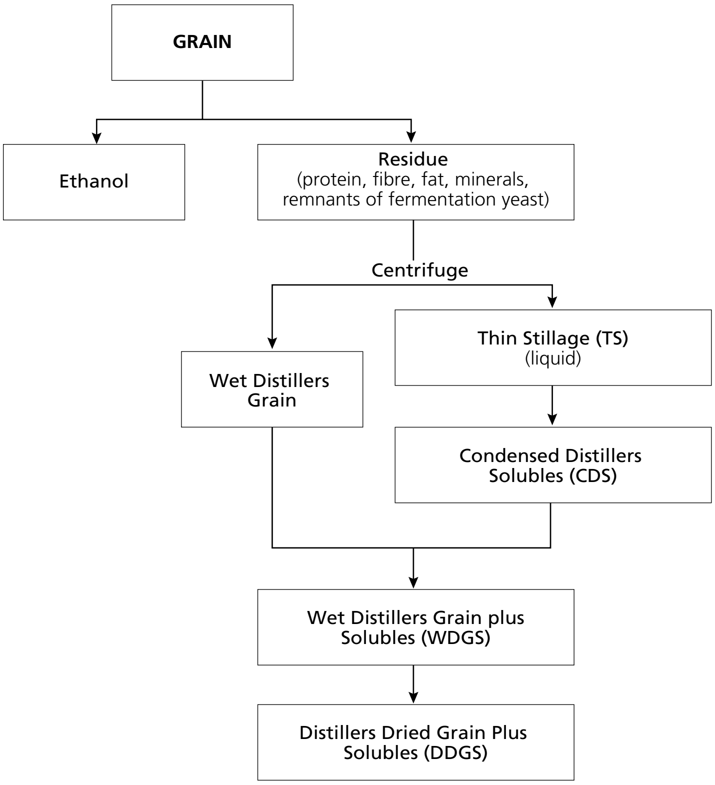
Grain ethanol co-products

The process for the production of ethanol from grain and the associated co-products – whole stillage, thin stillage, condensed distillers solubles (CDS), wet distillers grain (WDG), wet distillers grain with solubles (WDGS) and dried distillers grain with solubles (DDGS) – is set out in Figure 1 and has been described, together with the composition of the co-products (Braid, 2007).

Research papers are available on the use of cereal ethanol co-products in the diets of a range of intensively farmed animals: beef and dairy cattle, pigs, poultry (broilers, laying hens and turkeys) and fish, and cover all the stages of production from weaning to finishing (Al-Suwaiegh *et al.*, 2002; Anderson *et al.,* 2006; Cheng and Hardy, 2004; Lumpkins, Batal and Dale, 2005; Lumpkins, Batal and Dale, 2004; Whitney and Shurson, 2004; Whitney *et al.,* 2006). In general, the research findings are positive about the value and use of cereal ethanol co-products to replace a portion of grain or protein meal, or both, in intensive livestock diets.

The wet cereal ethanol co-product, WDGS, has a limited storage time of 3–5 days at 22 °C (Walker, 2004). On a dry matter basis, WDGS (30 percent DM) is expensive to transport and must also be handled according to any wet-waste transport requirements set by the local environmental protection agency. Drying WDGS to form DDGS uses 30–40 percent of the total energy requirements of a cereal ethanol plant (Ham *et al.*, 1994). However, DDGS can be readily transported, stored and added to pelleted feeds,

FIGURE 1
Co-products of a dry-grind cereal ethanol plant



Source: Braid, 2007.

making it more accessible to livestock industries and more marketable. DDGS can be used in diets without affecting production or reducing the quality of animal products – meat, milk, eggs, etc. – at rates of up to 20–40 percent for cattle; 10–25 percent for pigs; 9–15 percent for poultry and 15–22.5 percent for fish (Braid, 2007). DDGS is particularly useful for ruminants, providing a combination of rumen by-pass protein, digestible fibre and energy.

The information below is culled principally from ABARE (2010a).

In Australia, the Dalby Biorefinery produces ethanol from grain sorghum and, unlike many grain ethanol plants, does not produce DDGS, whereby thin stillage is condensed to form condensed distillers solubles (CDS) then added back to the wet distillers grain prior to drying. Instead, Dalby Biorefinery relies on the separate sale of wet distillers grain (WDG) and CDS for disposal of its ethanol co-products.

At full capacity, the Dalby plant produces 134 000 t/yr of WDG with a moisture content of 65 percent, equivalent to some 47 000 t of dried distillers grain. All of the WDG from the Dalby plant is sold direct to a beef feedlot in southern Queensland. The CDS, high in protein, fats, minerals and digestible fibre, is sold on to a livestock feed processor to be mixed with cane sugar molasses to form a highly nutritious feed supplement for horses and ruminants.

The Manildra Group at Nowra, NSW, uses a waste-starch stream from their flour-to-gluten plant, together with some low-grade wheat and grain sorghum, to produce ethanol and DDGS. At full capacity, the Manildra Group's current plant can produce 175 000 t/yr of DDGS. Some goes to beef feedlots, but the primary market is the NSW south coast dairy industry, which uses the DDGS either as inclusion in the grain supplement fed during milking or as a drought supplement (Mark Honey, 'Riversdale', pers. comm.).

Potentially, the current total annual amount of WDG and DDGS from ethanol production in Australia is equivalent to 225 000 t of dried distillers grain. To put this into perspective, this represents just 4.8 percent of the estimated 4 642 000 t of grain used annually in Australia for beef cattle in feedlots and for dairy cows (Hafi and Connell, 2003). It is difficult to accurately estimate the effect on availability and price of cereal grain for livestock use in Australia due to the current diversion of grain to ethanol production. Almost half of Australia's ethanol production comes from the Manildra Group's use of waste starch from food processing, i.e. from grain external to the livestock feed market. In addition, with approximately 60 percent of Australia's grain production going to export, international grain prices are a major influence in setting local prices.

There has been some concern from livestock producers that the diversion of cane sugar molasses to the production of ethanol would affect the availability and price of molasses, which is used as an energy supplement and carrier for minerals such as phosphorous for grazing livestock, particularly in northern Australia. On average, Australia produces 1 025 000 t of molasses annually (Anon., 1996–2007; ASMC, 1996–2007). At full capacity, CSR Distillers in Queensland would use approximately 225 000 t, or 22 percent of annual production, to produce 60×10^6 L ethanol per year. This increase in demand may affect availability and price, particularly in drought years. However, in part, the diversion of this molasses to the production of biofuel is offset by the addition of the 38 000 t/year of CDS from the Dalby Biorefinery into the molasses market for livestock energy supplementation.

Biodiesel co-products

There are two co-products from the production of biodiesel that can be used as feed for livestock: oilseed meal following the extraction of the bio-oil from the oilseed prior to its conversion to biodiesel, and crude glycerol, a co-product of the transesterification process. The majority of the biodiesel producers listed in Table 2 rely on a combination of tallow and used cooking oils as the feedstock for their plants and consequently do not produce an oilseed meal co-product.

Canola, a cultivar of rapeseed (*Brassica napus*), a common European feedstock for the production of biodiesel, is grown in Australia, which in 2009 produced 1 920 000 t of canola oilseed (ABARE, 2010b), of which 65 percent was exported as whole oilseed and the balance crushed in Australia for the production of canola oil for human use. The canola meal derived from this production of canola oil is used in the intensive livestock industries: poultry, pigs and dairy cows. Canola meal is not a co-product of Australia's biofuels industry as canola is not used for the production of biofuels in Australia.

However, there is a *Brassica* sp. that is increasingly being used in biodiesel production, *Brassica juncea*. As a non-food feedstock, this is described in the section on new production systems.

National Biodiesel Pty Ltd at Port Kembla, NSW, are in the process of developing a new facility for the production of soy biodiesel that will have a significant impact on the availability of Australian-produced biofuel co-products once it reaches its stated capacity. Based on projections, it will deliver more than 800 000 t of soybean meal per annum, initially from imported soybean. In 2009–10, Australia imported 512 000 t of soybean meal to meet the feedstock demand of the pig and poultry industries as the total Australian production of soybean was only 59 600 t. As this facility is not in production it has not been included in Table 2.

Glycerol

Glycerol occurs naturally in animal and vegetable fats where it is about 10 percent of the lipids. Crude glycerol is a co-product of the production of biodiesel and must

TABLE 2
Biodiesel production facilities in Australia, 2009

Facility	Capacity ($\times 10^6$ L/yr)	Feedstock	Co-products
Biodiesel Industries Australia, Maitland, NSW	15	Used cooking oil, vegetable oil	Crude glycerol
Biodiesel Producers Ltd., Wodonga, Vic	60	Tallow, used cooking oil	Crude glycerol
Smorgon Fuels, Melbourne, Vic	100	Juncea oilseed, tallow, used cooking oil, vegetable oil	10 000–15 000 t/yr juncea mustard meal; crude glycerol
Various small producers	5	Used cooking oil, tallow, industrial waste, oilseeds	Juncea meal; crude glycerol
Total biodiesel capacity	280		

Notes: NSW = New South Wales; Vic = Victoria. *Source*: ABARE, 2010a.

be refined to 95–99 percent purity for use as food grade glycerol. Under current transesterification biodiesel refining processes, 79 g of crude glycerol is produced for every litre of biodiesel (University of Idaho, 2006). Based on the total Australian plant capacity of 180×10^6 L of biodiesel (Table 2), this represents potentially >14 000 t/yr of crude glycerol produced in Australia. With large increases of biodiesel production around the world, there is considerable interest in utilizing crude glycerol in novel ways, including as a dietary energy source for livestock.

In Australia, the Pork Co-operative Research Centre, in association with Murdoch University, Western Australia, have carried out a two-part study in which the chemical compositions of crude glycerol samples from seven Australian biodiesel producers were analysed and the effects of feeding crude glycerol to growing-finishing pigs were assessed (Hansen *et al.,* 2009). The chemical composition of the crude glycerol varied greatly between samples. The pH ranged from 2.0 to 10.8, moisture from 0 percent to 16.1 percent, ash from 0 percent to 29.4 percent and methanol from <0.01 percent to 13.94 percent. One of the test samples, with a pH of 2.0, 76.1 percent glycerol and 1.83 percent ash, was selected for the feeding trial.

In this trial, groups of 12 Large White × Landrace female pigs of 50.9 ± 5.55 kg live weight were fed mash diets containing 0, 4, 8, 12 or 16 percent glycerol for approximately 10 weeks prior to slaughter. All diets were formulated with a digestible energy of 13.5 MJ/kg with crude glycerol replacing grain (wheat and barley) as the energy source. In addition to recording daily feed intake, weight gain and meat quality at slaughter, the pigs were blood tested each week for plasma glycerol to assess the metabolism of the glycerol. When ingested, glycerol absorbed from the intestinal tract, is converted to glucose in the liver. If the gluconeogenetic capacity of the liver is exceeded, excess glycerol remains in the plasma, to be excreted in the urine (Kijora *et al.,* 1995). Identifying the limits of glycerol conversion should contribute to understanding the effective levels of glycerol that can be fed to replace other energy sources.

In this study, the plasma glycerol levels increased markedly when dietary glycerol exceeded 4 percent, which suggests that the limit on glycerol conversion had been reached and potentially the energy supply to the pigs was lower. Even so, once the pigs had adapted to the diets by the end of the second week, the daily feed intake, weight gain, feed conversion ration, P2 backfat and meat quality were unaffected *(P* >0.05*)* by the inclusion of up to 16 percent crude glycerol in the diet.

There are issues with the feeding of crude glycerol.

- The large variation between crude glycerols derived from biodiesel production is of concern when contemplating its use in livestock feeds. It would appear that monitoring of the chemical composition is vital when formulating diets containing crude glycerol from biodiesel production.
- High ash content may be associated with the use of sodium or potassium salts as catalysts during the process (Hansen *et al.,* 2009), or the use of used cooking oils, or both.
- Methanol is a known toxin in humans, and countries have established maximum permitted levels for methanol in crude glycerol for animal feed: 0.015 percent in USA, 0.1 percent in Canada, 0.2 percent in Germany and 0.5 percent in the European Union as a whole (Hansen *et al.,* 2009); Parsons, 2010).
- There can be feed handling problems. The mash diets in the study described containing >8 percent glycerol formed firm aggregates within 24 hours after mixing. It has been reported that up to 12 percent of crude glycerol can be added to feed prior to pelleting without affecting pellet quality.
- Crude glycerol derived from the use of tallow for the production of biodiesel should not be used in ruminant feedstocks due to the possibility of transmission of bovine spongiform encephalopathy (BSE).

In summary, the small biofuels industry in Australia, based on the use of residues, is currently not a significant challenge to the availability of cereal grains for the intensive livestock industries and only provides relatively small amounts of co-product for livestock feed. Individual biofuel plants do provide an opportunity for local livestock producers to include co-products in livestock rations or for use as supplementary feed, an opportunity that has been embraced. An expansion of the current first-generation biofuels industry would increase the availability of protein feedstuffs – DDGS and oilseed meals – which could provide a useful source of supplementary protein for livestock grazing low-protein, dry summer pastures. DDGS is particularly suitable for this role in ruminants, as unlike whole grain, DDGS is low in fermentable carbohydrate and will not lead to the ruminal acidosis associated with high starch loads in some grain, making it a safe supplement that can be fed ad libitum.

NEW PRODUCTION SYSTEMS FOR BIOFUELS AND BIO-ENERGY IN AUSTRALIA

In many countries throughout the world, there is continuing development of new technologies and production systems for biofuels and bio-energy. The Australian government actively supports the development of non-food biofuel production systems through research programmes such as the Second Generation Biofuels Research and Development (Gen 2) Program, which currently funds research into biofuels from micro-algae, sugar cane bagasse and short rotation coppicing (SRC) eucalypts (DRET, 2009). Some Australian States also support initiatives, such as the use of municipal waste for biofuels (Invest Victoria, 2010). This section will only deal with those developments that will affect livestock:

- through the utilization of a feedstock currently used by livestock;
- the production of a co-product potentially useful to livestock; or
- through a biomass production system that might be integrated with the livestock production systems in Australia and therefore livestock and biomass can be considered as co-products.

The new production systems that will be considered are:

- Oil-based biofuels from *Brassica juncea*, algae and *Pongamia pinnata*.
- Lignocellulosic-based biofuels from two types of feedstocks: stubble (the stalk residue from cereal grain) and SRC eucalypts. SRC eucalypts, commonly known as oil mallees, characteristically have many stems that emerge from an underground lignotuber. When harvested close to the ground, the lignotuber remains intact, enabling the tree to survive and the multiple stems to re-sprout, i.e. coppicing.

Oil-based biofuels

Brassica juncea

Brassica species are recognized for their ability, when used as break crops, to reduce diseases in cereals and to improve the production of the subsequent crops. The biofumigation effect of brassica species reduces crown rot (*Fusarium pseudograminearum*), root lesion nematode (*Pratylenchus thornei*) (Trethowan *et al.,* 2009) and take-all, a soil-borne disease of wheat in south eastern Australia caused by *Gaeumannomyces graminis* (Sacc.) Arx & Oliv. var *tritici* (Kirkegaard *et al.,* 2000), while the broad-leaf cover of brassica crops reduces weed infestation. Canola *(Brassica napus)* is grown in the higher rainfall areas of Australia as a break-crop and for the value of its oilseed, but its distribution is limited by its rainfall requirement. Consequently, some Australian State government agricultural research agencies, universities and private companies have been involved in the breeding and development of *Brassica juncea* varieties for use as a break crop in the drier and hotter areas of the Australian wheat belt, where the mean annual rainfall is <425 mm, for the production of biofuels and the feeding of livestock.

Some of the development is in the juncea varieties high in the "hot and spicy" glucosinolates for condiment mustard. However, the main varieties of interest are in the juncea canola group that retain the low-rainfall growth ability but have oil fatty-acid profiles and levels, and types of glucosinolates in the meal, similar to canola. Glucosinolates are found in all brassicas and produce a range of active secondary metabolites that are responsible for the biological effects associated with feeding brassica meals. These effects are relative to the concentration of glucosinolates in the diet, but vary with the type of glucosinolates and secondary metabolites in the meal.

Amongst the glucosinolates, sinigrin and progoitrin and the glucosinolate metabolite isothiocyanates are associated with the bitter taste of some brassica meals that lead to reduced feed intake, while other glucosinolate metabolites affect thyroid function or cause goitrogenicity, hepatoxicity, nephrotoxicity or endocrine disturbance due to non-specific antinutritional factors. In general, ruminants are more tolerant to glucosinolates than monogastric animals such as pigs and poultry. Tripathi and Mishra (2007) have published a comprehensive review of glucosinolates in animal nutrition. The content and type of glucosinolates vary between brassicas that have originated in the hot, dry conditions of the Indian sub-continent or the more temperate conditions of Europe. The availability of high-glucosinalate (HG) Indian mustards (glucosinolate content of 125 to >200 µmol/g) and low-glucosinolate (LG) European canola *Brassica* species (glucosinolate content of <10 to 30 µmol/g) has, through genetic manipulation, enabled plant breeders to retain the drought tolerance qualities of Indian mustards (*Brassica juncea*) while significantly reducing the glucosinolate content levels.

Smorgon Fuels Pty Ltd, Melbourne, in conjunction with the South Australian Research and Development Institute (SARDI), have developed a juncea variety, BioMaxDLJ200 for biofuel production and capable of growing in areas with average annual rainfall of less than 375 mm (SARDI, 2011). The Pork Cooperative Research Centre, in association with Rivalea Australia and Smorgon Fuels, have carried out a trial to evaluate juncea meal in growing pigs (Collins *et al.,* 2011). Groups of 14-week-old entire male Large White × Landrace pigs (live weight 40.4 ± 0.41 kg) were fed formulated diets as ad libitum pellets for 35 days, in which juncea meal replaced canola meal to make up diets containing 0, 6, 12, 18 or 24 percent juncea meal.

Juncea oilseed was sourced from crops grown in Victoria, New South Wales and South Australia, which was crushed using an expeller press and the resultant meal analysed for chemical composition and gross energy content, amino acid profile and glucosinalate concentration. There was very little difference between the canola meal and the juncea meal in amino acid profile, with the juncea meal higher in fat content and lower in fibre. The glucosinolate concentration, based on ten samples of the juncea meal, was 13–19 µmol/g, average 15.9 µmol/g. The glucosinolate concentration of the canola meal was not assessed but could be assumed to be in the 4–5 µmol/g range of the meal from canola cultivars grown in southern Australia, which has been shown to not produce adverse effects in pig weaner diets when included at up to 25 percent of the diet.

While there was a linear decline in feed intake associated with increasing juncea meal concentration ($P < 0.001$), resulting in a reduction in growth rate over the whole test period, the conclusion of the trial was that the juncea meal could be fed at up to 18 percent of the formulated diet without affecting growth performance over the 35 days of the trial. At this level, the glucosinolate concentration was 2.85 µmol/g diet. At 24 percent of the diet, there was reduced feed intake and slower growth rate in the pigs. Feed wastage throughout the study period was assessed as not significant. These results are in line with the findings of others (Opalka *et al.,* 2001; Roth-Mailer, Bohmer and Roth, 2004) where glucosinolate concentrations in diets of 2.2 µmol/g or less did not affect growth performance in pigs.

It is estimated that somewhere between 13 000 and 19 000 ha of *Brassica juncea* was grown in Australia in 2010, providing 10 000–15 000 t of meal (Nelun Fernando, Smorgen Fuels Pty Ltd, pers. comm.). Currently this has little impact on the protein meal market in Australia, where some 400 000 t of Australian grown canola meal and 500 000 t of imported soybean meal is used annually in the intensive livestock industries (ABARE, 2011).

Micro-algae

There is currently no commercial algal biofuel production in Australia. Algal production systems based on 400 ha raceways co-located with the major CO_2 production sites in Australia could produce up to 10.7×10^6 t of algal biomass each year (Farine *et al.,* 2012). Following oil extraction, the remainder algal biomass could be used for the production of bio-energy, for other co-products or, if suitable, be available as a protein feed or supplement for livestock. Micro-algae can be used in animal nutrition, primarily in aquaculture, but also as a vitamin and mineral supplement for farm animals and pets (Spolaore, 2006). However, the majority of the Australian sites noted in Farine *et al.* (2012), would rely on CO_2 flue-gas from coal-fired power stations, which can contain heavy metals and other toxins that are likely to be taken up by the algae, rendering the algal biomass co-product unsuitable as animal feed (DOE, 2010).

Pongamia

The oil-seed tree *Pongamia pinnata* is native to the Indian sub-continent and South-East Asia but has become naturalized in small areas along the coastal fringe and associated rivers in the tropical north of Australia. In India and Asia, it has traditionally been used as a fuel for cooking and lighting. More recently it has been recognized as a candidate for biofuel production in Australia, which has led to *Pongamia pinnata* (L.) Pierre, becoming a focus of academic and commercial research and development. At the time of writing, there are only small areas of trial plots with no commercial production of oil or associated oil-seed meal. The potential of the tree has, however, been recognized (Kazakoff, Gresshoff and Scott, 2011; Scott *et al.,* 2008) and a clear R&D strategy has been proposed (Murphy *et al.*, in review).

There is interest in developing large plantations in northern Australia to produce feedstock for aviation biofuel, local transport, and for GHG mitigation, with the pongamia co-products to be combusted for regional power generation and biochar, a carbon-rich co-product used for soil amendment (CleanStar Ventures, 2011), or for use as a protein supplement for grazing cattle, although 80–90 percent of the seed storage protein is now known to be similar to soybean 7S beta conglycinin, known to be a nutritionally poor source of protein (Scott *et al.,* 2008).

There has been considerable research, mainly in India since the early 1970s, on utilization of this protein meal as animal feed. The meal contains karanjin (a flurano-flavinoid) and pongamol in the residual oil that make it unpalatable. It also contains anti-nutritional factors such as phytates, tannins and protease inhibitors that affect rumen metabolites and the digestibility of protein and carbohydrates (Vinay and Sindhu Kanya, 2008).

Oil extraction carried out by the usual method of expeller pressing leaves 15–20 percent oil in the cake (expeller-pressed karanj cake – EKC). Solvent extraction removes more oil, and should increase the palatability of the meal and reduce toxicity, but research results indicate that inclusion of solvent-extract pongamia meal (solvent-extracted karanj cake – SKC) in mixed diets still reduces both feed intake and growth rates.

Researchers have sought additional ways of detoxifying the meal, aimed at reducing the anti-nutritional factors through water leaching and the addition of mild acid or alkali. Vinay and Sindhu Kanya in a laboratory study (Vinay and Sindhu Kanya, 2008) used a 2 percent HCL treatment for 1 hour to reduce anti-nutritional factors: phytate (81 percent), tannin (69 percent) and protease inhibitors (84 percent).

A review of recent studies gives a good indication of the problems associated with using the pongamia meal derived from the production of biofuels as an animal feed. A long-term (34-week) performance trial of lambs was undertaken using diets containing either 24 percent EKC or 20 percent SKC pongamia meal, replacing half of the usual de-oiled groundnut cake as the source of protein . In this trial there were no further treatments of the meal to reduce anti-nutritional factors. The outcome of this long-term trial was that dry matter intake; digestibility of protein and carbohydrates; growth rate; and wool production were all reduced in the lambs receiving the diets containing either EKC or SKC. The authors identify other research with similar outcomes. In addition, by the end of the trial, the lambs had reduced bone density (osteoporosis), testicular degeneration, and liver and spleen lesions (Singh *et al.,* 2006).

In a study of growth performance in chickens, in which SKC was subject to one of three different treatments for anti-nutritional factors (untreated SKC, 1.5 percent NaOH SKC, 3 percent $Ca(OH)_2$ SKC) and EKC to one treatment (2 percent NaOH EKC), the pongamia meal was used to replace 12.5, 25 or 50 percent of soybean meal in the diet. The results showed depression of growth as well as severe pathological changes occurring in the chickens once the replacement level exceeded 25 percent, irrespective of the method of oil extraction or the anti-toxicity treatment. The pathological changes included lymphoid cell degeneration, and liver, kidney and spleen pathology (Panda *et al.,* 2008).

These growth performance trials in lambs and broiler chickens, despite efforts to reduce residual oil and toxicity factors in the meal, demonstrate that *Pongamia pinnata* meal is only useful and safe as an animal feed at low levels of inclusion. Other trials mentioned in the literature indicate that similar results have been found with cattle and goats (Konwar, Banerjee and Marshall, 1987; Srivastava *et al.,* 1990).

Finally, it should be noted that there is a benefit from pongamia containing the unpalatable karanjin and pongamol, as it allows the integration of grazing livestock in *Pongamia pinnata* plantations with minimal risk of the animals grazing and damaging the trees. At a trial plot in southern Queensland where the trees are 3–4-years old, sheep are grazed in the plantation to control grass and weed growth and to provide some additional income from the land (George Muirhead, pers. comm.).

LIGNOCELLULOSIC-BASED BIOFUELS

The technologies to use lignocellulosics such as cereal and forest residues for the production of biofuels are rapidly developing (Mohan, Pittman and Steele, 2006). In Germany, Choren Industries, Daimler AG, use a Fischer-Tropsch process to manufacture SunDiesel®, a biodiesel, from cereal stubble (straw) and forestry residues (Daimler AG Communications, 2011). Abengoa Bioenergía has pilot plants in Salamanca, Spain, and Nebraska, United States, using fermentation processes for the production of cellulosic ethanol from stubble, and is building a commercial-scale plant in Kansas, United States (Abengoa Bio-energy, 2011).

There are no obvious co-products suitable as animal feed from these processes. There may be a potential co-product from the fermentation process for cellulosic ethanol where the C_6 sugars from cellulose and hemicellulose are converted, but the lignin and C_5 (pentose) sugars remain in combination with the yeast remnants. Currently, all remnants from this process are being combusted for energy and not being promoted as an animal feed (Dr Andrew Warden, pers. comm.). There are, however, other opportunities and challenges for the livestock industries in the production and use of these lignocellulosic biomasses for second-generation biofuels in Australia, which will be discussed.

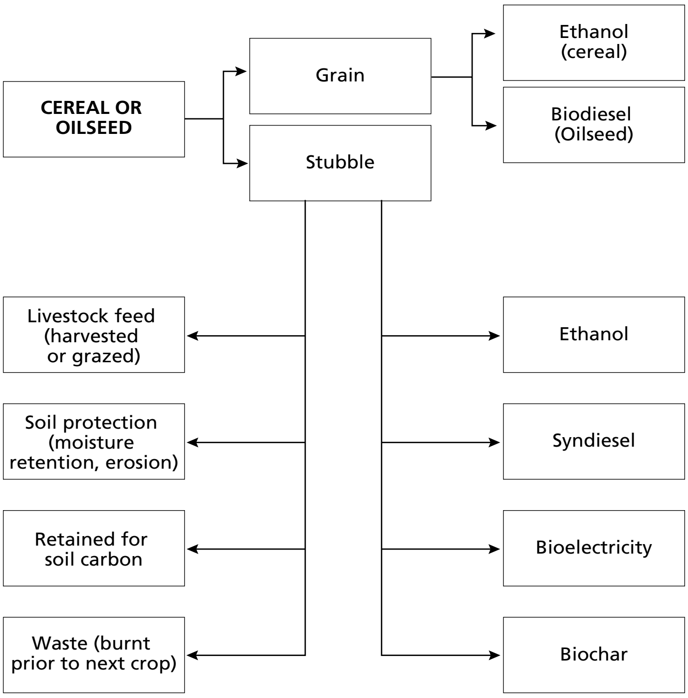
Stubble

There are a number of possible alternative uses for stubbles, including its use as livestock feed and the production of biofuels, as shown in Figure 2.

In Australia, while there are no commercial-scale plants, there is interest in the potential of cereal crop stubble for biofuel production. CSIRO has estimated the amount of cereal residues produced and available in Australia using a methodology based on harvest index combined with land-use maps and national statistics. Having allowed for the amount that can be physically harvested and that must be retained for soil protection, moisture conservation, retention of organic matter and carbon build-up, CSIRO has calculated that the straw available nationally, on average, is 21×10^6 t/year. There is considerable variation due to climate, with the highest year since 2000 being 39×10^6 t and the lowest 4×10^6 t. If converted to ethanol, this is potentially equivalent to 25–50 percent by volume of Australia's petrol consumption (Herr *et al.,* 2010; O'Connell *et al.,* 2008).

Many farmers in Australia's grain growing areas practise mixed farming, combining livestock and cropping in their enterprise mix to reduce variability in income and financial risk (Fisher, Tozer and Abrecht, 2010). Since the 1980s, minimum-till and no-till cropping has revolutionized cropping systems through improving soil structure, better erosion control, the retention of soil moisture and timeliness of planting (D'Emden, Llewellyn and Flower, 2009; Flower,

FIGURE 2
Alternatives for cereal or oilseed stubble



Source: O'Connell *et al.,* 2009.

Crabtree and Butler, 2008) which has allowed the expansion of cropping in the mixed farming regions (Fisher, Tozer and Abrecht, 2010). Ideally, no-till cropping systems include full stubble retention and this has brought into question the role of livestock grazing stubble in such systems. However, when stubble loads are high, retained stubble can impede the sowing of the following year's crop, and farmers are faced with reducing the stubble through various means, including grazing, harvesting or burning.

There are specific tradeoffs between harvesting of stubble for bio-energy and the current use of stubble by grazing livestock, that require further consideration. The nutritional benefits of stubble for livestock and the impacts of livestock grazing compared with stubble retention or stubble harvesting on soil, water, nutrient cycles and pest management in a no-till cropping system requires quantification in order for the terms of the tradeoffs to be defined more clearly.

The benefits of grazing stubble include the feedstock values, i.e. digestibility, metabolizable energy (ME) and protein of the cereal straw, leaf, chaff, spilt grain and weeds that makes up stubble, and other variables, including pasture growth elsewhere on the farm during the period livestock graze stubble, and the related effects of rain events and stocking rates.

While there is some information from stubble grazing trials on the uptake of the various components of grazed stubble and the effect on livestock production indicators, current research is directed towards modelling the whole farm system (Moore and Lilley, 2006; Thomas *et al.,* 2010).

In integrated grazing-cropping systems, both the grazing of cereal crops early in their winter growth phase and the post-harvest summer grazing of stubble may be used to fill feed gaps in the south east winter-rainfall area of Australia (Moore, Bell and Revell 2009). Long-season cultivar wheats (e.g. cv. Mackellar), developed for dual-purpose winter grazing and grain production, tend to leave heavier stubble loads that need to be reduced prior to re-sowing the growing area. Moore and Lilley (2006), modelled the use of grazing to manage these high stubble loads in a project that looked at the effect on sheep of grazing to removed stubble or the harvesting of the stubble and later use of stubble as a supplementary winter feed. Using the APSIM cropping systems model (Keating *et al.,* 2003) and GRAZPLAN, a grazing systems model (Freer, Moore and Donnelly, 1997), Moore and Lilley (2006) found that the sheep grazing stubble would lose weight and have reduced wool production compared with sheep grazing dry pasture. In addition, the daily intake of conserved stubble used as a winter feed supplement for pregnant ewes was dependent upon the availability of alternative green pasture and was only beneficial at very low levels of green pasture. These findings are in line with those of Rowe *et al.,* (1998), who, in a trial of supplementary feeding of Merino sheep grazing stubble, found that once spilt grain and any germinated grain and weeds were consumed, in the absence of supplementation, particularly with a protein source such as lupin grain, the sheep lost weight (Rowe *et al.,* 1998).

Thomas and co-workers, using similar modelling methodology, concluded "that the value of grazing crop stubbles cannot be predicted well using energy intake from stubble grazing", finding that the estimated increase in farm gross margin was less than half the predicted value of the stubble energy content (Thomas *et al.,* 2010). The modelling also demonstrated the complex effects of the many variables and consequent difficulties in assessing the value of stubble. Overall, the model predicted a negative effect on lamb birth weight, survival and liveweight at sale when pregnant ewes are grazed on stubble.

The no-till, full stubble retention cropping system was developed in Australia to improve soil composition, reduce topsoil erosion by wind and water and to retain moisture in the system. Fisher, Tozer and Abrecht (2010) and Herr *et al.,* (2010) examined the effects on the soil, water, nutrient cycles and pest management in a no-till cropping system due to livestock grazing or the harvesting of stubble for bio-energy, and provide the basis for the discussion here.

The role of stubble in the protection of post-harvest soils from wind and water erosion is dependent upon the amount of biomass left in the paddock. Herr *et al*. (2010) identify a technical limit to harvesting stubble, with a minimum aboveground cutting height of 12.5 cm. They calculate that at this height, in a 2 t/ha grain crop, 30 percent of the aboveground biomass is left *in situ,* equivalent to 0.9 t/ha. In order to avoid wind and water erosion, the authors recommend this should be increased to 1–1.5 t/ha. Similarly, Fisher, Tozer and Abrecht (2010) quote guidelines for managing erosion (Carter, 2002) as recommending grazing management should be such that 1 t/ha of cereal stubble should be retained primarily to avoid loss of topsoil through wind erosion following loosening through the passage of livestock.

The recognition that conventional cultivation combined with stubble burning has led to significant losses of soil organic carbon (SOC) in Australian crop lands (Luo, Wang and Sun, 2010) has been one of the drivers for the development of no-till, full stubble retention cropping systems. Consequently, a proposal to remove stubble from the system for the production of bio-energy and the effect of this on SOC is of concern, and has been examined by Herr *et al.* (2010). Having considered all the current information, including simulation models, they conclude that the effect on SOC by retaining stubble is limited, as much of the standing stubble is not incorporated into the soil and is lost to the system through decomposition and photodegradation, and that partial removal of stubble may not have a significant impact on SOC levels, although the research to quantify this in a reliable manner has yet to be conducted.

Both reports identify the greatest potential for retaining or improving SOC is the use of long-phase (4–6-year) rotations with perennial pastures in the cropping system. Fisher, Tozer and Abrecht (2010) identify research that has demonstrated that wheat yields were greater with long pasture phases compared with 2-year pasture-wheat or continuous wheat rotations, due to improved soil structure, increased SOC and decreased incidence of root diseases.

Both harvesting stubble for bio-energy or removal through grazing affect the nutrient cycle in the system. Herr *et al.* (2010) identify the amounts of nutrients – nitrogen, phosphorous, potassium and sulphur – removed in harvested stubble and provide information for farmers on replacement amounts and costs. By their calculation, for a 2 t/ha wheat crop, the harvesting of straw will remove 7 kg/ha N, 0.7 kg/ha P, 14 kg/ha K and 0.7 kg/ha S. Fisher, Tozer and Abrecht (2010) also identify the loss of potassium with the removal of biomass, i.e. lucerne, from a cropping-pasture system, but primarily they consider nutrient cycling in terms of the redistribution of the nutrients during grazing, and the re-introduction of some nutrients, particularly nitrogen, from leguminous pasture phases. Most of the nutrients removed by livestock during stubble grazing are excreted back into the system, with some concentration in stock camps, and loss of nitrogen due to urine volatilization, although Fisher, Tozer and Abrecht (2010) consider these impacts have been overstated as they are based on trials undertaken in small grazing plots. The direct loss of nutrients exported from the paddock as meat and wool when stubble is grazed may not be significant due to the poor growth rates associated with grazing stubble.

One of the recognized benefits of grazing stubble is the option it provides for the management of weeds, particularly the developing herbicide-resistant strains of ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*). However, the efficacy of this is limited by the need to time grazing relative to the germination of the weeds and the choice of livestock. A recent option devised to reduce weed problems aims to collect all crop residues, including weed seeds, direct from the grain harvester and bale it for removal from the crop area (see http://www.glenvarbaledirect.com.au/). Such a system would fit well with the harvesting of stubble for bio-energy.

In summary, once spilt or germinated grain and weeds have been consumed, there is little of nutritional value for livestock grazing on stubble. Even when modelled as part of a whole farm system, the value for livestock of grazing stubble is variable, often marginal or negative. In terms of the effect of grazing stubble compared with the harvesting of stubble in no-till systems, careful management of grazing livestock or harvest practices can mitigate many of the potential problems. It is apparent that the most beneficial practice in long-term soil maintenance is the use of long-phase perennial pasture rotations in the cropping-livestock system. This will provide the major opportunity for livestock within the system, whether stubble is harvested for bioenergy or grazed.

Trees for bio-energy and biofuels – SRC eucalypts

Much has been written on the impact on the Australian ecosystem from 200 years of European settlement due to a combination of land clearing for human habitation and agriculture, overgrazing with introduced livestock species, and forestry (Hobbs and Yates, 2000; Saunders, Hopkins and How, 1990). In parts of the agricultural lands, the long-term effects of the replacement of deep-rooted perennial vegetation with shallow-rooted annual crops and pasture species have been rising water tables, increased groundwater flows, water and soil erosion, and expanding areas of dryland salinity (Stizaker, Vertessy and Sarre, 2002). It is estimated that "cleared land", defined as land with <5 percent tree cover, occupies some 70 million hectares of the wheat-sheep and high rainfall zones (Reid and Landsberg, 2000).

The recognition of the role of trees in the conservation of biodiversity, the reduction of land degradation due to wind erosion, dryland salinity and water logging, together with private and government initiatives, has led to some significant on-farm re-vegetation through plantings of native trees and shrubs. The recent interest in the additional use of tree plantings on agricultural land for bio-energy, for lignocellulosic biofuels and for carbon sequestration has added a potential new land use and income stream for farmers, which could be integrated with their usual agricultural production activities from the land that they manage (Abel *et al.,* 1997; GHD Hassall, 2010).

One such system is the on-farm plantings of SRC eucalypts or oil mallees, of which *Eucalyptus loxophleba* subsp. *lissophloia* and *E. polybractea* are the most commonly grown. Originally planted in an effort to control dryland salinity, SRC eucalypts have undergone 25 years of research and development in Western Australia and are now seen primarily as energy plantings for low to medium rainfall areas (300–600 mm annual rainfall) that can be integrated into existing agricultural cropping and grazing systems, with the associated benefits of reducing the risk of dryland salinity, restoration of biodiversity and provision of shade and shelter for livestock. The design of the planting systems, referred to as alley farming, consist of belts of SRC eucalypts with alleys of crops or pastures 70–80 m in width between the rows. Plantings are generally along the contour, with the area occupied by the trees approximately 8 percent of the paddock area (Bartle and Abadi, 2010; Smith, 2009; Wu *et al.,* 2005).

This new, integrated agricultural and bio-energy land use has potential benefits for all grazing livestock in the provision of shade and shelter. This is especially so for lambing ewes, when trees act as windbreaks such as occurs with the addition of alleys of SRC eucalypts as energy plantings as described.

The windbreak effect: shelter from wind and cold

Since the 1960s, Australian researchers have been examining the benefits of various types of windbreak shelter in reducing lamb mortalities, as these have been of particular concern in the cold, over-cleared sheep grazing areas of Victoria and New South Wales.

In the absence of established tree shelter belts, researchers set up lambing studies in the western district of Victoria and at Armidale, NSW, using sheet iron (Lynch and Donnelly, 1980), Sarlon garden mesh (Lynch and Alexander, 1977), cypress (*Cupresus macrocarpa*) hedges (Egan *et al.,* 1972; McLaughlin *et al.,* 1970), patches of un-grazed, rank *Phalaris tuberosa* (Egan, Thompson and McIntyre, 1976) and strips of an unpalatable hybrid *Phalaris (P. tuberosa × P. arundinaceae)* (Alexander and Lynch, 1976) to provide windbreaks. Table 3 collates the outcomes of these studies.

