Philosophical Transactions of the Royal Society B: Biological Sciences, 27 September 2010, Volume 365, Number 1554, Pages 2991-3006
http://rstb.royalsocietypublishing.org/content/365/1554/2991

Specification of Driver Review DR4: Energy and the Food System

Energy and the Food System

Jeremy Woods[1*], Adrian Williams[2], John K. Hughes[3], Mairi Black[1], Richard Murphy[4].

[1] Porter Alliance, Centre for Environmental Policy, Imperial College London, London, SW7 2AZ, UK
[2] Natural Resources Management Centre, Department of Natural Resources, Cranfield University, Bedford, MK43 0AL, UK.
[3] Agri-Environment and Land Use Strategy, Food and Environment Research Agency, Sand Hutton, York YO41 1LZ. UK.
[4] Porter Alliance, Department of Biology, Imperial College London, London, SW7 2AZ, UK

Date of receipt:

* Correspondence: Dr. Jeremy Woods
Centre for Environmental Policy,
Imperial College London,
London, SW7 2AZ, UK

Telephone +44 (0)20 7954 9328
Fax +44 (0)20 7594 9334
E-mail jeremy.woods@imperial.ac.uk

Abstract

Modern agriculture is heavily dependent on fossil resources. Both direct energy use for crop management and indirect energy use for fertilizers, pesticides and machinery production, have contributed to the major increases in food production seen since the 1960s. However, the relationship between energy inputs and yields is not linear. Low energy inputs can lead to lower yields and perversely to higher energy demands per tonne of harvested product. At the other extreme, increasing energy inputs can lead to ever smaller yield gains. Although fossil fuels remain the dominant source of energy for agriculture, the mix of fuels used differs due to the different fertilization and cultivation requirements of individual crops. Nitrogen fertilizer production uses large amounts of natural gas and some coal, and can account for more than 50% of total energy use in commercial agriculture. Oil accounts for between 30 and 75% of energy inputs of UK agriculture, depending on the cropping system. Whilst agriculture remains dependent on fossil sources of energy, food prices will couple to fossil energy prices and food production will remain a significant contributor to anthropogenic greenhouse gas emissions. Technological developments, changes in crop management, and renewable energy will all play important roles in increasing the energy efficiency of agriculture and reducing its reliance of fossil resources.

Keywords: Energy in agriculture, fossil energy, agricultural greenhouse gas emissions, land use, agroforestry, policy

1 Energy Use for food production

The IPCC's 3rd Assessment report (IPCC 2001) estimated that by 1995, agriculture accounted for about 3% (9EJ) of global energy consumption, but more than 20% of global greenhouse gas emissions. Figure 1 highlights the trend of increasing energy inputs to agriculture since 1971 and shows the high degree of variability both between regions and over time, for example, the collapse in energy inputs in the former Soviet Union after the fall of the iron curtain in 1989.

[INSERT FIGURE 1 HERE]

Substantial areas of agricultural land also came out of production as these (former USSR) farms became exposed to global competition with governments unable to continue subsidising production.

The links between, agricultural energy inputs, yields, economic returns, land requirements and land use change needs further research. However, land use change has major implications for greenhouse gas (GHG) emissions and carbon stocks, particularly where forest-land is cleared or where previously arable land is allowed to revert to forest. These issues are discussed briefly in the 'indirect emissions' section below but are not a major focus in this paper.

If energy consumption by agriculture continued to grow at the annual rate outlined by the IPCC for 1995 (IPCC 2001), total energy inputs into agriculture would have exceeded 10EJ in 2005, equivalent to a share of about 2% of global primary energy consumption. Therefore, agricultural demand for fossil energy, whilst growing, represents a relatively insignificant and shrinking share of the overall fossil energy supply market. On the other hand, as yields and the inputs needed to support those yields increase, agriculture is becoming more dependent on fossil fuels, either directly for tillage and crop management or through the application of energy intensive inputs e.g. nitrogen fertilizer and pesticides. Furthermore, the embodied energy in tractors, buildings and other infrastructure necessary to support agriculture and food supplies is likely to continue to grow as developing agricultural producers invest in the infrastructure needed to increase yields and become competitive in the global food commodity markets as outlined in Figure 2.

