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Opportunities for energy efficiency and biofuel production in Australian wheat farming systems

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Background: The use of grain for food and biofuels is of high international interest amid rising fossil energy costs, energy security and climate change. Energy efficiency must be improved in high-input agriculture in order to provide net benefits from biofuels. **Results:** Options for reducing energy inputs into selected examples of Australian grain farms were investigated. Nitrogen fertilizer and diesel accounted for the bulk of nonrenewable energy use (over 73%) and targeted options for reducing their consumption can save from 25 to over 70% in energy use. **Conclusion:** Strategies to implement energy efficiency improvements into grain farming and improve the sustainability of agricultural production systems are effective but usually incur some production penalties. The trade-offs between energy use and production are discussed.

The prospects of peak oil usage and a changing climate are forcing many to reconsider the availability and economics of energy use and emissions in a range of sectors. Biofuels have been mooted as contributing to fuel security while providing greenhouse gas (GHG) savings in comparison to fossil fuels. Due to the many studies highlighting the fairly minimal GHG and energy returned on energy investment (EROI) savings achieved from biofuels based on high-input agricultural systems [1–3], there are now clear expectations in many policy environments to increase sustainability of biofuels. For example, the 2009 European Parliament and Council directive on the promotion of the use of bioenergy from renewable sources sets out a number of objectives for the increased use of renewable energy sources, including sustainability requirements of biofuels and agricultural products, from both inside and outside Europe, in light of food security, fuel security and environmental sustainability [4].

These objectives are designed to steer biofuel production away from high-input food production systems. However, given that large-scale second-generation biofuel production is not yet a commercial reality, potential strategies to reduce the energy impacts of the agricultural production part of a biofuels value-chain include reducing energy inputs, increasing **energy efficiency** and producing fuel to run the farm itself. This study aims to quantify the extent to which on-farm energy self-efficiency is physically possible within Australian grain farming systems. This has implications for the sustainability of biofuels derived from agricultural feedstocks and in particular those based on grain, given the increasing price volatility of high-energy inputs and the energy security and food security trade-offs.

In Australia, agriculture and rangeland grazing account for 58% of total land area (443 million hectares [5]) and contributed an estimated 15.6% of Australia's GHG emissions in 2006 [6]. In that year, 24.3 million hectares were sown for crops, of which half was wheat producing 25.7 million tonnes of grain, 60% of which was exported [5]. Grain production is therefore an important industry, sustaining rural communities and providing a valuable domestic food source and economic export. While it has the potential to be one of the main contributors to the future

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Key term

Energy efficiency: Energy that is produced in the system in relation to the energy used to create it, also known as energy returned on energy invested.

fuel mix, either through grain or agricultural residue, grain production has been identified among the most vulnerable industries to the impact of a decline in international oil supplies [7].

The increasing accountability of agricultural emissions may provide the impetus to reduce GHG emissions from the agricultural sector. Reducing energy inputs, in particular fertilizer and diesel, can provide a mechanism of lowering the GHG emissions in grain production systems [8]. This has implications for the production of grain for biofuels, as well as the food market given the increasing concern regarding the 'carbon burden' of food production itself [4,9]. Thus, improving the energy efficiency of Australian grain farming systems should be a priority, helping to reduce costs and buffer farmers from the long-term increases in energy prices (diesel and other farm inputs), securing future growth needs and opening up their products to the low-emissions transport fuel market [10,11].

Oil and natural gas prices were at all-time highs in 2008 and the grains industry in Australia is faced with the prospects of long-term increases in real prices and volatility of prices in energy (particularly chemical fertilizers and diesel). Regardless of whether international oil supplies continue to grow steadily [12,13] or if there is a near-term peak in international production resulting in declining future oil supplies, energy prices in Australia are likely to increase [7]. At the same time, the introduction of an emissions trading scheme (ETS) may also impact on the grain production industry by indirectly increasing costs of fossil-based inputs [7,14]. However, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Future Fuels Forum [7] showed that fuel price is less sensitive to carbon price than to changes in oil price and in the event of a decline in international oil supplies, fuel-saving technologies alone would not be sufficient to meet the fuel supply gap and reduced fossil fuel demand would be necessary.

Broadacre grain-growing systems in Australia would be vulnerable to increases in the price of fertilizers, as well as high diesel prices. This reflects the vulnerability of other wheat-producing regions around the world; for example, Shoemaker *et al.* found that wheat systems have the highest share of costs proportioned to energy of all crops in the US agricultural sector [15], and the availability of cheap energy in the last two decades has allowed global agricultural energy efficiency to worsen [16,17]. Australian agriculture is increasingly dependent on synthetic sources of nitrogen [18], yet scarcity of natural gas supplies may also lead to rising nitrogen fertilizer prices [19]. Smil suggests improvements of 20–25% in nitrogen fertilizer use efficiencies could be achieved in affluent countries and up to 50% in more recently modernized countries, by using better agronomic practices [11]. This provides farmers with a potential pathway for reducing production costs and maintaining profit margins if wheat prices do not increase alongside energy prices.

During the oil shocks of the 1970s, farmers in many countries responded by investigating energy efficiency and biofuel production, including Australia who undertook several years of focused research in this area [20–25]. In addition, novel practices such as conservation tillage provided successful gains in energy efficiency [11,26]. Conservation tillage (also referred to as 'min till', 'no till' or 'zero till') reduces the number of tractor passes over fields, instead using herbicides and pesticides for weed and pest control. When oil prices stabilized at lower levels in the 1980s, interest in energy efficiency and biofuels waned. However, conservation tillage was shown to have a range of other benefits, such as reduced soil erosion and better water storage and it has become widely practiced in Australian grain-growing regions.

The aim of this study is to investigate broad opportunities for reducing reliance on fossil energy sources and improve energy efficiency in Australian wheat farms. Four main energy-saving strategies are presented in this article (along with a baseline): the historical scenario of moving from regular tillage to no till; reductions in nitrogen fertilizer usage using legume rotations; rotations including oilseeds that provide the opportunity to produce biodiesel on-farm for fuel agricultural machinery and reduce the energy and emission costs of diesel or indeed to continue to operate and produce food in the case of a near-term peak oil scenario; and, finally, a combination of the three. Energy savings, however, may incur a production penalty – less overall production due to a lower input regime. The opportunities for reducing energy inputs and the production trade-offs of each option are explored and quantified in this article. The results are then compared with similar efforts in the literature to explore the parallels between similar systems and provide a baseline for further research.

Experimental

Life-cycle energy analysis (LCEA) is a subset of life cycle assessment (LCA) focusing only on energy flows. It has been chosen as the method to demonstrate the dependence of farms on energy inputs both directly and along the supply chain of agricultural inputs and to contrast these with the farms capacity to produce its own energy supply through cropping.

An LCEA was calculated for ten 'model' wheat farms representing historical, current and prospective wheat and rotational farming systems. Comparisons were made between these different model farms to investigate potential energy and energy efficiency savings across Australian grain production systems. These production systems are generally split into three broad agro-climatic regions – southern and western Australia (which are capable of cropping each year on winter rainfall and here were treated as one) and the northern Australian region (which relies on stored soil moisture from summer rainfall requiring a fallow period between each crop). Conservative values for crop performance were used in modeling each farming system, to report achievable potential energy savings that are valid across the breadth of each agronomic zone.

Table 1. List of treatment effects and the associated modeled farming systems used to analyze the energy variation according to management decisions.