Overall, the provision of shelter under the full range of weather conditions at the sites during mid- to late-winter lambing (July-August) on average halved the mortality rate for both single-born lambs (13.9 percent to 7.5 percent) and multiple-born lambs (49.1 percent to 27.6 percent) (Table 3).

Revegetation and its capacity as shelter for ewes and lambs

An understanding of the capacity of revegetation to provide shelter for livestock, crops and pasture has been established through research undertaken under the National Windbreaks Program by Cleugh and co-workers (Cleugh *et al.,* 2002). This research used a combination of field and wind tunnel studies to accurately establish the spatial and scalar effects of windbreaks on wind speed and near surface air temperature, factors important to the survival of new-born lambs.

The spatial effects of windbreaks are described in terms of H, where H is the height of the windbreak. The known effects of a windbreak on near-surface wind speed and air temperature are described as follows:

- **Wind speed** The sheltered zone of reduced near-surface wind speed extends 5H upwind and over 30H downwind of a windbreak, with the maximum shelter near the surface occurring at around 6H downwind. Windbreak porosity (β) determines the reduction in wind speed. As a rough guide, wind speed reduction is similar to windbreak density ($1 - \beta$), i.e. a porosity of 30 percent equates roughly to a 70 percent reduction in wind speed at the most sheltered location, around 6H.
- **Air temperature** The spatial trend in near-surface air temperature mirrors that for near surface wind speed up

TABLE 3
Effect of shelter on lamb mortality during their first 48 hours – all weather conditions

Type of shelter	Location	Duration	Lamb mortality (%)				Significance	Reference
			Single born		Multiple births			
			Shelter	No shelter	Shelter	No shelter		
Phalaris hybrid strips	Armidale, NSW	14 days of lambing	10.2	13.9	n/a	n/a		Alexander and Lynch, 1976.
Phalaris hybrid strips	Armidale, NSW	5 year's pooled results	9.0	17.5	35.8	51.3	*P* <0.005	Alexander *et al.,* 1980.
Phalaris patches	Western Victoria	4 year's pooled results	9.3	12.0	18.5	32.7	*P* <0.01 (multiples)	Egan, Thompson and McIntyre, 1976.
Cypress hedges	Hamilton, Victoria	18 days of lambing	6.3	18.9	n/a	n/a	*P* <0.01	Egan *et al.,* 1972.
Phalaris hybrid strips	Armidale, NSW	15 days of lambing	5	11	41	68	*P* <0.01 (multiples)	Lynch and Alexander, 1977.
Sarlon garden mesh	Armidale, NSW	15 days of lambing	6	11	31	68	*P* <0.01 (multiples)	Lynch and Alexander, 1977.
Cypress hedges	Hamilton, Victoria	2 year's pooled results	6.9	13.4	11.7	25.5	*P* <0.01	McLaughlin *et al.,* 1970.
Average mortality rates (all weather conditions)			7.5	13.9	27.6	49.1		

Notes: n/a = not applicable. NSW = New South Wales.

to 15H, where near-surface air temperature returns to upwind value. The magnitude of rise in near surface air temperature increases with increasing shelter. The peak near surface air temperature rise from medium (40 percent) and low (30 percent) porosity windbreaks is about 0.7 °C and 1.4 °C respectively

This knowledge on the reduction in near-surface wind speed and the increase in near surface air temperature due to windbreaks can be combined with much earlier studies to provide a theoretical basis to the field trials on shelter and lamb mortalities.

Donnelly, from studies of mortalities of lambs born in the Canberra region in late winter/early spring, established the probability of single and multiple born lambs dying within three days birth related to maternal body weight and the Chill Index (Nixon-Smith, 1972) which is an index based on wind speed, rainfall and temperature (Donnelly, 1984).

The results of Cleugh *et al*. (2002), Donnelly (1984) and Nixon-Smith (1972) can be used to estimate the probability of mortality of lambs born with or without the benefit of a windbreak. Taking wind speed and temperature of 6.2 m/second and 8 °C from (Egan *et al.,* 1972) then applying a 40 percent reduction in wind speed and a 0.7 °C increase in near-ground temperature due to the effect of a windbreak, the calculated Chill Index is reduced from 1102 to 1034 kJ/m^2/h. When this reduction in Chill Index is applied to Donnelly's probability of mortality for lambs born to 55 kg Merino ewes, the probability of mortality of multiple born lambs is reduced from approximately 0.5 to 0.3 and for single born lambs from 0.2 to 0.1. This finding complements the research studies described, where the provision of various types of windbreak shelter has been found, on average, to halve mortalities of both single and multiple born lambs. The starvation-mismothering-exposure (SME) complex has been identified as the primary cause of lamb mortalities (Jordan and Lefeuvre, 1989). With the work of Cleugh *et al.* (2002) and Donnelly (1984) providing theoretical backing to other research on the effect of shelter on lamb mortalities, it can be concluded that the provision of shelter reduces the number of SME lambs leading to more lambs surviving and lower mortalities.

Sheep and pasture production and the benefits of shelter

A series of trials on the effects of shelter has also shown that it can improve pasture growth and sheep production. Bird *et al.* (2002) carried out two trials to assess the effect of windbreaks on pasture growth in south-western Victoria using single lines of established two-row tree windbreaks. The only clear differences over the four years of the trial were in the competition zone (0.5–1.0H) along the margins of the windbreaks, where competition from the trees reduced pasture production, and there was no significant effect in the sheltered zone. However, the windbreaks only provided shelter for 28 percent to 42 percent of the time and the authors concluded that, in that region, no single windbreak was capable of offering adequate protection. A second trial (Bird, Jackson and Williams, 2002) was designed to test this conclusion by providing more complete shelter through the use of a synthetic mesh windbreak of 50 percent porosity, surrounding small, uniform areas of land. The outcome of this trial was a small but significant increase in temperature of 0.1 ° to 0.9 °C in the sheltered plots compared with the open plots, and a consistent increase in pasture growth of about 9 percent (*P* <0.01).

Lynch and Donnelly also used synthetic windbreaks to study the effects of shelter on pasture production, liveweight change and wool production in sheep grazed at high stocking rates at Armidale (Lynch and Donnelly, 1980).

At the highest stocking rate (37.5 sheep/ha) wool production in the sheltered paddocks was increased by 31 percent over the 5 years of the trial, and the live weights of the sheep in the sheltered paddocks at 15 and 30 sheep/ha were significantly higher than those in the unsheltered paddocks, attributed to a combination of increased pasture production and a saving in metabolizable energy of the sheep in the sheltered paddocks.

Following Lynch and Donnelly's findings with artificial windbreaks and high stocking rates on high-input pastures, Reid and Thompson set up a project to look at the effect of natural windbreaks, consisting of a combination of native trees and shrubs, on sheep grazing low-input modified native pastures (Reid and Thompson, 1999). Sheep in the windbreak paddocks finished the year 13 percent heavier ($P = 0.067$) and cut 13 percent more wool per head (3.4 vs 3.0 kg, $P < 0.05$) than those in the paddocks without windbreaks. In the second year, stocking rates were varied based on calculations from pasture cuts in the paddocks the previous spring, resulting in 34 percent more sheep being carried in the windbreak paddocks (5.1 vs 3.8 sheep/ha) than on the paddocks without windbreaks, with the sheep maintaining higher body weights throughout the year.

Alexander, in a project to assess the effect of hybrid *Phalaris* strip windbreaks on lamb mortalities, also measured the effect on the subsequent growth rate of lambs (Alexander and Lynch, 1976). The mean growth rate for lambs up to 21 days of age from the sheltered paddocks was 6.6 percent greater ($P < 0.05$) than for those from the unsheltered, despite the lambs only being sheltered for a few days before being moved to an unsheltered lucerne pasture 1–3 days after being born.

Shade: shelter from heat

While shade and the shelter from heat are recognized as important factors in animal production, land cleared for cropping usually has very little shade for livestock to utilize. The provision of shade reduces radiant heat and the use of shade by livestock during hot, sunny weather is well recognized (Blackshaw, Blackshaw and Kusano,1987; Daly, 1984). The type of shade is also important, with trees seen as providing the most beneficial shade through protection from the radiant heat of sunlight combined with the cooling effect of evapotranspiration from the leaves (Blackshaw and Blackshaw, 1994).

Heat, such as that found in north-western Queensland, where there are consistently high daily temperatures, affects ewe fertility, causes hyperthermia, particularly in non-adapted ewes, with a decline in uterine blood flow, retarded foetal growth, lower birth-weight and less viable lambs (Hopkins, Nolan and Pepper, 1980; McCrabb, McDonald and Hennoste, 1993; Parker, 2006). Shade assists neonate lambs in reducing heat stress, panting, exhaustion, failure to suck and subsequent death due to starvation. Modelling from meteorological data indicates that the most severe heat effects are limited to northern Australia (Parker, 2006), although reproductive wastage in sheep due to the effects of heat on ram fertility and ewe fecundity may be seen at other sites further south. In a South African trial, it was found that the provision of artificial shade for autumn lambing ewes showed a significant improvement in lamb weaning weight and first-year lamb growth (Cloete, Muller and Durand, 2000).

For cattle, shade has been shown to improve milk yield, milk fat yield and reduce mastitis scores in dairy cows (Ingraham, Stanley and Wagner, 1979). Concern about the effects of radiant heat on the welfare of feedlot cattle has led to research on heat stress in beef cattle. Blackshaw and Blackshaw, in a review of heat stress in cattle and the effects of shade on production and behaviour (Blackshaw and Blackshaw, 1994), found the breed of cattle to be the most significant factor, with *Bos indicus* breeds having a much greater ability to adapt to heat than *Bos taurus* breeds. However, all cattle showed a reduction in feed intake and an increase in water intake in response to heat, with one study showing that the provision of cooled water to *Bos taurus* breeds improved all production parameters. Cattle grazing in tropical Queensland were observed to spend 9–11 hours in shade in the summer and to continue to ruminate during the middle of the day if in shade but not so in the sun. Trials on the effect of artificial shade on production of cattle in feedlots were variable, often confounded by breed differences, although the benefits for shade to pure *Bos taurus* breeds such as Herefords were significant.

The foregoing discussion indicates that for the grazing livestock industries, the re-introduction of some trees for biofuels and bio-energy into cleared agricultural lands will provide direct benefits for the livestock in terms of shade, shelter and animal welfare, thus enhancing industry productivity, while for agriculture more generally there would be longer-term benefits through land conservation. At the same time, the development of new, second-generation biofuels based on lignocellulosic feedstocks production systems, as described earlier, may have an impact on the availability of grain to the intensive livestock industries, were some current grain-producing land to be planted with SRC eucalypts as feedstock for biofuel or bio-energy. If this is combined with a loss of cropping productivity associated with climate change, as Bryan, King and Wang (2010b) predict in their models, this could be significant.

EXPANDING LAND USE FOR BIO-ENERGY AND BIOFUEL – THE EFFECT ON LIVESTOCK INDUSTRIES

Although the development of bio-energy and biofuel industries has been slow in Australia, the drivers of fuel security and regional development are as strong as ever and the industries continue to enjoy support through State Government mandates and Federal Government excise relief for biofuels and the Renewable Energy Target scheme (Department of Climate Change and Energy Efficiency, 2011) for bio-energy. In addition, at this time it is the Australian government's declared intention to introduce a pricing mechanism for carbon, which would provide further incentive for the development of alternative energy sources, including biofuels and bio-energy.

In this section we consider how further development of first- or second-generation biofuels and bio-energy affect the livestock portion of mixed cropping-grazing farming in Australia.

Bryan, King and Wang (2010b) have considered this question at a landscape scale. Using a mixed farming area of South Australia and adjoining regions in Victoria, they modelled four-year rotations for cropping (wheat-wheat-lupins-wheat), mixed cropping-grazing (wheat-grazing-lupins-grazing), continuous grazing (grazing-grazing-grazing-grazing) and biofuels (continuous wheat-canola rotations for the production of ethanol and biodiesel). The aim was to assess the impact of establishing a first-generation biofuels industry in the area and to quantify the trade-offs between biofuel, food (grain, meat) and fibre (wool) production (Bryan, King and Wang, 2010).

To do this they used APSIM (Keating *et al.,* 2003) to spatially model production of food and biofuel under baseline, mild, moderate and severe climate change scenarios. The effect of introducing farm subsidies tied to the net greenhouse gas (GHG) emissions abatement achieved by a switch to biofuels was calculated based on the GHG emissions and energy cycle of the biofuels and food agriculture systems. Finally, they calculated economic returns with or without subsidy, then applied a rational economic model of adoption where farmers switch to biofuels agriculture where it is more profitable than food agriculture and continue with food agriculture in all other areas.

The modelling predicted that at baseline climate and no carbon subsidy, the take up of biofuels agriculture on the economically viable areas would use 44 percent of the arable land in the modelled area, reducing sheep meat production by almost 60 percent and wool production by 78 percent. As would be expected, with a subsidy of AUD 30/tonne CO_2-eq, the model predicted the use of arable land for biofuels agriculture rising to 54 percent, further reducing sheep meat and wool production. However, under the severe climate change scenario with no carbon subsidy, the economically viable area for biofuels agriculture was predicted to be just 10 percent of the arable land. While all productivity decreased at each climate change scenario, the percentage decrease in canola for biodiesel was almost double that of sheep.

The approach is a useful one, but the model had several fundamental problems:

- The model was based on the growing of biomass feedstocks for first-generation biofuels only and did not examine the case for second-generation biofuels.
- The carbon payments were made to farmers when no reduction in carbon emissions were achieved at the farm level, as the same high input crops were grown. Instead, the reduction in carbon emissions is achieved further along the value chain at the point where biofuels replace fossil fuels. This lacks logic. As such, it is unlikely to be a policy action in Australia under the current government.
- Rational economics are applied for the adoption of farming systems, which does not include risk or farmers' perception of risk. As stated earlier, the primary reason for mixed cropping-grazing systems is the reduction of risk though a balance of enterprises. The predicted relative productivity decreases from the modelling could be interpreted to suggest that farmers may continue to combine grazing with cropping for food or biofuels to reduce the risks associated with seasonal variations and climate change, and to utilize the grazing phase of cropping rotations so necessary for re-building soil carbon and subsequent crop productivity.

Modifying the approach to address these problems, and include feedstocks relevant to new-generation technologies, would be a very useful next step.

In a similar piece of research, Bryan, King and Wang, (2010a) modelled, at a landscape scale, the planting of woody biomass (SRC eucalypt) over the same area of South Australia and Victoria, again with spatial modelling of agricultural production and woody biomass plantings under climate change scenarios. A drawback of this model is the use of plantations rather than integrating SRC eucalypt alleys into agricultural lands, which has the potential to provide greater benefits in production and conservation. Economic returns were calculated based on three biomass prices (AUD 30, AUD 40 and AUD 50/t), biomass planting and maintenance costs, and average agricultural prices and costs, including those for sheep and wool. In addition, the effects on dryland salinization, wind erosion and carbon emissions were estimated. Although the economic model included sheep, results were given as agricultural production without identifying changes in production from sheep.

The relative value of biomass and agricultural production varied with the price assigned to biomass, climate change scenario and area within the study region, so in some areas, even under moderate climate change, biomass became more profitable than agriculture. However, pasture, a predictor of sheep production, was found to be the least sensitive to climate change.

Overall, biomass tended to be more viable than agriculture in marginal agricultural areas. At the landscape scale, it was found that, as well as the economic benefits, biomass production can provide benefits by controlling dryland salinity, wind erosion and carbon emissions reduction.

These results suggest that the integration of biomass production in the form of SRC eucalypts with pasture and livestock grazing may provide a good outcome in resilience and land conservation while maintaining economic productivity of the land.

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

Integration of cropping, grazing and bio-energy production presents a complex set of biophysical, social and economic interactions that will need to be well understood to ensure sustainable development of such land use. While some recent research at landscape scale has been reported here, there is need to continue this at a range of scales, including sociological, to better understand likely land use changes in Australia associated with developing bio-energy industries.

Knowledge from this research will be needed in the continuing development of certification of sustainable biofuel production. Current certification, such as the Roundtable on Sustainable Biofuels (RSB) Certification Scheme, and the sustainability standard upon which it is based (Roundtable on Sustainable Biofuels, 2011), have been developed from certified sustainable forest management and as such tend to address sustainability issues as applying to single land use energy crops. Assessment of the sustainability of the combined production of food, fibre and bio-energy biomass from integrated land use will require re-examination of the criteria and indicators within biofuel sustainability standards.

CONCLUSIONS

The current small biofuels industry in Australia, based largely on the use of co-products of grain and sugar industry, is not a significant challenge to the availability of feedstocks for the intensive livestock industries, and only provides a relatively small amount of co-product for livestock feed. An expansion of the current first-generation biofuels industry would increase direct competition for grain, but would also increase the availability of protein feedstuffs – DDGS and oilseed meals – which could provide a useful source of supplementary protein for livestock grazing low-protein, dry, summer pastures. DDGS is particularly suitable for this role in ruminants.

New non-food biomass production systems for biofuel and bio-energy are being researched and developed in Australia. These include the use of lignocellulosic feedstocks from agricultural residues and on-farm plantings of SRC eucalypts; and new bio-oil feedstocks such as the low-rainfall oilseed crop *Brassica juncea,* the oilseed tree *Pongamia pinnata* and algae. Much work remains yet to be done to fully design, test and implement suitable production systems.

Research has been undertaken in Australia into the use of biodiesel co-products in pigs. Both juncea meal following oil extraction from *Brassica juncea,* and crude glycerol from the transesterification process to convert bio-oils to biodiesel have been trialled.

Algal biofuel production has yet to be commercialized anywhere in the world. The algal meal remaining after the extraction of bio-oil may not be suitable for livestock feed due to the use of CO_2 flue-gas from coal-fired power stations, which may contain heavy metals and other toxins that are likely to be taken up by the algae.

Pongamia pinnata plantations are being developed in Australia for the production of biofuel, which could result in the availability of pongamia meal for livestock feed. However, despite considerable research and effort to reduce residual oil and toxicity factors in pongamia meal, studies have shown that *Pongamia pinnata* meal is only useful and safe as an animal feed at low inclusion levels.

There is a benefit from pongamia containing the unpalatable karanjin and pongamol, as it allows the integration of grazing livestock in *Pongamia pinnata* plantations with minimal risk of the animals grazing and damaging the trees.

The harvesting of stubble for bio-energy should have little impact on grazing livestock in mixed grazing-cropping farming systems. There is little of nutritional value in stubble for grazing livestock. When modelled as part of a whole farm system, the value for livestock of grazing stubble is variable, often marginal or negative. The use of long-phase perennial pasture rotations in the cropping-livestock system is the most beneficial practice in the long-term maintenance of cropping soils and will always provide the major opportunity for livestock within the system, whether stubble is harvested for bio-energy or grazed.

The re-introduction of trees for bio-energy and biofuels into cleared agricultural lands in Australia will provide direct benefits in livestock productivity and animal welfare through the provision of shade and shelter, as well as long-term benefits through land conservation for the grazing livestock industries. The integration of biomass production in the form of SRC eucalypts with pasture and livestock grazing may provide a benefit in improved resilience and land conservation while maintaining economic productivity of the land.

The development of new, second-generation biofuels may have an impact on the availability of grain to the intensive livestock industries, as some current grain-producing land is planted with SRC eucalypts as feedstock for biofuel or bio-energy. Combined with a loss of cropping productivity associated with climate change, this could be significant.

ACKNOWLEDGEMENTS

The author thanks Dr Peter Gresshoff, University of Queensland, Dr Roger Campbell, Pork CRC, and Rob Gooden and Nelun Fernando, Smorgon Fuels Pty Ltd, for their help and advice during the preparation of this chapter. The continuing support of CSIRO's Energy Transformed Flagship and the members of the Sustainable Biomass Production team at CSIRO Ecosystem Sciences is gratefully acknowledged.

BIBLIOGRAPHY

ABARE. 2011. Oilseeds.xls. Available at http://adl.brs.gov.au/anrdl/metadata_files/pe_abarebrs99001676_11b.xml, Accessed on 20 November 2011.

ABARE. 2010a. *Energy in Australia 2010.* Canberra, Australia.

ABARE. 2010b. *Australian Crop Report.* Report No. 154, June 2010. Canberra, Australia.

Abel, N., Baxter, J., Campbell, A., Cleugh, H., Fargher, J., Lambeck, R., Prinsley, R., Prosser, M., Reid, R., Schmidt, C., Stizaker, R. & Thorburn, P. 1997. *Design Principles for Farm Forestry: A guide to assist farmers to decide where to plant trees and farm plantations on farms.* Rural Industries Research and Development Corporation. Canberra, Australia

Abengoa Bioenergy. 2011. Biomass enzymatic hydrolysis. Available at http://www.abengoabioenergy.com/corp/web/en/nuevas_tecnologias/tecnologias/hidrolisis/index.html Accessed on 20 November 2011.

Al-Suwaiegh, S., Fanning, K.C., Grant, R.J., Milton, C.T., & Klopfenstein, T.J. 2002. Utilizatiion of distillers grains from fermentation of sorghum or corn in diets for finishing beef and lactating dairy cattle. *Journal of Animal Science,* 80: 1105–1111.

Alexander, G. & Lynch, J.J. 1976. Phalaris windbreaks for shorn and fleeced lambing ewes. *Proceedings of the Australian Society for Animal Production,* 11: 161–164.

Alexander, G., Lynch, J.J., Mottershead, B.E. & Donnelly, J.B. 1980. Reduction of lamb mortality by means of grass wind-breaks: results of a five-year study. *Proceedings of the Australian Society for Animal Production,* 13: 329–332.

Anderson, J.L., Schingoethe, D.J., Kalscheur, K.F. & Hippen, A.R. 2006. Evaluation of dried and wet distillers grains included at two concentrations in the diets of lactating dairy cows. *Journal of Dairy Science,* 89(8): 3133–3142.

Anon[ymous]. 1996–2007. *Australian Sugar Year Book.* Rural Press Queensland Pty Ltd, Ormiston, Australia.

ASMC [Australian Sugar Milling Council]. 1996–2007. *Annual Review.* Australian Sugar Milling Council, Brisbane, Australia.

Bartle, R.J. & Abadi, A. 2010. Towards sustainable production of second generation bio-energy feedstocks. *Energy Fuels,* 24: 2–9.

Bird, P.R., Jackson, T.T. & Williams, K.W. 2002. Effect of synthetic windbreaks on pasture growth in south-western Victoria, Australia. *Australian Journal of Experimental Agriculture,* 42(6): 831–839.

Bird, P.R., Jackson, T.T., Kearney, G.A. & Williams K.W. 2002. Effect of two tree windbreaks on adjacent pastures in south-western Victoria, Australia. *Australian Journal of Experimental Agriculture,* 42(6): 809–830.

Blackshaw, J.K. & Blackshaw, A. W. 1994. Heat stress in cattle and the effect of shade on production and behaviour: a review. *Australian Journal of Experimental Agriculture.* 34: 285–295.

Blackshaw, J.K., Blackshaw, A.W. & Kusano, T. 1987. Cattle behaviour in a saleyard and its potential to cause bruising. *Australian Journal of Experimental Agriculture,* 27: 753–757.

Braid, A.L. 2007. *Biofuel Co-Products as Livestock Feed.* Rural Industries Research and Development Corporation (RIRDC) Publication No. 07/175. Canberra, Australia.

Bryan, B.A., King, D. & Wang, E. 2010a. Potential of woody biomass production for motivating widespread natural resource management under climate change. *Land Use Policy,* 27: 713–725.

Bryan, B.A., King, D. & Wang, E. 2010b. Biofuels agriculture: landscape-scale trade-offs between fuel, economics, carbon, energy, food and fibre. *GBC Bioenergy,* 2: 330–345.

Carter, D. 2002. The amount of stubble needed to reduce wind erosion. Farmnote No. 67/2002. Department of Agriculture, Perth, Western Australia.

Cheng, Z.J. & Hardy, R.W. 2004. Nutritional value of diets containing distiller's dried grain with solubles for rainbow trout, *Oncorhynchus mykiss*. *Journal of Applied Aquaculture,* 15(3/4): 101–113.

CleanStar Ventures. 2011. Our ventures. CleanStar Australia Pty Ltd. Available at http://www.cleanstarventures.com/pages/our-ventures/australia.php Accessed on 12 May 2011.

Cleugh, H.A., Prinsley, R., Bird, P.R., Brooks, S.J., Carberry, P.S., Crawford, M.C., Jackson, T.T., Meinke, H., Mylius, S.J., Nuberg, I.K., Sudmeyer, R.A. & Wright, A.J. 2002. The Australian National Windbreaks Program: overview and summary of results. *Australian Journal of Experimental Agriculture,* 42(6): 649–664.

Cloete, S.W.P., Muller, C.J.C. & Durand, A. 2000. The effects of shade and shearing on the production of Merino sheep in the Swartland region of South Africa. *South African Journal of Animal Science,* 30(3): 164–171.

Collins, C.L., Lealiifano, A., Henman, D., King, R.H. & Gooden, R. 2011. Evaluation of Juncea Meal for Growing Pigs. Co-operative Research Centre for an Internationally Competitive Pork Industry.

D'Emden, F., Llewellyn, R. & Flower, K. 2009. Is the no-till revolution complete in WA? pp. 304–307, *in: Crop Updates*. Department of Agriculture and Food, Western Australia and the Grains Research and Development Corporation.

Daimler AG Communications. 2011. CO_2 champion with modern diesel technology. Available at http://www.daimler.com/Projects/c2c/channel/documents/1546307_PI_smart_e.rtf. Accessed on 20 November 2011.

Daly, J.J. 1984. Cattle need shade trees. *Queensland Agricultural Journal,* 109: 21–24.

Department of Climate Change and Energy Efficiency. 2011. RET Scheme Update. Available at http://climatechange.gov.au/government/initiatives/renewable-target/progress.aspx Accessed on 20 June 2011.

Donnelly, J.R. 1984. The productivity of breeding ewes grazing on lucerne or grass and clover pastures on the Tablelands of southern Australia. III. Lamb mortality and weaning percentage. *Australian Journal of Agricultural Research.* 35: 709–721.

DRET. 2009. Second Generation Biofuels Research and Development (Gen2) Program. Available at http://www.ret.gov.au/energy/clean/cei/gen2/Pages/gen2.aspx Accessed on 11 May 2011.

Egan, J.K., McLaughlin, J. W., Thompson, R. L. & McIntyre J. S. 1972. The importance of shelter in reducing neonatal lamb deaths. *Australian Journal of Experimental Agriculture and Animal Husbandry,* 12: 470–472.

Egan, J.K., Thompson, R. L. & McIntyre J. S. 1976. An assessment of overgrown *Phalaris tuberosa* as shelter for newborn lambs. *Proceedings of the Australian Society for Animal Production,* 11: 157–160.

F.O. Licht. 2009. F.O. Licht's World Ethanol and Biofuel Report. Vol. 7, Nos. 9.13.14 and 9.13.15.

Farine, D.R., O'Connell, D.A., Raison, R.J., May, B.M., O'Connor, M.H., Herr, A., Taylor, J.A., Rodriguez, L.C., Campbell, P.K., Dunlop, M.I.A., Poole, M.L., Crawford, D.F., Jovanovic, T., Braid, A.L. & Kriticos, D. 2012. An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission reduction in Australia. *Global Change Biology Bioenergy,* 42(2): 148–175.

Fisher, J., Tozer, P. & Abrecht, D. 2010. *Review of livestock impacts on no-till systems.* Grains Research and Development Corporation, Canberra, Australia.

Flower, K., Crabtree, B. & Butler, G. 2008. No-till cropping systems in Australia. pp. 457–467, *in:* T. Goddard, M.A. Zoebisch, Y. Gan, W. Ellis, A. Watson and S. Sombatpanit (editors). *No-Till Farming Systems.* World Association of Soil and Water Conservation, Special Publication No. 3. Funny Publishing, Bangkok, Thailand. Available at http://www.waswc.org Accessed 07 January 2012.

Freer, M., Moore, A.D. & Donnelly, J.R. 1997. GRAZPLAN: decision support systems for Australian grazing eneterprises. II. The animal biology model for feed intake, production and repoduction and the GrazFeed DSS. *Agricultural Systems,* 54: 77–126.

Geoscience Australia and ABARE. 2010. *Australian Energy Resource Assessment.* Canberra.

GHD Hassall. 2010. The implications of greenhouse mitigation policies on the demand for agricultural land. Research Report, Australian Farm Institute, Surry Hills, Australia.

Graham, P., Braid, A., Brinsmead, T., Haritos, V., Herr, A., O'Connell, D., Raison, J., Reedman, L., Rodriguez, L. & Taylor, J. 2011. *Flight path to sustainable aviation: towards establishing a sustainable aviation fuels industry in Australia and New Zealand*. CSIRO Energy Transformed Flagship, Newcastle, Australia.

Hafi, A., & Connell, P. 2003. *Feed Grains: Future Supply and Demand in Australia.* ABARE eReport 03.21. Prepared for the Grains Research and Development Corporation, Canberra, Australia.

Ham, G.A., Stock, R.A., Klopfenstein, T.J., Larson, E.M., Shain, D.H. & Huffaman, R.P. 1994. Wet corn distillers by-products compared with dried corn distillers grains with solubles as a source of protein and energy for ruminants. *Journal of Animal Science,* 72(12): 3246–3257.

Hansen, C.F., Hernandez, A., Mullan, B.P., Moore, K., Trezona-Murray, M., King, R.H. & Pluske, R.J. 2009. A chemical analysis of samples of crude glycerol from the production of biodiesel in Australia, and the effects of feeding crude glycerol to growing-finishing pigs on performance, plasma metabolites and meat quality at slaughter. *Animal Production Science,* 49: 154–161.

Herr, A., Farine, D.R., Poulton, P., Baldock, J., Bruce, J., Braid, A., Dunlop, M., O'Connell, D. & Poole, M. 2010. *Harvesting cereal residue for energy in Australia - Take it or leave it?* Phase II report to GRDC of O'Connell *et al.* (2008) Opportunities for energy efficiency, regional self-sufficiency and energy production for Australian grain growers. CSIRO, Canberra, Australia.

Hobbs, R.J. & Yates, C.J. (editors). 2000. *Temperate eucalypt woodlands in Australia: biology, conservation, management and restoration.* Surrey Beatty & Sons, Chipping Norton, Sydney, Australia.

Hopkins, P.S., Nolan, C.J. & Pepper, P.M. 1980. The effects of heat stress on the development of the foetal lamb. *Australian Journal of Agricultural Research,* 31(4): 763–771.

Ingraham, R.H., Stanley, R.W. & Wagner, W.C. 1979. Serious effects of tropical climate on shaded and nonshaded cows as measured by rectal temperature, adrenal cortex hormone, and milk production. *American Journal of Veterinary Research,* 40: 1792–1797.

Invest Victoria. 2010. Victoria signs onto bio-ethanol plant with Coskata. Available at http://www.invest.vic.gov.au/230310VictoriasignsontobioethanolplantwithCoskata Accessed on 12 May 2011.

Jordan, D.J. & Lefeuvre, A.S. 1989. The extent and cause of perinatal lamb mortality in 3 flocks of Merino sheep. *Australian Veterinary Journal,* 66(7): 198–201.

Kazakoff, S.M., Gresshoff, P.M. & Scott, P.T. 2011. *Pongamia pinnata*, a suitable feedstock for biodiesel production.

pp. 233–254, *in:* N.G. Halford and A. Karp (editors). *Energy Crops.* Royal Society of Chemistry.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.J., Hargraves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, P.J., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCowan, R.L., Freebairn, D.M. & Smith, J.C. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy,* 18: 267–288.

Kijora, C., Bergner, H., Kupsch, R.D. & Hagemann, L. 1995. Glycerol as a feed component in the diet of fattening pigs. *Archives of Animal Nutrition-Archiv Fur Tierernahrung,* 47: 345–360.

Kirkegaard, J.A., Sarwar, M., Wong, P.T.W., Mead, A., Howe, G. & Newell, M. 2000. Field studies on the biofumigation of take-all by brassica break crops. *Australian Journal of Agricultural Research,* 51: 445–456.

Konwar, B.K., Banerjee, G.C. & Mandal, L. 1987. Effect of feeding de-oiled karanja (*Pongamia glabra*) cake on growing calves. *Indian Veterinary Journal,* 64: 399–402.

Lumpkins, B., Batal, A. & Dale, N. 2005. Use of distillers dried grains plus solubles in laying hen diets. *Journal of Applied Poultry Research,* 14(1): 25–31.

Lumpkins, B.S., Batal, A.B. & Dale, N.M. 2004. Evaluation of distillers dried grains with solubles as a feed ingredient for broilers. *Poultry Science.* 83(11): 1891–1896.

Luo, Z., Wang, E. & Sun, O.J. 2010. Soil carbon changes and its responses to agricultural practices in Australian agro-ecosystesm: A review and synthesis. *Geoderma,* 155(3-4): 211–223.

Lynch, J.J. & Donnelly, J.B. 1980. Changes in pasture and animal production resulting from the use of windbreaks. *Australian Journal of Agricultural Research,* 31: 967–979.

Lynch, J.J. & Alexander, G. 1977. Sheltering behaviour of lambing Merino sheep in relation to grass hedges and artificial windbreaks. *Australian Journal of Agricultural Research,* 28(4): 691–701.

McCrabb, G.J., McDonald, B.J. & Hennoste, L.M. 1993. Lamb birthweight in sheep differently acclimatized to a hot environment. *Australian Journal of Agricultural Research,* 44(5): 933–943.

McLaughlin, J.W., Egan, J.K., Poyton, W.McL. & Thompson, R.L. 1970. The effect upon neonatal lamb mortality of lambing systems incorporating the use of partial and complete shelter. *Proceedings of the Australian Socety of Animal Production,* 8: 337–343.

Mohan, D., Pittman, C.U. & Steele, P.H. 2006. Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy Fuels,* 20(3): 848–889.

Moore, A.D. & Lilley, J. 2006. Managing high stubble loads: Is grazing the answer? *In:* N.A. Turner and T. Johnson (editors). *Ground Breaking Stuff.* Proceedings 13th Australian Agronomy Conference. Perth, Western Australia.

Moore, A.D., Bell, L.W. & Revell, D.K. 2009. Feed gaps in mixed-farming systems: insights from the Grain & Graze program. *Animal Production Science,* 49: 736–748.

Murphy, H.T., O'Connell, D., Abadi, A., Betar, A., Braid, A., Brodie, H., Dowse, J., Gresshoff, P.M., Jovanovic, T., Kriticos, D., Lamont, M., McKay, M., Muirhead, G., Raison, J., Ruddle, B., Scott, P., Seaton, G., Stuckley, C., Thistlewhaite, R., Wheaten, B. & Wylie, P. In review. A common-view of the opportunities and challenges for Pongamia in Australia.

Nixon-Smith, W.F. 1972. The forecasting of chill risk ratings for new-born lambs and off-shears sheep by use of a cooling factor derived from synoptic data. Bureau of Meteorology, Canberra, Australia.

O'Connell, D., Farine, D.R., Dunlop, M., Poole, M., Grant, T., Herr, A., Poulton, P., Unkovitch, M., Baldock, J. & Woodward, W. 2008. *Opportunities for energy efficiency, regional self-sufficiency and energy production for Australian grain growers.* Phase I report to GRDC. CSIRO. Canberra, Australia.

O'Connell, D., Braid, A., Raison, J., Handberg, K., Cowie, A., Rodrigeuz, L. & George, B. 2009. *Sustainable production of bio-energy: A review of global bio-energy sustainability frameworks and assessment systems.* RIRDC Publication No 09/167. Canberra, Australia.

Opalka, M., Dusza, L., Koziorowski, M., Staszkiewicz, J., Lipinski, K. & Tywonczuk, J. 2001. Effect of long-term feeding with graded levels of low glucosinolate rapeseed meal on endocrine status of gilts and their piglets. *Livestock Production Science,* 69: 233–243.

Panda, A.K., Kumar, A.A., Singh, S.D. & Sastry, V.R.B. 2008. Growth performance and pathological lesions in broiler chickens fed raw or processed *karanj* (*Pongamia glabra*) cake as protein supplement. *Indian Journal of Animal Sciences,* 78(9): 997–1001.

Parker, A.J. 2006. Modelling the effects of heat stress in southern Australian sheep flocks. *2006 RSPCA Scientific Seminar. The Five Freedoms and beyond: Improving welfare of production animals.* Canberra, ACT, Australia.

Parsons, G.L. 2010. *Effects of crude glycerin in feedlot cattle*. PhD thesis. Kansas State University, USA.

Reid, N. & Landsberg, J. 2000. Tree decline in agricultural landscapes: what we stand to lose. pp. 127–166, *in:* R.J. Hobbs and C.J. Yates (editors). *Temperate Eucalypt Woodlands in Australia: Biology, Conservation, Management and Restoration.* Surrey Beatty & Sons, Chipping Norton, Sydney, Australia.

Reid, N. & Thompson, D. 1999. Economics of windbreaks and sheep production on the Northern Tablelands. *In:* Proceedings of the Australian Association of Natural

Resource Management Symposium on *Sustainable and Practical Vegetation Management into the New Millennium - Economics and Environment*. Coffs Harbour, NSW, Australia.

Roth-Mailer, D.A., Bohmer, B.M. & Roth, F.X. 2004. Effects of feeding canola meal and sweet lupin (*L. luteus, L. angustifolus*) in amino acid-balanced diets on growth performance and carcass characteristics of growing and finishing pigs. *Animal Research,* 53: 21–34.

Rowe, J.B., Brown, G., Ralph, I.G., Ferguson, J. & Wallace, F.J. 1998. Supplementary feeding of young Merino sheep, grazing wheat stubble, with different amounts of lupin, oat or barley grain. *Australian Journal of Experimental Agriculture,* 29: 29–35.

Roundtable on Sustainable Biofuels. 2011. RSB Cerification. Available at http://rsb.epfl.ch/page-24930-en.html Accessed 20 November 2011.

SARDI [South Australian Research and Development Institute]. 2011. 2011 SARDI Sowing Guide. See p. 20. Available at http://www.sardi.sa.gov.au/__data/assets/pdf_file/0011/45965/canola2011.pdf Accessed 08 August 2011.

Saunders, D.A., Hopkins, A.J.M. & How, R.A. (editors). 1990. Australian Ecosystems: 200 years of Utilization, Degradation and Reconstruction. *Proceedings of the Ecological Society of Australia,* Vol. 16. Geralton, Western Australia, Australia.

Scott, P.T., Pregelj, L., Chen, N., Hadler, J.S., Djordjevic, M.A. & Gresshoff, P.M. 2008. *Pongamia pinnata*: an untapped resource for the biofuels industry of the future. *Bioenergy Research,* 1: 2–11.

Singh, P., Sastry, V.R.B., Garg, A.K., Sharma, A.K., Singh, G.R. & Agrawal, D.K. 2006. Effect of long-term feeding of expeller pressed and solvent extracted karanj (*Pongamia pinnata*) seed cake on the performance of lambs. *Animal Feed Science and Technology,* 126(1-2): 157–167.

Smith, F.P. 2009. Assessing the habitat quality of oil mallees and other planted farmland vegetation with reference to natural woodland. *Ecological Management & Restoration,* 10(3): 217–227.

Spolaore, P., Joannis-Cassan, C., Duran, E. & Isambert, A. 2006. Commercial applications of micro-algae. *Journal of Bioscience and Bioengineering,* 101(2): 87–96.

Srivastava, J.P., Gupta, B.S., Thakur, S. & Verma, A.K. 1990. Utilization of de-oiled karanja (*Pongamia glabra*) cake in kid grower rations. *Indian Journal of Animal Nutrition,* 7: 15–20.