Embodied energy is all the energy used in the creation of a product. In the Life Cycle Assessment (LCA) analyses described subsequently, it is assumed that the long term phosphorous (P) and potassium (K) requirements of all crops must be met.

[INSERT FIGURE 2 HERE]

Fossil energy inputs into agriculture have generally been outweighed by yield improvements that deliver positive energy ratios (energy out: energy (fossil) inputs) “i.e. the energy content of the harvested crop is greater than the fossil energy used to produce the crop,” as highlighted by Samson et al. (2005), in Figure 3. However, over the full lifecycle of a crop, particularly where energy-intensive drying and processing are required, in some cases more fossil energy can be used than is contained in the final product. A detailed assessment of the energy inputs and GHG emissions from UK agriculture follows. Whilst much of this assessment is specific to the UK, the heterogeneity in inputs, energy carriers, energy intensities and resulting greenhouse gas emissions for different crops is considered a conservative representation of commercial agriculture globally.

[INSERT FIGURE 3 HERE]

1.1 Contemporary UK agriculture

This section covers the main commodities produced in the UK and is from the perspective of LCA, which is a standard method for assessing the “cradle to grave” environmental impacts of a product or process. The detailed breakdown that follows comes from the work of Cranfield University and is reported in various outputs (Williams et al. 2006; Williams et al. 2009; Audsley et al. 2010). The work was parameterised for England and Wales, although much applies in other parts of the UK. The original study included three field crops (bread wheat, oilseed rape and potatoes), four meats (beef, poultry, pork and lamb), milk and eggs. Tomatoes were included as the main protected crop. Apples and strawberries were analysed in a later study, together with overseas production of apples, potatoes, tomatoes, strawberries, lamb, beef and poultry meat. Primary production up to the farm gate was included in all these studies, although in Williams et al. (2009), the end point was the regional distribution centre. This section only covers production to the farm gate.

With LCA, all energy use is traced back to resources in the ground, so that overheads of extraction and distribution are included in reported energy figures. All inputs are considered, so that the embodied energies in fertiliser, machinery, buildings and pesticides are included along with the direct energy of diesel and other fuels (also known as energy carriers). Estimates for the energy inputs into animal production include inputs for the production of all feed crops e.g. UK feed wheat, UK field beans, American soy and forage (grazed grass and conserved grass or maize) and for feed processing and distribution. All breeding overheads are also included, so that the final values represent the totality of energy used per commodity.

One of the challenges of these analyses is how to allocate burdens when crops are multi-functional. Oilseed rape is grown primarily for oil, but a useful meal is also produced as the result of oil extraction, which can be used as an animal feed. It is common practice with products of disparate properties to allocate burdens by economic value, rather than simply by weight or energy content and this approach has been used here.

1.1.1 Arable crops

Energy inputs to produce the UK’s main crops (Table 1) range from 1 to 6 GJ/t. However, each agricultural product has very different properties and uses, making comparisons using a single metric problematic. Oilseed rape stands out as being the highest energy consumer per tonne of product, resulting from relatively low yields and high fertiliser requirements, but the grain is more energy-rich than cereals or legumes. Bread wheat receives more fertiliser than feed wheat, in order to obtain the high protein concentrations that are required for bread making and so takes more energy than feed wheat. Although field beans require no nitrogen (N) fertiliser, they have much lower yields than wheat and more diesel is used per tonne of beans produced.

[INSERT TABLE 1 HERE]

Cereals tend to follow the same pattern, in terms of energy inputs and wheat is used here as a proxy for cereals in general (Figure 4). UK Wheat also has a similar energy input intensity to US maize production as shown in Table 1. In non-organic bread wheat production, over half of the energy used is in fertilisation and about 90% of that energy is in N, typically ammonium nitrate and urea. Bread wheat is unusual in that urea is applied relatively late in the growth season, as a foliar feed. Direct field energy is just under a quarter of the input. Post harvest energy inputs are mainly for grain drying and cooling, which were calculated here on a long term basis: this clearly varies yearly according to climatic conditions. Pesticide manufacture accounts for less than 10% of energy input, but a lack of modern data leads to higher degrees of uncertainty about the impacts of pesticide use, with the most recent publically available analysis by Green (1987). In contrast, organic production uses more diesel per unit production, owing to lower yields and the obligation to use the plough, coupled with extra cultivations for weed and pest control.