Treatment effect	Farming systems
Reference case: Southern vs northern wheat	Southern Australia farm wheat/wheat rotation (no till) Northern Australia farm wheat/fallow year in/year out rotation (no till)
Moving to no tillage (southern and northern)	Southern Australia farm wheat/wheat rotation (till) Southern Australia farm wheat/wheat rotation (no till) Northern Australia farm wheat/fallow year in/year out rotation (till) Northern Australia farm wheat/fallow year in/year out rotation (no till)
Reduced fertilizer use (legume rotations for nitrogen supply)	Southern Australia farm wheat/wheat rotation (no till) Southern Australia farm wheat/low nitrogen-benefit legume year in/year out rotation (no till) Southern Australia farm wheat/high nitrogen-benefit pasture year in/year out rotation (not till)
On-farm fuel supply (canola rotations for biodiesel)	Southern Australia farm wheat/canola year in/year out rotation (no till) Southern Australia farm wheat/canola (10% to biodiesel for on-farm use) year in/year out rotation (no till)
Combination of the above	Southern Australia farm wheat/canola year in/year out rotation (no till) Southern Australia farm wheat/canola (10% to biodiesel for on-farm use)/high nitrogen-benefit pasture 3-year rotation (no till) Southern Australia farm wheat/canola (100% to biodiesel for on-farm use)/high nitrogen-benefit pasture 4:1:5 rotation (no till)

Modeling design

Five treatment effects were explored in this analysis, which includes a baseline and four energy reduction strategies, for which a total of ten farming systems were defined (Table 1). The spread of systems chosen was deliberately broad and were modeled using average inputs for the regions and management choices to highlight the differences in energy use across systems. The five comparisons made were:

- Wheat produced farm-wide each year with no till (the southern baseline case) versus wheat produced on 50% of the land in rotation with a year-long fallow and no till (the northern baseline case);
- Wheat produced farm-wide each year with no till versus wheat produced farm-wide each year using conventional tillage (a historical case, although still occasionally used);
- Wheat produced farm-wide each year with no till versus wheat produced on 50% of the land in rotation with a crop (lupin) or pasture legume (sub-clover) with no till;
- Wheat produced farm-wide each year with no till versus wheat produced on 50% of the land in rotation with canola (rapeseed in Europe) where 10% of the canola is used for biodiesel with no till;
- Wheat produced farm-wide each year with no till versus wheat produced in two novel systems including canola rotations for biodiesel production and legume rotations for nitrogen, both using no till.

Each treatment effect, represented in Figure 1, represents an energy reducing management strategy that is achievable by using different rotation and tillage strategies. The energy savings of each treatment choice was made by comparing the energy budgets, calculated using LCEA, of the relevant farming systems. A very simple model farm was used to represent northern Australia wheat farms to highlight some of the regional variation. However, due to the complexity of opportunistic management and options of both summer and winter cropping in that region, further analyses were limited to the much larger southern (winter cropping) regions. Livestock were also omitted, as the aim of these analyses was to identify energy reduction opportunities from cropping activities. However, the inclusion of livestock may affect nitrogen flows and subsequent availability of nitrogen to the crops.

The SimaPro LCA software package (PRé Consultants, The Netherlands) was used to perform the LCEA [27]. All energy flows were included but the source of energy was tracked so as to separate fossil and nonfossil energy inputs, using

Key terms

Conventional tillage: Preparation of agricultural fields by ploughing to loosen the soil, mix organic matter and control weeds.

Biodiesel from Canola: Transesterification process where oil pressed from canola seed is reacted with methyl alcohol and a catalyst to form biodiesel (with glycerol as a co-product).

a cumulative energy demand by end use impact factor. Energy inputs across the supply chain were included for materials and service inputs to the agriculture system. Process data were sourced from the database of European process data [101] and, where possible, Australian data were used from the Australian life-cycle inventory (LCI) database [102]. Data for the on-ground activities in each system (such as nutrient application rates and fuel usage) were collated from agricultural researchers (southern systems) [Poole M, Unpublished Data] and commercial agronomic consultants (northern systems) [Milne G, Ward L, Pers. Comm.]. Values were also compared with statistical averages available from census data [5]. These inputs are summarized in Table 2.

These took into account the variations of inputs into each farmed hectare according to the previous rotation on that hectare (in particular the yield and nitrogen application rates) as shown in Figure 1. Some base assumptions were used for calculating the diesel inputs, where diesel usage for one spray was 2 liters per hectare (l/ha), diesel usage for tilling/harvesting was 7 l/ha, no pesticides or herbicides were used in conventional tillage systems and yield benefits were gained in mixed rotations. For example, 24 l/ha diesel usage in one rotation of a no till continuous wheat system was made up of one seeding run (7 l/ha), four spray runs (4 × 2 l/ha), truck transport on farm (2 l/ha) and one harvesting run (7 l/ha); while the same system under tillage uses 38 l/ha (from additional tillage runs). Actual fuel use varies considerably across farms according to soil types and machinery configurations, however, the values were chosen as representative of common practice based on agronomic and statistical data [5].

The nitrogen fertilizer decision support tool 'Select Your Nitrogen' (SYN) was used to derive the nitrogen application rates required to achieve the desired wheat yields (1.8 tonne per hectare [t/ha] in wheat/wheat and 2.2 t/ha in wheat/legume) in various rotational situations [103]. The nitrogen 'benefit' was defined as the approximate residual nitrogen available to a post-legume wheat crop, which reduces the fertilizer nitrogen requirement of that crop in the rotation. This benefit depended on many factors such as the type of legume, the harvest removal of nitrogen in a grain legume crop (in this case, lupins, *Lupinus angustifolius*) or the percentage of legume in a pasture (in this case subclover, *Trifolium subterraneum*). Some typical examples of nitrogen benefits and nitrogen requirements for a subsequent wheat

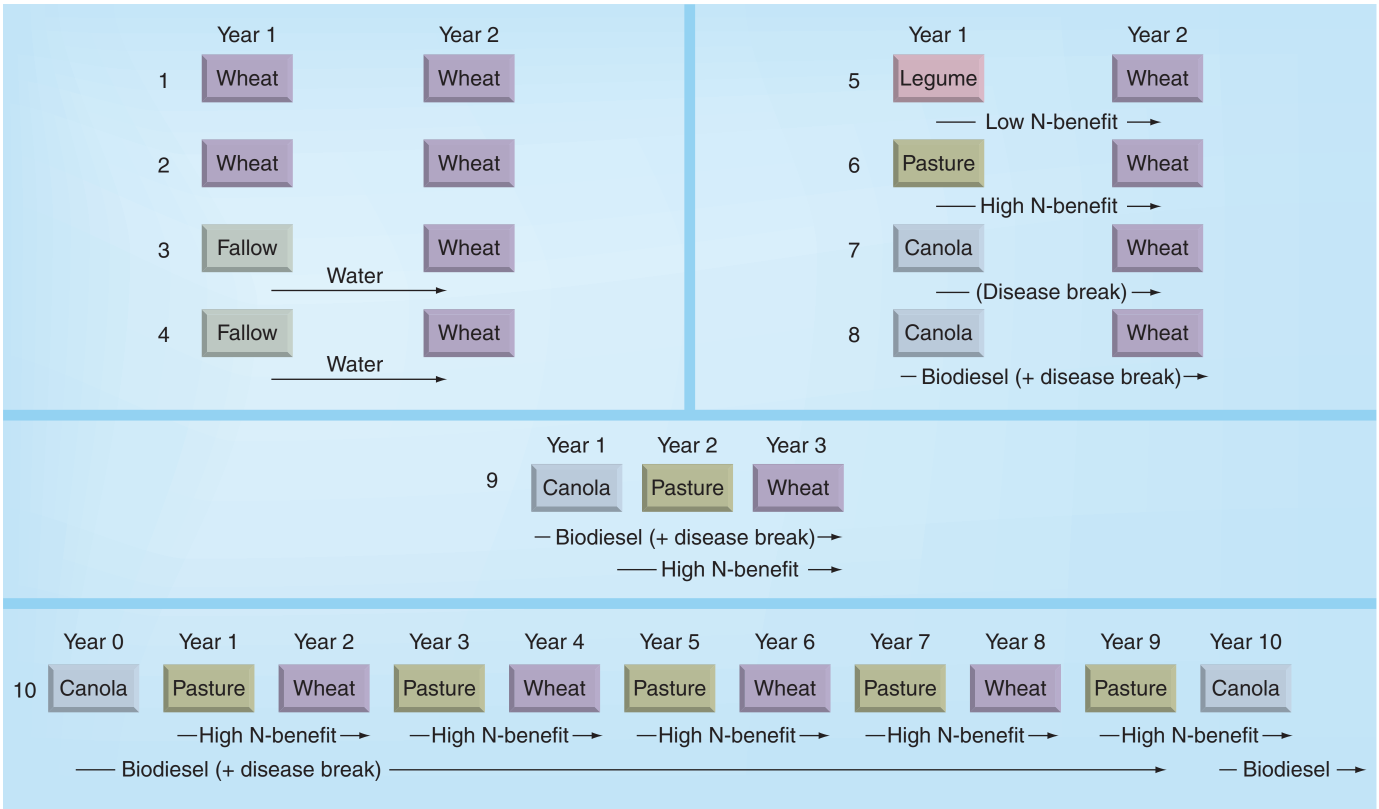

Figure 1. Rotational benefit carryover in the modeled farm scenarios. Energy use in systems 1–8 represents the average energy used in years 1 and 2. System 9 results are averaged from years 1 to 3. System 10 results are the average of years 1–10, however, the system is assumed to be continuously repeating and therefore receives the benefits from at least one previous year (year 0).

Table 2. Inputs into each modeled rotation per hectare of the crop farmed according to the previous rotation farmed on that land.