Stizaker, R., Vertessy, R. & Sarre, A. 2002. *Trees, water and salt: an Australian guide to using trees for healthy catchments and productive farms*. Rural Industries Research and Development Corporation, Canberra, Australia.

Thomas, D.T., Finlayson, J., Moore, A.D. & Robertson, M.J. 2010. Profitability of grazing crop stubbles may be overestimated by using the metabolisable energy intake from the stubble. *Animal Production Science,* 50: 699–704.

Trethowan, R., Mahmood, T., Rapp, G. & Lancaster, J. 2009. Improving Indian mustard for biodiesel production in northwestern NSW. *Bio-energy Australia 2009 Conference.* Gold Coast, Queensland.

Tripathi, M.K. & Mishra, A.S. 2007. Glucosinolates in animal nutrition: A review. *Animal Feed Science and Technology,* 132(1-2): 1–27.

DOE [United States Department of Energy]. 2010. National Algal Biofuels Technology Roadmap. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program.

University of Idaho. 2006. Characterisation of crude glycerol from biodiesel production from multiple feedstocks. Available at http://www.uiweb.uidaho.edu/bio-energy/NewsReleases/Technote06.pdf Accessed on 15 April 2011.

Vinay, B.J. & Sindhu Kanya, T.C. 2008. Effect of detoxification on the functional and nutritional quality of proteins of karanja seed meal. *Food Chemistry,* 106: 77–84.

Walker, P. 2004. Vacuum preservation: a method for storing wet distillers grains. Available at http://ilift.traill.uiuc.edu/distillers/research/storage.cfm Accessed on 30 July 2007.

Whitney, M.H. & Shurson, G.C. 2004. Growth performance of nursery pigs fed diets containing increasing levels of corn distiller's dried grains with solubles originating from a modern Midwestern ethanol plant. *Journal of Animal Science,* 82(1): 122–128.

Whitney, M.H., Shurson, G.C., Johnston, L.J., Wulf, D.M. & Shanks, B.C. 2006. Growth performance and carcass characteristics of grower-finisher pigs fed high-quality corn distillers dried grain with solubles originating from a modern midwestern ethanol plant. *Journal of Animal Science,* 84(12): 3356–3363.

Wu, H., Fu, Q., Giles, R. & Bartle, J. 2005. Energy balance of mallee biomass production in Western Australia. *Proceedings of Bioenergy Australia Conference 2005 – Biomass for Energy, the Environment and Society.* Melbourne, Australia.

Chapter 26

An assessment of the potential demand for DDGS in Western Canada: institutional and market considerations

Colleen Christensen,[1] Stuart Smyth,[2] Albert Boaitey[2] and William Brown[2]

[1] Feeds Innovation Institute, University of Saskatchewan, Canada

[2] Department of Bioresource Policy, Business and Economics, University of Saskatchewan, Canada

E-mails for correspondence: colleen.christensen@usask.ca

ABSTRACT

The rise of the ethanol industry in Western Canada during the start of the twenty-first century has precipitated the development of market opportunities for co-products from the ethanol industry. Previously, dried distillers grain with solubles (DDGS) was imported from the United States for use in the beef feedlot industry, but the potential for more regionalized, if not localized, production now exists. As with the development of any new market, there are challenges and opportunities. This chapter provides an overview of the development, potential and challenges facing the DDGS market in Western Canada.

INTRODUCTION

The Canadian grain-based ethanol industry has been growing consistently over the past decade (Coyle, 2007). The driver for this growth comes largely from provincial and federal government subsidies for the development of new biofuels, and since the ethanol plants are based on the use of grain feedstocks, they are located in areas of high wheat production. A major consequence of this expansion is the production of dried distillers grain with solubles (DDGS)—a feed ingredient that can be incorporated into livestock feed rations as supplemental protein or an energy source. For livestock producers in Western Canada, the availability of distillers grain presents enormous opportunity. The region's high livestock numbers and abundance of grain offer significant potential for the production of ethanol and the marketing of distillers grain. Already, seven out of the fifteen grain-based ethanol producers in Canada are located in the region. With two more proposed plants to be located in Alberta, the total regional ethanol production capacity could increase to 704 million litres/year from the current 514 million litres/year (CRFA, 2010a). This implies an increased supply of domestically produced distillers grain.

Under the present circumstance, an understanding of the DDGS market in Western Canada is critical for both suppliers and consumers (primarily beef feedlots). For the latter, an in-depth understanding of market trends and structure would enhance the potential to reap full benefits from the availability of the feed ingredient. The former might reap even greater benefits as information on market structure and trends could, in the short term, enhance current marketing efforts, and the overall competiveness and viability of the enterprise in the long term.

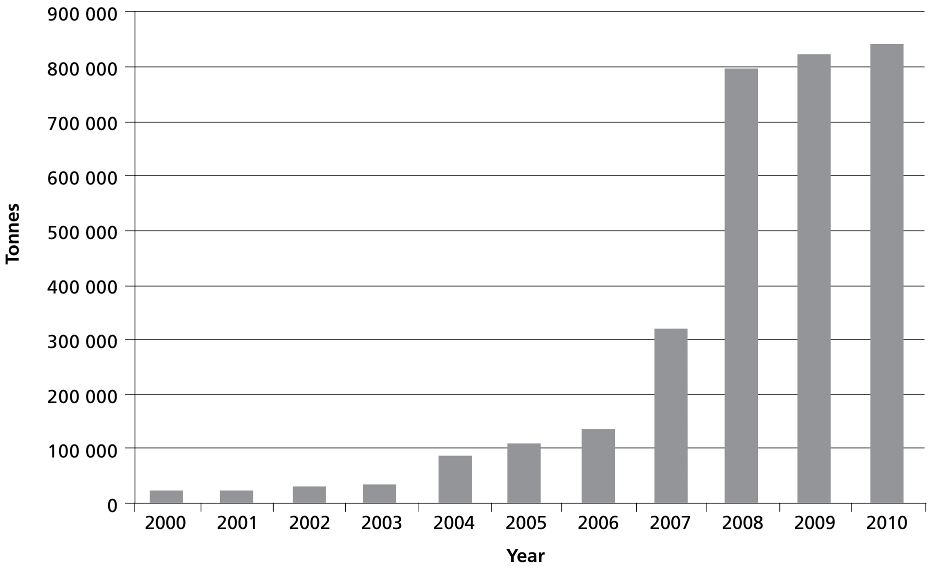
For livestock producers in Western Canada, the proximity to the supply of distillers grain from the United States could make the feed ingredient a critical component of the feed market. The United States is the world's largest producer of distillers grain. The production of the ethanol co-product has increased dramatically over the last decade, from 2.7 million tonne in 2000 to 30.5 million tonne in 2009 (CRFA, 2010a). It is projected to reach 88 million tonne by 2016, based on assumptions of aggressive industry expansion (Tokgoz *et al*., 2007). This high level of production has resulted in the situation where the international feed market is gradually gaining prominence as an important market for the use of DDGS as a feed ingredient. In 2009, over 5 million tonne of distillers grain were exported, accounting for approximately 15 percent of total production (USDA-FAS, 2011). Canada and Mexico are the main markets for the product.

Over time, Canada has emerged as an importer of maize distillers grain. A livestock production system that mimics that of the United States, the absence of tariffs under the North American Free Trade Agreement (NAFTA) and the option to ship by rail has facilitated the movement of the commodity from the United States to Canada (Fox, 2008). This is aside from market factors such as the recent high prices of traditional feed grains. In 2008, imports of United States distillers grain were nearly 800 000 tonne, up over 475 000 tonne from 2007 (USDA-FAS, 2011). Figure 1 shows the trend in Canadian distillers grain imports. Imports

MAIN MESSAGES

- **There is a potential demand from the beef feedlot industry of 1.4 million tonne of DDGS products in Western Canada, of which 40 percent can be supplied domestically.**
- **When the exchange rate between the Canadian dollar and the United States dollar exceeds $CAN 0.80, Canadian ethanol firms will import United States maize to use as feedstock.**
- **Standardization of DDGS product quality will be an important component in the development of a domestic DDGS industry in Canada.**
- **The successful development of a domestic DDGS industry will require a strong and committed champion to drive the development and structure of the market.**
- **Animal nutrition research has identified the biological impact of DDGS, and therefore use of this ingredient can be fully made based on economic indicators.**
- **Additional research on the use of DDGS or fractions of DDGS in monogastric diets is necessary prior to being able to make purely economic decisions on its use in their diets.**

FIGURE 1
Canadian DDGS imports from the United States



Source: USDA-FAS Database, 2011.

of DDGS from the United States has slowly increased over time. There was a doubling of imports between 2007 and 2008, reflecting the availability of the product due to growth of the United States ethanol industry and increasing utilization by Canadian livestock producers.

The importing of maize-based DDGS into Western Canada is a recent phenomenon, due to the abundance and price of this product in the United States following the growth of their ethanol industry. Locally produced barley has, and continues to be, the major feed ingredient, but due to the competitive pricing practices of United States DDGS exporters, maize-based DDGS has recently increased its market share. One major factor that affects this is the currency parity between the Canadian and United States currencies. With the Canadian dollar at present in a strong position relative to the US dollar, feed companies in Western Canada are now able to economically include maize-based DDGS as an ingredient. With the rate of United States maize-based DDGS imports strongly correlated to the currency exchange rate, the continuation of this trend in imports is uncertain.

Competition from United States maize-based DDGS will be a challenge for the development of a Western Canadian wheat-based DDGS industry. Many of these challenges extend beyond actual product attributes and enter the realms of regulation and economics. As mentioned above, the Canada-United States border can no longer be viewed as a barrier to market development, not to mention the proximity of supply, so competition from international production sources will be an integral component of DDGS industry development. The size of the United States ethanol industry is many times that of the industry in Western Canada, which creates economies of scale for the United States production of maize-based DDGS. As with the development of markets for new products, niches exist and can be exploited for economic advantage.

There has been minimal research in terms of market analyses for DDGS in Western Canada, although some studies on the United States market do exist (e.g. Dooley, 2008; Dhuyvetter *et al.* 2005). This chapter addresses this research gap by estimating a potential market for distillers grain in Western Canada. The following section provides an overview of the scale and scope of the agriculture industry in Western Canada. The subsequent section discusses the economic challenges in creating markets for new products. This is followed by an assessment of the potential of a new DDGS market in Western Canada. The conclusions follow a concise discussion of information gaps, and knowledge and research needs.

CHANGES AND TRENDS IN WESTERN CANADIAN AGRICULTURE

Size, concentration and location of the beef feedlot industry

In Western Canada, the co-products from the ethanol industry are primarily fed to beef cattle. Beef management systems include cow-and-calf operations, operations that feed for background growth of cattle, and feedlots where animals are fed until they are finished to a desired slaughter weight. Cow-and-calf and backgrounding operations involve pasture grazing, where some DDGS may be fed to supplement forages. The use of DDGS in pasture management systems represents a minor component of DDGS use. The majority of DDGS use in Western Canada is in beef feedlot operations.

In Western Canada, the most common grain in beef rations is barley. In terms of energy and protein requirements, barley has consistently been the commodity of choice for livestock feed. Other grains that may enter the ration include wheat and oats. The use of DDGS in beef rations has increased with the expansion of ethanol production, the common incorporation rate being 20 percent of the ration.

The beef livestock finishing management system is very intensive. Animals are brought into a feedlot and will be fed differently depending on the weight of the animal. Steers and heifers that are brought in as weaned cattle are typically fed so that they gain approximately 1 kg/day. They are started on a ration made up primarily of forages, and progressively more grains are added to the ration until the ration is approximately 90 percent grain. Steers coming in at heavier weights, such as 350 kg, are moved to the high-grain diet more quickly than weaned calves. At the end of the programme, a typical rate of gain is 1.3 kg/day on the high-grain ration. Cattle typically spend 100–150 days in a feedlot prior to being sold to a beef processing facility. Steers are normally processed at a weight of 600–650 kg and heifers are normally processed at 525–575 kg.

There are currently 12.9 million head of cattle in Canada (Statistics Canada, 2011a). The beef inventory has slowly decreased over the past decade. Table 1 presents the beef inventory by province and region. There has been a decline of 16 percent in the number of cattle in Canada in the past decade. In part this was precipitated by the Bovine spongiform encephalopathy (BSE) case in Western Canada in the early part of the last decade. The detection of this one animal closed the United States border to Canadian beef, depressing beef prices.

There are more than 4000 feedlots in Alberta (ABP, 2011), with a wide range in size. There are approximately 100 feedlots with more than 1000 head, which produce more than 75 percent of the cattle in Alberta. Saskatchewan feedlots are much fewer: approximately 250 feedlots finish more than 400 000 cattle, with the top 30 feedlots finishing nearly 80 percent of the cattle (SCFA, 2011). Manitoba has approximately 225 feedlots, ranging in size from 80 to 6500 head (Government of Manitoba, 2011). The size of the beef industry in British Columbia is considerably smaller, with less than 50 feedlots in operation.

The majority of beef feedlots in Western Canada are located in south or south-central Alberta, due to proximity to beef processing facilities. There are several processing facilities located throughout Western Canada, but beef processing is largely concentrated in southern Alberta. It is unlikely that the changes in beef feedlot location that have occurred in the United States with the expansion of the domestic ethanol industry will be mirrored in Western Canada.

TABLE 1
Canadian beef inventory

Year	Canadian beef cattle herd ('000s)							
	BC	AB	SK	MB	ON	QC	Atlantic	Total
2001	815	6 500	2 900	1 425	2 130	1 360	295	15 425
2005	710	5 930	3 040	1 490	2 189	1 415	289	15 063
2011	519	5 190	2 645	1 220	1 765	1 310	255	12 900

Notes: BC = British Columbia; AB = Alberta; SK = Saskatchewan; MB = Manitoba; ON = Ontario; QC = Quebec; Atlantic = Atlantic provinces.
Sources: Statistics Canada, 2002, 2006a, 2011a.

Development of the ethanol industry

Although significantly smaller than that of the United States, the Canadian ethanol industry has not been exempt from the recent enthusiasm for renewable fuel production. The Canadian industry comprises 15 operational plants, with a total operating capacity of about 1.82 billion litres per year (CRFA, 2010b). Not unlike other major ethanol producers, grains are the main feedstock used in the production of biofuel in Canada. Geographically, Canadian wheat-based ethanol production is predominant in the west and maize-based production is mostly in eastern Canada.

In 2011, seven ethanol plants were operating in Western Canada, all of which were producing DDGS (Table 2). The ethanol production plants range in capacity from 475 000 to 400 million litres per year, using various feedstocks. In Western Canada, the main feedstock used has been wheat, producing DDGS with more protein and less fat than DDGS from maize, although it is not uncommon for the plants to import maize from the United States to be used as feedstock. Decisions are largely based on the current price differential between United States maize and Canadian feed wheat. Some ethanol plants in Western Canada do have contract requirements that dictate that the feedstock must be local or regional feed wheat. Most have the freedom or flexibility to use the cheapest feedstock available for the production of ethanol.

Seven ethanol plants produce the DDGS supplying livestock operations in Western Canada. There is approximately 460 000 tonne of wheat DDGS produced in Western Canada each year (Table 2), with most sold into beef feedlot operations, especially those concentrated in southern Alberta. The second-highest usage of DDGS is for dairy markets, the exception being Terra Grain Fuels, which sells mainly into the dairy market. There is some DDGS utilized by swine operations, but this market comprises only a small percentage of the total livestock use. The high fibre content of DDGS makes DDGS a less attractive ingredient for monogastric animals. The majority of production is as DDGS. However, Permolex produces a modifed distillers' grains with the gluten removed and Poundmaker Ag Ventures Ltd feeds the thin stillage and wet distillers' grains directly to the feedlot adjacent to the facility.

DDGS USE IN RATIONS

A variety of products result from the ethanol manufacturing process and which can be utilized in the beef industry. Figure 2 illustrates the process for producing ethanol from grain and identifies the various co-products. The co-products that are utilized in cattle rations are a product of the distillation process. Whole stillage is produced when the fermented beer slurry is pumped through the distillation system. Ninety-five percent pure ethanol is removed from the top of the system and whole stillage is removed from the bottom of the distillation system. Whole stillage consists of grain residue, the unfermented grain particles, yeast cells and fibre, oil and protein liberated from grain cells, and water. Following centrifugation, thin stillage and wet distillers grain are produced. Although the main co-product utilized in Western Canada is DDGS, all ethanol companies have the capacity to produce and sell wet distillers grain and thin stillage or condensed distillers solubles (CDS). DDGS is the primary product, as drying the co-products increases the storage life, eases handling and is cheaper to transport as water has been evaporated with drying. Variation in co-product production occurs because of variations in the feedstock material used in a facility, facility modifications of the process described in Figure 2, degree of drying, and protein damage due to drying.

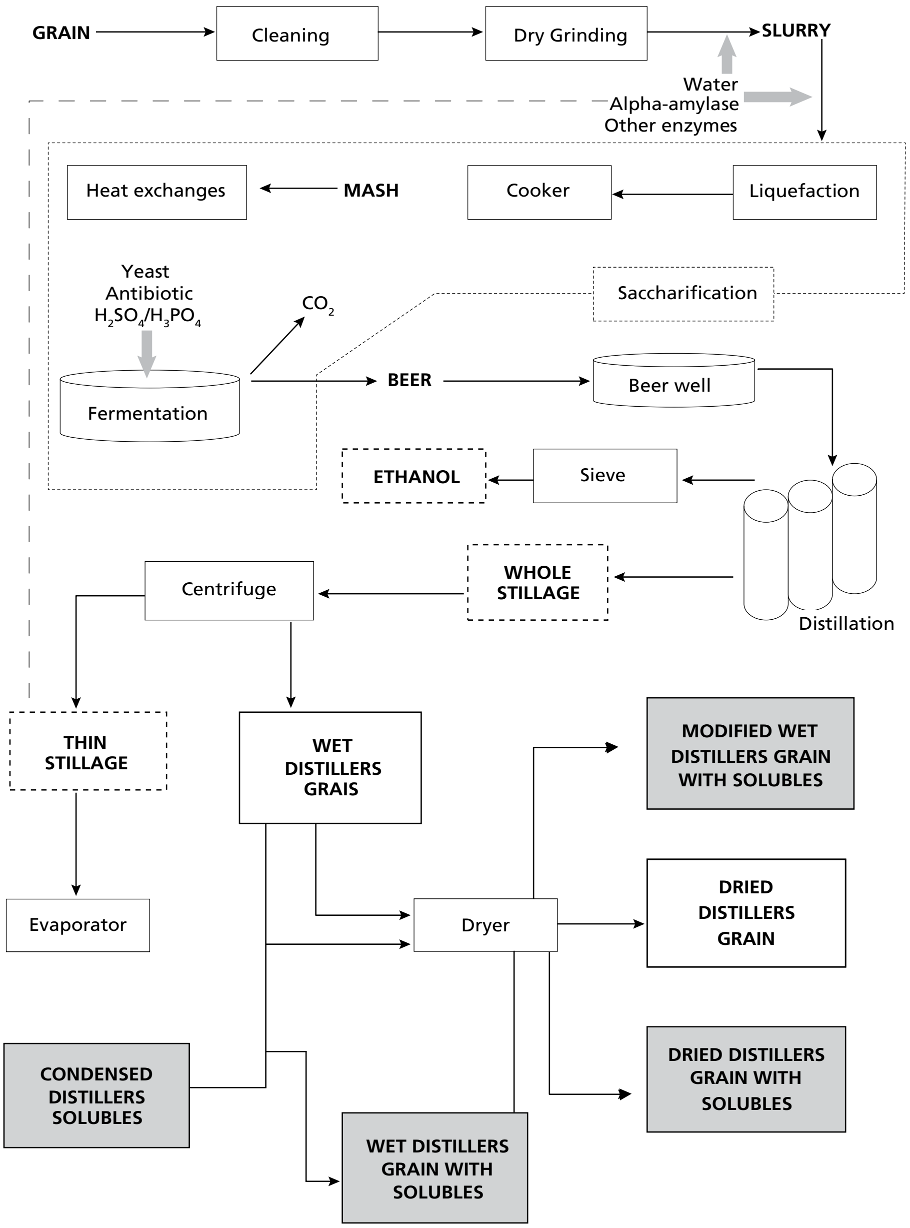
A study by Walter *et al.* (2010) examined the use of wheat or maize DDGS in a small pen trial at the University of Saskatchewan, Canada. Their intent was to determine the relative feed value of the two sources of DDGS, which differ in terms of fat and protein content. Maize or wheat DDGS were fed at 20 or 40 percent of the diet. The DDGS ingredients replaced dry-rolled barley in the ration; the control ration contained dry-rolled barley, the most commonly fed base ingredient in Western Canadian feedlot rations. Once animals met a target weight of 645 kg they were shipped to slaughter. The performance data for the trial is presented in Table 3. Both DDGS groups were similar to the dry-rolled barley control group. There was no significant difference in average daily gain for any of the treatment groups, except at the 40 percent inclusion rate of maize DDGS. At this level the dry matter intake and

TABLE 2
Ethanol plants operating in Western Canada in 2011

Plant	Feedstock	Feedstock use (t/yr)	Ethanol production (litres)	DDGS production (t)
Permolex International Inc., AB	wheat	110 000	42 000	modified
Husky – Lloydminster, AB	wheat[(1)]	353 600	130 000	130 000
Husky – Minnedosa, MB	wheat[(1)]	353 600	130 000	130 000
Poundmaker Ag Ventures Ltd., SK	wheat	32 640	12 000	feedlot
Norwest BioEnergy Inc., SK	wheat	68 000	25 000	25 000
NorAmera BioEnergy Corp., SK	wheat	68 000	25 000	25 000
Terra Grain Fuels Inc., SK	wheat	408 000	150 000	150 000
Total		1 393 840	514 000	460 000

Notes: (1) = may manufacture using a wheat+maize mix. AB = Alberta; MB = Manitoba; SK = Saskatchewan.

FIGURE 2
Wheat DDGS as a co-product of the ethanol production process



Source: Nuez, 2010, adapted from Rausch and Belyea, 2006.

TABLE 3
Baseline and performance data summary of a DDGS feeding trial

	Control	20% wheat DDGS	40% wheat DDGS	20% maize DDGS	40% maize DDGS	PSEM	*P* value
Initial weight (kg)	375	376	377	376	376	0.8	0.7
Slaughter weight (kg)	654	649	648	652	653	2.28	0.34
Average daily gain (kg)	1.62	1.63	1.73	1.66	1.68	0.03	0.13
Dry matter intake (kg/day)	10.4	10.2	10.9	10.2	8.8	0.11	<0.01
Gain:feed ratio	0.156	0.159	0.158	0.163	0.192	0.002	<0.01
Hot carcass weight (kg)	371.9	370.8	374.8	375.3	375.6	5.34	0.54
Dressing percentage	58	58.6	59.2	59.4	59	0.27	0.01
Grade fat	7.8	8.2	9	8.2	9	0.41	0.18
Estimated lean yield (%)	61.2	60.6	59.8	60.6	60	0.45	0.23

Notes: PSEM = pooled standard error of the mean; *P* value = probablity value. *Source*: Walter *et al*., 2010.

gain feed ratio improved over the control and other treatment groups. There were no differences in carcass quality in the DDGS-fed animals relative to the control diet. This trial illustrates that both maize and wheat distillers grain can be used in beef rations at up to 40 percent inclusion rate with no deleterious effects on animal performance or carcass characteristics relative to the commonly fed barley control ration.

Poundmaker Agventures Inc. is the only integrated ethanol and feedlot facility in Canada and is the only feedlot using wet mash and thin stillage as their feed input. Poundmaker Agventures is located in Lanigan, Saskatchewan, and operates a small 12 million litre facility, which produces two streams of products – thin stillage and wet distillers grain – that are fed to the beef in the feedlot on site. Poundmaker produces approximately 250 000 litres of thin stillage per day. Thin stillage is the water recovered from centrifugation of the whole stillage. It has low levels of solids, approximately 8.5 percent; the thin stillage is piped to the feedlot 1000 m away and distributed through an additional 1000 m to the water bowls in the feedlot. The approximately 8 000–16 000 animals receiving thin stillage need no supplemental water. Poundmaker also produces 50 tonne of wet distillers grain daily, with 23–24 percent solids. The wet distillers grain are picked up by a feed truck and directly mixed with barley silage at 10–20 percent of the ration.

OPPORTUNITIES FOR DEVELOPMENT OF THE DDGS MARKET IN WESTERN CANADA

Studies such as Walter *et al.* (2010) have illustrated the impact of maize or wheat DDGS on both animal performance and meat carcass quality. With the understanding of the biological indicators, livestock owners can begin to make decisions regarding the inclusion of DDGS in livestock rations based on the economics of the DDGS ingredient. Least-cost formulation is used to determine when specific ingredients are brought in or taken out of a ration. Cost of the ingredient, plus cost of transportation and ability to store ingredients, are included in the economic decisions.

Transportation logistics influence strongly the potential range of distribution of DDGS. Most imported maize-based DDGS from the United States is transported by railway. Transshipment sites for transfer of DDGS from rail to truck are needed as feedlots do not have the ability to receive ingredients by rail. In Western Canada, several transshipment sites are located in southern Alberta. These sites reduce transportation costs compared with trucking in DDGS. As a result, more maize DDGS is used in southern Alberta than in central Alberta or Saskatchewan.

CHALLENGES OF CREATING NEW MARKETS

In a competitive marketplace made up of many informed buyers and sellers, a market exchange is an institution that very effectively governs the production and consumption of products. The prices generated in a market system create Adam Smith's 'invisible hand' to match the marginal cost of providing a product to the marginal value of that product to industry. In a great many instances in the market place, a simple exchange of products at an agreed upon price is a low-cost transaction that provides the correct incentives for the buyer and sellers. When the marketplace fails to operate in a manner such that the marginal benefit is not equal to the marginal cost of the action, then a market failure is said to exist. Market failures can be addressed through government, collective or private actions.

A market failure that has attracted attention in the investment literature is referred to as the hold-up problem. The hold-up problem, according to Milgrom and Roberts (1992), is "the general business problem in which each party to a contract worries about being forced to accept disadvantageous terms later, after it has sunk an investment, or worries that its investment may be devalued by the actions of others." The hold-up problem may be induced by other forms of market failure, but deals more specifically with the investment decision. Because the hold-up problem often prevents otherwise advantageous investment it can create market failures that are real obstacles to industry development, such as the development of the new feed markets for DDGS in Western Canada.

There is a relationship between the presence of transaction-specific and asset-specific investments and the potential for *ex post* hold-up (Williamson, 1983; Grossman and Hart, 1986; Tirole, 1988; Choate and Maser, 1992). With asset-specific (specialized) investments, the value of the asset in its specific use is far greater than its value in the next-best use. In order for the initial specific investment to be undertaken, the real rents to each party (returns in excess of *ex ante* investment) must not be negative. However, when one party's *ex post* opportunity cost is reduced to the initial investment, its bargaining power is also reduced, and it is less likely for this party to cover the initial investment. This party will recognize the potential for *ex post* hold-up and will therefore be unwilling to incur the *ex ante* investment cost. Hence, if the initial investment is high enough relative to the respective *ex post* opportunity cost, the initial investment will not be undertaken by that party and market failure will occur since the specific transaction is Pareto superior to all alternative transactions.

Addressing market failures through institutions

Institutions encompass a set of rules, both formal (e.g. statutes) and informal (e.g. norms), that constrain the behavioural relationship among individuals or groups (North, 1990). Institutions are effective rules, not nominal rules, with an emphasis on enforcement (Eggertsson, 1994). They can be established, enforced and policed, either by an external authority or by voluntarily acceptance. They are predictable, stable and applicable in situations that are repetitive. Institutions define the decision-makers' utility choice set and their structure of incentives.

The establishment and enforcement of property rights allows attributes to be traded within a market system. In many cases, if property rights can be effectively assigned, then a market for the attribute will develop and the market failure will be addressed. In some cases, the assignment of property rights is not sufficient to address a market failure. In these cases, other private, collective or public actions may be lower-cost alternatives.

There are several forms of private action that can address market failures. In particular, Williamson (1983) suggested common ownership (e.g. vertical integration) as a response to site specificity. Additionally, Klein and Crawford (1978) concluded that

> *"the lower the appropriable specialized quasi-rent the more likely that transaction will rely on a contractual relationship rather than common ownership. Conversely, integration by common or joint ownership is more likely the higher the appropriable specialized quasi-rents of the assets involved."*

Klein and Crawford (1978) defined the quasi-rent as "value of the asset is the excess of its value over its salvage value, that is, its value in its next best use to another renter."

Williamson (1983) argues that the potentially opportunistic party making an *ex ante* credible commitment to the exchange can support transactions that are (potentially) subject to hold up. *Ex ante* credible commitment usually takes the form of partial redistribution of specific investment costs to the potentially opportunistic party.

Long-term contracting can be another solution to some market failures. Specifically, Joskow (1987) states that, with many types of asset-specific investments, long-term explicit contracts can reduce the potential for *ex post* hold-up. However, with this solution it may be very costly to identify all the contingencies of the investment. Hence, appropriate institutional arrangements may be a solution to the threat of a hold-up.

Institutional responses

Particular institutions tend to be better suited than others to govern particular types of transactions. Picciotto (1995) classifies institutions into three general types and then describes what type of attributes these institutions best govern. One type of institution is represented by the hierarchy or government sector. This institutional structure's stakeholders are all the citizens of the state. The incentive in this sector is the re-election of the politicians so as to maintain power. Hence, they pursue goals for the best interest of the whole society. A second set of institutions is represented by the participation sector. This sector has stakeholders who voluntarily join because they believe that benefits can be obtained by collective action. The members of the participating sector represent a group in society with a common interest. The last sector is the private sector. The individuals who own property rights are the stakeholders of this sector. The main incentive here is to maximize their return to asset investment (profit). Hence, each sector represents different individuals and has different incentives.

Each institutional structure tends to be more effective than others at producing particular types of goods. The government sector is best at producing public goods (e.g. justice) that are consumed by all citizens, and where the voice of interest groups is not important. Public goods are characterized by low excludability and low subtractability (rivalry). In this case, the low excludability makes privatization infeasible and the broad common interest in provisions is best represented at the government level where free riding can be eliminated.

The participation sector is best at governing common-pool goods (e.g. marketing services) or public goods where voice is important. These goods have the problem of excludability, which prevents them from becoming private goods. In addition, the benefits of common-pool goods are often restricted to a group of individuals or firms that are in the position to use the goods. In this case, it is in the common interest of the group to manage the good to their mutual benefit. It is also often the case that some group has greater interest in providing the good than the public at large and has more of the information required to manage the resource, making voice important.

The private sector tends to dominate whenever property rights can be assigned to make the goods excludable and the goods produced are subtractable. The property of exclusion allows private firms to charge for the use of the good. This allows the producers of the good to sell at the marginal cost of production. Where hold-up problems exist, transactions take place within larger private institutions or between institutions with long-term contractual arrangements. Excludability is not a sufficient condition for a good belonging in the private sector. If a good has low subtractability then there are economies of size in its provision, resulting in the failure of a natural monopoly and creating the potential need for government intervention.

Applications to credence goods

Introducing new products is difficult under almost any circumstance, but especially so when the product offers new or different quality traits. Given that the quality of DDGS is dependent on the quality of the feedstock entering the biofuel plant, the quality of the DDGS is going to be considerably variable. There has been an increasing volume of research on the theoretical and practical challenge of introducing new products.

TABLE 4
Product attributes and public and private responses

	Search attributes	Experiential attributes	Credence attributes
Public role in setting rules for the transaction	Consumer labelling laws to prevent fraud	Regulations ensuring consistent quality	Health, safety and environmental regulations Product liability and tort laws
Private mechanisms for managing the transaction	Voluntary labelling	Patents and trademarks backed up by identity-preserving production and marketing systems	Patented products offering private or brand warranties, or both, backed up by identity-preserving production and marketing systems

TABLE 5
Relationships between regulations, standards and private brands

Regulations for public-good purposes	Regulations based on standards	Commercial and private standards	Private brands become standards	Private brands and warranties
Driver: Public-good market failures without regulation	Driver: Common-pool goods requiring voice; collective rather than firm-based or regulatory based			Driver: Private, firm-based profit maximization

In the production system, the public sector has tended to establish the general environment for private actors to effect transactions (Table 4). Laws and regulations usually set the base rules for health and safety (e.g. the Canadian Feeds Act sets rules for animal feed usage). The private sector frequently establishes common-property or private mechanisms to manage the transactional elements to the attributes. Companies employ trademarks, brands and warranties to assure customers of the value of their product. Experience has shown, however, that the costs of developing private standards are high; for many agriculture products there are efficiencies that can be gained through collective action (e.g. the Canola Council of Canada story described in Gray *et al*. 1999).

In essence, both public regulation and commercial product standards can only really be understood in the context of all mechanisms used to manage markets (Table 5). At one extreme, governments or agents for governments set regulations to achieve public goals, such as health and safety, or environmental objectives. At the other extreme, private companies develop brands and provide private warranties to assure consumers of the quality of their products. In the middle, an array of public, private and collective actors may be critical. The long-term achievement of consistent quality in credence goods markets will require action on the part of all three types of actors (Smyth and Phillips, 2001, examine the canola industry to illustrate this point).

The challenge for the emerging DDGS market in Western Canada is going to be that of consistency of quality, as quality will vary greatly depending on the quality of the seed grain that enters the ethanol plant and the specific processing conditions of a biofuel plant. Federal regulations exist that ensure that at least a minimal description of DDGS is included with each shipment. However, if a robust quality control testing regime is not in place, out-of-specification variation may not be identified. Feedlot firms will be extremely hesitant to enter into supply contracts (either long or short term) if the consistency of the feed quality is not guaranteed.

Two options exist for the DDGS industry: they can rely either on federal regulators to establish rigid standards for DDGS feed quality, or on the biofuel plants, in cooperation with the feedlots, developing industry standards to which both parties agree. The former option will include industry consultation, but the end result will be that the standards will be forced upon the industry and the industry input will be rather minimal. The latter option provides the DDGS industry with great flexibility in the development of standards, with the remaining challenge for the industry being to find a means of enforcing the standards and to develop response protocols in the event of specific products failing to meet expectations.

EMERGING DDGS MARKET

Based on current capacity of ethanol plants and grain-to-distillers grain conversion factors, the potential supply of distillers grain in Western Canada has been estimated (Table 2), based on a grain-to-ethanol conversion rate of 365 L/tonne of feedstock and a distillers grain yield rate of 290 kg/tonne of wheat (Racz, 2007). Consistent with the ethanol production capacity distribution across Western Canada, Saskatchewan is the leading supplier of distillers grain, with an annual estimated volume of 272 600 tonne (65 percent), with Alberta (10 percent) and Manitoba (25 percent) cumulatively accounting for the remainder of the region’s total supply of distillers grain.

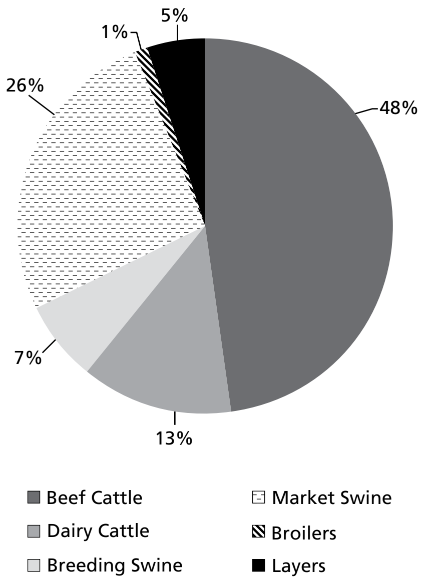
Based on livestock inventory, inclusion and adoption rates, it is possible to estimate the potential demand for DDGS in Western Canada (Table 6 and Figure 3).

TABLE 6
Calculation of potential DDGS feed ingredient usage in livestock in Western Canada

	Western Canada population	Daily Intake as fed (kg DDGS/day)	Days fed per year	DDGS consumed (kg/head/year)	Total DDGS ('000 tonne/yr)
Beef Cattle	1 933 700	2.80	120	336	649 700
Dairy Cattle	233 260	2.05	365	746.59	173 800
Breeding Swine	586 940	0.55	310	169.09	99 000
Market Swine	4 333 360	0.23	365	82.95	358 700
Broilers	29 803 780	0.0091	56	0.51	15 100
Layers	12 971 685	0.014	365	4.98	64 400
Total					1 360 700

Sources: Cattle numbers by class from Statistics Canada, 2011a; Hog numbers from Statistics Canada, 2011b; Poultry numbers from Statistics Canada, 2006b.

FIGURE 3
Potential livestock demand for DDGS in Western Canada



The total potential DDGS consumption is calculated by determining the number of animals from Statistics Canada sources, the daily intake and the total days on feed. Feed inclusion rates are largely representative of feeding practices in Western Canada, although some producers could feed in excess of the rates used. For example, a 20 percent inclusion rate of DDGS is used in the beef cattle estimate, even though research (Walter *et al.,* 2010) has indicated that up to an inclusion rate of 40 percent can be used in the rations.

It is estimated that the cattle sector market demand for DDGS would be about 823 000 t. Of this, the beef cattle sub-sector remains dominant. In the monogastric sector, hogs represent a potential key market, with demand mainly driven by the feed requirements for market hogs.

Among the various livestock species analysed, the demand for poultry seems to be the lowest. This result is not unexpected considering that inclusion rates are lowest for this livestock category.

Overall, the current estimate for the potential DDGS demand for Western Canada is approximately 1.4 million tonne per year. However, this estimate is sensitive to the underlying assumptions of inclusion and adoption rates, intake values and days on feed. For example, Dooley (2008) noted that large-size operations are more likely to feed the co-product relative to their small-size counterparts due to scale advantages. This notwithstanding, the use of a 100 percent adoption rate is a critical assumption in estimating an upper market boundary for the co-product.

Available market estimate

This section estimates the potential demand for the various provinces under similar assumptions. Given this demand and local DDGS supply, surpluses or deficits are estimated for the different provincial markets. This is to give an overview of the available market for imports and future increases in domestic supply. The present analysis implicitly assumes the domestic utilization of all distillers grain produced and the absence of inter-provincial trade.

It is observed that the overall available market for DDGS is about 70 percent of the total market demand (Table 6). With the exception of Saskatchewan, which is likely to export the commodity, all the other provinces have substantial supply deficits. Of the three provinces, however, it is posited that Alberta is likely to be the main market for DDGS in Western Canada as demand is mainly driven by the beef cattle sector (40 percent). The available market for DDGS in Manitoba and British Columbia in contrast is mainly driven by the hog (50 percent) and poultry (80 percent) sectors respectively. Traditionally, adoption and inclusion rates have been lowest for these sectors, and hence it remains unlikely that these provinces would be important markets for the co-product. Although, of the two provinces, Manitoba would more likely be the larger market because of the relative higher inclusion rate for hogs.

Evidence from available DDGS import data (Table 8) supports the analysis of the previous section. Alberta is

TABLE 7
Estimate of the available market for DDGS in Western Canada

Province	Potential DDGS demand	Demand as % of total potential market demand	Domestic DDGS production	Supply Surplus or (Deficit)	Potential available market (%)
Manitoba	435 000	31	104 000	(331 000)	+76
Saskatchewan	299 000	21	272 000	(27 000)	+9
Alberta	517 000	37	40 000	(477 000)	+92
British Columbia	136 000	10	0	(136 000)	+100
Total	1 360 000	100	416 000	(971 000)	69

Notes: Potential available market indicates proportion of market potentially available to imported DDGS.