Potato cropping is energy intensive compared to cereals and legumes. For example, the energy used in storage is much larger than other crops: potatoes are kept cool and a proportion is maintained over the year. This is in contrast to traditional low energy clamping systems, in which losses were much higher, but the supply season shorter. Early potatoes are generally not stored on farms, so energy requirements for field operations incur a major fraction of total energy inputs, which also include irrigation inputs as well as the high energy costs of planting, cultivating and harvesting. However, because potatoes are high yielding crops, they have low energy input requirement per tonne harvested. If calculated per tonne of harvested dry matter, because the harvested biomass is 80% water for potatoes, compared to 15 to 20% for wheat grain, for example, potatoes would have a higher energy intensity factor.

Sugarcane production under Brazilian conditions and management is also high yielding and has a high water content (70% moisture content) when harvested. The relatively low energy inputs needed for the production of this semi-perennial crop and lower moisture content compared to potatoes, means that when accounting for energy intensity on a dry weight basis, sugarcane would have a lower energy intensity than UK wheat. Even when processed to ethanol and/or crystalline sugar, because of the use of residual biomass arising from sugar extraction, to provide power and heat, fossil energy inputs are minimised.

[INSERT FIGURE 4 HERE]

The types of energy used vary between crops and production systems (Figure 5), and also location. In the UK, as with most of Europe, N fertiliser production uses mainly natural gas. However, according to He (2009) in China, coal currently provides about 80% of the energy inputs into nitrogen fertiliser production rising from 71% in 2004. Diesel comes from crude oil. Electricity used either directly (e.g. cooling grain) or indirectly in machinery manufacture, also uses coal, nuclear and some renewables. The dominant energy carrier in non-organic wheat production is thus natural gas, but it is crude oil in organic wheat production and in China it would be coal. The embodied energy in machinery is an overhead of about 40% of the energy used in diesel, reflecting the high wear environment of cultivating and harvesting, as well as continually high power demand on engines, compared with road transport.

[INSERT FIGURE 5 HERE]

Although fertiliser manufacture is energy-intensive, reducing fertiliser use has mixed effects. Energy input per ha is reduced, but so is yield, thus increasing the relative input of cultivation energy per t. Reducing yield also implies a need to displace production elsewhere in order to maintain supply. This could be in areas that are less suitable and / or lead to land use change, e.g. conversion of grassland to arable, with the consequent loss of soil carbon (C). It does appear, however, that some reduction in N supply can reduce energy use per t bread wheat (Figure 6). However, a very large reduction in N application can cause sufficient yield loss that cultivation becomes the dominant energy demand and energy use per tonne increases again.

[INSERT FIGURE 6 HERE]

1.1.2 Animal production

The energies used per tonne of the main outputs of animal production are all substantially higher than crops (Table 2). This results from the concentration effect as animals are fed on crops and concentrate these into high quality protein and other nutrients. Feed is the dominant term in energy use (average of about 75%), whether as concentrates, conserved forage or grazed grass. Direct energy use includes managing extensive stock, space heating for young birds and piglets and ventilation for pigs and poultry. Housing makes up a relatively small fraction of total energy inputs, and is even lower for more extensive systems, like free-range hens. For egg production, the energy demand of manure management is more than offset by the value of chicken manure as a fertilizer, hence the negative value.

[INSERT TABLE 2 HERE]

The energy carriers used in animal production vary less than crops (Table 3). About one third is from crude oil and another third from natural gas. However, because animal feed production and supply requires 70 to 90% of the total energy inputs for livestock production, animal husbandry may be more vulnerable to high and volatile energy costs compared to the direct supply of arable crops. This could lead to increased pressure on extensive grazing, reversing the trends over the recent decades of decreasing land area requirements per kg livestock production.