Input	Rate
Yield	
Wheat after wheat	1.8 t/ha[§]
Wheat after fallow	2.0 t/ha[¶]
Wheat after legume	2.2 t/ha[§]
Wheat after canola	2.2 t/ha[§]
Canola after wheat	1.0 t/ha[§]
Crop legume (lupin) after crop	0.9 t/ha[§]
Canola after legume	1.0 t/ha[§]
N application (in Urea[†])	
Wheat after wheat	40 kg/ha[#]
Wheat after fallow	55 kg/ha[#]
Wheat after low N-benefit legume	20 kg/ha[#]
Wheat after high N-benefit legume	5 kg/ha[#]
Wheat after canola	40 kg/ha[#]
Canola after wheat	40 kg/ha[#]
Canola after high N-benefit legume	10 kg/ha[#]
P application (in Superphosphate†)	
Wheat after wheat	10 kg/ha[§]
Wheat after fallow	8 kg/ha[¶]
Wheat after legume	10 kg/ha[§]
Crop legume (lupin) after crop	15 kg/ha[§]
Pasture legume (sub-clover) after crop	10 kg/ha[§]
Wheat after canola	10 kg/ha[§]
Canola after wheat	10 kg/ha[§]
Canola after legume	10 kg/ha[§]
Fuel usage (diesel[†] or biodiesel[†])	
Wheat after wheat (till)	38 l/ha[§]
Wheat after wheat (no till)	24 l/ha[§]
Wheat after fallow (till)	27 l/ha[¶]
Wheat after fallow (no till)	20 l/ha[¶]
Wheat after legume (no till)	24 l/ha[§]
Wheat after canola (no till)	24 l/ha[§]
Canola after wheat (no till)	28 l/ha[§]
Canola after legume (no till)	28 l/ha[§]
Crop legume (lupins) after crop	24 l/ha[§]
Pasture legume (sub-clover) after crop	5 l/ha[§]
Fallow after wheat (no till)	14 l/ha[§]
Fallow after wheat (till)	49 l/ha[§]
Herbicide (no till rotations only)	
Wheat after wheat (Glyphosate[†])	2 kg/ha[§]
Wheat after wheat (Diuron[‡])	0.5 kg/ha[§]
Wheat after wheat (MCPA[‡])	0.5 kg/ha[§]
Wheat after fallow (MCPA[‡])	0.9 kg/ha[¶]
Wheat after fallow (2,4D[‡])	0.9 kg/ha[¶]
Herbicide (no till rotations only) (cont.)	
Wheat after legume (Glyphosate[†])	2 kg/ha[§]
Wheat after legume (MCPA[‡])	0.5 kg/ha[§]
Wheat after legume (2,4D[‡])	0.5 kg/ha[§]
Crop legume (lupins) after crop (glyphosate[†])	1 kg/ha[§]
Pasture legume (sub-clover) after crop (glyphosate[†])	2 kg/ha[§]
Pasture legume (sub-clover) after crop (atrazine[‡])	0.25 kg/ha[§]
Wheat after canola (glyphosate[†])	2 kg/ha[§]
Wheat after canola (MCPA[‡])	0.5 kg/ha[§]
Wheat after canola (2,4D[‡])	0.5 kg/ha[§]
Canola after wheat (Glyphosate[†])	2 kg/ha[§]
Canola after wheat (MCPA[‡])	0.75 kg/ha[§]
Canola after wheat (2,4D[‡])	0.75 kg/ha[§]
Canola after legume (Glyphosate[†])	2 kg/ha[§]
Canola after legume (MCPA[‡])	0.75 kg/ha[§]
Canola after legume (2,4D[‡])	0.75 kg/ha[§]
Fallow after wheat (Glyphosate[†])	4.5 kg/ha[§]
Fallow after wheat (2,4D[‡])	3 kg/ha[§]
Herbicide (till rotations)	
Wheat after wheat (Diuron[‡])	0.5 kg/ha[§]
Wheat after wheat (MCPA[‡])	0.5 kg/ha[§]
Wheat after fallow (MCPA[‡])	0.9 kg/ha[¶]
Wheat after fallow (2,4D[‡])	0.9 kg/ha[¶]
Pesticide	
Crop legume (lupins) after wheat (generic[‡])	2 kg/ha[§]
Pasture legume (sub-clover) after wheat (cyanazine[‡])	0.25 kg/ha[§]

[†]Australian mix [102].
[‡]European mix [28].
[§]Data from [Poole M, Unpublished Data].
[¶]Data from [Milne G, Ward L, Pers. Comm.].
[#]Data from [103].

Table 2. Inputs into each modeled rotation per hectare of the crop farmed according to the previous rotation farmed on that land.

[†]Australian mix [102].
[‡]European mix [28].
[§]Data from [Poole M, Unpublished Data].
[¶]Data from [Milne G, Ward L, Pers. Comm.].
[#]Data from [103].

crop are shown in Table 3. These values were used in the LCA models where low nitrogen-benefit rotations (20 kg/ha of nitrogen are applied to a crop following lupins) and high nitrogen-benefit rotations were used (5 kg/ha of nitrogen are applied to a crop following a 90% sub-clover in pasture mix). Although the true nitrogen benefits of legume rotations are likely to vary widely, this study used constant values to allow comparisons to be made between systems rather than investigating variation within a single **crop rotation**. The energy inputs into the legumes were added to the

Key term

Crop rotation: Successive growing of different crops to provide nutrients to the soil, a disease break or to store water (a crop-less fallow rotation) to benefit the next crop.

Table 3. Nitrogen application rates required after legume rotations to achieve yields of 1.8 t/ha (no legume) and 2.2 t/ha (after a legume rotation) of wheat†.

Treatment	N benefit from legume crop (kg N/ha)	N applied to following crop (kg N/ha)
No legume‡	0	50
20% legume in pasture mix	10	40
40% legume in pasture mix	20	30
60% legume in pasture mix	30	20
80% legume in pasture mix	40	10
100% legume, pasture or crop	50	0

†Calculated from [103].
‡Equivalent to the southern wheat/wheat system, however, the modeled system used a conservative 40 kg/ha of fertilizer, which the model predicted would output an equivalent yield.

energy budgets of the wheat, however, in the case of crop legumes, the system benefited from the production of the lupin crop.

For biodiesel production from a canola crop, 10% of the canola crop was assumed to provide sufficient biodiesel to power operations for one rotation of wheat. This is based on the Poole *et al.* analysis that showed most Australian grain farming regions can satisfy their cropping diesel requirements using between 7 and 15% of the cropping area for biodiesel production from canola [28]. The inventory data used for the canola-derived biodiesel used an Australian conversion plant, which is most likely higher in energy inputs than a simple transesterification process on-farm with only a small input of methanol required [102].

Calculation of energy efficiency of the farming systems involved dividing the output energy in one tonne of grain products with the total energy inputs. In the case of mixed rotation systems, the tonne of grain products was made up of all output grains from the farm proportionally according to the production amount. That is, a 1.0 t/ha canola crop rotated with a 2.2 t/ha wheat crop amounted to 312 kg of canola and 688 kg of wheat making up the one tonne of grain (and the relative inputs into producing each). Alternatively, 1.0 hectare under wheat and pasture rotation is made up of the inputs into 0.5 hectares of wheat (with 1.1 tonnes of wheat produced) plus all of the inputs into 0.5 hectares of pasture (which has no grain output). Energy values of grain were taken from the literature: wheat grain 18 MJ/kg [17], canola seed 26 MJ/kg [29] and lupin grain 20 MJ/kg [30].

▪ System boundaries

The inputs as per the system boundaries (**Figure 2**) included fertilizers, herbicides, pesticides, fuel used by farm machinery, the farm machinery itself and farm infrastructure, as well as the residuals of one farming rotation that became inputs into the following year's rotation (e.g., the nitrogen residual from a rotation of a legume was a nitrogen input for the following wheat crop). As the system boundaries remained the same across each of the farming systems investigated in this study, the results from each can be interpreted individually and also compared with each other.

▪ Functional units

Life-cycle energy analysis requires results to be reported against a functional unit, however, the function of a farm unit cannot be simplified to one crop, as integrated framing units grow a range of products to maximize the financial performance of the farm. For this reason, two functional units have been used to describe these energy flows:

- Areal basis – 'energy use per hectare per year'. In some cases, this included certain portions of the area under different crops simulating a rotation system (i.e., 0.5 ha of wheat and 0.5 ha of pasture per hectare of production per year);
- Production basis – 'energy use per tonne of net grain produced'. The energy flows in systems are allocated in relation to the outputs achieved (i.e., the energy required to produce one tonne of wheat). In some cases, the tonnage contained portions of different crops (i.e., 688 kg of wheat grain and 312 kg of canola seed).