TABLE 8
Annual maize DDGS imports from the United States (2000–2009)

Province	Average annual value	Share
Manitoba	$CAN 8 382 909	29%
Saskatchewan	$CAN 1 365 665	5%
Alberta	$CAN 17 411 275	60%
British Columbia	$CAN 2 015 858	7%
Western Canada	$CAN 29 175 706	100%

Source: Industry Canada, 2011.

the main market for imports of United States maize-based DDGS, followed by Manitoba. The large beef cattle herd in southern Alberta accounts for this high demand. Imports for Saskatchewan and British Columbia are less than 10 percent of total potential demand.

Substitute feed ingredient price

Feed rations are calculated using the least-cost scenario for all feed ingredients. The work of Walter *et al.* (2010) indicates how beef cattle would perform on maize-based DDGS. Robinson (2011) used the animal performance data obtained by Walter and co-workers to identify the price of maize-based DDGS at which feedlot operators would benefit from using the maize-based DDGS. Robinson obtained prices for barley and maize for a 16-month period (Figure 4). Based on common feedlot operational costs and the work of Walter *et al*. (2010), Robinson calculated the break-even point for the 16-month period (Figure 5).

Given the feed-to-gain ratio determined by Walter *et al.* (2010) and common feedlot operational costs, feedlot operators would obtain a $CAN 1/head advantage or better if the ratio of the cost of maize-based DDGS was less than 125 percent of that of barley. Walter *et al.* (2010) also determined that, on average, animals on maize DDGS were in the feedlot three days fewer than control animals. Figure 8 includes the cost savings to the feedlot operator when average daily gain, as well as feed-to-gain ratio for maize DDGS inclusion at 20 percent of the ration, is calculated.

A key factor that affects the demand and usage of a feed ingredient is the price of substitute feeds. Livestock producers usually substitute among feed ingredients in order to take advantage of price variations. A major con-

FIGURE 4
Barley and maize DDGS prices, Lethbridge basis ($CAN)

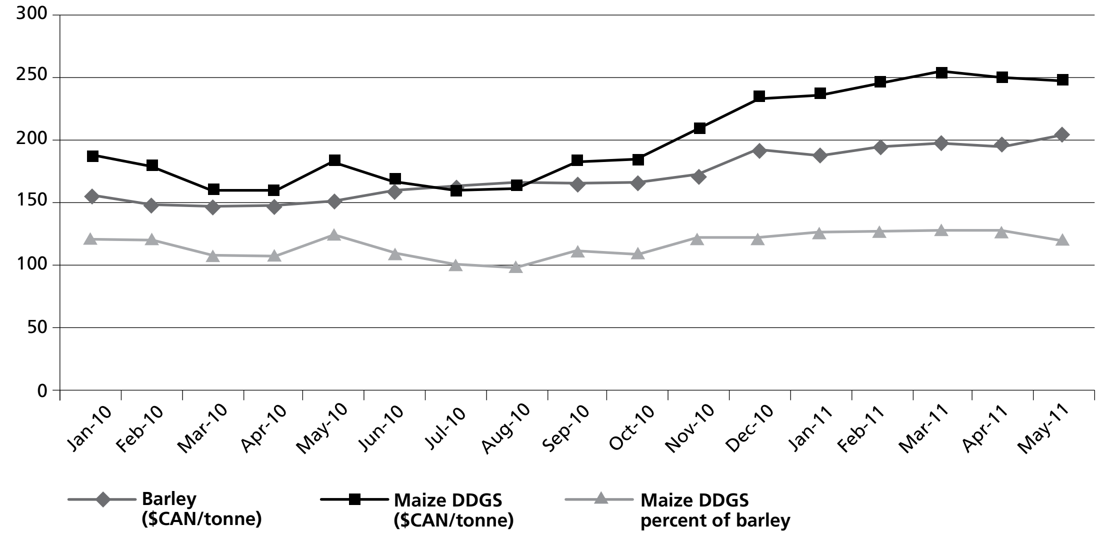
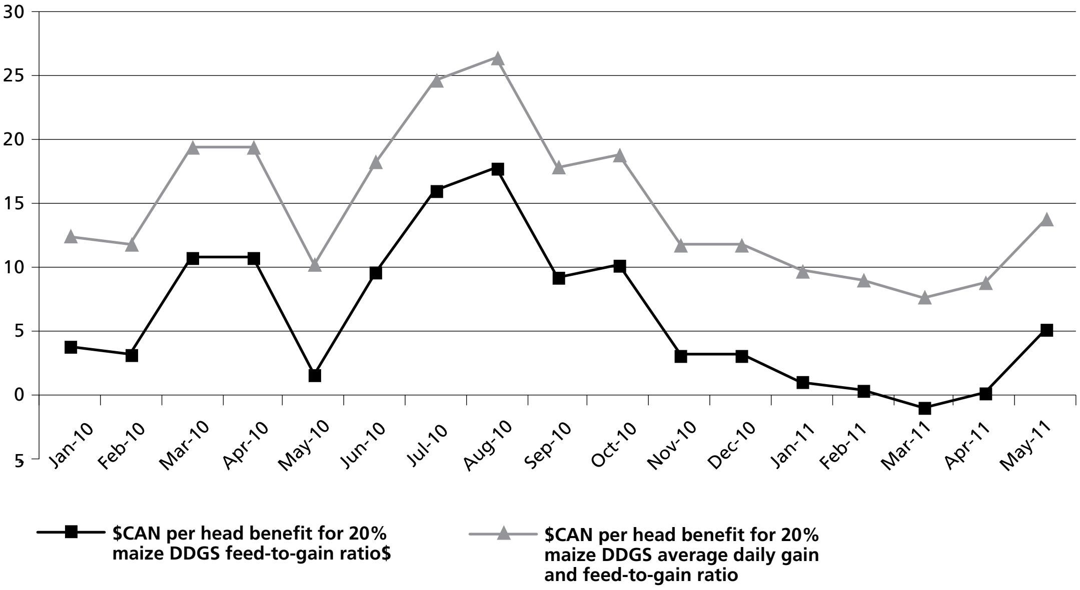


FIGURE 5

Break-even analysis for maize DDGS utilization at a 20 percent inclusion rate



Note that break even is paying up to 125 percent of the cost of barley for maize-based DDGS. There is a potential loss for rations where maize price exceeds that of barley by more than 125 percent.

sideration regarding the competitiveness of DDGS as an ingredient is its energy and protein value *vis-à-vis* other feed ingredients. If formulation models are rigid, wheat-based DDGS tends to be a substitute for protein-based feeds and maize-based DDGS tends to be a substitute for energy-based feeds. Therefore, it can be deduced that wheat-based DDGS attains a higher value as other protein-based feed prices increase. Given other protein-based feed prices staying constant, the value of maize-based DDGS increases and replaces wheat-based DDGS as the price of energy-based feeds increase (Boaitey, 2010). Discussions with livestock producers in Western Canada revealed that rations formulated without limits on protein are common (McKinnon, Univ. Saskatchewan, pers. comm.). When rations are formulated without an upper limit restriction on protein, wheat-based DDGS, with its higher protein content, becomes more prominent.

Supply chain logistics and economic impacts

Given the proximity of the Canadian and United States markets, especially regarding the supply of feedstocks for ethanol plants and consequent DDGS production, an important market factor will be the exchange rate between the Canadian and United States currencies. Dessureault (2009) estimated that in 2010, 75 percent of Canadian ethanol was derived from maize, 23 percent from wheat and 2 percent from other feedstock. Most of the maize feedstock is used in Eastern Canada, while wheat feedstock is used in Western Canada. With the wheat-based ethanol plants in Western Canada, there is little competition with livestock feedlots, given the reliance of feedlots on barley as the major ingredient for their feed supplies. However, when it is cheaper for ethanol plants in Western Canada to import United States maize for use as feedstock, rather than buy wheat produced in Western Canada, ethanol firms will use maize. When this occurs, the ethanol subsidies received by the Canadian ethanol firms are essentially used to support United States maize growers in the American Midwest, as opposed to grain farmers in Western Canada. This raises a host of interesting policy issues that are beyond the scope of this chapter.

As noted above, the United States ethanol and co-product industry is over 60 times the size of the Canadian industry, producing over 30 million tonne of DDGS in 2009, compared with 0.5 million tonne in Western Canada. The 800 000 tonne currently exported to Western Canada account for less than 3 percent of total United States DDGS supply. Some projections have the United States ethanol industry tripling capacity over the next five years, which would also increase the supply of DDGS. One would expect that, with the potential increase of supply, there would be a corresponding decrease in the price in Canada of imported maize-based DDGS.

As the Canada-United States dollar exchange rate fluctuates, the price of maize-based DDGS changes for the livestock feed industry in Canada, and the competitiveness of wheat-based DDGS is affected. Given the current strength of the Canadian dollar *vis-à-vis* the United States dollar, United States maize-based DDGS is much more competitive than Canadian wheat-based DDGS, to the point where making ethanol out of imported United States maize may be more profitable that using wheat in Western Canada. Boaitey and Brown (2011) have estimated that when the Canadian dollar is above US$ 0.80, it will be cheaper for the livestock industry in Western Canada to import United States-produced, maize-based DDGS. The Canadian dollar was last below US$ 0.80 in the early months of 2009, so since then it has been cheaper for the Canadian livestock industry to import United States DDGS. Given that the Canadian dollar is currently on par with the United States dollar and has been so for virtually all of 2011, a decline in the Canadian currency is not anticipated in the near future. Indeed, Boaitey (2010) observed that the vast majority of livestock rations in the southern Alberta feedlots are based on imported maize-based DDGS from the United States.

The cost of transportation can change over time and this can affect the competitiveness of wheat-based DDGS and maize-based DDGS. Maize-based DDGS usually has to be transported longer distances, from ethanol plants in the United States, but wheat-based DDGS is less dense and therefore fewer tonnes can be loaded into the same size of vehicle, thereby raising the cost of transportation (McKinnon, Univ. Saskatchewan, pers. comm.) Taken in tandem, the greater density of maize-based DDGS and the price sensitivity of a high Canadian dollar mean that the economics for Canadian wheat-based DDGS supplies are poor. Western Canada imported about 800 000 tonne of maize-based DDGS each year in 2008–2010, which amounts to approximately two-thirds of the total DDGS demand, giving the maize-based DDGS firms a sizeable market share. Given that American Midwest ethanol plants are able to export maize-based DDGS into southern Alberta – the feedlot market nearest to the source of supply – implies that if maize-based DDGS suppliers can serve this market, they will be able also to economically serve all other feedlot markets in Western Canada. The combination of quantity of supply and the ability to economically export DDGS from the American Midwest to southern Alberta implies that the United States DDGS suppliers have considerable market power and might be able to use pricing strategies to disadvantage Canadian wheat-based DDGS production.

Overall, the market for DDGS in Western Canada would most likely be determined by the interplay of local supply, the supply of traditional feeds, United States ethanol expansion and market factors such as freight rates and currency exchange rates. However, producers and marketers of the product can facilitate its utilization by promoting increased inclusion rates amongst livestock producers in Western Canada.

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

The development of new markets is a process filled with opportunities, challenges and pitfalls. While the development of a new market for Canadian wheat-based DDGS is not as complicated as the development of the market for a new food product, we have shown that it is neither as simple nor easy as one might first think.

There are roles for both the public and private sectors in the development of this market. To address the feedlot operators' concerns about consistency of quality, it is possible that the sector might turn to the federal government to regulate the quality of wheat-based DDGS products. This could be done through an update of the Canadian *Feeds Act*. Given that the quality of the final product is so heavily dependent on quality of the wheat entering the biofuel plant, it is unlikely that the biofuel or the feedlot industry would engage in this option.

A more likely outcome to control for issues of product consistency would be for the biofuel industry to begin to brand their DDGS products in an attempt to create value for their specific DDGS products as being of higher quality or consistency than those of their competitors. This may, or may not, include some form of a product warranty if the feedlot tests a batch of DDGS products and finds them not meeting some set quality parameter. The biggest challenge for the emerging DDGS market in Western Canada is going to be that created by the competition that does, and will, exist from cheaper United States maize-based DDGS. Without a doubt, there is a considerable degree of United States produced maize entering Western Canada to be used in the production of ethanol, resulting in local and regionally based competition for wheat-based DDGS production. One must also bear in mind the competition that already exists with the United States production of DDGS from their own domestic biofuel production and their ability to export maize-based DDGS products into Western Canada at competitive prices.

One of the potential hold-up problems that might affect the development of a DDGS industry in Western Canada is the nature of feedlot industry contract preferences. Feedlots have a preference for short-term contracts of two or three months duration. While a series of contracts might be with the same supplier, the length of the contracts is always of a short-term nature. The inability to secure longer-term contracts would be a barrier to ethanol plants trying to enter the feed industry. The longer the supply contract, the lower the risk of entering into the market, but with the feedlot industry preference for short-term contracts, the risk of entering the DDGS market might be too great for ethanol plants.

A major limitation of Boaitey (2010) was the lack of adequate price data on wheat DDGS. Aside from the industry in Western Canada being relatively young, most of the ethanol producers contacted were unwilling to provide Boaitey with such data. As a result, approximation techniques were used to derive the price of wheat DDGS. This might affect the validity of some of the conclusions made from the time-series analysis, especially regarding the interrelatedness between wheat DDGS and prices of barley and canola meals. The effect of approximation pricing on the least-cost ration results may not be as significant.

Secondly, Boaitey does not incorporate nutrient management costs. It indirectly isolates feed costs from other costs incurred as a result of certain feeding practices. Future studies could incorporate these costs to ascertain how conclusions may differ. Any incorporation of nutrient management costs in addition to improving the price data for key feed ingredients, such as wheat DDGS, in future studies would provide a better understanding of the economic value of distillers grain. Furthermore, future research could consider the effect of nutrient variability on the conclusions of the present study.

As Table 6 has indicated, the demand for DDGS, if consistently used in livestock rations, is greater than the production of DDGS by Western Canadian companies. The mandate of the Feed Opportunities from the Biofuels Industries (FOBI) research network (www.ddgs.usask.ca) was to investigate the use of DDGS by all livestock sectors to determine both the biological parameters affected by DDGS and the economics of DDGS use. For the beef sector, research was conducted on inclusion limits and biological performance (Walter *et al.*, 2010). Biological performance parameters such as average daily gain and feed-to-gain ratio, as well as potential negative health impacts such as liver abscesses, were investigated. No negative health impacts were observed at any level of DDGS inclusion. With this data, it becomes possible to fully calculate cost of production, including cost of feed with operational costs. The impact is that higher inclusion rates of DDGS may be accepted into the diet, even if it increases the length of stay in the feedlot, given a lower, favourable cost of the ingredient.

Given that the biological implications of the use of DDGS are known for the feedlot industry, more research on market indicators are required to fully understand how the beef feedlot industry might utilize domestic wheat DDGS or maize DDGS imported from the United States. Existing supplier relationships tend to be very strong, with feedlots continually purchasing feed supplies from the same firm. The ability of ethanol plants, be they in Canada or the United States, to break this strong bond will need to be examined to determine the full market potential for suppliers of DDGS-based feed ingredients. While United States maize-based DDGS products can be cheaply transported by rail to the feedlot industry in southern Alberta, the requirement for a transshipment capacity is fundamental, and the farther away that a feedlot is from a transshipment point, the greater the propensity to continue to utilize existing supply relationships that are predominantly based on barley grain.

Use of DDGS by monogastrics such as poultry and swine was also investigated in the FOBI research network. The research was not as focused on commercial parameters as the network's ruminant research because the use of DDGS as a feed ingredient is not as widespread in monogastrics. Yet, if the quantities of DDGS produced is going to continue to increase with the expansion of the ethanol industry, assessments of impacts on nutrition, health and biological performance will be needed. The FOBI research network investigated the potential to fractionate DDGS. Removal of the fibre from DDGS to produce a high-protein concentrate would increase the acceptance of DDGS in monogastric diets. Although preliminary trials were promising, additional research is necessary to develop a cost-effective method of separating fibre from DDGS.

The preferred form of co-products for sale by ethanol companies is predominantly as wet DGS. However, transportation costs and storage issues for the co-product in this form mean that sales of wet DGS only occur within a limited radius around ethanol facilities. A 50-mile [80 km] radius is generally accepted in North America as the maximum distance it is economically feasible to transport wet distillers grain (Konecny and Jenkins, 2008). However, a study from Australia (Bonnardeaux, 2007) suggests that a 125-mile [200 km] radius is economically viable. Transporting products greater distances requires drying the distillers grain; dryers imply expensive capital and operational costs. Research programmes such as FOBI have explored additional fractionation technologies, which could potentially diversify bio-ethanol facility product lines. However, the costs of purchasing and developing these new product lines may be prohibitive.

Further research must be done by individual buyers regarding the variability of the DDGS that they purchase. Nuez (2010) and Nuez and Yu (2010) indicate that there is variability both between batches and between plants in the quality (protein content and digestibility) of DDGS. Until individual plants develop standardized processing parameters and quality assurance programmes, quality must be addressed by the buyer.

CONCLUSIONS

We have shown that the potential annual supply of DDGS feed ingredients from ethanol plants in Western Canada could be close to 500 000 tonne, while demand for the same products could be more than 800 000 tonne more, with a possible demand of 1.4 million tonne of DDGS products. The shortfall in supply will have to be filled from somewhere, and the logical source would be imported

United States maize-based DDGS products. The development of the DDGS industry in Western Canada, regardless of whether it derives from domestic wheat-based ethanol or United States maize-based ethanol, has three crucial parameters.

First, the development of a Canadian-based DDGS industry is directly connected to the exchange rate between the United States and Canadian currencies. Ethanol plants will use the cheapest available input, which is often going to be United States maize-based DDGS. The combination of the availability of United States maize and the commodity price means that when the Canadian dollar is above an exchange rate of US$ 0.80, it will be more economical for Canadian livestock firms to import United States maize-based DDGS to use as a feed ingredient. This means that the potential for the development of a Canadian wheat-based DDGS industry is completely price sensitive, and given the current exchange rate between the two currencies, the further development of a Canadian wheat-based DDGS industry should not be expected.

Second, the geographical disconnect between the supply and the demand is going to be an economic barrier to the use of DDGS by feedlots. Most supplies of DDGS feed inputs are going to come from the ethanol plants, which are predominantly located in Saskatchewan. The greatest percentage of the demand for the product will come from the highly concentrated beef feedlot industry in southern Alberta. The disconnect between the two end points of the potential supply chain could reach 1000 km. The additional transportation costs for the feedlot industry will directly affect the profit margins of the feedlots, and the local supply and price of feed barley is likely to mandate barley as the preferred feed ingredient. The lower volume of wheat-based DDGS that can be transported per transport unit (railroad car or lorry) compared with maize-based DDGS is a further barrier, not to mention that, at present, feedlot firms in southern Alberta are able to import United States maize-based DDGS more economically than purchasing wheat-based DDGS from Saskatchewan.

Third, the high degree of quality variability in DDGS products for factors such as protein and fat content will have to be addressed before the beef feedlots will begin to contemplate a shift in feed ingredients. With the feedlot preference for short-term contracts already in existence, the quality variability of DDGS will probably only reinforce this preference, and the length of contracts for DDGS inputs may be even shorter in the absence of any form of standardization from DDGS suppliers.

The ultimate success of a developed DDGS market in Western Canada will require a champion that is willing to drive the process. The few ethanol plants currently operating in Western Canada do not have the economies of scale to likely be the driver, compared with the United States, where the higher number of ethanol plants has resulted in a market surplus of DDGS products. With an economic efficiency radius of 50 miles from an ethanol plant, it may be that the market will develop more rapidly for wet distillers grain. Regardless of the product or the location, the development of a market for any form of distillers grain is going to require a strategic plan, capital, and some dedicated human resources to ensure there is a sustained momentum to develop and maintain the market for this new feed product. While the opportunities are quite apparent, the challenges in developing this market will, without a doubt, be numerous.

BIBLIOGRAPHY

ABP [Alberta Beef Producers]. 2011 [online]. Data from the ABP Web site. See: http://albertabeef.org/industry/beef-production-chain/ Accessed 6 October 2011.

Boaitey, A. 2010. Distillers grain and the livestock industry in Western Canada. M.Sc. Thesis, Department of Bioresource Policy, Business and Economics, University of Saskatchewan Canada.

Boaitey, A. & Brown, W.J. 2011. Biofuels expansion and the livestock industry in Western Canada. *Journal of International Farm Management*, 5(4): 1–24.

Bonnardeaux, J. 2007. Potential uses for Distillers Grains. Report prepared for the Western Australia Department of Agriculture and Food. Available at: http://www.agric.wa.gov.au/objtwr/imported_assets/content/sust/biofuel/potentialusesgrains042007.pdf Accessed on 12 January 2011.

CRFA [Canadian Renewable Fuels Association]. 2010a. Ethanol: Canadian production list at November 4th 2010. Available at: http://www.greenfuels.org/en/industry-information/plants.aspx Accessed on 11 January 2011.

CRFA [Canadian Renewable Fuels Association]. 2010b. *Growing Beyond Oil: Delivering our Energy Future – A report card on the Canadian renewable fuels industry*. See: http://www.greenfuels.org/uploads/documents/crfareportcardenglish2010final.pdf Accessed 1 December 2011.

Choate, G. & Maser, S. 1992. The impact of asset specificity on single-period contracting. *Journal of Economic Behavior & Organization*, 18(3): 373–389.

Coyle, W. 2007. The future of biofuels – a global perspective. *Amber Waves,* 5: 5. Available at: http:www.ers.usda.gov/amberwaves Accessed 3 December 2009.

Dessureault, D. 2009. *Biofuels Annual – Canada, Global Agricultural Information Network – GAIN*. USDA Foreign Agricultural Service, GAIN Report Number CA9037.

Dooley, F.J. 2008. U.S. Market Potential for Dried Distillers Grain with Solubles. Working paper #08-12. Department of Agricultural Economics, Purdue University, USA. Available at: http://ageconsearch.umn.edu/handle/45968 Accessed 13 September 2011.

Dhuyvetter, K.C., Kastens, T.L. & Boland, M. 2005. The US Ethanol Industry: Where will it be Located in the Future? Agricultural Issues Centre, University of California, Davis, USA. Available at: http://www.agmanager.info/agribus/energy/Ethanol%20Industry(AgMRC)--11.25.05.pdf Accessed 13 September 2011.

Eggertsson, Th. 1994. The economics of institutions in transaction economics. pp. 19–50, *in:* S. Schiavo-Campo (editor). Institutional change and the public sector in transactional economics. *World Bank Discussion Paper,* No. 241. Available at http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/1994/05/01/000009265_3970311122426/Rendered/PDF/multi_page.pdf Accessed 8 October 2011.

Fox, J.A. 2008. The Value of Distillers Dried Grains in Large International Markets. Midwest Agribusiness Trade Research and Information Centre. See: http://www.card.iastate.edu/books/distillers_grains/pdfs/chapter6.pdf Accessed 1 December 2011.

Government of Manitoba. 2011 [online]. Data from the Government of Manitoba Web site. See: http://www.gov.mb.ca/trade/globaltrade/agrifood/po_livestock/beef.html Accessed 6 October 2011.

Gray, R., Malla, S. & Phillips, P.W.B. 1999. The Effectiveness of the Research Funding in the Canola Industry. Saskatchewan Agriculture and Food. Available at: http://www.usask.ca/politic/phillips/pdfs/Canola%20Research%20Industry.pdf Accessed 13 September 2011.

Grossman, S. & Hart, O. 1986. The costs and benefits of ownership: A theory of vertical and lateral integration. *Journal of Political Economy*, 94: 691–719.

Industry Canada. 2011. Trade Data Online. Available at: http://www.ic.gc.ca/sc_mrkti/tdst/tdo/tdo.php?lang=30&headFootDir=/sc_mrkti/tdst/headfoot&productType=HS6&cacheTime=962115865#tag Accessed 11 January 2011.

Joskow, P. 1987. Contract duration and relationship-specific investments: empirical evidence from coal market. *American Economic Review,* 71: 168–185.

Klein, B. & Crawford, R.G. 1978. Vertical integration, appropriable rents, and the competitive contracting process. *Journal of Law and Economics*, 21: 297–326.

Konecny, R. & Jenkins, A. 2008. An optimization model of the ethanol distillers grain market in Nebraska. *Economics & Business Journal: Inquiries & Perspectives*, 1(1): 118–127.

Milgrom, P.R. & Roberts, J.D. 1992. *Economics of Organization and Management*. Prentice-Hall, Englewood Cliffs, NJ, USA.

North, D.C. 1990. *Institutions, Institutional Change and Economic Performance*. Cambridge University Press, Cambridge, UK.

Nuez, W.G. 2010. Variation and availability of nutrients in co-products from bio-ethanol production fed to ruminants. M.Sc. Thesis. Department of Animal and Poultry Science, University of Saskatchewan, Canada.

Nuez, W.G. & Yu, P. 2010. Estimation of ruminal and intestinal digestion profiles, hourly effective degradation ratio and potential N to energy synchronization of co-products from bioethanol processing. *Journal of the Science of Food and Agriculture,* 90: 2058–2067.

Picciotto, R. 1995. Putting institutional economics to work: from participation to governance. *World Bank Discussion Paper*, No. 304.

Racz, J.V. 2007. Canadian biofuel industry: Western Canadian perspective and opportunities. Presentation to the *Capturing Feed Grain and Forage Opportunities Conference*. 11–12 December 2007, Red Deer, Alberta, Canada.

Rausch, K.D. & Belyea, R.L. 2006. The future of coproducts from corn processing. *Applied Biochemistry and Biotechnology*, 128: 47–86.

Robinson, B. 2011. Feeding DDGS in Alberta feedlots: practical and economic implications. Presentation to the *Insights into use of DDGS in Western Canadian feedlot diets.* 9 June 2011. Lethbridge, Alberta, Canada.

SCFA [Saskatchewan Cattle Feeders Association]. 2011 [online]. Data from the SCFA Web site. See: http://www.saskcattle.com/joomla/index.php?option=com_content&task=view&id=16&Itemid=38 Accessed 6 October 2011.

Smyth, S. & Phillips, P.W.B. 2001. Competitors co-operating: establishing a supply chain to manage genetically modified Canola. *International Food and Agribusiness Management Review*, 4: 51–66.

Statistics Canada. 2006a. *Cattle Statistics*. Volume 5, No. 1, Catalogue No. 23-012-XIE Available at: http://dsp-psd.pwgsc.gc.ca/Collection/Statcan/23-012-XIE/23-012-XIE2005002.pdf Accessed on 11 May 2011.

Statistics Canada. 2006b. *Poultry Inventory.* Catalogue No. 23-012-XIE. Available at: http://www.statcan.gc.ca/pub/95-629-x/1/4123813-eng.htm Accessed on 31 August 2011.

Statistics Canada. 2011a. *Cattle Statistics*. Volume 10, No. 1, Catalogue No. 23-012-X. Available at: http://www.statcan.gc.ca/pub/23-012-x/23-012-x2010002-eng.pdf Accessed on 11 May 2011.

Statistics Canada. 2011b. *Hog Inventories.* Catalogue No. 23-010-X. Available at: http://www.statcan.gc.ca/pub/23-010-x/2010001/part-partie1-eng.htm Accessed on 30 August 2011.

Statistics Canada. 2002. *Cattle Statistics*. Volume 1, No. 1, Catalogue No. 23-012-XIE. Available at: http://dsp-psd.pwgsc.gc.ca/Collection/Statcan/23-012-XIE/23-012-XIE2002001.pdf Accessed on 11 May 2011.

Tirole, J. 1988. *The Theory of Industrial Organization*. MIT Press, Cambridge, Mass., USA.

Tokgoz, S., Elobeid, A., Fabiosa, J., Hayes, D.J., Babcock, B.A., Yu, T.-H., Dong, F., Hart, C.E. & Beghin, J.C. 2007. Emerging biofuels: outlook of effects on the US grain, oilseed, and livestock markets. CARD Staff Report 07-SR

101. Centre for Agricultural and Rural Development, Iowa State University, USA.

USDA-FAS [United States Department of Agriculture, Foreign Agricultural Service]. 2011. US Trade Exports-HS 10-Digit Codes. FASonline database.

Walter, L.J., Aalhus, J.L., Robertson, W.M., McAllister, T.A., Gibb, D.J., Dugan, M.E.R., Aldai, N. & McKinnon, J.J. 2010. Evaluation of wheat or corn dried distillers grains with solubles on performance and carcass characteristics of feedlot steers. *Canadian Journal of Animal Science*, 90(2): 259–269.

Williamson, O. 1983. Organization form, residual claimants, and corporate control. *Journal of Law and Economics*, 26: 675–680.

Chapter 27

Biofuels: their co-products and water impacts in the context of life-cycle analysis

Michael Wang and Jennifer Dunn
Center for Transportation Research, Argonne National Laboratory, Argonne, IL 60439, United States of America
E-mail for correspondence: mqwang@anl.gov

ABSTRACT

Life-cycle analysis (LCA) of biofuels, including maize ethanol, sugar cane ethanol, cellulosic ethanol and biodiesel, must incorporate the impact of co-products. Distillers grain with solubles, an animal feed co-produced with maize ethanol, is one such co-product. Electricity, a significant co-product of cellulosic ethanol production, can provide significant greenhouse gas credits over the life cycle of a biofuel. This chapter examines biofuel production technologies and biofuel co-products, and methods for allocating energy and water consumption and environmental burdens among the biofuel and its co-products. Allocation methodologies include displacement, mass-based, energy-based, market-value-based and process purpose. It is also possible to combine these approaches in a hybrid methodology. We present LCA results (energy consumption and GHG emissions) for maize and cellulosic ethanol, and examine the effect of co-product allocation methodologies on these results. We also discuss water consumption in the life cycle of maize and cellulosic ethanol. As biofuel production technology matures, it is likely that the portfolio of biofuel co-products will evolve, requiring LCA practitioners to re-assess their effect on the life-cycle impacts of biofuels.

INTRODUCTION

Life-cycle analysis (LCA) is a tool to systematically examine the energy and environmental impacts of products, processes and systems (Allen and Shonnard, 2002; ISO, 2006). Its application to biofuel production has expanded rapidly in recent years, but not without controversy. Applying LCA to biofuels raises issues such as accounting for greenhouse gas (GHG) emissions from land-use change (LUC), allocating the environmental impacts of biofuel production among co-products, including animal feed, and assessing the impact of biofuel production on water quality and consumption. In this chapter we present recent advances in the application of LCA to biofuels, including the impact of technology developments, improved estimates of LUC impacts, advancements in the understanding of animal feed as a co-product of ethanol plants, and advances in quantifying water consumption impacts of biofuel production.

BIOFUEL PRODUCTION TECHNOLOGIES

Production of biofuels in the United States has escalated since the United States began its fuel ethanol programme in 1980. United States production of maize ethanol was 76 million litres in 2000. In 2010, it had increased to 49 billion litres (RFA, 2011). Production of bio-ethanol is increasing worldwide. In the European Union (EU), for example, 3.7 billion litres of ethanol were produced in 2009, up six-fold from 2002 (ePure, 2010). In Brazil, which is the second-largest ethanol producer in the world, ethanol accounts for 40 percent of the gasoline market (Wang *et al.*, 2008). Brazil's 2008/2009 ethanol production was 28 billion litres, more than double production in 1990-1991 (UNICA, 2011).

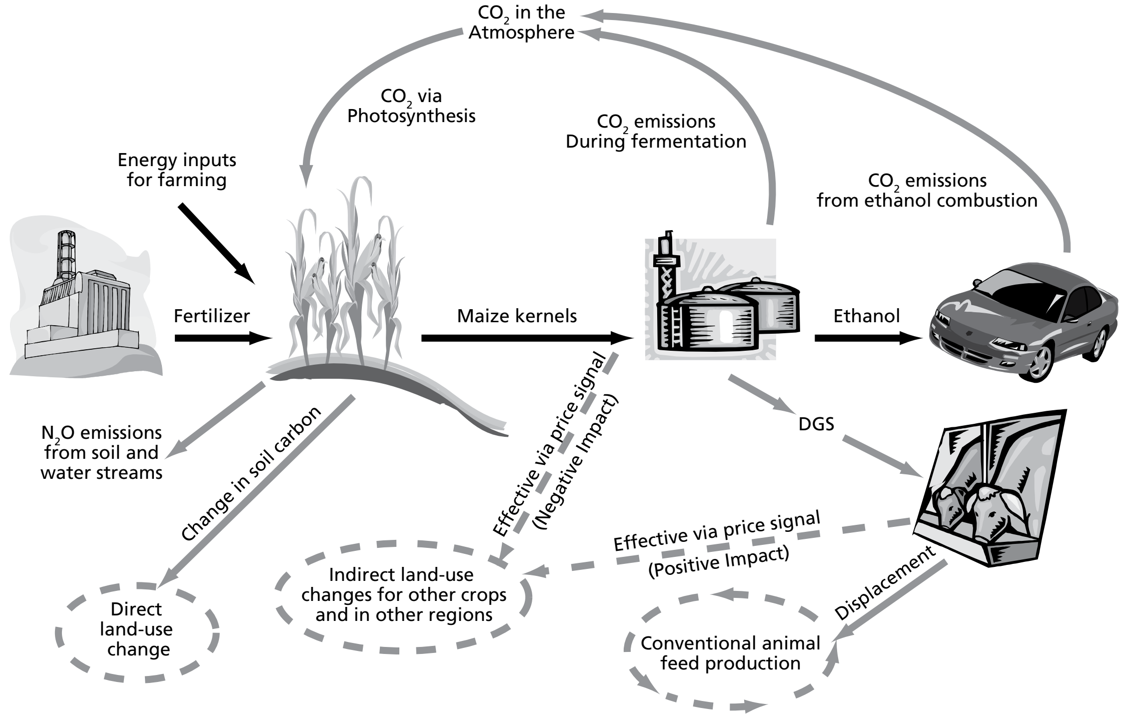
Biofuels can be classified as first, second or third generation. First-generation biofuels derive from cereal, oil and sugar crops, which are converted to fuels with mature technology. Of the first-generation fuels, maize ethanol has received the most attention in the LCA arena. Figure 1 depicts the life cycle of this biofuel, which is the most widespread fuel alternative to gasoline in the United States.

Ethanol plants use dry- or wet-milling technologies. In wet-milling plants, maize kernels are soaked in SO_2-containing water. De-germing of the kernels and oil extraction from the germs follows. The remaining kernel material is ground, producing starch and gluten. The former is fermented to ethanol. In dry-milling plants, starch in milled maize kernels is fermented into ethanol. Residual materials are generated that have value as commercial animal feed, called distillers grain with solubles (DGS), which can be sold in wet (WDGS) or dried form (DDGS). Integration of maize fractionation in the dry-milling process permits production of germ and fibre co-product streams from whole maize kernels prior to fermentation. Front-end fractionation has

MAIN MESSAGES

- **Maize, cellulosic, and sugar cane ethanol have been the subject of life-cycle analysis with the GREET model, as has been biodiesel produced from soybean.**
- **Co-products of biofuels, including animal feeds such as distiller grain with solubles, have significant effects on life-cycle energy consumption and greenhouse gas emissions associated with biofuels.**
- **In the past decade, production of maize ethanol has become more energy efficient, both on the farm and at the factory.**
- **Land-use change greenhouse gas emissions can significantly affect life-cycle impacts of biofuels, and these remain a subject of active research and debate.**
- **Biofuels offer life-cycle energy consumption and greenhouse gas emission advantages compared with conventional petroleum-derived fuels. Co-products influence these life-cycle impacts. The allocation methodology selected to divide well-to-pump life-cycle burdens among co-products influences life-cycle results, at times considerably.**
- **Water consumption impacts for biofuels are dependent upon the growing location and associated irrigation practices. Cellulosic ethanol has the potential to have a lower water consumption impact than gasoline.**

FIGURE 1
System boundary of life-cycle analysis of maize [corn] ethanol

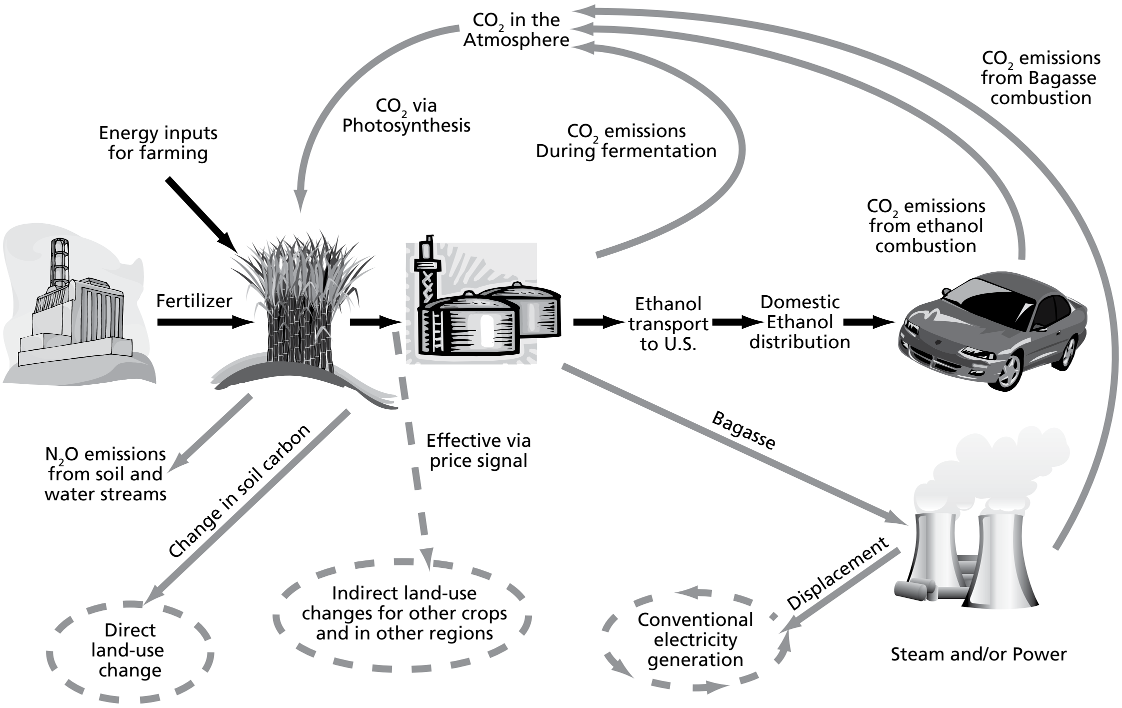


emerged as a promising technology to reduce energy use, increase ethanol yield and produce valuable co-products. Dry mills can also adopt a maize-oil extraction step, in which maize oil is removed from the stillage, or distillation column output stream, and used as animal feed or as a biofuel. Dry mills have eclipsed wet mills as the dominant maize ethanol production technology and currently account for nearly 90 percent of the total United States capacity (Wang *et al.*, 2011).

In Brazil, ethanol is produced from sugar cane, as Figure 2 illustrates. Sugar cane mills extract sugar juice from the cane. The juice is fermented to produce ethanol and possibly sugar. Combustion of solid residues (bagasse) from juice extraction produces steam and electricity, which mills integrate into the plant to improve energy efficiency. Brazilian mills have exported surplus electricity beyond the plant gate since 2000.