Results

▪ Pathways of energy use

Results from the LCEA can be shown in a number of ways, including network diagrams where the pathways and relative contributions of each component of the system are quantified. This clearly identifies the key contributors to the energy used and the areas of reliance on fossil energy. The network diagrams (**Figure 3**) show the energy contributions made by the southern farm wheat/wheat no till and northern farm wheat/fallow no till systems, which are two commonly practiced management styles in their respective regions. In this system, nitrogen fertilizer was the largest energy input to crop production. If the diagrams in **Figure 3** are further broken down, it shows that nearly 100% of the embodied energy in urea was sourced from natural gas used in the manufacturing process. Combining fertilizers and machinery fuel use accounted for over 73% of the system's energy use in either system.

The percentage values of both network diagrams are useful to make comparisons between these two common systems. They showed the differences in the amount of absolute energy inputs, but also similarities in the relative contributions of each individual input type. The main flows of energy through both these model farms, which reflect current practice in Australia (farms 1, 2, 3, 4 and 7; Figure 1), were through diesel and nitrogen, with 5–8% of energy in infrastructure, 9–14% in herbicides (0% in tillage systems) and 7–11% in phosphate fertilizers.

▪ No tillage

Results are shown for both till and no till methods in a southern farm wheat/wheat system and a northern farm wheat/fallow system in Table 4. For the southern farm wheat/wheat with tillage system, energy use was 4.3 GJ/ha/year, whereas the southern farm wheat/wheat no till system was slightly less at 4.0 GJ/ha/year, an energy saving of approximately 9% in a move to no till. This was a result of the net reduction in diesel use, but was partially offset by the greater use of chemicals such as herbicides.

For the northern farm wheat/wheat with tillage systems, energy use was 3.2 GJ/ha/year and thus was lower than the southern systems because of the fallow rotation. Having no tillage decreased energy use by 0.6 GJ/ha/year (to 2.6 GJ/ha/year or 19%). This difference in reductions between the southern and northern systems was attributable to greater tractor operations in the northern farm wheat/fallow system (four intensive operations in this case, mostly in the fallow rotation) compared with the southern farm examples (two intensive tractor operations saved). Lower farm-scale energy use of the wheat/fallow rotation was due to less crop inputs (only half as much area is cropped for two identically sized farms).

The amount of energy required to produce a tonne of grain was lower in the southern farming systems (2.2–2.4 GJ/t in no till and till respectively) compared with the northern farming systems (2.6–3.2 GJ/t no till and till). While this may seem to be counter-intuitive, these results were due to the increased output per total farm hectares in a continuous system, where every tonne produced was attributed its direct inputs, compared with half the output in a wheat/fallow rotation, where every tonne was attributed the inputs of both a cropping year and a fallow year. Thus, while a northern farming system had less external inputs compared with an identically sized southern farm, the reduced cropping area across the entire farm meant that more growing land was required in the region to produce the same amount of grain.

The per hectare results of the LCEA analyses are independent of yield. Yield is an important factor in the calculation of energy use per tonne. While fixed values for yield were used, the ratio of energy to yield is roughly an inverse proportion. For example, the southern farm wheat/wheat no till system energy use of 2.4 GJ/t for a yield of 1.8 t/ha approximately doubles to become 4.9 GJ/t at a reasonable low yield limit of 0.9 t/ha achievable with the same inputs in a dry season. Similarly, the energy use per tonne decreases to 1.4 GJ/t as yield increases to an upper limit of 3 t/ha achievable in a good season and using the same management.

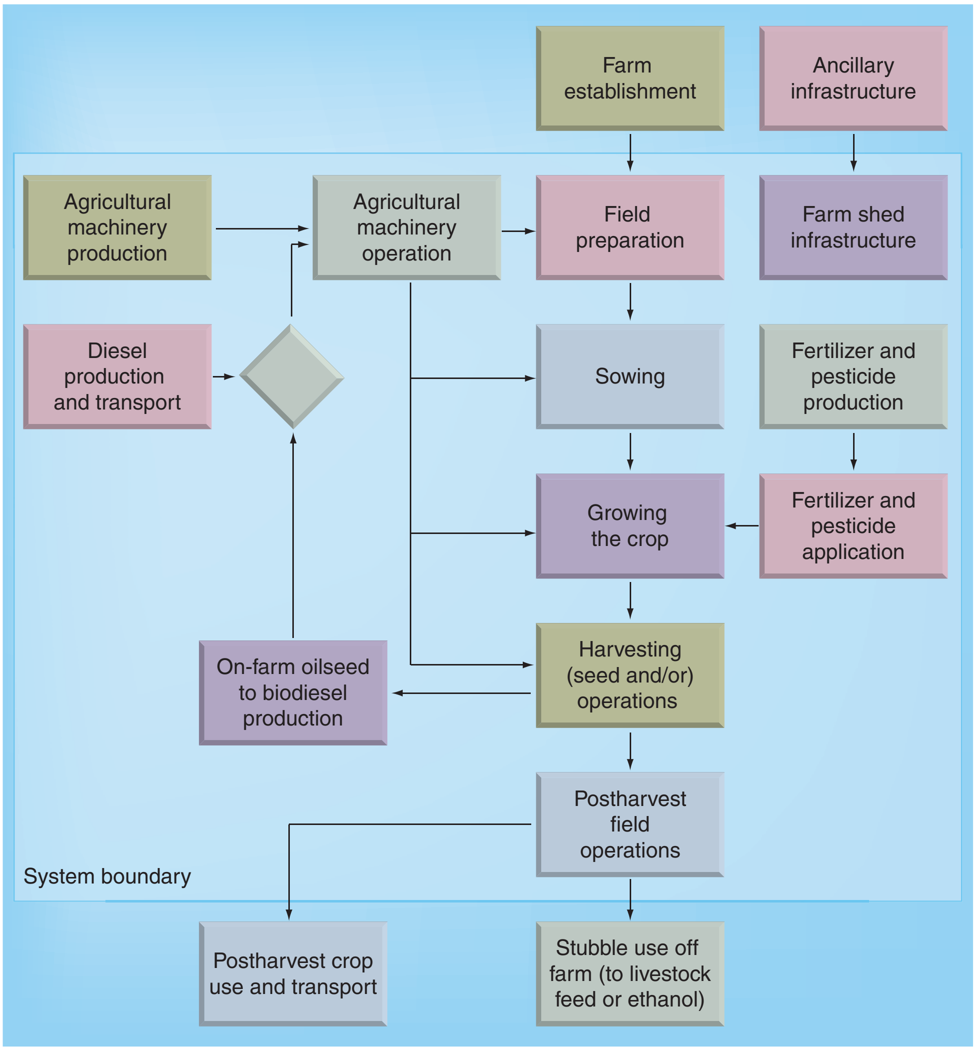

Figure 2. Systems boundaries for life-cycle energy analyses. These boundaries define the scope of the analysis and include the cumulative sum of inputs and processing of each component.

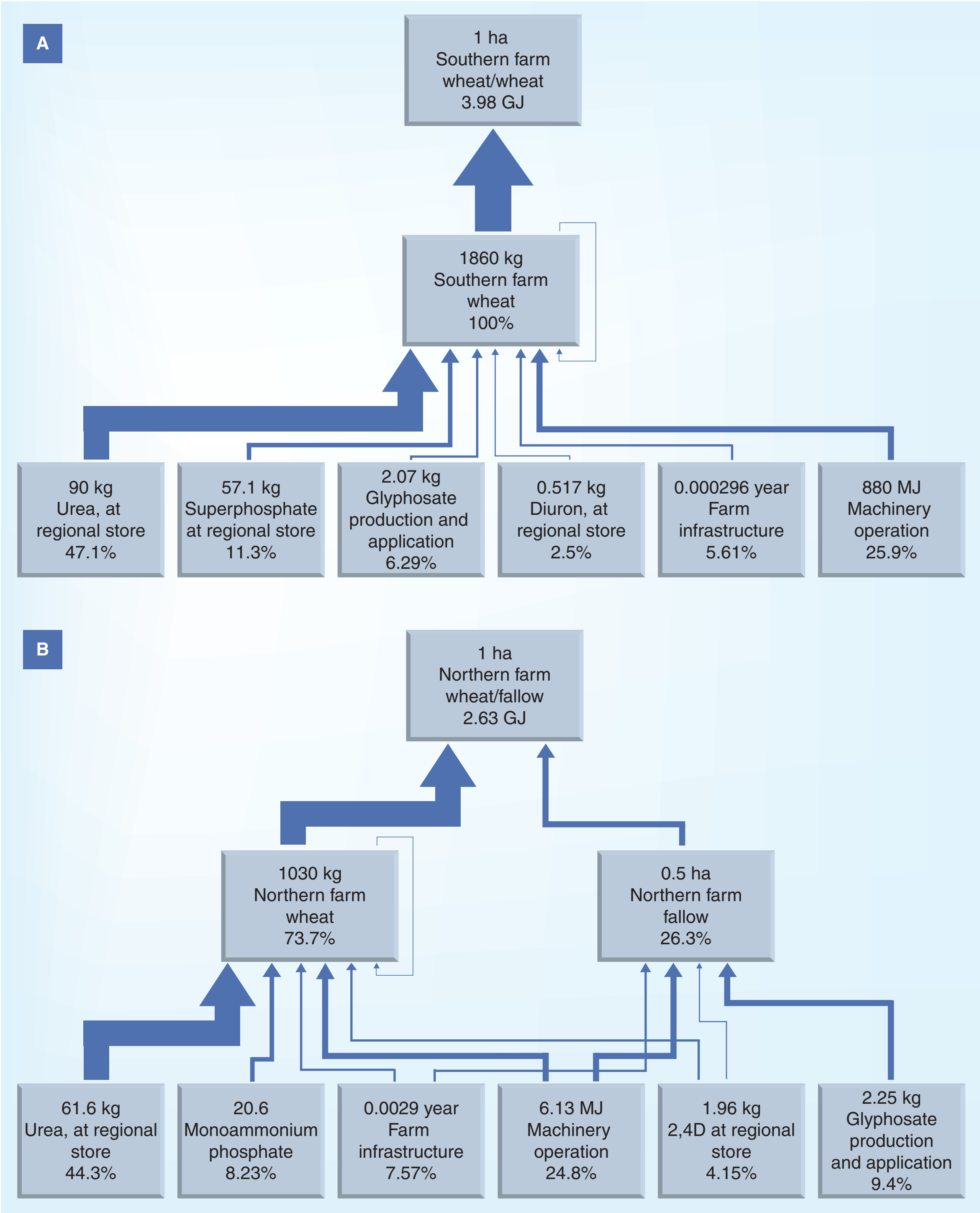

Figure 3. Energy inputs into one farmed hectare of (A) a southern farm wheat/wheat system (no till) and (B) a northern farm wheat/fallow system (no till). Thickness of the lines represent the relative contribution of each input to the total (percentage of energy contributed and actual applied amount are shown in each box, total amount is shown in the top box). The amount applied is the average application on the same farmed hectare over 2 years (which are identical in the southern system). Thus, the energy contribution into one hectare of a northern farm is equivalent to half a hectare of wheat and half a hectare of fallow. In the case of grain, a 1.8 t/ha wheat crop in the south includes the energy requirement of 1.86 tonnes of wheat grain due to the initial 60 kg/ha of seed applied at sowing. Contributions of less than 1% of total energy are not shown.

▪ Potential to reduce dependency on nitrogen fertilizer

As previously identified, the main energy input into a wheat farming system was nitrogen fertilizer. Rotations with nitrogen fixing crops, a practice undertaken in Australia more commonly than among other developed nations [31], reduce the fertilizer requirements of the subsequent crop [17,18,26,32]. Table 5 compares the energy usage of southern wheat systems using legume rotations with the commonly practiced continuous wheat rotation on the same farm.

There was a decrease of 1.5 GJ/ha/year (38%) in energy used from reduced fertilizer application to a wheat crop due to previous 20 kg/ha/year nitrogen-benefit legume rotation, compared with the base case southern farm wheat/wheat no till. A wheat rotation following a higher-rate nitrogen-fixing legume, in this case 35 kg/ha/year nitrogen benefit, provided savings of 2.5 GJ/ha/year (63%) energy applied from lower fertilizer inputs. However, these systems yielded only approximately half the amount of wheat each year compared with continuous wheat.

The energy usage per tonne of production was still lower when using nitrogen-fixing rotations. At low levels of nitrogen benefit (20 kg/ha/year), savings of 0.5 GJ/t/year (or 25%) were possible, although this included some return on the legume crop itself (0.9 t/year). By achieving high nitrogen-benefit rotations (35 kg/ha/year) between every wheat rotation, the energy savings increased to 0.9 GJ/t (wheat only as the legume was a pasture) or 40%. This almost halved the total energy inputs into each tonne of wheat produced. Thus, a farm using such a rotation may use as little as one quarter of the energy of a similarly sized continuous cropping farm (half the output at half the energy expenditure per unit output) when expressed on a per tonne production basis.

▪ Potential to supply fuel on farms

A model farm capable of producing its own fuel needs via biodiesel production from canola or a similar oilseed, was analyzed. A small part of the canola crop, in this case 10%, was returned to the farm in the form of biodiesel. Table 6 shows the energy savings achieved (1.0 GJ/ha/year or 23%) by using 10% of the canola crop in a southern farm wheat/canola to produce biodiesel.

In production terms, the energy input was less in the southern farm wheat/canola with 10% of canola used for biodiesel no till at 2.0 GJ used per tonne of production each year on average, compared with the base case of a southern farm wheat/canola no till, which used 2.5 GJ/t. Thus a saving of 20% (0.5 GJ/t) is achievable by directly substituting diesel with biodiesel produced on-farm. These numbers were particularly sensitive to canola yield (1 t/ha used in this analysis), as a higher proportion of the oilseed crop would be required for fuel if yield decreases, hence the grain output from the system would also be lower.

▪ Potential to supply fuel on farms & reduce nitrogen dependency

Energy use in the self-reliant fuel system was dominated by fertilizer nitrogen. More innovative and challenging solutions for external fossil energy inputs using existing technologies were calculated in two systems. These relied on meeting the farm's fuel needs via biodiesel manufactured on the farm from canola and making most use of legume nitrogen to meet nitrogen demand. Table 7 shows that energy inputs could be reduced by 51% in 1:1:1 rotations of canola and legume with wheat (southern farm wheat/canola/high nitrogen-benefit

Table 4. Comparison of energy usage per hectare and per tonne of grain produced per year in southern grain production systems and northern grain production systems with and without tillage averaged across both rotations.

	Energy applied (GJ/ha/year)	Energy applied (GJ/t)
Southern grain production systems		
Southern wheat/wheat (till)	4.35	2.41
Southern wheat/wheat (no till)	3.98	2.21
Savings	0.37	0.2
Northern grain production systems		
Northern wheat/fallow (till)	3.24	3.24
Northern wheat/fallow (no till)	2.63	2.63
Savings	0.61	0.61

Table 5. Comparison of energy usage per hectare and per tonne of grain produced per year in wheat and low N-benefit legume rotations and wheat and high N-benefit pasture rotations with continuous wheat rotations in Southern grain production systems.

	Energy applied (GJ/ha/year)	Energy applied (GJ/t)
Wheat and low N-benefit legume rotations		
Southern wheat/wheat (no till)	3.98	2.21
Southern wheat/low N-benefit legume (no till)	2.46	1.66
Savings	1.52	0.55
Wheat and high N-benefit pasture rotations		
Southern wheat/wheat (no till)	3.98	2.21
Southern wheat/high N-benefit pasture (no till)	1.46	1.33
Savings	2.52	0.88

Table 6. Comparison of energy usage per hectare and per tonne of grain produced per year in wheat/canola rotations using fossil diesel versus producing biodiesel with 10% of the canola production for use on the farm.

	Energy applied (GJ/ha/year)	Energy applied (GJ/t)
Southern wheat/canola (no till)	4.20	2.51
Southern wheat/canola – 10% of canola to biodiesel (no till)	3.25	2.00
Savings	0.95	0.51

pasture with 10% canola to fuel no till) to 70% in a more tailored system (southern farm wheat/canola/high nitrogen-benefit pasture 4:1:5 with 100% canola to fuel no till) per hectare.

Using the tonne of production output as the functional unit showed that the southern farm wheat/wheat no till used 2.2 GJ/t/year and the southern farm wheat/canola/high nitrogen-benefit pasture with 10% canola to fuel no till received an energy input reduction of 0.39 GJ/t (or 18%) to 1.8 GJ/t. Furthermore, the savings of a 4:1:5 rotation of wheat/canola/high nitrogen-benefit pasture were 0.9 GJ/t (39%), whereas the southern farm wheat/canola/high nitrogen-benefit pasture (4:1:5) with 100% canola to fuel no till system had an energy input of just 1.3 GJ/t. The positive energy savings of such a novel system show that reduced fossil energy inputs outweigh the decrease in tonnage of production.