Second-generation biofuels are produced from lignocellulosic feedstocks such as maize stover, forest

FIGURE 2
System boundary of life-cycle analysis of sugar cane ethanol



residue and dedicated energy crops (switchgrass, miscanthus and various other plants). Figure 3 sketches the life cycle of ethanol from switchgrass. Conversion technologies for these feedstocks are at pilot-plant scale now, and research and development activities abound in China, the EU and the United States (e.g. Feng *et al.,* 2011; Scordia *et al.*, 2011). Because commercial-scale lignocellulosic facilities are in development, techno-economic analyses and LCAs of this technology are based on process models, such as those produced by the National Renewable Energy Laboratory (Humbird *et al*., 2011). In general, prior to fermentation, cellulosic feedstocks must undergo a chemical, thermal or biological pre-treatment step to release sugars from biomass and separate lignin. The subsequent fermentation step converts the sugars to ethanol. Combustion of lignin can fuel on-site steam and power generation. As with sugar cane ethanol plants, this on-site power can be used at the plant and possibly exported to the grid. This ability of second-generation biofuels to produce power as a co-product is an attractive characteristic. Further, feedstocks such as maize stover and forest residues do not compete directly with food production. Feedstocks such as dedicated energy crops pose less competition with food production than do grains and oilseeds as biofuel feedstocks.

Third-generation biofuels include biodiesel and renewable diesel from algae, and other hydrocarbon fuels similar to gasoline and diesel (sometimes called drop-in fuels) from cellulosic biomass via gasification, pyrolysis and hydro-liquefaction. Significant research and development efforts are underway to develop technologies for these third-generation biofuels. Besides biofuels from algal oil, algal feedstocks can provide significant amounts of biomass for methane production via anaerobic digesters. The bio-methane can be further used for electricity production. Production of hydrocarbon fuels from biomass can co-produce other energy products such as electricity and fuel gas.

MARKET POTENTIAL OF BIOFUEL CO-PRODUCTS

As noted above, the production of starch and lignocellulosic ethanol results in the generation of several co-products. This section discusses co-products from these pathways, as well as co-products generated from soybean and rapeseed-derived biodiesel. Table 1 catalogues co-products yields in various selected biofuels pathways analysed by Argonne National Laboratory (2010).

ANIMAL FEED BY-PRODUCTS OF MAIZE STARCH ETHANOL MANUFACTURING

As discussed above, DGS, used as animal feed, is a co-product at dry-mill ethanol plants. A plant’s decision to produce WDGS or DDGS must weigh the competing costs of the energy to dry DGS to make DDGS against the shorter shelf life and increased transportation costs of heavier WDGS,

FIGURE 3
System boundary of life-cycle analysis of cellulosic ethanol

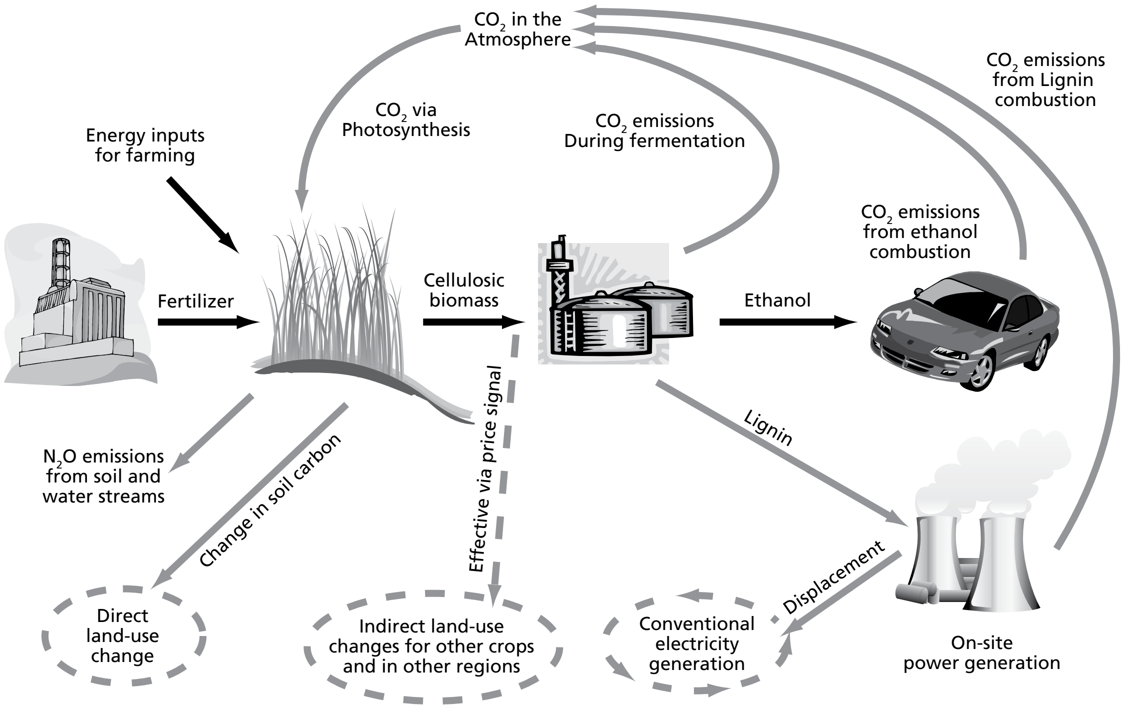


TABLE 1
Product yields of different biofuel production pathways

Product	Yield
Maize to ethanol: per litre of maize input	
Ethanol: undenatured litres[(1)]	0.28
DGS: kg (dry matter)	0.19
Switchgrass to ethanol: per dry tonne of switchgrass input	
Ethanol: undenatured litres	374
Electricity credit: kWh	226
Soybean crushing: per litre of soybean input	
Soy oil: kg	0.14
Soy meal: kg (dry matter)	0.53
Soy oil to biodiesel: per kg of soy oil input	
Biodiesel: kg	0.96
Glycerin: kg	0.21
Soy oil to renewable diesel: per kg of soy oil input	
Renewable diesel: kg	0.66
Fuel gas: kg	0.17
Heavy oils: kg	0.12

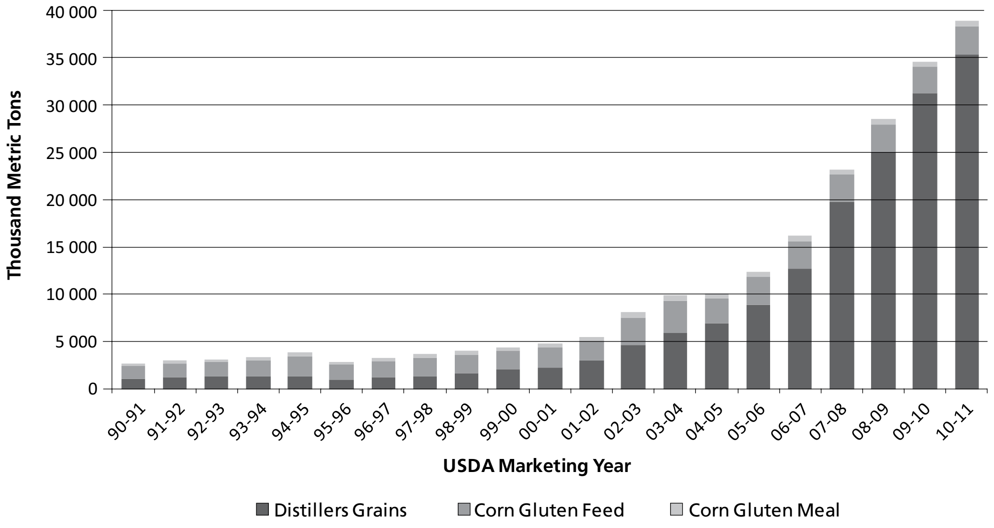
Notes: (1) Ethanol yield for average of wet and dry mills.
Source: Argonne National Laboratory, 2010.

which limits its customer base to a roughly 100-mile radius. In 2007, approximately one-third of dry- ethanol mills reported selling WDGS rather than DDGS.

Production of DGS continues to increase in the United States, as Figure 4 depicts. DGS provides between 10–20 percent of dry-mill ethanol plant revenues (Arora, Wu and Wang, 2010). Table 2 outlines the United States DGS market size on the basis of grain consuming animal units (GCAU). With 100 percent market penetration of given DGS inclusion rates for different animals, the market for DGS across all animal types would exceed the amount of DGS produced if the United States produces 56 billion litres of ethanol in 2015, as Congress has legislated. Assuming 100 percent market penetration and using the 2010 market price for DGS (US$ 136 per tonne) (ERS/USDA, 2011), the total value of DGS produced would be US$ 5.1 billion. Approximately 19.6 percent of the US production of DGS could be exported (Arora, Wu and Wang, 2010).

Table 3 compares maize ethanol co-product properties to those of conventional animal feeds. Experience with feeding DGS to livestock has revealed some benefits to replacing traditional feed with DGS. For example, beef cattle fed with DGS gain weight faster and can be brought to market sooner than conventionally-fed animals, which also affects ethanol life-cycle GHG emissions, as will be discussed later. In short-term studies, dairy cattle produced more milk when their diet included up to 30 percent co-products and energy and protein sources were also replaced at equal levels with maize grain and soybean meal. Long-term studies did not find a detrimental or beneficial effect to including DGS at this level. Because of its availability, price and effect on performance, consumption of DGS has expanded beyond the traditional feeding of ruminants (beef and dairy cattle) to

FIGURE 4
Domestic production of DGS



Source: RFA, 2011.

TABLE 2
United States distillers grain market size as DDGS on an as fed or sold basis (Arora, Wu and Wang, 2010)

Animal type	GCAU (10^6 units)	Feed per GCAU(1) (tonne/unit)	DGS inclusion (%)	Potential DGS usage at different market penetration levels ($\times10^3$ tonne)	
				50%	100%
Dairy	10	4.0(2)	20	4 020	8 041
Beef	20	2.2	20	4 236	8 472
			40	8 472	16 943
Swine	26	2.2	10	2 821	5 642
Poultry	31	2.2	10	3 278	6 556
Total market size(3)				18 591	37 181

Notes: GCAU = grain consuming animal units. (1) Includes energy feeds (i.e. grains), oilseed meals, animal-protein feeds, grain-protein feeds and other by-product feeds. Excludes feeding of distillers grain because of data unavailability. No roughage (i.e. alfalfa hay) is included. (2) Corrected on the basis of the feed consumption report by Anderson *et al.*, 2006, assuming an annual feeding period of 300 days and a feed DM content of 85.5%. Represents the maize and soybean meal portion of the diet. Total feed per dairy-GCAU is 8.21 tonne/year. (3) 40% inclusion for beef.

TABLE 3
Properties of maize ethanol co-products and conventional animal feeds on a dry matter basis

Animal feed and other co-products	Dry matter (%)	Crude protein (%)	Fat (%)	Low heating values (MJ/kg)
Maize	85.5	8.3	3.9	18.7
Soybean meal	87.8	50.1	1.4	18.5
DDGS	89.2	30.8	11.2	20.2
WDGS	30.0	36.0	15.0	20.2(3)
d-DGS(1)	92.3	34.0	2.7	20.2(3)
HP-DDG(2)	87.5	48.6	3.4	20.2(3)
Maize gluten feed	89.4	23.8	3.5	18.5
Maize germ	90.6	17.2	19.1	NA
Maize oil	—	—	—	17(4)

Notes: (1) De-oiled DGS. (2) High-protein dried distillers grain. (3) Assuming low heating values equal to DDGS on a DM basis. (4) Assuming low heating value equal to soybean oil.

monogastric animals (swine, poultry). DGS-fed monogastric animals have not exhibited superior performance.

The incorporation of technologies such as maize fractionation and maize oil extraction have enabled the production of new, higher-value co-products that may enter the market and change the co-product mix. These co-products include high-protein dried distillers grain (HP-DDG), maize gluten feed, maize germ, de-oiled DGS and maize oil. As these co-products displace significant amounts of conventional feed, LCA practitioners must monitor their market penetration and effect on the environmental impacts of ethanol.

Electricity generation with cellulosic ethanol

Cellulosic ethanol plants have the potential to produce electricity from the combustion of lignin. The National Renewable Energy Laboratory (NREL) calculates a net export of electricity of 0.61 kWh per litre of cellulosic ethanol produced from maize stover and switchgrass (Wang, Huo and Arora, 2011). Using the 2010 rate for industrial electricity in the United States (6.54 cents per kWh) (EIA/DOE, 2011), the electricity generated during the production of cellulosic ethanol could be worth US$ 0.04 per litre, or US$ 9 million annually for a 227 million L/year capacity cellulosic ethanol plant (Humbird *et al.*, 2011).

Electricity generation with sugar cane ethanol

During the production of sugar cane ethanol in Brazil, 0.25 kWh/litre ethanol of surplus electricity is generated. In 2009, the rate for industrial electricity in Brazil was US$ 0.159 per kWh (IEA, 2011). The electricity co-produced at a sugar cane ethanol plant could therefore be worth the same amount per litre in Brazil as in a cellulosic ethanol plant in the United States, or US$ 0.04/L.

Sugar is also a by-product of sugar cane ethanol manufacturing. Market demand determines the split between sugar and ethanol produced at sugar cane ethanol plants.

Co-products with biodiesel

Biodiesel can be made from several feedstocks, depending on the region of production: soybeans (North America), rapeseed oil (Europe) and palm oil (Southeast Asia). Palm oil by-products with market potential include palm kernel oil, which can replace coconut oil; palm kernel extract (an animal feed); and glycerin (a feedstock for specialty chemicals) (Bauen *et al.,* 2010). Rapeseed oil by-products include rapeseed meal (an animal feed) and glycerin (Bauen *et al.,* 2010). Animal fat and waste cooking oils can also serve as biodiesel feedstocks, but co-products of animal origin are not permitted to enter the animal food chain.

Figure 5 shows the pathways and co-products for biodiesel and renewable diesel from soybeans. Renewable diesel, with properties very similar to petroleum diesel, is produced via hydrogenation or hydrotreating. In the biodiesel pathway, soybean meal, an animal feed, is an output of the soybean crushing operation, which also produces soybean oil. Subsequent transesterification of soybean oil produces biodiesel and glycerin.

FIGURE 5
Biodiesel and renewable diesel pathways based on soybean

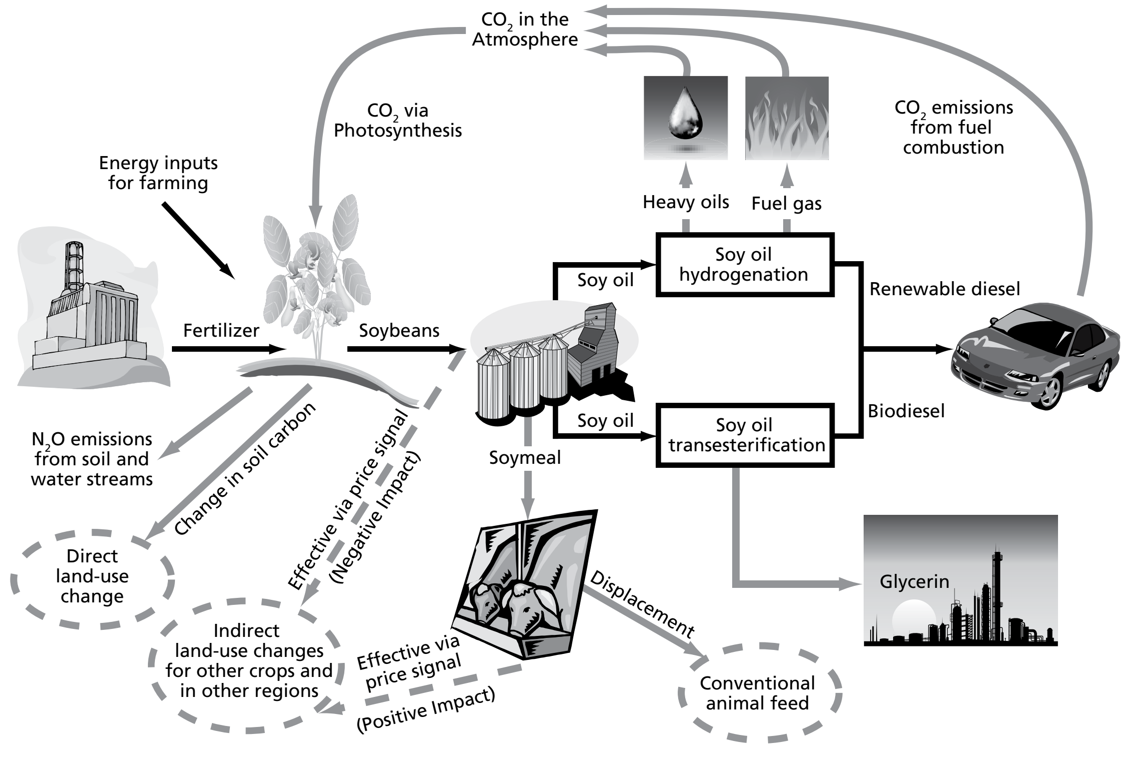
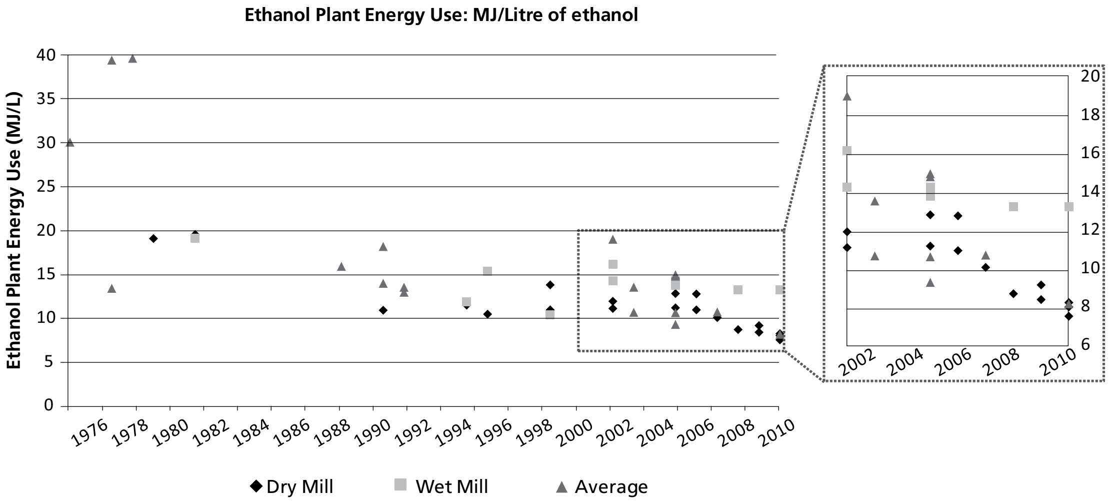


FIGURE 6
Historical trend of United States maize ethanol plant energy use (MJ per litre of ethanol)



Source: Wang *et al.*, 2011

LCA OF BIOFUELS

Improvements in energy efficiency of maize ethanol plants

Recently, Argonne National Laboratory updated the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model's simulation of ethanol life-cycle impacts (Wang *et al.,* 2011). One enhancement in this analysis is Argonne's accounting for the shifts in the predominant ethanol production technology and enhancements in energy efficiency in ethanol production over the previous eight years. As discussed earlier, energy-efficient dry maize ethanol mills have become the dominant technology in maize ethanol production. Figure 6 illustrates the increasing energy efficiency of maize ethanol plants as a result of this trend. In this figure, average values are for dry- and wet-mill ethanol plants combined. For a single year, the values for dry mills, wet mills and combined dry and wet mills are sometimes from different studies. As a result, average values are sometimes outside the range of the individual values for dry mills and wet mills.

Reduction in fertilizer use and enhanced energy efficiency on maize farms

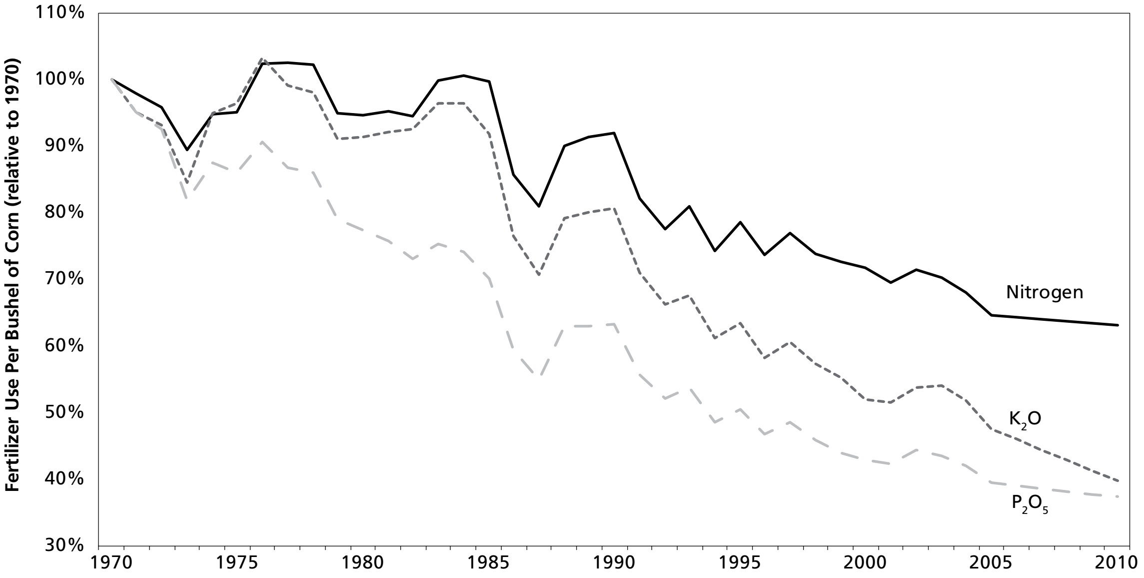
Agricultural practices have become more efficient in the past several decades, consuming less fuel and chemicals per litre of maize harvested. United States Department of Agriculture (USDA) data indicate that fertilizer intensity (kg fertilizer/litre of maize harvested) is decreasing. This decrease, depicted in Figure 7, reduces the environmental impact of ethanol production (Wang, Wu and Huo, 2007). For example, from 1975 to 2010, United States farms decreased nitrogen fertilizer application by 37 percent. In addition to cutting upstream impacts from fertilizer manufacturing, less N fertilizer application reduces life-cycle GHG emissions in a second way because nitrogen fertilizer releases nitrous oxide (N_2O), a potent GHG, when it undergoes nitrification and denitrification on farm fields. Further reducing maize ethanol's life-cycle energy consumption, farming operations in the United States have become more energy efficient, consuming less diesel fuel, natural gas, propane and electricity as Figure 8 illustrates. Note that in 1996, wet weather in the US Midwest caused abnormally high energy use during harvest.

CO-PRODUCTS

Displacement effects of animal feed by-product

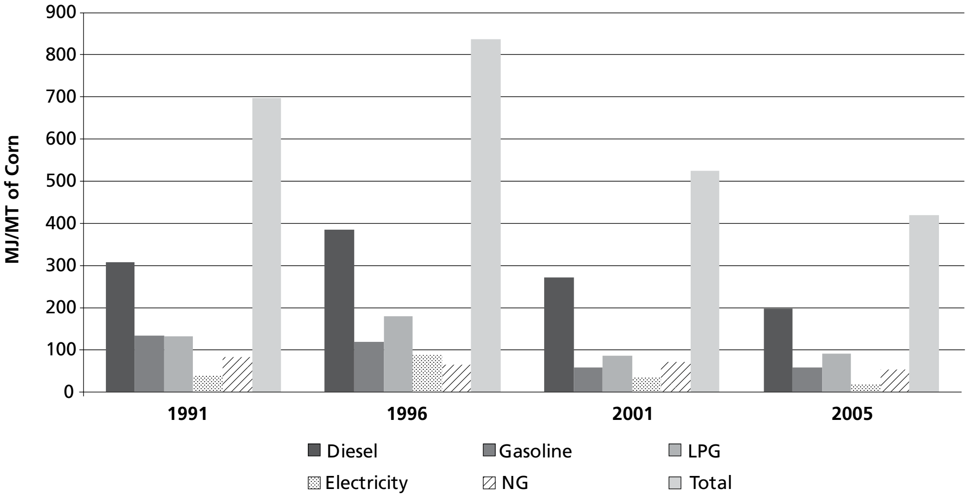
As discussed previously, animal feeds co-produced with maize ethanol can offset the need for conventional livestock feeds, including maize, soybean meal and urea, and in fact may offer improved animal performance when included in animal diets. Sales of ethanol co-produced animal feeds in the animal feed market reduce the energy and environmental impacts of producing conventional animal feeds. Incorporating the displacement of conventional feeds by DGS and other animal feed into the LCA of ethanol therefore provides GHG "credits" for the biofuel. These credits are considered direct credits that are simulated in GREET. Argonne has updated GREET parameters, called displacement ratios, that reflect the displacement of conventional animal feeds by the by-products of ethanol production (Arora, Wu and Wang, 2010). Table 4 contains these ratios at the feedlot level, where feedlot is defined as an animal feeding operation used in factory farming for finishing livestock (e.g. beef and dairy cattle, swine, turkeys and chickens).

FIGURE 7
Relative intensity of United States maize farming fertilizer use from 1970 to 2010



Source: Wang *et al.*, 2011

FIGURE 8
Energy consumption in United States maize farming, 1991 to 2005 (MJ per tonne)



Sources: Shapouri, Duffield and Graboski, 1995; Shapouri, Duffield and Wang, 2002; Shapouri, and McAloon, 2004; Shapouri *et al.*, 2008.

Analysis using these updated ratios shows that DDGS and WDGS could displace 27.9 million tonne of maize, which is 20 percent of the maize projected to be required for ethanol production in 2015 according to the United States Environmental Protection Agency (EPA) renewable fuel standard. With a maize yield of 14 797 litres per hectare by 2015 in the United States, the DDGS and WDGS production levels equate to maize yields from 2.6 million hectare of maize fields. DGS could also displace significant amounts of soybean. The reduced demand for both maize and soybean could produce LUC credits in computable general equilibrium (CGE) modelling for maize ethanol production.

Land-use change

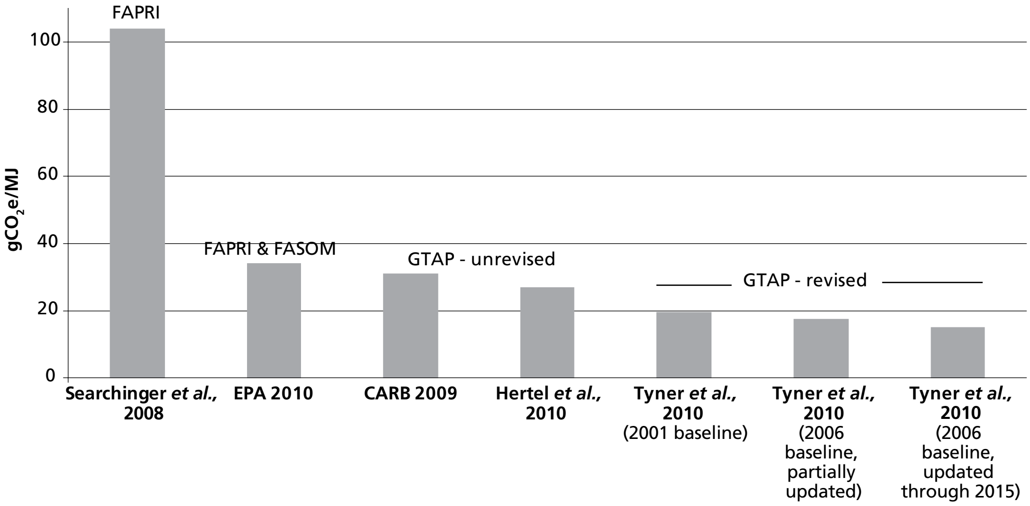
Since early 2008, several studies using economic models simulated direct and indirect LUC associated with the production of maize ethanol and other biofuels in the United States. At first, these economic models did not address several key issues, including crop yield increases in response to increased commodity price, future grain supply and

TABLE 4
Distillers grain with solubles displacement ratios at the feedlot level

	Displacement ratio between DGS and conventional feed (kg/kg of DGS on a DM basis)					
	Dry DGS			Wet DGS		
Livestock	Maize	Soybean Meal	Urea	Maize	Soybean Meal	Urea
Beef Cattle	1.203	0.000	0.068	1.276	0.000	0.037
Dairy Cattle	0.445	0.545	0.000	0.445	0.545	0.000
Swine	0.577	0.419	0.000			
Poultry	0.552	0.483	0.000			
Average	0.751	0.320	0.024			
				Dry and Wet DGS Combined		
				0.788	0.304	0.022

Source: Arora, Wu and Wang, 2010.

FIGURE 9
GHG emissions as a result of land use changes associated with maize ethanol (g CO_2e/MJ)



demand trends without ethanol production (the so-called reference case for global food supply and demand), and accurate modelling of the substitution of conventional animal feed with DGS. One model that permits calculation of LUC is Purdue University's Global Trade Analysis Project (GTAP) model, which has been developed primarily to evaluate global agricultural commodity trade linkages.

GTAP has recently been modified to model maize ethanol production. Figure 9 compares the revised GTAP model predictions of GHG emissions resulting from LUC with previous studies for maize ethanol programmes. The previous studies either used other models (Iowa State University's Food and Agricultural Policy Research Institute (FAPRI) model, Texas A&M's Forest and Agricultural Sector Optimization Model (FASOM)) or older GTAP versions.

The most recent GTAP model version predicts significantly lower LUC and resulting GHG emissions than previous studies. For example, Searchinger *et al.* (2008), who used the FAPRI model, predicted GHG emissions (in gCO_2e/MJ of ethanol) that were 70 percent higher than calculations by California Air Resources Board (CARB, 2009) and Hertel *et al.* (2010), who used an earlier version of GTAP. Revisions to GTAP resulted in an estimate of GHG emissions 85 percent below that of Searchinger *et al.* (2008), as reflected in the results of Tyner *et al.* (2010).

Although the advances made in this work are significant, it should be noted that research is ongoing to further reduce uncertainties in incorporating LUC into economic models. In particular, uncertainties still exist in CGE models, including (1) modelling of DGS and other co-produced animal feeds; (2) global growth in food supply and demand; (3) global available land types and their potential grain production yields; and (4) below- and above-ground carbon stocks for different land cover types.

BIOFUEL LCA RESULTS

Figure 10 displays life-cycle carbon dioxide equivalent (CO_2e) emissions for petroleum gasoline, six types of maize ethanol, three types of cellulosic ethanol, and sugar cane ethanol. Maize ethanol produced at coal-powered plants

FIGURE 10

Life-cycle GHG emissions of petroleum gasoline, maize [corn] ethanol, cellulosic ethanol and sugar cane ethanol

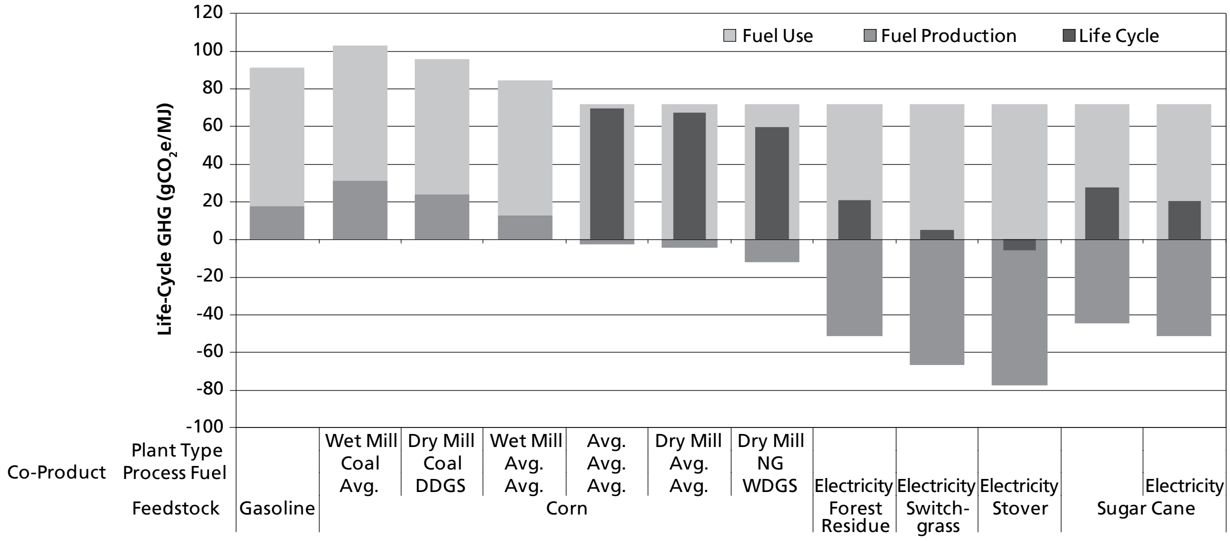
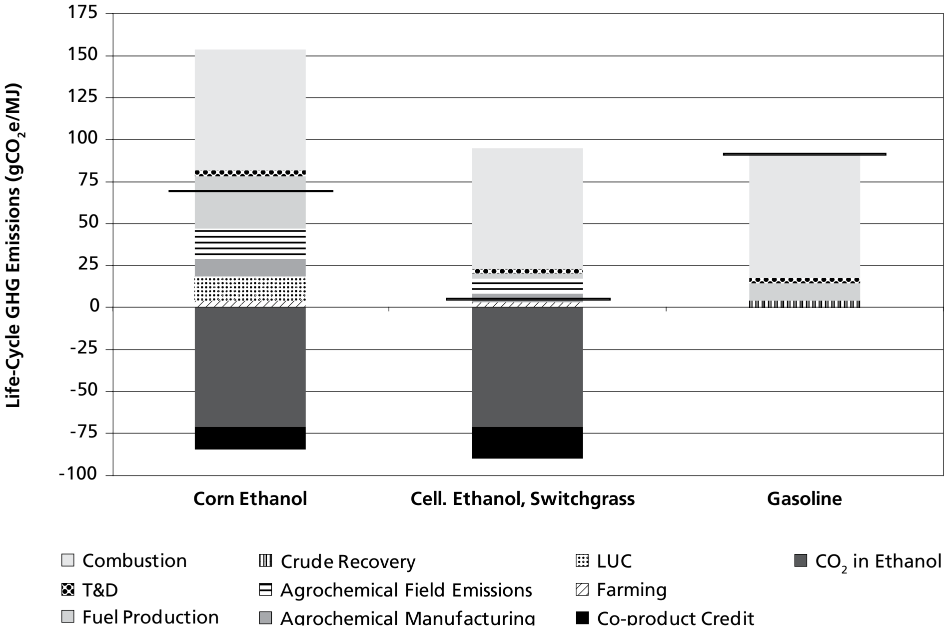


FIGURE 11

Life-cycle GHG emissions sources of maize [corn] ethanol, switchgrass-derived cellulosic ethanol and petroleum gasoline (g CO2e/MJ)



does not offer GHG reductions compared with gasoline. Maize ethanol produced at a dry-milling plant using an average fuel mix (i.e. a mix of natural gas and coal for the ethanol industry), however, does offer a GHG emissions reduction compared with gasoline.

Cellulosic ethanol, regardless of feedstock type, offers significant reductions in GHG emissions compared with gasoline, in part because cellulosic feedstock production requires less energy and fertilizer inputs, and because of the benefits of generating electricity as a co-product. Similarly, sugar cane ethanol has lower life-cycle GHG emissions than gasoline. The benefit is more pronounced when considering electricity as a co-product.

Figure 11 presents GHG emission sources for three fuel types. It is clear that CO_2 uptake during crop growth and co-product benefits result in the reduced GHG emissions advantages of bio-ethanol. Emissions during the use phase constitute the bulk of GHG emissions for both maize and cellulosic ethanol (based on switchgrass).

CO-PRODUCT ALLOCATION METHODOLOGIES AND IMPACTS ON LCA RESULTS

Biofuel co-products introduce complexity into biofuel LCA. Wang, Huo and Arora (2011) explore six methods of allocating energy and emissions impacts among biofuel co-products. Table 5 conveys the differences in methodology among these approaches and the advantages and drawbacks of each. Wang, Huo and Arora (2011) considered the pathways and the displaced products listed in Table 6. The life-cycle impacts of gasoline and diesel were included in the analysis as baseline fuels, and Wang and co-workers allocated impacts among petroleum refinery co-products by their energy contents. Not every pathway was analysed with all co-product allocation methods. For example, electricity is massless, so evaluation of the switchgrass-to-ethanol pathway did not include a mass-based allocation analysis.

We present well-to-wheel (WTW) energy consumption and GHG emissions results for the biofuel pathways in this analysis. Figure 12 illustrates total energy use for the production of the two petroleum-fuel-based cases and for four biofuel pathways. The feedstock for biodiesel and renewable diesel is soybeans (Figure 5). All biofuel pathways consume more energy than the petroleum-based fuels because, when biomass feedstocks undergo conversion to biofuels, a larger amount of energy is lost. When considering fossil energy use in Figure 13, however, biofuels consume less fossil energy in their life cycles than do petroleum-based fuels. This is because while energy in a petroleum feedstock is fossil energy, energy in biomass is not fossil energy. Sometimes, energy debates on biofuels vs petroleum fuels centre on total energy. But the renewable energy in biofuels is not relevant to energy issues such as energy resource deple-

TABLE 5
Co-product allocation methodologies in LCA

Code	Method	Description	Benefits	Drawbacks
D	Displacement	Determine life-cycle impacts of conventional products to be displaced by biofuel co-products. Account for the displacement of these impacts by the biofuel co-product in the biofuel LCA.	Tends to represent actual effects of creating multiple products.	Must conduct LCAs for conventional, displaced products. May produce distorted results when a significant amount of biofuel co-product is produced.
M	Mass-Based	Allocate energy use and emissions burdens by mass output shares.	Straightforward assumptions. Typically used in consumer product LCAs.	Problematic when co-products have different uses (e.g. electricity vs fertilizer) or no mass (electricity).
E	Energy-Based	Allocate energy use and emissions burdens by energy output shares.	Applicable when majority of products are energy (e.g. fuels or electricity).	Problematic when co-products have different uses (such as nutrition for animal feed).
$	Market Value	Allocate energy use and emissions burdens by economic revenue shares of individual products.	Normalizes all products to a common basis regardless of use.	Subject to price fluctuations, including those in the future. Does not reflect physical processes consuming energy and generating emissions.
P	Process-Purpose	Estimate energy use and emissions burdens of individual processes in a facility, and assign to products.	Straightforward when unit processes produce a single product.	Many processes have multiple product outputs. Requires detailed energy and emission data at process level for a facility. Energy and emissions upstream of the facility still require use of other allocation methods.
H	Hybrid Allocation	Combine one or more of above methods.	Obtain more precise allocation of impacts.	Increases complexity of analysis. Creates inconsistency of allocation methods.

Notes: The code column refers to horizontal axis labels in Figures 12 to 14, q.v.

TABLE 6
Conventional products to be displaced by biofuel co-products for the displacement method

Biofuel pathway	Co-products	Displaced products	GHG Credit (g CO_2e/MJ biofuel)
Maize to ethanol	DGS	Maize, soybean meal, urea	12
Switchgrass to ethanol	Electricity	United States average electricity	19
Soybeans to biodiesel	Soybean meal	Soybeans	24
	Glycerin	Petroleum glycerin	0.46
Soybeans to renewable diesel	Soybean meal	Soybeans	34(1)
	Fuel gas	Natural gas	0.38
	Heavy oil	Residual oil	0.26

Notes: (1) The GHG credit in grams per MJ of fuel of soybean meal for renewable diesel is larger than that for biodiesel because fuel yield in MJ per unit of soybean is smaller for renewable diesel than for biodiesel. Thus, normalization of soymeal credit to fuel production results in larger credits for renewable diesel than for biofuels.