Energy efficiency of the farming systems

Energy efficiency (the ratio of energy content in the grain products to the energy inputs) is a common way to represent the energy usage in farming systems and is a metric frequently used in the debate regarding the benefits (or not) of production of energy from agricultural systems. The applied energy inputs, the energy outputs and the calculated efficiency ratios are shown in Table 8 for each of the farming systems.

The performance of different systems varied markedly in terms of energy efficiency for grain production. The least efficient system modeled was the northern farm wheat/fallow till system, with a ratio of 5:6. Three of the farming systems were more than twice as efficient as this: the southern farm wheat/canola/high nitrogen-benefit pasture with 10% canola to fuel no till system; the southern farm wheat/canola/high nitrogen-benefit pasture (4:1:5 rotation) with 100% canola to fuel no till; and the southern farm wheat/high nitrogen-benefit legume no till.

Synthesis of energy inputs & production output penalties

Four main strategies (plus a baseline) for saving energy have been presented:

- The historical move to conservation tillage
- Legume rotations for nitrogen
- Canola rotations for biodiesel
- A combination of the three

A comparison of these strategies is provided in Figure 4. The introduction of rotations into wheat had a production penalty owing to reduced wheat cropping area. However, some yield benefits were derived from this rotation and therefore a 1:1 rotation with a legume or oilseed yielded about 60% of the wheat production, plus any oilseed or legume crops. In an ambitious energy saving scheme, where only 40% of the land would be under wheat, approximately 50% of the production could be achieved compared with continuous wheat rotations.

Table 7. Comparison of energy usage per hectare and per tonne of grain produced per year in 1:1:1 rotation of wheat/canola/high N-benefit pasture where 10% of the canola crop is used for on-farm biodiesel and 4:1:5 rotation of wheat/canola/high N-benefit pasture where 100% of the canola crop is used for biodiesel against a standard wheat/canola rotation.

	Energy applied (GJ/ha/year)	Energy applied (GJ/t)
1:1:1 rotation of wheat/canola/high N-benefit pasture where 10% of the canola crop is used for on-farm biodiesel		
Southern wheat/wheat (no till)	3.98	2.21
Southern wheat/canola/high N-benefit pasture (1:1:1) with 10% of canola to biodiesel (no till)	1.97	1.82
Savings	2.01	0.39
4:1:5 rotation of wheat/canola/high N-benefit pasture where 100% of the canola crop is used for biodiesel		
Southern wheat/wheat (no till)	3.98	2.21
Southern wheat/canola/high N-benefit pasture (4:1:5) with 100% of canola to biodiesel (no till)	1.18	1.34
Savings	2.80	0.87

Discussion

These analyses show the energy use impacts of widely different grain-growing systems practiced in Australia. They demonstrated the dominance of nitrogen fertilizers and fuel in energy use, which generally accounted for approximately 75–80% of total consumption. This aligns with similar studies around the world that have found the pools of energy in conventional agricultural systems lie primarily in nitrogen fertilizer and diesel (Table 9).

Table 8. Energy efficiency of each modeled farming system calculated as the ratio of energy output of one tonne of grain equivalent in each farming system (proportioned between crops) to the energy inputs into growing the crops which make up that tonne.

Farm	Energy out† (MJ)	Energy in (MJ)	Ratio (out/in)
Southern farm wheat/wheat till	18,000	2414	7.5
Southern farm wheat/wheat no till (base case)	18,000	2210	8.1
Northern farm wheat/fallow till	18,000	3238	5.6
Northern farm wheat/fallow rotation no till (base case)	18,000	2627	6.9
Southern farm wheat/low N-benefit legume no till	18,609	1657	11.2
Southern farm wheat/high N-benefit pasture no till	18,000	1328	13.5
Southern farm wheat/canola no till	20,500	2512	8.2
Southern farm wheat/canola 10% canola to fuel no till	20,322	1996	10.2
Southern farm wheat/canola/high N-benefit pasture 10% canola to fuel no till	20,322	1816	11.2
Southern farm wheat/canola/high N-benefit pasture (4:1:5) 100% canola to fuel no till	18,000	1344	13.4

†Energy out in mixed rotations include all crop components proportionally (see functional unit section).

While GHG emissions in wheat farming systems may be linearly related to energy inputs, primarily in fertilizer and diesel usage [8], and provide an indication of direct savings in CO_2 emissions, this study has not undertaken a detailed analysis of global-warming potential. Such an analysis would require greater coverage of issues such as emissions from the soil under each crop type, of which very little data is available for most Australian soils. Legume rotations in particular would require greater detail, including emissions from residual nitrogen and variation due to environmental factors such as soil type, soil structure and climatic conditions. Furthermore, this analysis did not take into account many common elements of grain farming systems including livestock production, stubble burning and land use change, which would also reduce the correlation between energy inputs and emissions. A detailed analysis for biofuel production from grain would also require further treatment of co-products, such as dried distillers grains and solubles and crop residues, as these may greatly lower the effective land area required per unit of biofuel produced [33].

The oil-shocks of the late 1970s drove a number of changes in conventional farming systems [11,26], focusing on diesel usage in particular [34]. One outcome has been the decreased energy usage, of between 9 and 19%, in moving from conventional tillage to no till management in the modeled Australian wheat farming systems, saving up to 0.6 GJ/ha/year. These figures are similar to other studies, where savings from adopting various conservation tillage strategies ranged from 5–9% [35], 11–16% [17], 19% [36], through to 26% [37]. These strategies over time have helped reduce energy input in some areas [34] and found to be the best overall practice in terms of energy efficiency across all farms [37]. However, conservation tillage can only provide limited opportunity for saving energy and further increasing energy efficiency on-farm [17,36].

Although Australian wheat farming systems were shown in this study to have relatively low energy inputs (1.3–2.5 GJ/t) compared with similar cropping in other countries (e.g., 3.9 GJ/t in the USA [34]), nitrogen fertilizer application is still the major energy contributor on-farm and is still rising [17,26,32]. This is important in an economy of rapidly increasing energy costs [19] and strategies for reducing nitrogen fertilizer inputs should be the first priority for farmers in the event of an energy crisis [19,26,35,38].

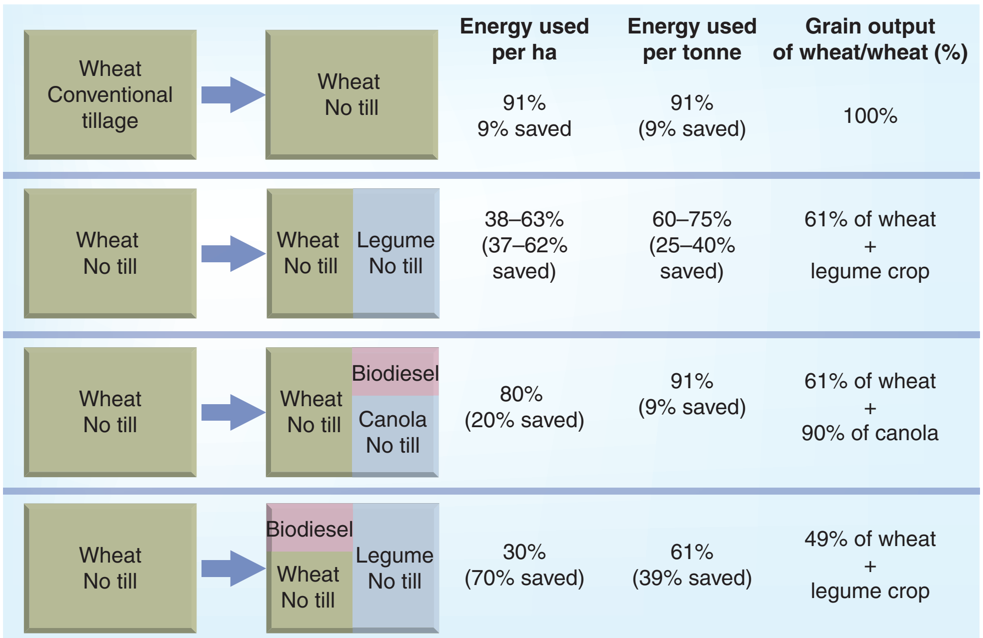

Figure 4. Energy usage and savings potentially achievable against the production penalties of reducing tillage, introducing legume rotations, using canola for biodiesel and a combination of legume rotations and biodiesel production.

Table 9. Nitrogen fertilizer and diesel fuel percentage of total inputs reported in similar studies.