FIGURE 12
Well-to-wheels total energy use of petroleum fuels and biofuels (J/MJ). *Notes:* For codes, see Table 5; EtOH = ethanol

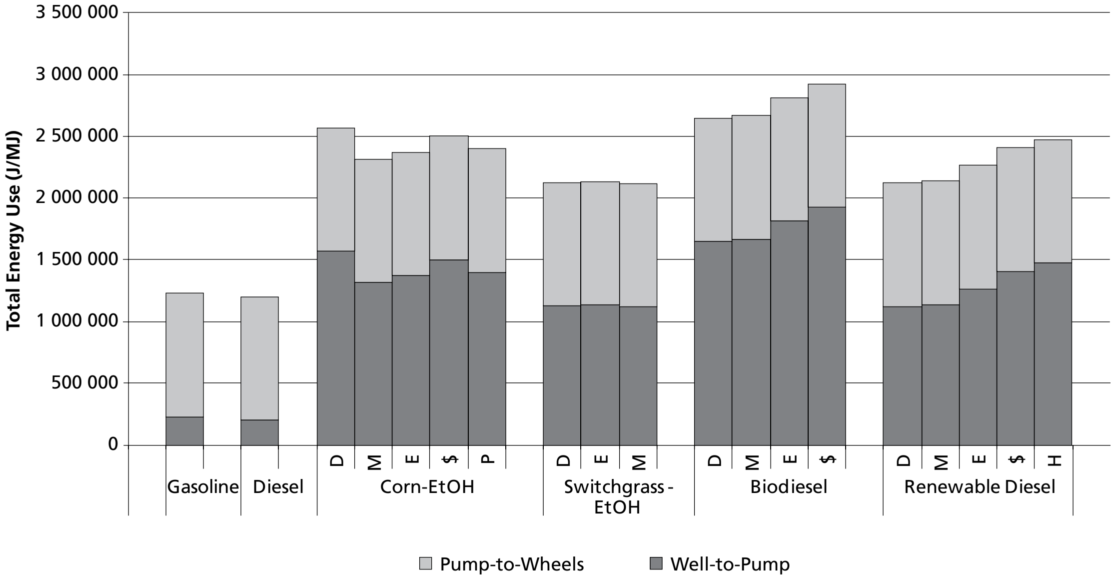
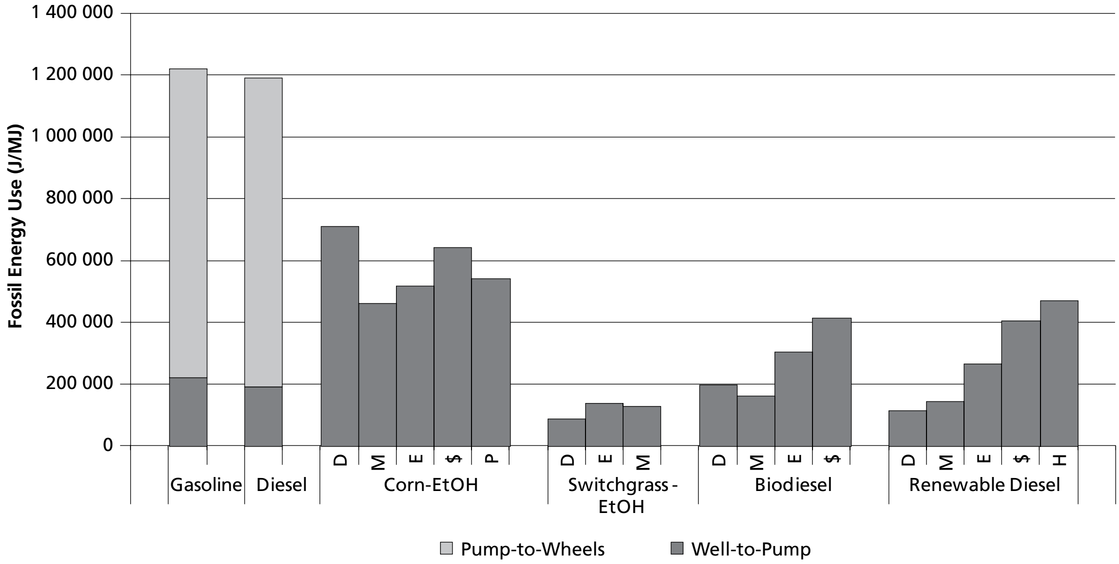


FIGURE 13
Well-to-wheels fossil energy use of petroleum fuels and biofuels (J/MJ) *Notes:* For codes, see Table 5; EtOH = ethanol

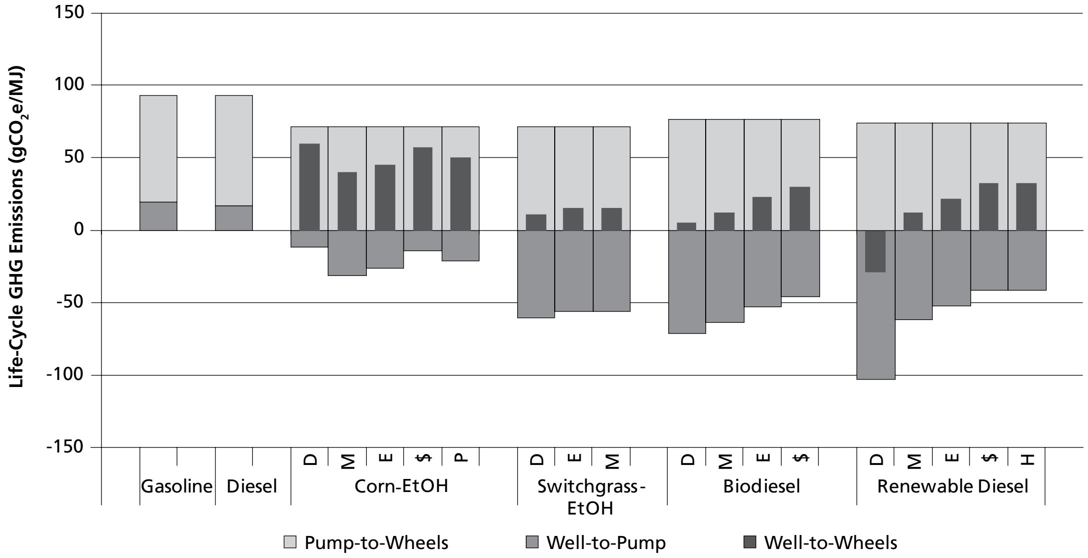


tion and national energy security. More meaningful energy debates should focus on fossil energy or imported energy (such as petroleum energy in the United States context). Figure 14 depicts WTW GHG emissions for each of the pathways analysed. The horizontal axis labels in Figures 12 to 14 refer to the code column in Table 5.

In Figures 13 and 14, the effect of co-product allocation methodologies is strongest for biodiesel and renewable diesel. This result stems from the high mass of a non-fuel product (soybean meal) that is produced as a by-product of soybean crushing and oil extraction in the pathways of these two fuels. In the biodiesel pathway, for example, crushing one litre of soybeans yields 0.14 kg and 0.53 (dry) kg of soy oil and soy meal, respectively. Four times more animal feed than oil is therefore produced, strongly affecting model outputs as the allocation methodology changes.

FIGURE 14

Well-to-wheels GHG emissions of petroleum fuels and biofuels (g/MJ) *Notes:* For codes, see Table 5; EtOH = ethanol



The biofuels community has not standardized its approach to allocation of environmental impacts among co-products in biofuel LCA. Based on the results of this analysis, however, Wang, Huo and Arora (2011) recommend that LCA practitioners apply the following convention:

- When an energy product is the main product, non-energy products can be called by-products. Other energy products can be called co-products.
- When energy and non-energy products are produced equally (according to mass, energy or revenue allocation), both products can be called co-products.

In the former case, the displacement method can be used for energy product LCA. In the latter case, the displacement method may not be appropriate for an LCA of the energy product. To cite an example considered herein, in a dry-mill maize ethanol plant, ethanol and DGS are produced at rates of 0.22 and 0.19 kg/L, respectively, and thus may be treated as co-products with the displacement allocation methodology.

Most importantly, LCA practitioners must maintain transparency when delivering biofuel LCA results, clearly explaining their allocation methodology in dealing with joint products and conducting sensitivity analyses of different allocation methods. For detailed discussions, see Wang, Huo and Arora (2011).

WATER CONSUMPTION ALLOCATION BETWEEN ETHANOL AND CO-PRODUCTS

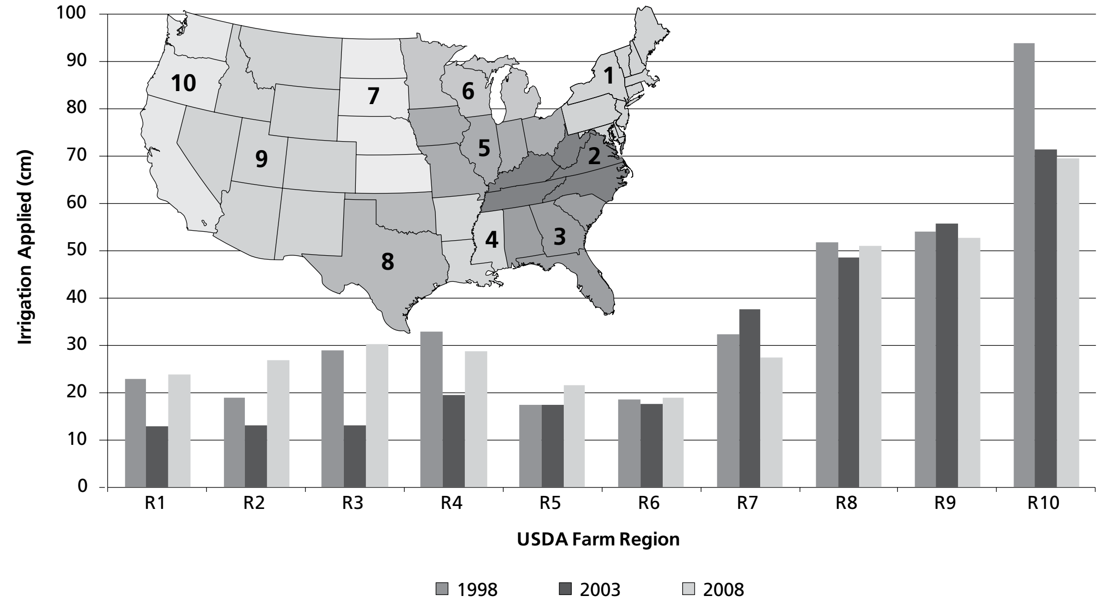
Co-products of starch and cellulosic ethanol production affect not only the allocation of energy consumption and GHG emissions, but of water consumption as well. A recent study (Wu and Chiu, 2011) considered water consumption in the production of first- and second-generation biofuels, comparing water consumption in these fuel pathways to water consumption during the production of traditional gasoline from United States conventional crude, Saudi Arabian crude and Canadian oil sands. The authors also allocated water use among biofuels and their co-products (DDGS and electricity). The study included in its scope the feedstock production (growth and harvesting) and fuel production steps of the fuels' lifecycles. It defined water consumption as the difference between freshwater input during both feedstock and fuel production and used water that is recycled or returned to water bodies. Irrigation water, process water and make-up water for fuel processing were considered water inputs. Consumed and recycled water were considered total water output. Finally, water loss includes evaporation, discharge, disposal and uptake into products.

The study included USDA Regions Five, Six and Seven (Figure 15) because the bulk of the nation's biofuel feedstock and ethanol derives from these regions. The authors estimated consumptive irrigation water use for each region and determined ethanol plant water consumption use in the regions.

For cellulosic ethanol, the authors assumed the switchgrass feedstock to be grown without irrigation. Water consumption during fuel processing was determined from a NREL process model (Humbird *et al.*, 2011) because technology for converting lignocellulosic feedstocks to biofuels is not yet fully commercialized.

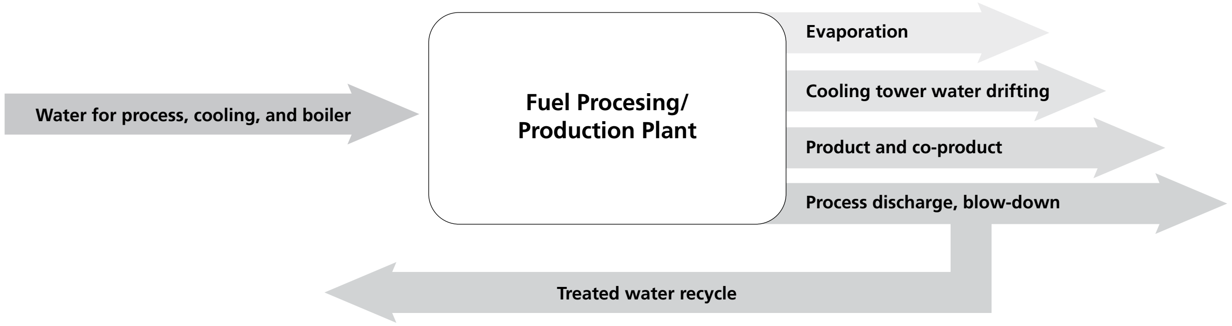
Ethanol manufacturing from maize uses water during grinding, liquefaction, fermentation, separation and drying.

FIGURE 15
Irrigation rate for irrigated maize by USDA Region



Sources: USDA, 2003, 2008.

FIGURE 16
Water inputs and outputs for bio-ethanol production and oil refining



Source: Wu and Chiu, 2011.

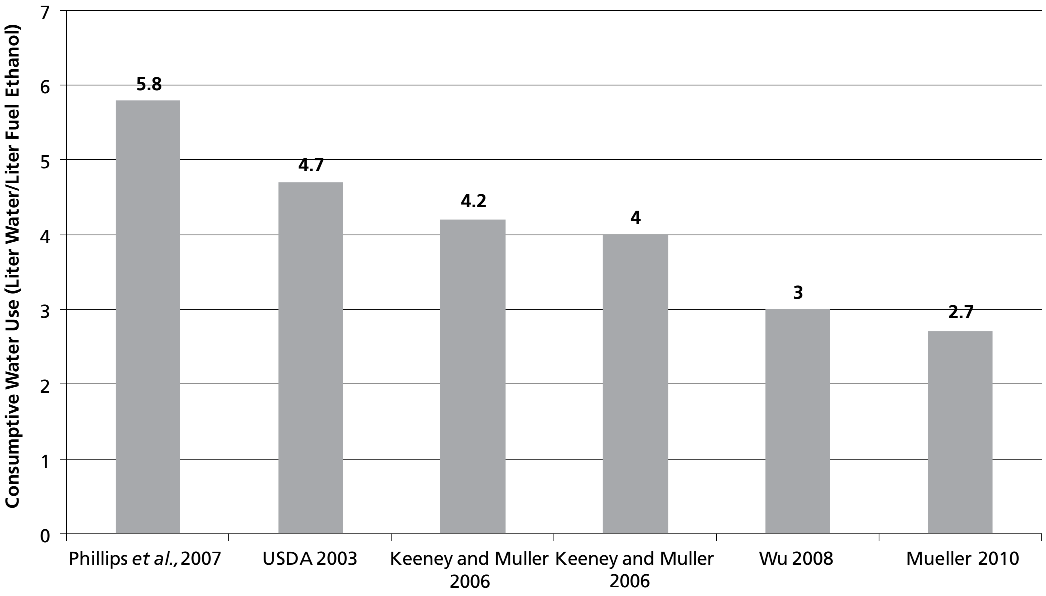
The process also consumes water as a source of cooling and heating. Figure 16 depicts the division among water sinks during ethanol production, the most significant of which are the cooling tower and the dryer.

Water management practices in maize farming and ethanol production are favourably affecting ethanol's water consumption footprint. Although the feedstock production phase is generally the most water-intensive phase in a biofuels' life cycle, water management practices in the agricultural sector are improving such that the volume of irrigation water declined 27 percent over the last 20 years while maize yields consistently increased. Data from different sources (Figure 17) illustrate that water use during ethanol production is also decreasing. Water stewardship practices in ethanol production include increasing process water recycling and steam integration. Plant siting at a location where the facility will not unduly affect groundwater levels is also critical to reducing the water impacts of ethanol production.

Table 7 outlines water consumption during growth, harvesting and conversion of maize to ethanol for USDA Regions Five, Six and Seven. In this table, consumptive water during crop production (irrigation) and conversion is divided between maize ethanol and its co-product, DDGS, based upon a heuristic that in dry-mill plants, one-third of the carbon in the maize kernel is converted to each

FIGURE 17

Average water consumption in existing maize dry-mill ethanol plants



Source: Wu *et al.*, 2011.

TABLE 7

Consumptive water use from maize farming to ethanol production in USDA Regions 5, 6 and 7 (litre water per litre denatured ethanol produced)

USDA Region	Region 5	Region 6	Region 7
Share of United States ethanol production capacity (%)(1)	50	15	23
Share of United States maize production (%)(2)	50	16	23
Maize irrigation, groundwater(3)	12	19	224
Maize irrigation, surface water (3)	2	3	12
Ethanol production(4)	3	3	3
Total (maize irrigation and ethanol production) without co-product allocation	17	25	239
Total water consumption with mass-based co-product allocation(5)	11	17	160

Notes: (1) Based on 2008 ethanol production capacity in operation (RFA, 2011). (2) Based on 2008 maize production (USDA-NASS, 2011). (3) USDA, 2008. (4) Production-weighted average (Wu, 2008). (5) Mass-based and carbon displacement-based allocation according to the heuristic that one-third of biomass in maize kernel goes to ethanol, one-third goes to CO_2 and one-third goes to DDGS.

TABLE 8

Water consumption for cellulosic ethanol production

Process	Average water consumption (litre/litre biofuel)	Electricity export (kWh/litre biofuel)	Average water consumption after co-product allocation (litre/litre biofuel)
Biochemical (Humbird *et al.*, 2011)	5.4(1)	0.47–0.55(3)	4.5–4.6
Gasification (Phillips *et al.*, 2007)	1.9(1)	0	1.9
Pyrolysis (Jones *et al.*, 2009)	2.3(2)	0	2.3

Notes: (1) Cellulosic ethanol produced from switchgrass. (2) Forest residue as feedstocks. (3) Maize stover 1.77 kWh/gal and Switchgrass 2.07 kWh/gal, both from a 2000-dry- ton/day ethanol plant. *Source*: Wu and Chiu, 2011.

of ethanol, DDGS and CO_2 emissions during conversion. Irrigation water is allocated with the same ratio (one-third assigned to maize, one-third assigned to ethanol).

Table 8 compiles water consumption during production of cellulosic ethanol from maize stover, switchgrass,and forest residue (Wu and Chiu, 2011). No irrigation water is included because, in contrast to maize, these feedstocks may not require irrigation. The electricity generated during cellulosic ethanol production can displace conventionally-produced electricity, the production of which consumes on average 1.6 litres per kWh in the United States (Wu and Chiu, 2011). As a result, 0.75 to 0.89 litres of water per litre of cellulosic ethanol are conserved when ethanol is produced via biochemical technology. The consumptive water use attributed to each litre of cellulosic ethanol produced is therefore 4.5 to 4.6 litres.

TABLE 9
Water consumption for ethanol and petroleum gasoline production

Fuel (feedstock)	Net water consumed	Major factors affecting water use
Maize ethanol(1)	11–160 L/L ethanol(2)	Irrigation requirements vary regionally because of different climate and soil types
Cellulosic ethanol(1)	0.47–0.55 L/L ethanol	Production technology
Gasoline (USA conventional crude)(3)	3.4–6.6 L/L gasoline	Age of oil well, production technology and degree of produced water recycle
Gasoline (Saudi conventional crude)	2.8–5.8 L/L gasoline	Age of oil well, production technology and degree of produced water recycle
Gasoline (Canadian oil sands)(4)	2.6–6.2 L/L gasoline	Geological formation and production technology

Notes: (1) Water consumption allocated between co-products. (2) USDA regions 5, 6 and 7 combined for maize. Irrigation water included for maize. (3) Petroleum Administration for Defense Districts II, III and V combined. (4) Includes thermal recovery, upgrading, and refining.
Source: Wu and Chiu, 2011.

This study also developed estimates of water consumption during production of petroleum-based fuels. Table 9 compares the net water consumed among bio- and petroleum-based fuels. Maize ethanol has the most significant water footprint of the fuels examined, although if maize is produced with little irrigation, the water consumption during its production will be closer to the lower end of the range reported in Table 9. It is also important to note that data for oil production has more gaps than data for biofuel production, leading to greater uncertainties in the figures reported for petroleum-based fuels.

Irrigation can have a significant negative impact on water consumption in biofuel production. Growing cellulosic crops like switchgrass in their native habitat without irrigation is critical to maintaining a low level of water consumption. At the same time, water consumption during fuel production in general is decreasing as water management practices in farming, oil recovery and fuel production improve.

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

The evolution of biofuel production technology and co-product types and uses reveal knowledge gaps and future research needs in the LCA of biofuels and their co-products. Second- and third-generation biofuels are a special case in that broad-scale commercialization is still on the horizon. Actual plant energy efficiencies and co-product generation are still in the conceptual domain. As these technologies become mainstream, biofuel LCAs must be adapted to reflect real-world conditions. The agrochemical and energy intensity of feedstock growth and harvesting are also subject to uncertainty, given that many candidate feedstocks are under consideration and their production and harvest have yet to be optimized. Additionally, as co-product quantities and their end uses become clearer, LCAs must incorporate data that reflects their entry into the market and displacement of conventional products.

CONCLUSIONS

Biofuel production technology is rapidly advancing, especially in the case of second- and third-generation biofuels. LCAs conducted with current life-cycle inventory data for biofuels, however, indicate that biofuels probably offer significant environmental and energy consumption benefits in comparison with their traditional, fossil-fuel-based counterparts. All biofuel production pathways jointly produce fuels and other products. Biofuel LCA results can be influenced significantly by the methodologies used to deal with co-products. On the one hand, failure to address biofuel co-products in LCAs generates incorrect LCA results for biofuels, since co-products are often a critical factor for pathway selection and economics of biofuels. On the other hand, the choice of certain co-product methodologies can heavily influence biofuel LCA results. While a co-product methodology may not be universally accepted for different biofuel pathways and for different analysis purposes, transparency of methodology selection and consequent LCA implications need to be clearly presented in any given biofuel analysis.

Water consumption in biofuel production is influenced heavily by biofuel feedstock production. Regional variation in biofuel water consumption is pronounced because of potential irrigation need for biomass growth. Avoidance of irrigation for feedstock growth can help reduce a biofuel's water footprint dramatically. Furthermore, maize ethanol plants have experienced significant water use reductions over the past 20 years. In the future, water use will probably be limited in second- and third-generation biofuel plants.

ACKNOWLEDGEMENTS

Research for this chapter was supported by the United States Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Biomass Program (OBP) under contract DE-AC02-06CH11357. We acknowledge Mr Zia Haq of OBP for his support for this research.

BIBLIOGRAPHY

Anderson, J.L., Schingoethe, D.J., Kalscheur, K.F. & Hippen, A.R. 2006. Evaluation of dried and wet distillers' grains included at two concentrations in the diets of lactating dairy cows. *Journal of Dairy Science,* 89: 3133–3142.

Argonne National Laboratory. 2010. GREET model 1.8d.1 Available at http://greet.es.anl.gov/ Accessed 10 June 2011.

Arora, S., Wu, M. & Wang, M. 2010. Estimated displaced products and ratios of distillers' co-products from corn ethanol plants and the implications of life-cycle analysis. *Biofuels*, 1: 911–922.

Allen, D.T. & Shonnard, D.A. (editors). 2002. *Green Engineering: Environmentally conscious design of chemical processes.* Prentice Hall PTR, Upper Saddle River, New Jersey, USA. See pp. 421–432.

Bauen, A., Chudziak, C., Vad, K. & Watson, P. 2010. A causal descriptive approach to modelling the GHG emissions associated with the indirect land use impacts of biofuels. Final report. A study for the UK Department for Transport. Available at http://www.dft.gov.uk/pgr/roads/environment/research/biofuels/pdf/report.pdf Accessed 26 August 2011.

CARB [California Air Resources Board]. 2009. Proposed regulation for implementing low carbon fuel standards. Staff report: initial statement of reasons, Vol. 1. CARB, Sacramento, CA, USA. 374 pp.

EIA/DOE [Energy Information Administration, U.S. Department of Energy]. 2011. Average retail price of electricity to ultimate consumers by end-use sector, by state. Available at http://www.eia.gov/cneaf/electricity/epm/table5_6_b.html Accessed 9 June 2011.

EPA [United States Environmental Protection Agency]. 2010. Renewable Fuels Standard Program (RFS2) Regulatory Impact Analysis. Assessment and Standards Division, Office of Transportation and Air Quality. Report EPA-420-R-10-006. Washington, DC, USA.

ePure. 2010. Fuel ethanol production data. Available at http://www.epure.org/statistics/info/Productiondata Accessed 16 June 2011.

ERS/USDA [Economic Research Service, United States Department of Agriculture]. 2011. Feed grains database. Available at http://www.ers.usda.gov/Data/FeedGrains/ Accessed 9 June 2011.

Feng, Y., Liu, H.Q., Xu, F. & Jiang, J.X. 2011. Enzymatic degradation of steam pre-treated Lespedeza stalk (*Lespedeza crytobotrya*) by cellulosic-substrate induced cellulases. *Bioprocess and Biosystems Engineering*, 34(3): 357–365.

Hertel, T.W., Golub, A.A., Jones, A.D., O'Hare, M., Plevin, R.J. & Dammen, D.M. 2010. Effects of US maize ethanol in global land use and greenhouse gas emissions: estimating market-mediated responses. *Bioscience*, 60: 223–231.

Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D. & Dudgeon, D. 2011. Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol. Dilute-acid pretreatment and enzymatic hydrolysis of corn stover. *National Renewable Energy Laboratory Technical Report*, TP-5100-47764.

IEA [International Energy Agency]. 2011. Energy prices and taxes, fourth quarter 2010. IEA, Paris, France.

ISO [International Organization for Standardization]. 2006. Environmental management – life cycle assessment – principles and framework. Standard 14040.

Jones, S., Valkenburg, C., Walton, C., Elliott, D., Holladay, J. & Stevens, D. 2009. Production of gasoline and diesel from biomass via fast pyrolysis, hydrotreating and hydrocracking. *Pacific Northwest National Laboratory Technical Report*, PNNL-18284 Rev. 1.

Keeney, D. & Muller, M. 2006. Water use by ethanol plants – potential challenges. Institute for Agriculture and Trade Policy. Available at http://www.agobservatory.org/library.cfm?refid=89449 Accessed 30 June 2011.

Mueller, S. 2010. 2008 National dry mill corn ethanol survey. *Biotechnology Letters,* 32: 1261–1264.

Phillips, S., Aden, A., Jechura, J., Dayton, D. & Eggeman, T. 2007. Thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass. *National Renewable Energy Laboratory Technical Report*, TP-510-41168.

RFA [Renewable Fuels Association]. 2011. 2011 Ethanol Industry Outlook. Available at http://ethanolrfa.org/pages/annual-industry-outlook Accessed 9 June 2011.

Scordia, D., Cosentino, S.L., Lee, J.W. & Jeffries, T.W. 2011. Dilute oxalic acid pre-treatment for bio-refining giant reed (*Arundo donax* L). *Biomass & Bioenergy*, 35(7): 3018–3024.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. & Yu, T.H. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, 319: 1238–1240.

Shapouri, H. & McAloon, A. 2004. The 2001 energy balance of corn ethanol. U.S. Department of Agriculture, Office of the Chief Economist, Report. Washington, DC, USA. 6 p.

Shapouri, H., Duffield, J.A. & Graboski, M.S. 1995. Estimating the new energy balance of corn ethanol. *U.S. Department of Agriculture, Economic Research Service, Report*, AER-721. Washington, DC, USA 15 p.

Shapouri, H., Duffield, J.A. & Wang, M. 2002. The energy balance of corn ethanol: an update. *U.S. Department of Agriculture, Office of the Chief Economist Report,* AER-814. Washington, DC, USA. 16 p.

Shapouri, H., Gallagher, P.W., Nefstead, W., Schwartz, R., Noe, S. & Conway, R. 2008. Energy balance for the corn-ethanol industry. *U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses Report,* AER-846. Washington, DC, USA. 15 p.

Tyner, W.E., Taheripour, F., Zhuang, Q., Birur, D. & Baldos, U. 2010. Land use changes and consequent CO_2 emissions due to US corn ethanol production: a comprehensive analysis. Purdue University, West Lafayette, Indiana, USA. 85 p.

UNICA [Brazilian Sugar Cane Association]. 2011. Brazilian ethanol production. Available at http://english.unica.com.br/dadosCotacao/estatistica/ Accessed on 7 June 2011.

USDA [United States Department of Agriculture]. 2003. 2003 farm and ranch irrigation survey, Available at http://www.agcensus.usda.gov/Publications/2002/FRIS/index.asp Accessed 30 June 2011.

USDA. 2008. USDA 2008 farm and ranch irrigation survey. Available at http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/index.asp Accessed 15 August 2011.

USDA. 2011. Fertilizer Use and Price. Available at http://www.ers.usda.gov/Data/FertilizerUse/ Accessed 8 August 2011.

USDA/NASS. 2011. Database for corn yield. Available at http://www.nass.usda.gov/Data_and_Statistics/index.asp Accessed 15 August 2011.

Wang, M., Wu, M. & Huo, H. 2007. Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. *Environmental Research Letters*, 2: 024001.

Wang, M., Huo, H. & Arora, S. 2011. Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the U.S. context. *Energy Policy,* 39(10): 5726–5736.

Wang, M., Wu, M., Huo, H. & Liu, J. 2008. Life-cycle energy use and greenhouse gas emission implications of Brazilian sugarcane ethanol simulated with the GREET model. *International Sugar Journal,* 110: 527–545.

Wang, M.Q., Han, J., Haq, Z., Tyner, W.E., Wu, M. & Elgowainy, A. 2011. Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes. *Biomass and Bioenergy,* 35: 1885–1896.

Wu, M. 2008. Analysis of the efficiency of the U.S. ethanol industry, 2007. Available at http://www.ethanolrfa.org/page/-/rfa-association-site/studies/argonne2007.pdf?nocdn=1 Accessed 30 June 2011.

Wu, M. & Chiu, Y. 2011. Consumptive water use in the production of ethanol and petroleum gasoline – 2011 update. *Argonne National Laboratory Technical Report*, ANL/ESD/09-1 – Update.

Wu, M., Mintz, M., Wang, M. & Arora, S. 2009. Water consumption in the production of ethanol and petroleum gasoline. *Environmental Management,* 44: 981–997.

Chapter 28

Utilization of co-products of the biofuel industry as livestock feeds – a synthesis

Tim Smith[1] and Harinder Makkar[2]

[1] Former Head, Matopos Research Station, Bulawayo, Zimbabwe

[2] Livestock Production Systems Branch, Food and Agriculture Organization of the United Nations, Rome, Italy

E-mail for correspondence: Harinder.Makkar@fao.org

INTRODUCTION

This book has explored the history of the biofuels industry, and the current state of knowledge with particular reference to co-products and their uses. Furthermore, the perceived gaps in knowledge that could possibly increase the efficiency of use of what is available have been addressed, and predictions made as to how the industry is likely to develop over the next ten to twenty years. The information is summarized in seven sections: (1) Introduction; (2) Background; (3) Ethanol production, co-products and their nutritive value; (4) Biodiesel feedstocks, co-products and their nutritive value; (5) Micro-algae; (6) Economics and socio-economic aspects; and (7) Summary of perceived knowledge gaps and future research needs. The sources of information presented in this book are used as an indication of the major centres of activity for the industry, although there is little information on China, with its approximately 1200 beverage alcohol plants and an ethanol production industry contributing significant amounts of distillers grain to the livestock feed industry (Table 1). This table also presents the primary biofuel product (ethanol or biodiesel) and their co-products and the animal species to which they are likely to be fed.

Geographically, current interest is centred in North and Central America (13 contributions), Europe (5), India (5) and the rest of the world (5). In this book, 19 papers focus on the co-products of ethanol production and 16 on those with those resulting from biodiesel production, with several contributions dealing with more than one co-product. Ruminant nutrition (cattle, buffalo and small ruminants) was a subject in 19 papers, non-ruminants (pigs and poultry) in 14, and fish in 4. The original interest in North America and Europe was in first-generation feedstocks in the form of cereal-based ethanol production and soya- or rapeseed-based production of biodiesel. This generated a continually expanding range of co-products for livestock: ruminants, non-ruminants, poultry and in aquaculture. However, there is now increasing interest in the development of second-generation feedstocks such as cellulosic sources, trees, shrubs and arable crop residues. Ethanol from these materials is produced from cellulose rather than the sugar and starch in first-generation feedstocks. Micro-algae are also of considerable interest and capable of producing co-products, some of which need detoxification before feeding to livestock.

TABLE 1
Country of origin and major topics covered in each chapter of this publication*

Topic	Ethanol	Biodiesel/ Bio-oil	Micro-algea	Ruminants	Non-ruminants	Aquaculture	Humans	Environment issues
Country								
Australia	25	25		25	25			
Brazil	15	14		15	14			14
Canada	26			26	26			
France	9				9			
Germany	7, 11	11, 21		7, 11	11	21		
India	12, 16, 20, 24	20, 22	24	12, 16, 20 22, 24	12, 22, 24	24	24	12, 16, 20, 22, 24
Israel		18		18				18
Malaysia		13		13	13	13		13
Switzerland		19		19	19			
UK	2							2
USA	1, 3, 4, 5, 6, 10, 23, 27	1, 3, 8, 10, 17, 23, 27		1, 5, 6, 8, 27	1, 10, 14, 27	23		1,4, 5, 6, 8,17, 23, 27
TOTALS	19	16	1	19	14	4	1	17

* Numbers in the body of the table denote chapter number in book (see Appendix 1).

Scene setter

Distillers grain co-products have been fed to livestock for more than a century. Currently production far exceeds that of glycerol. Emerging new markets include aquaculture, horses, companion animals and human foods, but these market applications need research support.

Shurson, Tilstra and Kerr

Economics

Today, grain, sugar and oilseeds are the major agricultural commodities for biofuels. This could lead to modest increases in livestock and poultry production costs, but substitution of co-products for traditional feedstuffs could mitigate these increases.

Cooper and Weber

Jatropha

Jatropha is a drought tolerant shrub or tree growing wild on degraded land in Central and Southern America, Africa and large tracts of Asia. Seeds are rich in oil and the kernel meal rich in crude protein. After treatment, both *Jatropha curcas* and *J. platyphylla* residues can replace over half the protein in diets of fish. Non-toxic *Jatropha* species could be valuable feed resources for the future.

Makkar, Kumar and Becker

Small-scale approaches

In India, decentralized crushing and syrup-making units are based on sweet sorghum, providing food, feed, fodder and fuel. The system encompasses small-scale farmers and complements the centralized approach applicable to larger farmers.

Rao et al.

Micro-algae

Production of energy through photosynthetic organisms, like micro-algae, harnessing solar energy might be a viable solution avoiding competition for land, or land-based resources such as fresh water. Residues have potential as chemicals, foods and feeds, but prudent energy audits are needed.

Ravishankar et al.

Oil Palm

Oil palm residues come from the field and processing mills. Their diversity allows complete diets from oil palm products for various livestock species, including in aquaculture. Malaysia needs to increase ruminant production and there is huge potential to integrate this with the oil palm industry.

Wan Zahari, Alimon and Wong

BACKGROUND

Distillers grain (DG), originally a by-product of the alcoholic drink and beverages production industry, has been fed to livestock for many years, initially to pigs and dairy cows. The upsurge in the use of DG was itself a by-product of the search for transport fuel other than from fossil fuels, which in recent years has been supported by a large increase in research funding into the use of co-products (Shurson, Tilstra and Kerr, 3). Currently, co-products are an important feed resource in over 50 countries, for ruminants, non-ruminants and aquaculture (Table 1). The co-products are the residues after extraction of the biofuel, whether ethanol or biodiesel. Biofuels contribute to the twin objectives of increasing fuel security and reducing emissions of greenhouse gases (GHG) (Cooper and Weber, 1). In Europe, the use of fossil fuels for transport contributes an estimated 18 percent of all GHG emissions, a figure that has the potential to be reduced by half through increased efficiencies in use and a projected four-fold increase in the production of biofuels by 2020 (Hippenstiel *et al.,* 11). If achieved, this rate of increase would result in 6 percent of global fuel needs coming from biofuels. As the majority of currently used feedstocks to produce biofuels are crops grown on existing agricultural land, the requirements for food, feed and fuel must be balanced so that the quest for biofuels does not result in an inflationary rise in the cost, or shortage, of food or feed. This raises the question of second-generation feedstocks from cellulosic sources, the use of crop residues and stubbles and woody material grown on marginal land with a minimum of resources, including irrigation (Braid, 25). This approach raises the potential for promoting little-used and non-conventional feeds, such as oil-palm products (Wan Zahari, Alimon and Wong, 13; de Albuquerque *et al.,* 14), micro-algae (Ravishanker *et al.,* 24), Jatropha species (Makkar, Kumar and Becker, 21), lipid co-products (Wiesman, Segman and Yarmolinsky, 18), *Pongamia glabra* (karanj) and *Azadirachta indica* (neem) seed cakes (Dutta, Panda and Kamra, 22), sugar cane bagasse (Anandan and Sampath, 16) and *Camelina sativa* (Cherian, 17). Some may require detoxifying to produce safe livestock feed (Anandan and Sampath, 16; Dutta, Panda and Kamra, 22; Abbeddou and Makkar, 19; Makkar, Kumar and Becker, 21).

ETHANOL

Cereal feedstocks

The European Union has set targets both for the inclusion of non-fossil fuels for road transport and for reduction of GHG emissions, embodied in the Renewable Energy Directive (RED) and the Fuel Quality Directive (FQD) (Lywood and Pinkney, 2). The USA introduced the

Renewable Fuel Standard (RFS) in 2005, which led to the Energy Independence and Security Act of 2007 that sets targets for blending of biofuels with fossil fuels through to 2022 (Cooper and Weber, 1). In Europe, GHG emissions have been reduced in all areas of activity except public energy production (small increase) and road transport (large increase) (Lywood and Pinkney, 2). By 2020, 10 percent of fuels used for surface transport should come from non-fossil sources, and GHG emissions should be reduced by 60 percent with a 6 percent reduction in carbon emissions compared with 100 percent fossil fuel usage (Shurson, Tilstra and Kerr, 3). The present generation of petrol engines can tolerate 10 percent ethanol in the fuel mix. However, diesel engines currently have a maximum tolerance of 7 percent, which, because of the age of the global transport pool, points to a need for rapid improvement in tolerance levels if the 2020 target is to be met.

The feedstocks from which ethanol is produced largely reflect the agriculture area. In the United States of America (USA), maize [corn] (Table 2) is the dominant source (Shurson, Tilstra and Kerr, 3). The USA has also built an export trade in dried distillers grain with added solubles (DDGS), initially to Canada for beef production, but now expanded to a wider market, with an emphasis on pig and poultry production (Shurson, Tilstra and Kerr, 3). The development of wet processing encouraged the siting of plants near beef feedlots to minimize costs of drying and transporting distillers grain. This also encouraged many beef producers to become croppers. However, in the Southern Great Plains of the USA, sorghum is an important feedstock, thus giving rise to considerable quantities of co-products (Galyean *et al.,* 4). In Europe (Hippenstiel *et al.*, 11; Noblet, Cozannet and Skiba, 9) and parts of Canada (Christensen *et al.,* 26) the major cereal contributing to the industry is wheat. Christensen *et al.* (26) have traced the development of the ethanol industry in Western Canada from the beginning, when DDGS was imported from the USA, to the present time. Although imports are still important, locally grown Canadian wheat is now contributing significantly to the distillers grain market.