Country	Crop	Nitrogen fertilizer (%)	Diesel fuel (%)	Ref.
Japan	Wheat	25	51	[35]
USA	Wheat	47	25	[37]
Canada	Wheat (in rotations)	66–71	17–22	[17]
Canada	Wheat (in rotations)	43–51	24–37	[38]
Canada	Wheat (in rotations)	NA	37–59	[38]
Turkey	All	50.9	17.6	[16]
Italy	Rapeseed	25–35	38–51	[48]
Italy	Sunflower	24–26	45–50	[48]
Italy	Soybean	0–22	46–67	[48]
Denmark	Barley	48.5	24.6	[45]
Denmark	Various (organic)	NA	59	[40]
Italy	Maize	NS	22–48	[37]
USA	Corn	40–60	17–36	[36]

NA: Not applicable; NS: Not stated.

Aside from the increased costs associated with fossil fuels, the security of supply is also important. In the event of a near-term peak oil scenario, we have shown that it would be physically possible to have fuel supplied on-farm, which has been recognized as an important mitigation strategy [39]. This decreased the total energy usage in modeled traditional systems by 23%, while loss of output product (10% of the canola or 3% of the energy in this case) was small compared with the energy savings, with the opportunity to continue to produce food if circumstances dictated it as necessary. The results of Halberg *et al.* were similar, finding that the diesel usage of an organic farm could be replaced with 10% of the land [40].

Replacing diesel with biodiesel requires minor or no modification to most farm machinery, although there may be issues associated with complying with warranties on farm machinery [41]. There are currently also cost constraints in setting up the biodiesel manufacturing facilities, which can range from small on farm production to industrial-scale plants, and in meeting the fuel standards required to gain tax offsets [41].

The energy reduction options discussed so far provide insight into the ability of Australian wheat farming systems to be self-sustainable in energy and potentially reduce the GHG burden of their products. Over 70% reductions in energy inputs are possible in these systems when using minimum tillage, legume rotations and diverting some oilseed crops to biodiesel production for on-farm use. The area used for biodiesel production (10% of the crop area) is comparable to the estimations of the proportion of the farm used for energy production in the preindustrial era; Smil estimated that at least 20% of agricultural land was devoted to feed animals who worked on it [42].

The potential gains in energy efficiency may have other benefits owing to the reduction of applied synthetic nitrogen [11], which has not been considered here. These include reductions in both the sustained elevated nitrogen cycles in surrounding ecosystems from nitrogen leaching [18,38,43] and the GHG N_2O emitted through nitrogen volatilization [18,43]. Using legume rotations does result in decreased total grain production of the system, however, Crews and Peoples suggest that compensating measures for this can be taken by reducing wastes and losses along production chains, food exports and decreased consumption of meat (which uses at least ten times the resources of grain [44]) rather than increasing land area under production [18].

Several alternative systems have been proposed in the literature, such as using 20-year rotations of nitrogen-fixing perennials, usable as an energy crop and providing long-term soil benefits [45]. Hansson *et al.* suggest in their findings that producing a fuel for the market in exchange for a fuel usable on-farm may be more economically feasible than self-fuelling systems [39]. Finally, Pearson lists a number of best management practices for regenerative systems, which include livestock, facility, infrastructure and nutrient management guidelines, as well as energy efficiency and biodiversity goals [32]. Nevertheless, in a world where oil security and cost, as well as institutional parameters are rapidly changing [7], the potential for grain farms to become self sufficient in physical terms in diesel and nitrogen deserves continued exploration.

Our analyses demonstrated that there is considerable opportunity to modify grain farming systems in line with similar international studies, if energy availability, GHG accounting or cost become driving factors in future crop production. The resulting decrease in production is a critical trade-off as we are entering a period where food, energy and fuel security are in the international spotlight [46,47]. A low energy input, self-fueling system can produce approximately 40–50% of the grain output, which would be sufficient food security for Australia (where 60% of wheat is exported [5]). However, the opportunities of biofuel production for the general market based on low-emission grains may be limited and the GHG implications of such systems and the greater global imperatives for food security versus domestic (energy and food) security deserve wider consideration.

This study is one of the first to quantify energy inputs and outputs from broadacre grain cropping systems in Australia. It has shown that although the pools of energy use are similar to systems elsewhere in the world, the non-renewable energy inputs are low compared with other developed countries. This results in a positive energy output from current farming practices. Thus, this study makes a valuable contribution to the debate on the ability of agriculture to produce net energy outputs from existing crops, which may subsequently lead to energy efficient biofuels.

Future perspective

The demand for biofuels and other forms of bioenergy is increasing globally. Agriculture, in some form, will be expected to meet some of these demands. While in the medium- to long-term, the conversion of cellulosic biomass or algae are anticipated to provide the bulk of the biomass contribution, short-term goals may have to be met by using different strategies. For example, there is no prospect of Australian broadacre oilseed production satisfying the 17 GL/year national diesel demand, but using strategies such as local biodiesel production plants (either on-farm or 10–12 plants of 40–50 ML/year), it may be possible to almost entirely replace the national agricultural diesel usage (estimated at 500 ML/year). This alone would represent a national diesel usage reduction of approximately 3%, potentially mitigating over 1 MT of GHG emissions.

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Executive summary

- Energy efficiency on farms is a growing area of interest amid rising fossil energy costs and increasing concerns about energy security. Energy inputs into farming systems have grown steadily over the course of the past century, while energy efficiency has been falling. Life cycle energy analysis was used to model the energy pathways in 'typical' Australian wheat production systems of southern and northern Australian wheat-growing regions. Variations of these systems were used to investigate the energy reduction potential, with the aim of finding effective methods to reduce external fossil-based energy inputs.
- Nitrogen fertilizer was found to be the most energy intensive input in conventional farming systems, combining with high-energy inputs from diesel fuel usage to account for over 73% of the total energy usage.
- The effect of introducing no till to conventional tillage farming systems can provide direct energy savings. In both the Southern and Northern regions, similar energy savings of between 9 and 19% were found.
- Fallow rotations of the northern grain farming areas used less energy per hectare farmed each year, however, the southern system had better energy efficiency (i.e., less energy per tonne of grain produced each year).
- Legume rotations can be used to provide nitrogen and yield benefits to the following crop – energy inputs from 38% lower (for a rotation with a low N-benefit legume) to 63% lower (a high N-benefit legume rotation) per hectare per year, compared with no-till wheat. This translates to 25 and 40% savings per tonne produced each year, which could be improved using a high N-benefit legume that produces a crop.
- In a 1:1 canola rotation with wheat, using 10% of the canola for biodiesel can save approximately 20% of total energy input, while combining biodiesel production and legume rotations can achieve energy savings upwards of 70%.
- There is potential to reduce energy use and emissions in grain farming systems, with a production trade-off. Australia is in a good position to re-optimize efficiency of this farming system with this trade-off as legume and oilseed rotations are still common and farming systems are lower input than most other developed nations.

Bibliography

Papers of special note have been highlighted as:

- ■ of interest
- ■■ of considerable interest

1 Crutzen PJ, Mosier AR, Smith KA, Winiwarter W. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys.* 8, 389–395 (2008).

2 Bindrabana PS, Bulteb EW, Conijna SG. Can large-scale biofuels production be sustainable by 2020? *Agr. Syst.* 101(3), 197–199 (2009).

3 Pimentel D, Patzek T, Cecil G. Ethanol production: energy, economic, and environmental losses. *Rev. Environ. Contam. Toxicol.* 189, 25–41 (2007).

4 European Parliament. Directive of the European Parliament and of the council on the promotion of the use of energy from renewable sources amending and subsequently repealing directives 2001/77/*EC* and 2003/30/ec. *Directive 2009/28/EC* (2009).

5 Australian Bureau of Statistics. *2008 Year Book Australia.* Category number 1301.0 (2008).

6 Department of Climate Change. *National Greenhouse Gas Inventory 2006.* Department of Climate Change, Canberra, Australia (2008).

7 Commonwealth Scientific and Industrial Research Organisation and Future Fuels Forum. *Fuel For Thought – the Future of Transport Fuels: Challenges and Opportunities.* Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, Australia (2008).

■ **Road-mapping exercise that included a wide stakeholder group.**

8 Kustermann B, Kainz M, Hulsbergen KJ. Modeling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems. *Renew. Agr. Food Syst.* 23(1), 38–52 (2008).

9 Pimentel D, Williamson S, Alexander CE Gonzalez-Pagan O, Kontak C, Mulkey SE. Reducing energy inputs in the US food system. *Human Ecology* 36(4), 459–471 (2008).

10 Dunlop M, Turner G. A long-term view of Australian agriculture: history, future and lessons. *4th International Crop Science Congress* (2004).