Other cereals – triticale, barley and rye – can be used, either alone or in combination, but are not significant ethanol feedstocks compared with maize and wheat. The European targets for biofuel production will be met mainly through increased crop yields and continuing cropping of arable land that should have been released from use. The increased availability and use of co-products in livestock feed would partially replace a mixture of EU cereals and imported soyabean meal (Lywood and Pinkney, 2).

Sugar cane and other non-cereal feedstocks

Sugar cane (Table 2) is also a major feedstock for ethanol production. Patino *et al.* (15) estimated that, at the present time, on a global scale, 90 percent of ethanol output is accounted for by maize and sugar cane. In tropical regions of Central and Southern America and Asia, sugar cane is one of the most important crops, and its value as a feedstock is recognized (Anandan and Sampath, 16). Between 1990 and 2009, production of sugar cane in Asia increased by 53 percent, while the land area devoted to its growing only increased by 34 percent, suggesting an improvement in cultivation and harvesting techniques. Two of the major prerequisites for a successful sugar cane industry are a warm environment and water. Cooper and Webber (1) stress the importance of sugar cane as a feedstock in tropical countries with a high rainfall, quoting the example of Brazil, where 98 percent of ethanol production comes from this source. The same authors estimated that in 2010, 93 percent of ethanol production took place in the USA, Brazil and Europe. Other feedstocks listed by Rao *et al.* (12) and Cooper and Webber (1) included tropical sugar beet, sweet potato, cassava and sweet sorghum. In contrast sweet sorghum is favoured by Rao *et al.* (12) because of its tolerance to a wide range of harsh conditions and the number of options for its use, including human food, forage and biofuel production.

Sweet or forage sorghum requires 25 percent of the water needed by sugar cane, and substantially fewer growing days (Rao *et al.,* 12). In the decentralized process, developed for small-scale farmers to operate at a village level, they describe how crushing of the sorghum plant to obtain the juice and then boiling to concentrate this are key actions, with the two principle co-products, or residues, being the bagasse and grain. Grain free from mould is used for human consumption. The juice can then go forward for ethanol extraction or be retained in the village for fermentation to give a mash containing 6–10 percent ethanol. Currently, the system operates for the rainy season crop only because the needs of farmers for food and livestock feed are more easily met from crops grown in drier weather.

New and unconventional feedstocks

The feedstocks discussed above are regarded as first-generation crops. One of their limitations is that they could be seen as being in conflict with what are regarded as the prime objectives of cropping land, namely the provision of food and livestock feed. To combat this, and also to utilize materials traditionally regarded as unusable, there is increasing interest in what have become known as second-generation feedstocks (Shurson, Tilstra and Kerr, 3). These contain large amounts of cellulose (Table 2) and include crop residues (straws and stubble), shrubs and trees. An example is short rotation eucalypts grown for coppicing, which currently account for less than 5 percent of cleared land in Australia (Braid, 25). Trees can provide shade and shelter to the extent that lamb survival, especially those from twin births, is improved by their presence. The use of trees in alley farming is another possibility. Use of stubble requires moving the residue from the field and needs examining in the whole farm context because of disturbance to the nutrient cycle on arable land that might traditionally have been grazed. The total fuel ethanol capacity in Australia is estimated at 330 million litres per year (Braid, 25). Wang and Dunn (27) found that growing feedstocks without irrigation greatly reduced the water footprint of biofuels. They also reported the contribution of cellulosic by-products as a source of electricity. Unconventional raw materials should also be considered, the desirable characteristics being good levels of sugar or starch, good agronomic production, tolerance of low soil fertility, pest and disease resistance, and the ability to withstand environmental stress (Patino *et al*., 15). Among the crops suggested are sweet sorghum, sweet potato and cassava. Development of technology to produce biofuels and manage the co-products for livestock feed by farmers with little education and financial resources are the aims of the Rural Social Biorefineries (RUSBI) programme (Patino *et al.*, 15).

Several lipid co-products are produced during the biofuel production from a range of feedsock sources, and are likely to increase with greater sophistication of fractionation techniques during processing. They can provide both supplements and feeds for ruminants and have a role in meeting guidelines for human health, which call for a reduction in the saturated fatty acid content of the diet, with the essential and non-essential fatty acids coming from unsaturated sources (Wiesman, Segman and Yarmolinsky, 18). The inclusion of Megalac-protected fat or pre-formed calcium soaps in the diet, which avoid rumen degradation, do not adversely affect fibre digestion and also decrease the amount of stearic acid deposited in body tissues (Wiesman, Segman and Yarmolinsky, 18). Reductions in saturated fat in milk and increased omega-3 fatty acids in meat have been observed. However, for animal and public health security, the authors recommend adequate risk assessment of new products.

Ethanol production

Ethanol can be obtained from any cereal grain that stores starch in its endosperm, the choice between the major cereals being governed by environmental factors (Kalscheur *et al.,* 7). Distillers grain were originally obtained as by-products of distilling and brewing industries, the authors quoting the value attached to the slops recovered from George Washington's distillery in the late 1700s and fed to pigs and cattle. With the development of the biofuels industry during the 1970s and 1980s a large number of wet milling plants were built in the USA (Shurson, Tilstra and Kerr, 3), and at the same time dry grind facilities were also developed. The dry grind plants were small and for various reasons initially, many went out of business, although currently they are now dominant. Expansion of the industry has been helped in some States by legislation specifying inclusion levels of ethanol in motor fuel and by direct subsidies (Shurson, Tilstra and Kerr, 3). Shurson *et al.* (10) in their chapter describe diagrammatically dry grind (Figure 1 in Chapter 10) and wet milling (Figure 2 in Chapter 10) fuel ethanol production, and list the co-products from each process (see also Erickson, Klopfenstein and Watson, 5). They also confirm that these plants can handle any grain source or combinations of grain. A result of these activities has been the introduction of several co-products as livestock feed. This trend is on-going, increasing both in complexity and in the number of livestock

TABLE 2
Feedstocks used for ethanol production, their co-products and major areas of utilization

Feedstock	Co-product	Co-product utilization
Maize (3, 4, 7, 10, 23, 26); Sorghum (4); Wheat (2, 9, 11, 26); Triticale (5); Rye, barley (26); Co-products from biodiesel production (10)	DG; WDG or DDG; with added S (DDGS); HP additive (3, 4, 5, 6, 7, 10, 11, 23, 26); Maize oil, maize-condensed distillers soluble, maize gluten feed (5); Maize steep water, whole stillage (26); Ethanol co-products (6).	DG, DDGS, WDG, DDGS-HP for beef cattle (3, 4, 5, 11, 26) DG for dairy cattle (5, 7, 11) DG for pigs (3, 9, 10, 11) DG for poultry (3, 9, 11) DDGS as grazing supplements for ruminants (25, 26) Maize oil, maize solubles, maize gluten feed (5) DDGS for aquaculture (23) Manure (4)
Sugar cane (15, 16); Sugar beet, sweet sorghum (12); Cassava (15)	Vinasse (multi-nutritional blocks/pellets/meal) (16). Fertilizer, bagasse, paper and board (16); Sugar cane tops, bagasse and molasses (15); Sugar beet tops, fermentable palatable waste; Grain/bagasse/foam/froth/steam/vinasse/syrup from 'sugary' stems (12); Cassava residue plus sludge from cane processing (15).	Sugar cane co-products, including use of effluents [simple technology essential] for cattle (15); Food and commercial uses/cattle and other ruminants/poultry and composting (12); Some bagasse direct to forage traders (12); Sugar cane bagasse with supplements and cassava residue for cattle and other ruminants (15, 16), Electricity generation (27); Biogas (15).
Micro-algae (24)	Algae residues left after extraction of oil and/or materials used for ethanol production (24)	Fuel, food, feed and chemicals (24)

Notes: Numbers in the body of the table denote chapter numbers in this book. For a list, see Appendix 1. DG = distillers grain; WDG = wet distillers grain; DDG = dried distillers grain; S = DDG with added solubles (i.e. DDGS); HP = with high protein additive.

species that are benefiting. The increased efficiency of front-end fractionation for ethanol production and the potential for increasing the range of co-products available are discussed (Shurson, Tilstra and Kerr, 3; Cooper and Weber, 25). Rear-end oil extraction is also possible with dry milling, the oil being available as maize oil for livestock or to contribute with other vegetable oils in biodiesel production (Shurson, Tilstra and Kerr, 3; Cooper and Weber, 1). Within the USA, Shurson, Tilstra and Kerr (3) do not foresee an immediate increase in the number of wet milling plants, but possibly a small increase in the number of dry grind plants.

Comparisons of wet and dry processing of DGS (distillers grain with solubles) have been inconclusive, but there are practical considerations, such as handling and storage costs, with the wet product having a relatively short shelf life of up to seven days (dependent on ambient temperature, unless anaerobic storage is available, such as bunkers, pits or silage bags); it is advisable to avoid vertical tower storage because of problems of compaction and flow, creating problems with hygiene and auger-based mixing and delivery systems (Kalscheur *et al.,* 7). However, in 2007, dry mills sold a third of their distillers grain with solubles wet, rather than dry (Wang and Dunn, 27). For usage close to the plant, wet co-products avoid the costs of drying. In some situations, heat for drying can be supplied by burning process residues. Sorghum bagasse (Rao *et al.,* 12), biogas from sugar cane vinasse (Patino *et al.*, 15), and from sugar cane bagasse (Anandan and Sampath, 16) are suggested as sources of fuel.

The current extraction process for ethanol necessitates the use of sulphuric acid, thus increasing the level of sulphur in DG above that in the original grain and creating a potential cause of excess ruminal hydrogen sulphide (Galyean *et al.,* 4; Schoonmaker and Beitz, 6). Sugar and starch fermentation to produce ethanol is described by Lywood and Pinkney (2), as is the hydrolysis of lingocellulose feeds, which is then followed by fermentation to give ethanol. Both processes show high levels of efficiency. Appropriate processing plants for cellulosic materials are being developed (Shurson, Tilstra and Kerr, 3).

Co-products resulting from ethanol production

Notwithstanding the debate regarding the use of land for fuel rather than feed, the production of ethanol as a biofuel is the largest growth sector in the USA, where there are now 200 plants producing 35 million tonne of co-products annually (Shurson, Tilstra and Kerr, 3). Mjoun and Rosentrater (23) estimated ethanol production at 51 billion litres in 2010, over three times as much as in 2005, with 32.9 million tonne of distillers grain being produced, of which 2.7 percent came from the beverage industry and the remainder from maize-based ethanol production. Currently, in the USA, the beef industry uses 66 percent of the available DDGS, the dairy industry 14 percent, pigs 8 percent and poultry 12 percent, with little evidence of meaningful amounts being used in aquaculture (Mjoun and Rosentrater, 23). However, the authors note substantial increases in the amount of fish coming from aquaculture during the last decade, coupled with the high price of the traditional protein sources, fishmeal and soybean meal, and the comparatively low price of DDGS.

In Western Canada, the current annual demand for DDGS is estimated at 1.4 million tonne, but the local industry, based on wheat, can only produce around half a million tonne, the shortfall being met from the USA (Christensen *et al.,* 26). In Europe, the dominant feedstock for ethanol production is also wheat, although some other cereals, especially barley, may be added to the mix (Noblet, Cozannet and Skiba, 9). Rye is also used as a feedstock, but is restricted to colder areas (Kalscheur *et al.,* 7). The products of fermentation are expected to be 93 percent ethanol, 3 percent yeast and 4 percent glycerol (Noblet, Cozannet and Skiba, 9). Distillers grain from various feedstocks can be mixed with minimal changes in animal performance responses, although Kalscheur *et al.* (7) rate barley as the least productive cereal feedstock, because of the relatively high fibre and low starch content of the grain.

Shurson, Tilstra and Kerr (3) address food safety and note possible causes of contamination resulting from the process, including excess sulphur, mycotoxins (in adverse climatic conditions, especially excessive heat or moisture), harmful bacteria, and transfer of antibiotics to animal and human tissue. The formation of H_2S and the dangers it represents to both ruminants and non-ruminants are described by Schoonmaker and Beitz (6), who consider that it rivals cyanide in its toxicity. Endogenous H_2S is produced by the catabolism of S-containing amino acids, cysteine being important in this process, or by sulphate-reducing bacteria present in the digestive tract. But it is important to note that added sulphur used in the fermentation process is the primary culprit for ruminally produced hydrogen sulphide, not the dietary S-containing amino acids. At low levels, H_2S functions as a gaseous signalling molecule in animal tissues; at higher levels it inhibits oxidative processes in nervous tissue, which in ruminants can lead to a disorder of the nervous system known as polioencephalomalacia (PEM) (Schoonmaker and Beitz, 6).

Co-products from sweet sorghum processed in the decentralized system being promoted in India are the grain, bagasse, foam and froth, steam and vinasse (Rao *et al.,* 12). The grain produced in the wet season is often mouldy and unsuitable for human consumption and therefore used for alcohol production and livestock feed (there are three growing seasons per year); the bagasse can be used as a feed, either fresh or after ensiling; as fuel for a variety of uses, including in the evaporation stage of the process, but also increasingly can be seen as a ligno-cellulose source of ethanol, justifying further processing; the foam and froth can be used as livestock feed or fertilizer; if captured, the steam can be used as heat within the process; and the vinasse for irrigation (but it should not be allowed to enter a water course), as fertilizer or in an anaerobic digester as a source of methane (Rao *et al.,* 12).

Patino *et al.* (15) described the Rural Social Biorefineries (RUSBI) approach developed in Brazil for the production of 'local-use biofuels'. The vinasse (effluent) from the process, which is based on sugar cane, has been incorporated into multi-nutritional blocks, pellets and meal, primarily as a supplement for cattle. Depending on the feedstock and process used to produce the ethanol, up to 50–80 percent inclusion of vinasse is possible, the other ingredients being those normally associated with multi-nutrient block manufacture. Other uses include organic fertilizer, either wet, where there could be contamination of the soil or water courses depending on the distillation process used, or dried and mixed with other materials (Patino *et al.*, 15).

In 2008, Asian production of sugar cane produced 167.4 million tonne of bagasse, which has a variety of uses, including provision of low quality livestock feed, heating, electricity generation, biogas, paper and board manufacture, or as fertilizer. However, this material is also a cellulosic material with potential as an ethanol feedstock (Anandan and Sampath, 16). The authors also suggest various treatments to improve the nutritive value of the bagasse. Hydrolysis of ligno-cellulose feeds followed by fermentation can be used to produce bio-ethanol; gasification of ligno-cellulosic waste leaves a residue that can then be subjected to biodiesel synthesis (Lywood and Pinkney, 2). Wiesman, Segman and Yarmolinsky (18) describe the micro-nutrients found in lipid co-products, and their contribution to the well-being of the animal.

Nutritive value of ethanol co-products for livestock

Ruminants

Distillers grain (DG) is regarded as a cost-effective energy feed that also contain substantial amounts of crude protein (CP) with useful amounts of amino acids (although supplementary lysine may need to be added for high yielding dairy cows). DG is also rich in digestible phosphorus (P) compared with other feeds (Shurson, Tilstra and Kerr, 3). Because the process of producing ethanol reduces the starch but not the fibre content, the residual DG is higher in fibre than the whole grain from which it originated. However roughage should still be included in the diet because of the fineness of the fibre particles coming from the grain. There is also evidence that the rumen degradability of crude protein (RDP) is reduced, and un-degraded protein increased by the addition of DG, so the authors recommended a small urea supplement at 15 percent wet DG, but unnecessary at 30 percent DG where urea recycling should make up the dietary shortfall in RDP (Galyean *et al.,* 4). The authors noted that the fat in sorghum DG had beneficial effects, which could be replicated by the addition of yellow grease. Galyean *et al.* (4) also reported that DG in the diet increased the amount of manure and the amount of P excreted, which may have a bearing on the way in which the manure is complemented with traditional fertilizers. The authors found that wet DG at more than 10–15 percent of the diet might increase urinary N excretion and ammonia and nitrous oxide emissions.

Erickson, Klopfenstein and Watson (5) suggest that maize co-products are seen primarily as a source of dietary protein in feedlot diets, although at high levels of inclusion, when they replace substantial amounts of whole grain, the fat and fibre will contribute meaningful amounts of energy. They describe maize gluten feed (a product of wet milling) and DG with added solubles (DGS) as having a low starch content, thus removing the negative effects of diets containing large amounts of whole grain on fibre digestibility, and also reducing the acidosis challenge of grain-rich feedlot diets. It should be noted that DG can contain up to 10 percent glycerine, but as described by authors it is suggested that the effects of this on fibre digestion will be minimal (see also Drouillard, 8).

Conversely, with high forage diets, DGS can add the necessary CP and P, thus improving the rumen ecology for microbial protein production and digestion of fibre. Erickson, Klopfenstein and Watson (5) and Cooper and Weber (1) reported similar responses in intake and growth rate when wet, modified or dried DGS was added at up to 40 percent of the diet of feedlot cattle, and contributed to un-degraded or bypass protein (UDP) that could then be recycled to the rumen as urea, again contributing to microbial protein synthesis. Cooper and Weber (1) rated the feeding value of DDGS at approximately 1.2 that of maize. At up to 40 percent of the diet, modified and DDGS can have a feeding value up to 30 percent greater than maize, although the difference narrows at inclusion rates above 40 percent (Erickson, Klopfenstein and Watson, 5). However, if the level of sulphur exceeds 0.47 percent, which is common at the recommended level of dietary inclusion, performance can be reduced, and in some cases PEM can occur. Sulphuric acid is used in the treatment process to control pH, and although steps are taken to reduce residues, the amounts remaining in the DG vary. Erickson, Klopfenstein and Watson (5) suggest that ruminally degradable sulphur is a better measure of likely H_2S production than total sulphur in the diet. Schoonmaker and Beitz (6) give levels of acceptable sulphur similar to those given by Erickson, Klopfenstein and Watson (5), while pointing to variation in the ability of cattle to tolerate excess sulphur in the diet, with mild intoxication reducing daily liveweight gain (DWG) and feed efficiency, but when H_2S bypasses hepatic detoxification a more serious situation can develop. The problem can be mitigated by chemical analysis and careful formulation of feeds, but sulphur concentration can change between batches as well as among sources (Schoonmaker and Beitz, 6). Suggestions for managing diets with a high sulphur content include limiting where possible the amount of dietary sulphur (choice of mineral mix); adapting cattle to the high sulphur diet; and use of appropriate feed additives to combat the excess sulphur (suggestions include supplementary thiamine, appropriate antibiotics, minerals) (Schoonmaker and Beitz, 6).

Storage of DDGS can be problematic because of bridging, especially in vertical stores and if movement by auger is involved. The situation is worsened if the fat content of the product is above 10 percent or if water is added (Kalscheur *et al.,* 7). Mjoun and Rosentrater (23) reported that while DDGS should not replace fishmeal in aquafeeds it can be used in lieu of other plant proteins, such as soybean meal. However, the authors noted the degree of variation in DG, both among and within processing plants, but this may be less with DG derived from maize than DG from the beverage industry. They also drew attention to the density of DDGS, which could be related to the amount of solubles added to the dried DG, and again noted the importance of having a product that flows, particularly in aquaculture, to meet delivery requirements. Other concerns were the costs of transport and storage. The colour of DG is regarded as important, in that a dark colour is indicative of a Maillard reaction caused by overheating during processing, signalling a reduction in the digestible lysine content (Mjoun and Rosentrator, 23).

In Germany, wheat-based DDGS have successfully replaced traditional protein sources in dairy cows at up to 200 g of the protein per day, and can also be used as the main dietary protein source for fattening cattle (Hippenstiel *et al.,* 11). However, DDGS may be from a mixture of feedstocks, which will have a bearing on nutritive value. For instance, the CP of wheat is more likely to escape rumen degradation than CP of barley, the grain with the most neutral-detergent fibre (Hippenstiel *et al.,* 11). To stimulate a large increase in the feeding of DDGS in Canadian feedlots, Christensen *et al.* (26) asked that reducing variability in the composition of the product be addressed, particularly variability in fat and protein. They also reported trials where diets containing 40 percent of DDGS were successfully incorporated in feedlot diets, and that although the product could be provided in wet form, the expense of drying could in some circumstances be justified by ease of transport and a longer shelf life. Wet products such as WDG contain 23–24 percent solids, and thin stillage (liquid residue after removal of the grain) contains 8.5 percent solids. Condensed distillers solubles (CDS) result from evaporation of the thin stillage and can be added to either wet or dried DG to give wet distillers grain with added solubles (WDGS), or dried with the grain fraction to produce DDGS (see Figure 3 in Chapter 26). In one feedlot, situated next to an ethanol plant, thin stillage is pumped through the drinking system, thus eliminating the need for drinking water (Christensen *et al.,* 26).

Research into the use of DG for dairy cattle started in the middle of the twentieth century. The list of co-products available has increased considerably and is likely to continue increasing as the technology for extraction and fractionation becomes more sophisticated (Kalscheur *et al.,* 7). These authors make suggestions for feeding WDGS to dairy cattle through growth into lactation. For lactating cows, WDGS from maize is judged to be a good source of un-degradable (bypass) protein when fed at up to 30 percent of the diet, although peak milk production response will probably be around 21 percent. Supplementation with lysine may be necessary if the amino acid profile of the milk indicates that it is low. For dairy heifers, where restricted growth is often desirable to encourage development of mammary tissue, feeding WDGS will allow use of poorer quality forages, examples being soybean stalks or maize stover. For dry cows there is little direct information, but a similar feeding regime to that of growing heifers is probably adequate, although a 15 percent supplement of WDGS during the last four weeks of pregnancy has improved energy balance and resistance to ketosis in early lactation. With calves, 25–30 percent of the maize can be replaced with DGS if the rumen is fully functional, but lysine and methionine levels should be checked for adequacy (Kalscheur *et al.,* 7).

The value of DDGS produced from both wheat and other sources will depend on the original feedstock, although the method of processing is the dominant factor, with colour indicating the degree of heating involved (Noblet, Cozannet and Skiba, 9). After removal of the starch for ethanol, other components of the grain residue (such as fat, fibre and protein) are approximately three times as concentrated as in the original feedstock, although levels of the essential amino acids lysine and arginine will be reduced (Noblet, Cozannet and Skiba, 9). The authors suggest that processing should receive attention to assure a high quality, uniform product capable of diversification to allow production of more specific by-products, examples being with or without hulls, protein concentrates and germ separation. For poultry and pig diets, the authors suggest a link between colour of the product and digestibility of energy and amino acids.

Of the sorghum grain in rural India, the best (free of mould) is kept for human consumption, especially of the white varieties, but the remainder will be used for livestock (Rao *et al.,* 12). Because of its relatively high content of insoluble fibre sorghum is usually ascribed a feeding value of 95 percent that of yellow dent maize. The dairy industry in India (Rao *et al.,* 12), especially in the north of the country, is a major user of sorghum, both grain, the whole plant, and bagasse, which is important because every 10 tonne of sorghum crushed results in 5–6 tonne of bagasse. The bagasse can be fed fresh or ensiled, or sold into the forage supply chain. Fresh bagasse leaf residue can be successfully ensiled without additives, and then used as a general ruminant feed (dairy cows, buffalo and small ruminants). The fresh leaves can also be incorporated into feed blocks (Rao *et al.,* 12). Intake of bagasse could be enhanced by chopping. Other uses include paper making, fertilizer (limited because of possible deleterious effects on soil), and co-generation of energy (process heat and electricity).

Anandan and Sampath (16) stress that sugar cane bagasse is fibrous, of low nutrient density, and must be supplemented with other feed ingredients to support maintenance. The extent of its use is related to the availability of conventional cereal straws (paddy rice, wheat and sorghum). Tax breaks for using the sugar cane bagasse as fuel could also negatively influence its acceptance as a livestock feed. The amount of bagasse to be incorporated in ruminant diets will depend on the level of production expected, with a range of 30–40 percent in the diet for medium levels of production, and up to 60 percent for low-level production (Anandan and Sampath, 16). Supplements for use with bagasse will be those suitable for mixing with any low grade forage, including urea, molasses and locally available concentrates. Treatment of bagasse to improve its nutritive quality and digestibility has included physical, chemical and biological approaches, with the first two being the most successful so far. However steam treatment with alkali can cause changes in the bagasse that are harmful to livestock (Anandan and Sampath, 16). To improve the digestibility of fibrous forages (possibly the major source of ruminant feed globally), Kalscheur *et al.* (7) discuss the technique of ammonia fibre expansion (AFEX), which. together with enzymatic hydrolysis treatment of forages, may result in a high energy diet that is relatively low in degradable CP.

Non-ruminants

Cooper and Weber (1) noted a shift from the traditional use of DDGS as a substitute for the higher priced maize and soybean in cattle diets, towards pigs, poultry and fish, although the optimum levels of inclusion are still being determined.

Regular DDGS or high protein DDGS (HP-DDGS) after dehulling of the maize can be fed to pigs at all stages of the production chain. The energy of DDGS is similar to maize, unless the oil has been removed, but the energy content of HP-DDGS is slightly higher due to the reduced fibre content. The digestibility of P in DDGS is high. Growing pigs, from two to three weeks after weaning, can be fed diets containing 30 percent maize DDGS (gestating sows 50 percent) as long as all amino acid requirements are met. With finishers it may be necessary to withdraw DDGS three to four weeks before slaughter because the high level of polyunsaturated fatty acids in the maize oil (measured by iodine value – which is the ratio of unsaturated to saturated fatty acids in a lipid) could reduce pork fat quality. Diets for gestating sows can contain up to 50 percent DDGS, and lactating sows have acceptable performance when fed diets containing 30 percent DDGS, while dramatically reducing or replacing the soybean meal in the diet (Shurson *et al.,* 10). While more research is needed to understand the mechanisms, the authors report that DDGS in the diet may improve intestinal health in pigs. Inclusion of DDGS will also increase the amount of manure produced, reflecting reduced dry matter digestibility, although the loss of N and P can both be controlled (Shurson *et al.,* 10).

Hippenstiel *et al.* (11) found that wheat DDGS up to 20 percent of the diet of pigs did not affect growth, fattening and carcass composition. With laying hens, inclusion levels between 15 and 30 percent wheat DDGS had no effect on laying intensity, egg quality and hen health, but with broilers there was a suggestion that levels above 10 percent may reduce performance unless non-polysaccharide-degrading enzymes are added to the diet (Hippenstiel *et al.,* 11).

Wheat DDGS is seen as a source of energy, protein and P for poultry and pigs (Noblet, Cozannet and Skiba, 9). Crude protein in DDGS can be as high as 30 percent, but lysine levels are low and variable, with ileal digestibility lower than with whole wheat especially if the DDGS has any heat damage. The energy value of wheat DDGS is lower than whole wheat, the difference being dependent on the fibre content of the DDGS. However, wheat DDGS can be included at up to 30 percent in poultry and pig diets as long as the diet meets overall nutrient requirements (Noblet, Cozannet and Skiba, 9). In ruminants, H_2S can be a major problem; in non-ruminants, H_2S formed in the gastrointestinal tract is largely excreted or absorbed and detoxified in the liver, although there may be a link between inorganic sulphur and chronic intestinal disease (Schoonmaker and Beitz, 6).

With sweet sorghum it is the stalk that is used for ethanol production and the grain is a by-product. Most of the sorghum grain produced in India goes into the poultry industry (77 percent), followed by the dairy industry (16 percent), alcohol production (6 percent), and 1 percent for the production of starch (Rao *et al.,* 12). The inclusion levels of sorghum grain in poultry diets are normally 10 percent for layers and 15 percent for broilers, although the actual levels will depend on the price of maize, increasing in years when the price of maize is high (Rao *et al.,* 12).

Fish

Fish require specific amino acids (AA) rather than crude protein. Although DDGS has a similar AA profile to maize, it is deficient in lysine (Mjoun and Rosentrater, 23). Differences between species of fish should also be noted. The authors suggest two ways in which the diet can be balanced, either by including DDGS in a cocktail of protein feeds, or by the addition of synthetic AA. DDGS is rich in vitamins and P, but is low in Ca, Cl and trace minerals. Mjoun and Rosentrater (23) note that cereal feedstocks other than maize are being used in practise, but currently only DDGS from maize, and high protein DDGS (HP-DDGS), also from maize, have been tested for use in aquaculture. The use of barley is limited because of its high content of beta-glucans (Mjoun and Rosentrater, 23). Growth, feed utilization and flesh composition in a number of aquatic organisms, including Nile, hybrid and red tilapia; channel catfish; rainbow trout; yellow perch; common carp; freshwater prawn; Pacific white shrimp; reclaw crayfish; and sunshine bass, are summarized in Table 5 of Chapter 23 (Mjoun and Rosentrater, 23), together with the ingredients replaced by DDGS. Tilapia and channel catfish require supplementary lysine if DDGS exceeds 30 percent of the diet (Mjoun and Rosentrater, 23). Feed efficiency in rainbow trout is reduced if DDGS is included in the diet. The other species listed show some positive results, but more information is needed (Mjoun and Rosentrater, 23). In several trials, the flesh contained more protein and fat when DDGS was fed, but taste was not affected. If the protein and fat content of the flesh are unchanged, it could indicate an imbalance in the amino acid profile of the diet. There are few large-scale trials reported where DDGS is fed to fish, but there are indications that the digestibility of DDGS is lower than that of soybean meal or fishmeal, thus indicating that more of the feed is excreted into the pond and thereby becoming a possible source of pond pollution (Mjoun and Rosentrater, 23).

BIODIESEL

In 2010, a total of 140 plants produced 1.2 billion litres of biodiesel, but relatively little glycerol was used for livestock feeding, possibly due to its relatively high value elsewhere in pharmaceuticals and other industry applications. One litre of diesel production is accompanied by 0.08 kg of glycerine (Shurson, Tilstra and Kerr, 3), although Cooper and Weber (1) indicated a lower figure of 0.04 L of glycerine per litre of biodiesel produced. Stoichiometrically, 1 L of biodiesel production should result in the production of 1 kg of glycerine. Biodiesel production peaked in the USA in 2008 and has since fallen, to the extent that glycerol for livestock feed could become scarce because of its demand by other sectors (Shurson, Tilstra and Kerr, 3). However, the USA economy could handle 9.5 billion litres of biodiesel by 2015 (Cooper and Weber, 1). Biodiesel production is by one of three methods, all based on the use of methanol as the alcohol source (low cost and can be recycled) with sodium methoxide and potassium hydroxide used as catalysts (Cooper and Weber, 1).

Algae contain lipids, along with starch and cellulose present in cell walls. However, their feeding value, and also that of seaweed, is not yet known (Shurson, Tilstra and Kerr, 3).

Europe is the world leader in biodiesel production from vegetable oils, although currently rapeseed oil supported by imported soybean meal is the backbone of the industry (Abbeddou and Makkar, 19). The European need for biodiesel to meet inclusion targets in transport fuels by 2020 will depend on the division between petrol- and diesel-engined transport, which in turn will be price related and largely dependent on government support and taxation levels. If more biodiesel is required, this will be provided by rapeseed oil, providing residual rape meal, as well as through imports of biodiesel or vegetable oils, but the amount of co-products available for livestock feed will not increase tremendously. If the fuel demand and policy shift is toward needing more ethanol, then improvements in crop yields and cropping of underutilized arable land, together with production of livestock co-products of between 23 and 35 million tonne per year, would maintain the total arable output for food and feed at its current level (Lywood and Pinkney, 2).

The importance of the oil palm industry to the Malaysian economy cannot be understated, with palm oil and palm kernel oil in 2008 representing 30 percent of total global production, from 4.5 million hectare of land (Wan Zahari, Alimon and Wong, 13). Major products include palm oil, oleo-chemicals and biodiesel. In Brazil, two palms of importance are the oil palm, *Elaeis guineensis*, and babassu (*Orbignya phalerata*), both originally used in food, charcoal and soap production, but now increasingly as a source of biodiesel. The residue is available as a low-cost energy source for livestock (de Albuquerque *et al.,* 14).

There are other potentially productive sources of biodiesel, but for their residues to contribute fully as livestock feed, detoxification is required. These include Jatropha (Makkar, Kumar and Becker, 21; Anandan, Gowda and Sampath, 20) and castor (Anandan, Gowda and Sampath, 20). The possibilities for detoxification of other potential feed sources is discussed by Abbeddou and Makkar (19), Makkar, Kumar and Becker (21) and Dutta, Panda and Kamra (22).

Feedstocks used for biodiesel production

In the USA, soybean is the major feedstock for biodiesel, but in Europe rape is the chief home-grown source of oil (Hippenstiel *et al.,* 11), supplemented with imported soybean, animal fats and yellow grease. However, a number of 'non-conventional' crops and resources have been or are being investigated for potential use where they are abundant (Table 3).

Camelina sativa, also known as false flax, is an oilseed crop of the brassica family. For over 2000 years it has been cultivated in Europe for its oil and as a livestock fodder. It survives well on marginal land, needs very few inputs and no irrigation, thereby keeping conflict for scarce resources of land, water and fertilizer at a minimum. Because of its increasing use as a biofuel feedstock, more information is needed on the potential role of camelina as a feed ingredient, although there is some evidence of its suitability for ruminants. In Chapter 17, Cherian examines its role specifically as a feed for poultry.

Biofuel policy in India is based on the use of non-food feedstocks to avoid the possibility of conflict between the requirements of humans, livestock and biofuels targets, and also to create a tool in rural development to bring marginal land into production (Anandan, Gowda and Sampath, 20). However, the authors consider that the industry is unlikely to achieve its 2017 target contribution to transport fuel because of slow progress in establishing crops such as Jatropha (see also Makkar, Kumar and Becker, 21), low productivity and poor market infrastructure, compounded with competition for the same land by expansion of the sugar cane industry.

In Australia, Braid (25) describes the current biofuels industry as small (total current capacity 280 million litre per year), and biodiesel has been produced from tallow and used cooking oil. However, *Brassica juncea* and *Pongamia pinnata* are low-rainfall oilseed crops, both with residues (juncea and pongamia meals, respectively) with feed potential after detoxification (Braid, 25). *Pongamia pinnata* is a native species of India and South-east Asia, where the oil is used for cooking and lighting, and along the coast of

TABLE 3

Feedstocks used for biodiesel production, their co-products and major areas of utilization

Feedstock	Co-product	Co-product use by livestock
Soybean (3) Rapeseed (11) Vegetable oils (2) Maize oil (27)	Crude glycerine (3, 7, 8, 23); several uses, human foods/pharmaceuticals/commercial, etc. (8) Oil seed cake (mechanically extracted) and meal (solvent extracted); methanol should be removed (11)	Pigs (3, 10) Beef cattle (8) Fish (23) Dairy, beef, pigs and poultry (11) Glycerol as drench and supplement for dairy cattle (7)
Camelina sativa (17)	Camelina meal: derives from member of the brassica family that grows on marginal land, no irrigation needed. Meal is rich in amino acids and antioxidants (17)	Poultry (broilers and layers) (17)
Jatropha (20, 21)	Heated *J platyphylla* kernel meal (21) Detoxified *J. curcas* kernel meal and detoxified protein isolate (21) Heated kernel meal from non-toxic genotype of *J. curcas* (21)	Fish, turkeys and pigs (21)
Oil palm (13, 14) Oil palm (*Elaeis guineensis*) and babussa (*Oribgnya phalerata*) (14)	Rapidly expanding industry with several by-products from refining of crude palm oil or palm kernel oil; oil palm fronds, trunks, pressed fibre, empty fruit bunches, kernel cake and oil mill effluent are products available in the field and ex-processing {also solubles}, with aim of integrating livestock industry with oil palm production (13) Oil palm and babussa oil used for food, charcoal, soap and now biodiesel (14)	Ruminant feeding and complete diets based on oil palm for poultry, pigs and freshwater fish (13) Oil palm and babussa feed for collared peccary (*Pecari tajacu*) (14)
Seed oils (18)	Co-products derived during bioethanol and biodiesel production (18)	In livestock feed as feed additives (but also used in human food and cosmetics) (18)
Micro-algae (25, 24)	Algal residues left after extraction of oil (24)	Fuel, food, feed and chemicals (24)
Brassica juncea (25) *Pongamia pinnata* (25, 19) *Pongamia glabra* (22) *Azadirachta indica* (22, 19)	Juncea meal (residue after oil extraction, 25) *P. pinnata* meal (residue after oil extraction, 19, 25) *P. glabra* meal (Karanj seed cake) – de-oiling needed for complete detoxification (22) *A. indica* (neem seed cake) – water washing reduces toxicity (19, 22)	Juncea meal (pigs, 25) *P. pinnata* meal at low levels as livestock feed (25) (possible toxicity problems, 19) Karanj and neem seed cakes after treatment fed to ruminants and poultry (22)
Non-edible oils (19) *Ricinus communis* (castor) (20) Jatropha (21)	Oil cakes and meals; detoxification needed; meals that can be fed after treatment are *R. communis*; *Hevea brasiliensis* (livestock trials needed); *Crambe abyssinica*; *A. indica*; *P. pinnata* (19). Need for industrial and commercial uptake of detoxifying techniques for castor (6) With Jatropha, removal of phorbal esters necessary (21)	Ruminants used where oil cakes and meals were tested (19) Jatropha requires testing (21)

Notes: Numbers in the body of the table denote chapter numbers in this book. For a list, see Appendix 1.

northern Australia. The integration of trees into pasture land has many potential benefits for sheep and cattle (Braid, 25).

In India, four strategies were proposed to overcome the shortage of protein for livestock: (1) restricting exports of oilseed meals; (2) increasing areas of cultivation for growing high quality green forage crops; (3) increasing efficiency of use of existing protein feeds; and (4) identifying non-conventional oilseeds and, if necessary, taking measures to detoxify the resulting seed cake (Dutta, Panda and Kamra, 22). This last approach matches the Indian government's policy of increasing production of biodiesel without aggravating the conflict of interest between biofuel and food production, and resulted in identification of karanj and neem. In the past, the karanj plant (*Pongamia glabra*) has had many uses, including as a traditional medicine, with the oil supplying heat and light (Dutta, Panda and Kamra, 22: Table 1). However, extraction of the oil results in a seed cake that at present is often used as fertilizer, but which needs detoxifying before feeding to livestock (Dutta, Panda and Kamra, 22). Abbeddou and Makkar (19) discuss nine oleaginous crops suitable for oil extraction but that leave behind toxic co-products, which after detoxification could be used as protein feeds. The authors stress that detoxification techniques need to be suitable for up-scaling if sufficient material is to be handled to have an impact in the market. Makkar, Kumar and Becker (21) outline the potential for *Jatropha* spp., a hardy shrubby tree that grows in wild or semi-cultivated areas, often on degenerated land in Africa, Asia, and Central and Southern America. Its seeds contain 55–60 percent oil that yields good quality biodiesel and the residue is rich (60–66 percent) in CP (Makkar, Kumar and Becker, 21).

With the increased use of algae for oil production, research into technical aspects of using these sources is needed. Currently there is no commercial activity with algae, but as an industry suited to development in coastal regions of the world, it could be developed in Australia, with the co-products being used for energy generation or possibly in livestock nutrition (Braid, 25).

Biodiesel co-products

Crude glycerine is an important co-product from the biodiesel industry (Table 3). Its purity is measured by the amount of water it contains. Pure glycerol has less than 5 percent water and is also colourless. Crude glycerol contains increasing amounts of water and other impurities that affect the colour, with increasing shades of brown as the water and impurities increase (Shurson *et al.,* 10; Drouillard, 8; Cooper and Weber, 1). In the USA in 2010, 48 percent of glycerol was sold for high value uses, while 33 percent went to the livestock feed industry (Cooper and Weber, 1).

Glycerine at different purities may help to stabilize the hygienic quality of pelleted feeds without affecting the physical quality of the pellets. Mature cattle can consume 1 kg of glycerine per day, as a source of rapidly fermentable carbohydrate, while it is not clear if the sweet taste of this product acts as an intake stimulator (Hippenstiel *et al.,* 11). Drouillard (8) estimates that the yield of glycerine is approximately 10 percent of that of the oil or fat from which it is derived, with pure glycerine being used in human food and industrial processes including; beverages (glycerine contains 60 percent of the sweetness of sugar); pharmaceuticals; synthetic polymers; cosmetics and personal care products; and, after modification, as an emulsifying agent. Glycerine also has humectant properties beneficial in both food and feed production systems, in the latter for texturing properties and dust control, although reduced production costs of pellets and improved hygiene have also been noted (Drouillard, 8).

Camelina meal contains 36–40 percent crude protein, 11–12 percent fat and 4600 kcal/kg gross energy. Its protein is rich in essential AA, including lysine and methionine. The fat is rich in alpha-linolenic acid, the parent fatty acid of omega-3, and the antioxidant tocopherol, both necessary for healthy, productive poultry and quality poultry products for humans (Cherian, 17).

Castor cake is a high-protein product, but its use as livestock feed is restricted because of toxins, especially ricin, which means that a large proportion of the residue cake produced is used as organic fertilizer. However, treatments involving heat, water and alkali, especially the use of NaOH, have reduced the problem (Anandan, Gowda and Sampath, 20; see also Table 6 of Chapter 20 for a summary). If marketed at the current (2011) price, plus the cost of treatment, it would still be competitive with other protein feeds. The authors suggest that the use of castor cake, through its promotion and marketing, should be handled by a united approach involving all interested parties. All the major castor producing countries, namely India, China and Brazil, also have large numbers of livestock and therefore a large demand for protein feeds, to which detoxified castor cake could make a significant contribution (Anandan, Gowda and Sampath, 20).

Pongamia cake (karanj) is available in two forms, from either a mechanical-extraction process or a solvent-extraction process, but both contain anti-nutritional factors (Braid, 25). The use of karanj cake, both expeller and solvent extracted, is limited by the presence of three types of toxins: furanoflavones, tannins and trypsin inhibitors (Dutta, Panda and Kamra, 22). The AA profile of Karanj compares favourably with traditional proteins, and it contains more Ca, P and Na than soybean meal, but less Cu and Fe (Dutta, Panda and Kamra, 22).

Neem oil has traditionally been used for soaps, creams, toothpaste, etc., with the cake, which contains 35–49 percent CP, used as fertilizer or as a pesticide (Dutta, Panda and Kamra, 22). The bitter taste and variable composition of neem seed cake and neem seed kernel cake, due to depulping, de-corticating and oil extracting, affect its value as a feed. In addition, crude fibre and CP are both affected by the methods employed and degree of processing (Dutta, Panda and Kamra, 22).

Abbeddou and Makkar (19) summarized the potential for detoxification of seed cakes from non-conventional sources that could contribute protein for livestock. *Azadirachta indica*, the source of neem cake, after washing can be used at up to 45 percent of the concentrate in calf diets, while other treatments for this product include methanol, urea and alkali extraction. *Ricinus communis* meal cooked at 100 °C for 50 minutes could be added as 15 percent of chick diets, and, with the addition of 4 percent lime, included at 10 to 15 percent of the diet for sheep and beef cattle. HCN levels in *Hevea brasiliensis* meal could be reduced by soaking in water to allow fermentation, but livestock trials have not as yet been conducted. *Crambe abyssinica* meal de-hulled and subjected to a heat-carbonate treatment is acceptable to beef cattle, and can replace up to two-thirds of the soybean meal in the diet. *Pongamia pinnata* meal after washing with water or alkali treatment can be included at up to 13.5 percent of the concentrates in lamb diets. *Brassica juncea* has been selected as a break crop for cereal lands, particularly in hot areas and an extracted oilseed cake is available (Braid, 25).

The benefits of lipid co-products are summarized by Wiesman, Segman and Yarmolinsky (18), although many are also available from the production of ethanol. The advantages include acting as a source of vitamin E, required for many essential functions in both humans and livestock including growth and reproduction; as a source of carotenes, normally available to the grazing animal but lost when forage is conserved as hay or silage; and providing phytosterols, important in reducing the absorption of cholesterol, thereby helping to reduce cardiovascular disease (squalene has similar properties in this respect). They also have anti-inflammatory, anti-bacterial, anti-ulcerative and anti-tumour properties, and are beneficial to the immune system of piglets. Polyethenols are able to improve the efficiency of protein use in ruminants, reduce urea content of manure, inhibit bloat, and help combat sub-clinical helminth infections. Lecithins act as dust suppressors (dustiness has been identified as a constraint to intake by ruminants), emulsifiers and as a source of essential fatty acids (Wiesman, Segman and Yarmolinsky, 18). The authors stress the need for thorough testing of these products obtained from biodiesel production to avoid toxic compounds reaching humans and livestock. Shurson *et al.* (10) stress the problems likely to be encountered from an excess of methanol in the diet and in particular the need to control intake of glycerine in pigs because of the slow rate of excretion of methanol.

Nutritive value of biodiesel co-products

Ruminants

The two major co-products from the biodiesel process are protein-rich cakes or meals, and glycerol. The cakes and meals have long been major sources of CP in commercial livestock and poultry production, the market being dominated by soybean meal (Makkar, Kumar and Becker, 21). Glycerol, a glucose precursor, has traditionally been used as a drench for dairy cows to combat ketosis, often shortly after calving, because it is rapidly fermentable within the rumen and favours a decrease in the acetate-to-propionate ratio (Kalscheur *et al.,* 7). Increasing propionate benefits the supply of gluconeogenic substrate reaching the liver, and increasing butyrate encourages ruminal epithelial tissue growth, possibly leading to improved absorption of nutrients (Kalscheur *et al.,* 7). However, it can also be used as a supplement for transition cows, or as a replacement for maize at 10–12 percent of the diet, but its effect in causing a reduction in fibre digestibility is similar to that of starch (Kalscheur *et al.,* 7). The authors recommend analysis of individual batches of feed rather than depending on book values when formulating diets, and warn that some agricultural crops may not be ideal co-components in diets based on DG. For example, a combination of DDGS plus alfalfa hay results in a feed containing too much CP. Adding glycerine to the diet will favour a propionate-butyrate, rather than acetic, rumen fermentation, although this may be affected by the level of glycerine and the composition of the rumen flora (Drouillard, 8). Young cattle fed glycerine early in life and then fed a diet containing maize gluten feed, which had a glycerol content of 4.9 percent in the finishing period, have performed better than cattle fed the same finishing diet but without the addition of glycerine at the earlier stage, suggesting that rumen adaptation to glycerine may have a relatively long carry-over period (Drouillard, 8).

In Europe, rapeseed co-products are widely used in cattle, pig and poultry diets (Hippenstiel *et al.,* 11). Recommendations from Germany are available for daily amounts of both rapeseed meal (solvent extracted) and rapeseed cake (mechanically extracted), which range from 4 kg of rapeseed meal for a dairy cow (2 kg of rapeseed cake) to 0–100 g of the meal and 50–100 g of the cake for laying hens (Hippenstiel *et al.,* 11, especially Table 16). A safety quality assessment of rapeseed cake for cattle is required because variations in processing can affect the chemical composition, particularly that of crude fat and CP, making ration formulation using this product difficult. Rapeseed meal can completely replace soybean meal in dairy cow rations, although there may be differences in intake of energy, rumen degradability and amino acid profiles between the two sources (Hippenstiel *et al.,* 11). Hippenstiel *et al.* (11) also comments on the use of glycerine, stressing that methanol should be removed as far as is technically possible and that the methanol content of each batch should be declared.

Pongamia cake (Braid, 25; Abbeddou and Makkar, 19) is similar to soybean meal in many respects, but contains anti-nutritional factors (karanj and pongamol) that also make it unpalatable, although Abbeddou and Makkar (19) consider it a safe feed within limits after detoxification. However, because of the anti-nutritional characteristics and relative unpalatability, Braid (25) suggests *Pongamia pinnata* as a useful tree for incorporating into extensive pasture because of a relatively low risk of grazing damage. Feeding of untreated pongami or karanj cake to livestock reduced dry matter intake and caused histological changes to vital organs of ruminants and poultry, and this has led to various attempts to detoxify it, although they have been general rather than targeting a specific toxin (Dutta, Panda and Kamra, 22; Braid, 25). The most successful of these was de-oiling to ensure removal of the toxins during the extraction process, which is achieved through treatment with an alkali solution (1.5% NaOH plus 3% lime) or ammoniation with urea (Dutta, Panda and Kamra, 22). Carcass weight of lambs was reduced more with expeller cake than with solvent-extracted karanj, but chemical and physical attributes of the lambs were not affected. Both forms of karanj resulted in lighter carcasses than de-oiled groundnut meal (Dutta, Panda and Kamra, 22). The same authors reported that masking the taste of neem or urea ammoniation improved intake of neem seed kernel cake (NSKC) in ruminants. Neem seed cake (NSC) was found to reduce growth, impair the male reproductive system and, in some cases, result in haematuria. Treatments showing positive results with neem seed kernel cake include adding NaOH (1 percent) and boiling (this can reduce CP) and washing with water, which can result in a loss of dry matter. Another approach is to ensile the NSKC with either 2 percent NaOH for 24 hours or 2.5 percent urea for 5–6 day, followed by sun drying and grinding (Dutta, Panda and Kamra, 22). Although responses in feeding trials have been mixed, there are no reports of changes in rumen pH or total volatile fatty acids. Dutta, Panda and Kamra (22) suggest that both karanj and neem seed cake, if properly prepared, could replace 50 percent of the nitrogen in the diets of lambs. Although farmers in India show reluctance to feed castor meal (this could be related in part to a high economic return from sugar cane), there is evidence that ruminants can use it (Anandan, Gowda and Sampath, 20; see also Table 7 in Chapter 20), in some cases without detoxification of the ricin.

The two major by-products from palm oil processing are palm kernel cake (PKC), also known as palm kernel expeller (PKE), and crude palm oil (CPO) (Wan Zahari, Alimon and Wong, 13). There are two dominant processing methods used: solvent extraction and expeller. These result in palm products with a range of nutritive values arising from differences in agronomic factors and processing procedures. Expeller palm kernel meal (PKM) has a substantially higher oil content than the solvent-extracted material and the AA profile shows deficiencies in lysine, methionine and trytophan, which are currently being addressed (Wan Zahari, Alimon and Wong, 13). PKC is free of aflatoxins, heavy metals and chemicals, and can be stored for up to three months. However, the Malaysian palm oil industry also produces valuable by-products resulting directly from the field operations. These include oil palm fronds (OPF) from pruning, felling and harvesting that are available throughout the year, the yield being around 82.5 kg/palm/year (Wan Zahari, Alimon and Wong, 13). The fronds can be chopped and fed fresh, which is the common practice, ensiled, or processed for cubing or pelletting. Freshly chopped OPF is a common source of forage and can be fed at 40 percent of the diet, often with some added PKC, to buffalo, cattle and sheep. If ensiled, the diet will benefit from a urea supplement to offset the low level of CP in the silage. The second field residue is oil palm trunks (OPT), the life of a tree being 25–30 years (the criteria for felling and clearing are height of palm >13 m and/or a diminishing yield). The trunks can be chipped and ensiled, and, with added urea, have a similar nutritive value to that of rice straw, with the parenchyma being an excellent source of roughage for beef cattle (Wan Zahari, Alimon and Wong, 13). With beef cattle, a maximum inclusion of 85 percent PKC is recommended, and for dairy cows 30–50 percent PKC is recommended, often fed as a pellet with grass and other concentrates. However, with sheep, 30 percent PKC should be regarded as the maximum because of the high Cu content of the cake, which can cause long-term problems in this species (Wan Zahari, Alimon and Wong, 13).

Other products from the oil palm industry, which either have some use at present or merit research for future use, include palm oil mill effluent (POME), which after decantation can be used for ruminants; empty fruit branches, a field product, suitable for coarse forage, mulching and fibreboard production; palm press fibre (PPF), used for fuel, paper, fibreboard, etc., as well as for coarse forage (treatment with alkali or steam is not assured of success); and crude palm oil (CPO) is rich in vitamins A and D and can be used to reduce dustiness in the diet. Derivatives from CPO include palm fatty acid distillates (PFAD) and spent bleached earths (SBEs) (Wan Zahari, Alimon and Wong, 13).

Non-ruminants

Crude glycerine contains similar energy to that of maize for pigs. If affordable, sow diets can contain up to 9 percent and weaners at least 6 percent glycerine, which can be increased up to 15 percent for finishers. Inclusion of glycerol in a mechanized system can improve feed flow, but amounts of Na and methanol (toxic) in the diet should be checked (Shurson *et al.,* 10).

In poultry diets, Cherian (17) found that camelina meal could be incorporated at 10 percent in layer and broiler diets without affecting the performance of the birds or quality of the products, and reduce the omega-6 to omega-3 ratio in meat and eggs. Castor cake, after treatment to detoxify the ricin, has been fed successfully to poultry, but because of its high fibre and lignin contents is more likely to be better used by ruminants (Anandan, Gowda and Sampath, 20). Pigs fed *Brassica juncea* cake at up to 18 percent of the diet exhibited no ill effects, but at 24 percent of the diet *B. juncea* cake caused a reduction in intake, and thus growth rate declined (Braid, 25). Hippenstiel *et al.* (11) call for a greater understanding of the role of glucosinolates, more common in rapeseed cake than meal, in the diets of both pigs and poultry. Rapeseed meal is lower in lysine than soybean meal, and the crude protein is less digestible than in soybean meal, but contains more sulphur AA. Rapeseed products are not commonly used in poultry diets, and, when used, supplementary iodine may be necessary.

Limited amounts of PKC can be fed to poultry because of its high crude fibre content and the presence of polysaccharides and shells. A maximum of 20 percent PKC in the diet for broiler chicks and 20–25 percent for layers, while 30 percent is the maximum recommended for muscovy ducks (Wan Zahari, Alimon and Wong, 13). Higher levels of PKC in poultry diets would require balancing with fat, which would not be cost effective. Enzyme treatment and solid-state fermentation of the PKC are being investigated. After processing, POME can be fed to poultry, although at present this is not economical (Wan Zahari, Alimon and Wong, 13). Pigs, both growers and finishers, are often fed 20–25 percent of the diet as PKC, although the inclusion rate varies throughout the Malay peninsular. In Nigeria, inclusion levels can be as high as 40 percent.

Solvent-extracted karanj meal, after treatment with NaOH or lime, and expeller karanj cake treated with NaOH, have been fed to poultry, but were unpalatable as a sole feed (Dutta, Panda and Kamra, 22). The expeller cake was also unacceptable because of pathological changes in the vital organs of the birds (Dutta, Panda and Kamra, 22). Solvent-extracted karanj (complete removal of the oil renders this product safe for livestock) can be included at 6.4 percent of the diet of quail up to four weeks of age, after which supplementary methionine would be required. However, de-oiled karanj meal reduced the growth rate in quail chicks when it was above 4.45 percent of the diet, and in layer male chicks above 5 percent reduced growth. More research is needed (Dutta, Panda and Kamra, 22). De-oiled neem seed cake (NSC), raw NSC and un-decorticated expeller reduced growth in chicks. However, soaking expeller NSC and adding charcoal (0.4 percent w/w) and solvent extracted NSC improved growth, while a combination of acid, alkali and washing removed the bitter taste, making the cake acceptable to chicks. Saponification of neem oil (present in the cake) with 10 percent KOH completely detoxified the cake (Dutta, Panda and Kamra, 22.). Replacing groundnut meal with NSC at above 25 percent markedly reduced egg production, but replacing groundnut at 10 percent neem kernel meal treated with 2 percent NaOH had no effect on egg production (Dutta, Panda and Kamra, 22). Changes in carcass characteristics were small but some abnormalities were noted, including pale and shrunken muscles and fatty changes in the vital organs, and the anti-fertility effect of neem was confirmed (Dutta, Panda and Kamra, 22).

Research has shown that 40 and 22 percent of dietary energy can come from babussa (replacing maize) and oil palm (replacing wheat bran), respectively, thus reducing the cost of feed and not impairing production (de Albuquerque *et al*., 14).

Detoxified *J. curcas* kernel meal (DJCKM) has also been fed successfully to turkeys from 3 weeks of age, up to 20 percent of the diet, and growing pigs, where it has replaced 50 percent of the soybean meal protein in the diet (Makkar, Kumar and Becker, 21). The authors suggest DJCKM as a substitute protein when fishmeal and other conventional protein-rich feeds are in short supply and expensive.

Fish

With fish, the amount of PKC in the diet will depend on the species, with current recommended inclusion levels ranging from 30 percent for catfish to 20 percent for tilapia. However, ongoing work involving treatment with enzymes indicates that the levels of PKC could be increased, thus allowing a reduction in the amounts of imported maize in the diet (Wan Zahari, Alimon and Wong, 13).

Makkar, Kumar and Becker (21), seeking non-conventional alternative feedstocks, studied two species of *Jatropha*. The first of these, *Jatropha curcas*, contains toxic phorbol esters, but after oil extraction from the kernel and detoxification, the kernel meal has a CP content of 60–66 percent. The second species, *J. platyphylla,* has a CP content in the kernel meal of 65–70 percent after oil extraction, and although not toxic, its kernels contain the trypsin inhibitors lectin and phytate. Detoxified *J. curcas* kernel meal, heated (to inactivate trypsin inhibitors and lectins), *J. platyphylla* kernel meal and detoxified *J. curcas* protein isolate can replace 50, 62.5 and 75 percent of fish meal protein, respectively, in fish diets without compromising growth performance, nutrient utilization and health indicators (Makkar, Kumar and Becker, 21). A non-toxic genotype of *J. curcas* (free of phorbol esters, but containing trypsin inhibitors and lectins) is also available in Mexico. The heated kernel meal of this genotype is also an excellent feed resource (Makkar, Kumar and Becker, 21). Since jatropha meals are rich in phytate, addition of phytase in the diets of monogastric animals is necessary for effective utilization of the meals.

Crude glycerine derived from the production of biodiesel from pure or waste vegetable oil or rendered animal fat can contain between 38.4 and 96.5 percent glycerol, although the normal range is between 75 and 85 percent (Mjoun and Rosentrater, 23). The large-scale biodiesel producers supply high grade glycerol to the food, pharmaceutical and cosmetic industries, while that from the smaller producers is likely to contain more impurities, thus limiting its usage. Animal fat derivatives contain less glycerol and more impurities than from vegetable oil feedstocks. Trials with channel catfish and rainbow trout have shown that glycerol can be added to the diet at 10–12 percent and acts as a precursor for gluconeogenesis, but not lipogenesis. However, rainbow trout do not use glycerol efficiently as an energy source (Mjoun and Rosentrator, 23).

MICRO-ALGAE

All of the feedstocks considered above have been produced from agricultural land, either suitable for cropping or currently regarded as marginal. Phytoplanktons are the largest biomass producers in global aquatic systems, both marine and freshwater, at levels that sunlight can facilitate photosynthesis. Algae, the primary producer, are responsible for half of the annual global output of organic carbon (Ravishankar *et al.,* 24). The viability of biofuel production from micro-algae depends on full use of the algal biomass, which is rich in proteins and vitamins and therefore useful for food and feed. They contain chemicals, pigments, fatty acids, sterols and polysaccharides. They have anti-viral, anti-tumour and anti-bacterial properties and act as an antidote against HIV. Their 'farmed' production could be centred on coastal seawaters, thus removing competition for land and water resources needed for agriculture. Ravishanker *et al.* (24) propose five areas to be considered in developing their use: (1) algal biodiversity; (2) large-scale culture of micro-algae; (3) downstream processes for conversion to biofuels; (4) use of micro-algae for food and feed; and (5) technical and economic analysis of the bio-refinery concept to assess and promote adaptation. Algae thrive under a wide range of extreme conditions and have simple nutrient needs and a very fast growth rate, with the ability to accumulate fat up to 50 percent of the their biomass. The authors describe two methods of cultivating micro-algae, either in open ponds, which are relatively cheap and most of those used do not compete for land, or in closed system cultivation that can be more closely regulated (Ravishanker *et al.,* 24). Algae yield biofuels (diesel) by trans-esterification of algal lipids or hydrocracking (i.e. cracking and hydrogenation of biomass containing hydrocarbons). Ethanol can be released from either algal biomass or algal cake (Ravashanker *et al.,* 24). In Table 6 of Chapter 24, the authors give the food applications for micro-algae, together with the cultivation system and the countries currently involved, and in Table 7 compare the vitamin content of some algae with traditional foods. Many micro-algae contain vitamin B_{12} and some brown algae contain tocopherol. Micro-algae containing astaxanthin are also used as feed in aquaculture production, where they can be fed with, or replace, fishmeal, acting as colouring agents in such species as salmon, rainbow trout and koi carp. Improved growth rate and survival, and yolk colour have also been recorded in poultry (Ravishanker *et al.,* 24). Micro-algae have also been fed to ruminants and pigs. They are a good source of carbohydrates, and some contain cellulose, usable by ruminants. They tend to be deficient in the sulphur-containing AA, cysteine and methionine. Other uses listed by the authors include the presence of bio-active molecules (e.g. phycobiliproteins, polysaccharides) and production of biogas, which can provide bio-electricity as an alternative energy source to biofuel. This is an area of great promise waiting for economically viable technology to release its potential.

ECONOMICS

Cooper and Weber (1) foresee the future use of agricultural crops for biofuel resulting in a small increase in livestock feed costs, which will be offset to some extent by the use of co-products as feed and by increases in crop yields over time. Poultry production is a fast growing industry because of a rising world demand for animal protein. Feed costs represent 65 percent of poultry production costs, which could be reduced by largely un-researched co-products such as camelina meal, non-toxic jatropha, and detoxified jataropha meal (Cherian, 17; Makkar, Kumar and Becker, 21). Christensen *et al.* (26) discuss the difficulty of getting accurate data for the costs of wheat DDGS, including the costs of nutrient management. The authors explain the sensitivity of the industry in North America to the exchange rate between the USA and Canadian dollars, in that a strong Canadian dollar will favour importation of DDGS from the USA rather than developing the local industry. The same authors also register concern regarding the growth of the ethanol industry in Western Canada, where wheat is a major feedstock available in Saskatchewan, whereas the beef feedlot industry is concentrated in Southern Alberta. Full economic appraisal must include co-products because of their influence on pathway selection and economics of biofuel production (Wang and Dunn, 27). They suggest that wet distillers grain may be economically viable within a radius of 80 km of the ethanol plant because savings in drying costs will offset higher transport costs and a shorter shelf life (without ensiling). Patino *et al.* (15) call for upgrading of the vinasse produced from bioethanol production from cassava, sugar cane, sweet potato, and sweet sorghum from small-scale on-farm and rural group activities. The techniques should be simple, efficient and sustainable, but result in a product that can be added direct to feed or included in a multi-nutritional block. Larger-scale operations, from which more sophisticated products can be developed and promoted especially for cattle feeding, should also promote social inclusion and extension of knowledge (Patino *et al.*, 15).

Galyean *et al.* (4) considered economics to have been a major driver in growth of the industry. The need for leadership to drive a new industry is taken up by Christensen *et al.* (26), who suggest a combination of public and private forces to ensure adequate regulation of the market and maintenance of the profit motive (see Tables 4 and 5 of chapter 26). A counter argument is proposed by Drouillard (8), in that the recent rapid expansion in biodiesel production, which is predicted to continue until 2020, has caused a market glut of glycerol and thus is expected to cause the price of this product to fall, thereby increasing its acceptability as a livestock feed.

Decentralized groups producing syrup from sweet sorghum are a feature of production in India (Rao *et al.,* 12), where groups of small-scale farmers work together to produce syrup for ethanol production, leaving the co-products available for local use. This is in contrast to centralized production, based on large-scale producers. Feeding of sugarcane bagasse has not been successful economically, and using it for fuel currently shows a better return (Anandan and Sampath, 16). Wan Zahari, Alimon and Wong (13) suggested that market forces will drive the use of oil-palm by-products as livestock feed in Malaysia because of the acute shortage of traditional forage and the need for a large increase in livestock production to satisfy demand. Castor cake, of which there are large quantities in India, China and Brazil, even after the cost of detoxification is taken into account, could probably be marketed well below the price of traditional protein sources (Anandan, Gowda and Sampath, 20). Shurson, Tilstra and Kerr (3) make a case for co-products such as DG to be available on Futures Markets, and a recent development is that DDGS are now tradable on the Chicago Mercantile Exchange (CME) (G. Cooper, pers. comm.). A stumbling block to this being quality variation, which resulted in 2007 in a call for standard analytical procedures and clear definitions of the products. These authors present data that show USA exports to have increased from 1 million million tonne to 9 million tonne between 2004 and 2010, to an increasingly wide global market and for an increasing number of livestock species. Cherian (17) estimates that between 70 and 80 percent of the harvested weight of *Camelina sativa* is co-product, camelina meal, and 65 percent of the costs in poultry production are accounted for by the cost of feed. Establishing a demand for camelina meal may enhance the overall value of the crop and reduce the cost of feeding poultry. India, the country with the greatest population of livestock, is short of protein- and energy-rich feeds, a worsening situation because of shrinking grazing lands and liberalized export policies. This situation is forcing attention to non-conventional feeds, two of which, *Pongamia glabra* (karanj) and *Azadirachta indica* (neem) are discussed by Dutta, Panda and Kamra (22), with a third, *Jatropha* spp., described by Makkar, Kumar and Becker (21).

Socio-economics

The economics of production are not solely confined to finance. Abbeddou and Makkar (19), in their assessment of potential use of co-products from non-edible-oil-based biodiesel production as feedstuffs call for socio-economic analysis alongside the development and use of the detoxified materials. They foresee sustainability from feedstocks that are not in competition with human food and animal feed, and that grow in poor and marginal soils. They also note that many of the emerging co-products contain toxic or anti-nutritional factors, thus generating a need for detoxification or nutritional improvement. The case for micro-algae development is based partly on the lack of competition for land and water resources with traditional agriculture (Dutta, Panda and Kamra, 22).

Wang and Dunn (27) discuss the water footprint of biofuels, which is a combination of that needed to grow the feedstock and that needed in the production process. The demand for irrigation is, and will be, an important component, although the authors note that improved practices have reduced irrigation by 27 percent in the last 20 years, with some reduction of water use also in the production of ethanol They present a series of allocation methodologies to create a life-cycle analysis. The parameters include displacement, massed-based, energy-based, market-value-based and process purpose, which can be combined into a hybrid methodology (Wang and Dunn, 27).

When calculating reductions in GHG emissions, the savings in fossil fuel and use of a cleaner fuel are only one side of the equation, as energy expenditure and GHG emissions implicit in growing, transporting and processing the biofuel must be also be accounted for (Lywood and Pinkney, 2). These authors go on to explain the formula by which savings of GHG are calculated so that a ‘trading balance’ can be established. Over the next decade, it is likely that the biofuels industry will expand less rapidly than in the previous decade in its traditional areas because of controls put on expansion by several governments, such as China and the USA (Cooper and Weber, 1).

In Brazil, the Rural Social Biorefineries (RUSBI) approach has been developed for small-scale farmers, especially in remote and marginal areas, to promote agricultural development, food safety and energy self-sufficiency, as cooperatives rather than as associations in order to benefit most from the prevailing tax system (Patino *et al.*, 15). Similar developments in Colombia were adopted where petrol prices were high (Patino *et al.*, 15).

Braid (25) suggests that the biofuels industry is being driven by needs such as fuel security and government demand for a pricing mechanism for carbon. Wiesman, Segman and Yarmolinsky (18) comment on incentives to the biofuels industry, but also raise the question of penalties for non-inclusion of biofuels in transport fuel within government timeframes.

The approach to small-scale farmers has also been used in India with sweet sorghum being a major feedstock in a 'decentralized' system designed to encourage rural development (Rao *et al.,* 12). This allows small groups of farmers to develop local installations to produce syrup and sweet sorghum co-products and to send the syrup to a centralized unit for ethanol extraction (Rao *et al.,* 12), thus avoiding the high cost of transporting the whole crop to the centralized unit, and allowing local retention of the co-products. The viability of this approach depends on the sale of fodder bagasse, and producers are rapidly becoming aware of enhancing the value of this through chopping and supplementation (Rao *et al.,* 12).

Erickson, Klopfenstein and Watson (5) point to the increased N and P content of properly handled manure and the GHG benefits to the rating of ethanol compared with gasoline if DGS is produced, the amount of P often being sufficient to adopt a four-year rotation for this element. The savings in GHG largely accrue through the greater average daily gain (ADG) of feedlot cattle fed DGS, reducing the number of days in the feedlot, and, where transport distances allow, the feeding of wet DGS saves emissions associated with drying the DG (Erickson, Klopfenstein and Watson, 5).

Ravishanker *et al.* (24) argue that all photosynthetic processes should be subjected to a full audit at all stages of energy production, an approach currently missing. In Brazil, increased availability of potentially cheap energy sources for livestock, as a result of the expansion of biodiesel production, has created opportunities for rural farmers to intensify domestification of a wild game species, the collared peccary (de Albuquerque *et al.,* 14).

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

The biofuels industry has evolved rapidly over the last two or three decades with developments in processing techniques and an expansion of the range of plants and other natural energy sources being considered as feedstocks. On-farm application of the co-products, on which the viability of the industry depends, is often ahead of unbiased research to support its use, and there is a growing demand for standardization of products. This has generated a need for research to fill in the gaps of knowledge from existing progress, to seek answers to problems that are known to exist, and to be ready to answer questions raised by future developments. This is against the backdrop of an industry that started as an outlet for grain-based residues from the production of alcoholic beverages, which were fed to pigs and cattle, to one that has grown to importance in protecting the environment and safeguarding dwindling supplies of fossil fuels.

Tables 4 to 6 summarize the research seen as necessary at the present time, which includes assessing current and potential feedstocks, and the nutritional needs of most species of livestock, poultry, and aquaculture. Much of the potential research identified as needed is concerned with co-product feeding value, the need for standardization of products from within an individual plant and between plants, and the search for new feedstocks, particularly those indigenous to an area but underutilized, together with safety standards (including detoxification of seed meals where necessary). Coupled with this is the need to consider the species to which the co-product is to be fed.

The knowledge gaps identified in Chapters 1 to 27 inevitably show a degree of overlap, such that in some cases the positioning of a topic within the four tables may appear arbitrary. Table 4 concentrates on DG, including some of the potential constraints in its use. Table 5 brings together suggestions for investigating co-products from feedstocks other than cereals, including the programme on micro-algae. Table 6 lists areas for nutritional research relating to a specific livestock species, although it is accepted that the work involving jatropha co-products and camelina meal would have been equally at home in Table 5. Table 6 presents the areas that belong in neither Table 4 nor 5, but all of which have relevance if the co-products industry is to remain economically viable and to benefit all sectors of the livestock industry.

A major impetus to progress is the need to meet international targets to use biofuels for road transport and to reduce GHG emissions within an agreed timeframe. The success of the industry will depend in part on governments creating the enabling conditions for meeting the targets, and Lywood and Pinkney (2) suggest that this will be easier in Europe for bio-ethanol than for biodiesel. In Australia, sustainability will depend on re-examination of the criteria and indicators of standards for biofuels (Braid, 25). Establishment of a DDGS industry in Western Canada will have to be done against the backdrop of cheap imports from the USA and is unlikely to succeed unless public and private bodies work together (Christensen *et al.,* 26).

TABLE 4

A summary of researchable topics to complement current knowledge relating to distillers grain

Nutritional value of DDGS	Reduction of variability in batches of DDGS produced in the same plant and between plants Linking of chemical and physical characteristics of distillers grain co-products to better define energy values and amino acid profiles Use of infrared technology to evaluate DDGS Assessment of micronutrients and vitamins in DDGS (shortages and excesses of both) Nutritional comparisons between DDGS and WDGS Effects of maize oil extraction on the feeding value of DDGS	1, 3, 4, 5, 7, 9, 10, 26
Storage of DDGS	Role of antioxidants to prevent the growth of moulds and mycotoxins, especially in hot and humid conditions and where long-term storage of DDGS is likely	3
Environmental issues of WDG	An assessment of the reduction of negative environmental effects of wet DG used in feedlots, including water and electricity usage, especially compared with production of DDG Carbon footprints of livestock feeds, including cost of transport LCA studies on the use of co-products of biofuel industry as livestock feed	2, 4, 7, 9, 11, 12, 25
Dietary inclusion rates of DDGS	Appraisal of nutritional strategies to increase inclusion rates of DDGS in diets for livestock and poultry, while maintaining product quality	3, 10, 11
Higher added value co-products	Development and refinement of technology protocols for animal feeds, leading, for example, to a system of product warranty The production of yeast from sugar cane-based vinasse	15, 26
Associative effects of feeds	Interacting factors between elements of the diet including DMI, forage type and inclusion level, age and class of animal to be fed Forage replacement values of DGS, information particularly needed within the dairy sector	5, 7
DDGS in pig and poultry nutrition	Effects of feed processing techniques on energy and fibre digestibility Reduction in dietary fibre to enhance the CP content of the feed Effects of addition of enzymes on DDGS utilization Effects of DDGS on the immune system Impact of wheat DDGS on gut health Evaluation of new products resulting from improved fractionation in the ethanol manufacturing process	9, 10, 21, 26
DDGS in aquaculture	Standardization of product quality of DDGS as feed for fish Reduction of fibre levels in DDGS to improve digestibility Flowability of product needed in transport, storage and diet preparation, processes often involving use of augers Development of processing techniques specific for aquaculture, with adequate consideration of health and safety issues Product testing of new co-products coming on stream	23
Anti-nutrients in DG and the use of additives	Tannin concentrations (in sorghum WDG especially) and their impact on productivity, and possible harmful effects of mycotoxins in the diet The addition of probiotics and feed additives needs assessing	4
Effects of Maillard reaction	Understanding of Amardori compounds, especially how they affect both the destruction and unavailability of lysine	9
Hydrogen sulphide	The synthesis, nutritional and environmental factors needed to understand cellular and physiological effects of H_2S The role of diet composition and environmental strategies leading to better diagnosis and treatment for PEM	6
Wider use of DDGS	Evaluation of DDGS for use in aquaculture and in the diets of domestic pets, horses and rabbits	3
Distillers co-products	Assessment of nutraceutical properties of distillers co-products in respect of their role in human health and nutrition	3

Notes: Numbers in column 3 denote chapter numbers in this book. For a list, see Appendix 1. DDGS = dried distillers grain with added solubles; WDGS = wet distillers grain with added solubles; DG = distillers grain; DDG = dried distillers grain; LCA = life cycle analysis; DMI = dry matter intake; DGS = distillers grain with added solubles; CP = crude protein; WDG = wet distillers grain; PEM = polioencephalomalacia

TABLE 5

A summary of researchable topics to complement current knowledge relating to co-products from feedstocks other than cereals

Sugar cane bagasse	Economic analysis and feasibility studies to incorporate bagasse into appropriate livestock feeding systems	16
Castor cake as livestock feed	Detoxification (removal of ricin) before feeding of castor cake Promotion of castor cake as valuable protein source through linking of laboratory and field trials and collaboration with the feed supply industry	20
Oil palm by-products	Use of specialty fats, produced from oil palm, as feed for dairy cattle, poultry, swine and aquaculture Commercial applications, local use and export opportunities for oil palm by-products Use of co-products from oil palm and other locally occurring crops to develop a livestock industry based on currently non-domesticated livestock species (e.g. collared peccary)	13, 14
Rapeseed cake	Feeding rapeseed cake to pigs and poultry to best advantage; levels of inclusion, influence of the processing conditions on variation in nutritive value and the reduction of glucosinolates	11,
Glycerine (livestock)	Removal of methanol from glycerine which is injurious to livestock health Understanding of the mode of action and optimum inclusion levels of glycerine as a dietary energy source, and the role of glycerine feeding in the control of pathogens (e.g. *E. coli*). Effects of residual glycerine in distillers grain on fibre digestion	8, 11
Glycerine (aquaculture)	Recommendations for levels for feeding crude glycerine to fish Variability of product needs reducing Assessment of potential problems from the presence of residual methanol Assessment of long-term effects on fish health and the quality of the meat produced Processing, handling and storage of glycerine to be used in fish diets	21, 23
Lipid co-products and toxicity of unconventional seed meal	Examination of biodiesel lipid co-products for the presence of compounds toxic to animals and humans Development of methods for selective removal of primary toxins from *Pongamia glabra* and *Azadirachta indica*, both potential sources of feed protein, leading to an industrial process for detoxification Adequate testing of the efficiency of the detoxification process selected on the feeds, and also of the animal product resulting from their use before promotion on-farm Development of a detoxification processes for non-edible oil seed meals, including improvement of procedures that currently exist, and up-scaling where appropriate (these studies need relating to socio-economic analysis) Development of protein isolates and peptides to assist in eliminating toxins and other antinutritional factors	18, 19, 22
Development of micro-algae	Selection of the best organisms, together with sustainable culture methodologies, including use of marginal land, coastal areas, sea surfaces, etc., to minimize conflict with land-based resources Assessment of co-products from micro-algae, both for their feeding value and commercial application (potential use in diets for livestock, poultry and aquaculture)	24
Camelina meal for poultry	Nutritional value assessment of camelina meal for poultry of all age groups whether for meat or egg production Assessment of the need for additional enzymes The impact of camelina meal on meat quality Investigation of techniques for enhancing the nutritional value of camelina meal	17

Notes: Numbers in column 3 denote chapter numbers in this book. For a list, see Appendix 1.

TABLE 6

A summary of researchable topics to complement current knowledge and having relevance to the use of co-products as feed for livestock, poultry and fish

Effluent handling	Development of methods to reduce effluents from processing plants and that are suitable for both large and small-scale operations Conversion of vinasse into biogas (to be used as a source of energy and fertilizer) Identification and validation of flocculants and agglomerants	15
Decentralized systems suitable for groups of small-scale farmers in India	Identification of crops to extend the period of use of processing plants (currently one crop per year is processed) Identification of multi-purpose crops to meet household and livestock requirements Juice extraction and syrup conversion needs to be more efficient Improvement of quality of syrup produced Extension and training at all levels	12
Assessment of improved production methods, improved co-products and co-products resulting from new and unconventional feedstocks	Testing of new and unconventional feedstocks, developed from improved production Testing of new co-products leading to changing end uses Life cycle analysis of the use of these products required coupled with traditional nutritional appraisal Understanding of interactions between cropping, grazing and bio-energy production Nutritional assessment of co-products should be linked to studies on animal health and feed safety in livestock and poultry Effects of feeding new or enhanced co-products on milk quality	3, 5, 7, 25, 27
Marketing	Evaluation of: nutrient management costs; indicators for import and export criteria; differences between feedstocks; full economic appraisal encompassing field costs; and the net value of biofuel and co-product Understanding of associative relationships between traditional feeds and co-products is not understood and needs clarifying, supported by up to date information on production	1, 7, 26

Notes: Numbers in the body of the table denote chapter numbers in this book. For a list, see Appendix 1.

ACKNOWLEDGEMENTS

We are thankful to G. Copper, M.L. Galyean, G.C. Shurson and R.T. Zijlstra for critically reviewing the paper and for their invaluable suggestions.