11 Smil V. *Feeding the World.* MIT Press, Cambridge, MA, USA (2000).

12 Energy Information Administration. *Annual Energy Outlook 2008: with Projection to 2030* (2007).

13 Energy Information Administration. *Annual Energy Outlook 2008 (Revised Early Release)* (2008).

14 Department of Climate Change. *Carbon Pollution Reduction Scheme Green Paper.* Department of Climate Change, Canberra, Australia (2008).

15 Shoemaker R, McGranahan D, McBride W. *Agriculture and Rural Communities are Resilient to High Energy Costs.* USDA Economic Research Service (2006).

16 Hatirli SA, Ozkan B, Fert C. An econometric analysis of energy input–output in Turkish agriculture. *Renew. Sust. Energ. Rev.* 9(6), 608–623 (2005).

17 Zentner RP, Lafond GP, Derksen DA, Nagy CN, Wall DD, May WE. Effects of tillage method and crop rotation on non-renewable energy use efficiency for a thin black chernozem in the Canadian prairies. *Soil Till. Res.* 77(2), 125–136 (2004).

18 Crews TE, Peoples MB. Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. *Agr. Ecosyst. Environ.* 102(3), 279–297 (2004).

■■ **Provides an overview of the status of legumes and the opportunities they provide.**

19 Dawson JC, Huggins DR, Jones SS. Characterizing nitrogen use efficiency in natural and agricultural ecosystems to improve the performance of cereal crops in low-input and organic agricultural systems. *Field Crop Res.* 107(2), 89–101 (2008).

20 Gladstones JS. Potential savings in nitrogen fertilizer through wider use of legumes in farming. *The Impacts of Changes in Energy Costs on the Rural Sector of the Australian Economy.* Howes KMW, Rummery RA (Eds). Western Australian Department of Agriculture and Murdoch University, Bunbury, Western Australia (1980).

21 Holligan PJ. Some energy aspects of farm machinery. *The Impacts of Changes in Energy Costs on the Rural Sector of the Australian Economy.* Howes KMW, Rummery RA (Eds). Western Australian Department of Agriculture and Murdoch University, Bunbury, Western Australia (1980).

22 Howes KMW, Rummery RA. The impacts of changes in energy costs on the rural sector of the Australian economy. *The Impacts of Changes in Energy Costs on the Rural Sector of the Australian Economy.* Howes KMW, Rummery RA (Eds). Western Australian Department of Agriculture and Murdoch University, Bunbury, Western Australia (1980).

23 Poole ML. Conservation of energy with minimum tillage. *The Impacts of Changes in Energy Costs on the Rural Sector of the Australian Economy.* Howes KMW, Rummery RA (Eds). Western Australian Department of Agriculture and Murdoch University, Bunbury, Western Australia (1980).

24 Stewart GA, Gartside G, Gifford RM, Nix HA, Rawlins WHM, Siemon JR. *The Potential for Liquid Fuels from Agriculture and Forestry in Australia.* CSIRO, Canberra, Australia (1979).

25 Stewart GA, Hawker JS, Nix HA, Rawlins WHM, Williams LR. *The Potential for Production of 'Hydrocarbon' Fuels From Crops in Australia.* CSIRO, Canberra, Australia (1982).

26 Wood R, Lenzen M, Dey C, Lundie S. A comparative study of some environmental impacts of conventional and organic farming in Australia. *Agr. Syst.* 89(2–3), 324–348 (2006).

27 SimaPro 7. PRé Consultants, Amersfoort, The Netherlands (2008).

28 Poole ML, O'Connell DA, Farine DR, Herr A. Regional self-sufficiency for biodiesel. *Opportunities for Energy Efficiency, Regional Self-Sufficiency and Energy Production for Australian Grain Growers.* O'Connell DA, Farine DR, Dunlop M *et al.* (Eds). CSIRO, Canberra, Australia (2008).

29 Moerschner J, Lücke W. Energy investigations of different intensive rape seed rotations – a german case study. *Economics of Sustainable Energy in Agriculture.* van Ierland EC, Oude Lansink AGJM (Eds). Kluwer Academic Publishers, Dordrecht, The Netherlands, 27–40 (2002).

30 Margan DE. Energy and protein value of lupin seed as a production ration or as a supplement for sheep fed chaffed wheaten hay. *Aust. J. Exp. Agr.* 34(3), 331–337 (1994).

31 Unkovich MJ, Pate JS, Sanford P. Nitrogen fixation by annual legumes in Australian Mediterranean agriculture. *Australian J. Agr. Res.* 48(3), 267–293 (1997).

32 Pearson CJ. Regenerative, semiclosed systems. A priority for twenty-first-century agriculture. *Bioscience* 57(5), 409–418 (2007).

■■ **Review of agriculture and best management practices.**

33 Lywood W, Pinkney J, Cockerill S. Impact of protein concentrate coproducts on net land requirement for European biofuel production. *Glob. Change Biol. Bioenergy* 1(5), 346–359 (2009).

34 Piringer G, Steinberg LJ. Reevaluation of energy use in wheat production in the United States. *J. Ind. Ecol.* 10(1–2), 149–167 (2006).

35 Koga N. An energy balance under a conventional crop rotation system in northern Japan: perspectives on fuel ethanol production from sugar beet. *Agr. Ecosyst. Environ.* 125(1–4), 101–110 (2008).

36 Rathke GW, Wienhold BJ, Wilheim WW, Diepenbrock W. Tillage and rotation effect on corn-soybean energy balances in eastern Nebraska. *Soil Till Res.* 97(1), 60–70 (2007).

37 Bertocco M, Basso B, Sartori L, Martin EC. Evaluating energy efficiency of site-specific tillage in maize in NE Italy. *Bioresource Technol.* 99(15), 6957–6965 (2008).

38 Hoeppner JW, Entz MH, McConkey BG, Zentner RP, Nagy CN. Energy use and efficiency in two Canadian organic and conventional crop production systems. *Renew. Agr. Food Syst.* 21(1), 60–67 (2006).

39 Hansson PA, Baky A, Ahlgren S *et al.* Self-sufficiency of motor fuels on organic farms – evaluation of systems based on fuels produced in industrial-scale plants. *Agr. Syst.* 94(3), 704–714 (2007).

40 Halberg N, Dalgaard R, Olesen JE, Dalgaard T. Energy self-reliance, net-energy production and GHG emissions in Danish organic cash crop farms. *Renew. Agr. Food Syst.* 23(1), 30–37 (2008).

41 O'Connell D, Batten D, O'Connor MH *et al.* *Biofuels in Australia – Issues and Prospects.* Australian Government Rural Industries Research and Development Corporation, Canberra, Australia (2007).

■ **Reviews the status of biofuels in Australia.**

42 Smil V. Horse power: the millennium of the horse began with a whimper, but went out with a bang. *Nature* 405, 125 (2000).

■■ **Short communication reflecting on agricultural changes in the 1900s.**

43 Korsaeth A. Relations between nitrogen leaching and food productivity in organic and conventional cropping systems in a long-term field study. *Agr. Ecosyst. Environ.* 127(3–4), 177–188 (2008).

44 Smil V. Worldwide transformation of diets, burdens of meat production and opportunities for novel food proteins. *Enzyme Microb. Tech.* 30(3), 305–311 (2002).

45 Jorgensen U, Dalgaard T, Kristensen ES. Biomass energy in organic farming–the potential role of short rotation coppice. *Biomass Bioenerg.* 28(2), 237–248 (2005).

46 Stoeckel A. *High Food Prices: Causes, Implications and Solutions.* Australian Government Rural Industries Research and Development Corporation, Canberra, Australia (2008).

47 Von Braun J. *The World Food Situation: New Driving Forces and Required Actions.* International Food Policy Research Institute, Washington DC, USA (2007).

48 Venturi P, Venturi G. Analysis of energy comparison for crops in European agricultural systems. *Biomass Bioenerg.* 25(3), 235–255 (2003).

▪ Websites

101 ETH and Swiss Federal Offices. Ecoinvent data v1.01. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland (2003) www.ecoinvent.org

102 Centre for Design at RMIT and Life Cycle Strategies Pty Ltd. Australian LCI database version 2008.1. The Australian Life Cycle Inventory Database Initiative, Melbourne, Australia (2008) www.auslci.com.au

103 Bowden JW. Select your nitrogen: a decision tool for quantifying nitrogen availability and crop response in broad acre farming systems. Department of Agriculture and Food, Perth, Australia (2003) www.climatekelpie.com.au/manage-climate/decision-support-tools-for-managing-climate/syn-select-your-nitrogen