[INSERT TABLE 3 HERE]

2 Current Greenhouse Gas Emissions

Agriculture occupies more than 50% of the world's vegetated land (Foley et al. 2005) and accounts for between 10 to 20% of all anthropogenic GHG emissions, depending on where the boundaries are drawn between agriculture and the other sectors (IPCC 2006; International Fertilizer Industry Association 2009). However, its contribution to methane and nitrous oxide production is disproportionately large. On a global scale, agricultural processes are estimated to account for 50% of anthropogenic methane production and 80% of anthropogenic nitrous oxide production (Crutzen et al. 2008; Olesen et al. 2006). As in industry, at all production stages fossil fuel combustion for heat and energy represents a direct and major source of agricultural greenhouse gas emissions. In addition, anaerobic fermentation and microbial processes in soil and manure lead to releases of methane and nitrous oxide in both livestock and arable systems. Nitrogen fertiliser production alone consumes about 5% of the global natural gas supplies and significant amounts of nitrous oxide are emitted during the production of nitrate (Jenssen and Kongshaug 2003; Kindred et al. 2008; International Fertilizer Industry Association 2009). Furthermore, emissions as a result of land use change (mainly as carbon dioxide) can form a significant part of the agricultural impact on the atmosphere.

2.1 Arable Sources

The period between 1965 and 2000 saw a doubling of global agricultural production (Tilman 1999). The total area under cultivation has remained relatively static and this huge increase in output is primarily the result of massive increases in fertilisation and irrigation (Figure 2), as well as improved crop genetics. Global nitrogen fertiliser applications have increased more than six-fold over the past 40 years (Tilman 1999), although there has been considerable regional variation. The production of mineral and synthetic fertilisers, especially nitrogen using the Haber–Bosch

Process, uses large amounts of fossil energy, mainly natural gas, releasing around 465 Tg carbon dioxide into the atmosphere each year (International Fertilizer Industry Association 2009). It has been estimated that 30% of the total fossil energy used in maize production is accounted for by nitrogen fertiliser production (Tilman 1999) and that fertiliser production is responsible for up to 1.2% of all anthropogenic greenhouse gas emissions (Wood and Cowie 2004).

Fertiliser application can also lead to further emissions. Nitrification and de-nitrification of mineral and organic nitrogen fertilisers leads to the release of large amounts of nitrous oxide from soils (Snyder et al. 2009). The IPCC (2006) Tier 1 estimate is that 1% of all applied nitrogen is emitted in the form of nitrous oxide, although there is considerable uncertainty over this figure. Loss of nitrous oxide from arable soils accounts for around 1.5% of total anthropogenic greenhouse gas emissions (International Fertilizer Industry Association 2009). Modern techniques that reduce soil compaction, such as GPS-guided controlled traffic farming, can reduce nitrous oxide emissions by between 20 and 50% (Vermeulen and Mosquera 2009).

Emissions vary according to cultivation technique and crop type. Anaerobic turnover in rice paddies is a major source of methane (Olesen et al. 2006), although the anoxic conditions when paddies are flooded, minimise carbon dioxide release. Ploughing soils encourages microbial digestion of soil organic matter, leading to greater net carbon dioxide emissions. Energy use at all stages of arable production represents another significant source of carbon dioxide. However, differences in farming techniques, levels of mechanisation, scales of production, and soil and weather conditions in different regions make it difficult to quantify total fossil energy use and to extrapolate data from one agricultural system to another.

2.2 Livestock Sources

Meat, egg and milk production are estimated to account for half of all the greenhouse gas emissions associated with food production and represent about 18% of global anthropogenic emissions (Garnett 2009). In the UK, livestock farming generates 57.5 Tg carbon dioxide equivalent, which is around 8% of total UK emissions (Garnett 2009). Global demand for meat and dairy products is predicted to increase over the next 50 years due to human population growth and increased wealth. An important source of greenhouse gases in livestock farming is enteric fermentation in ruminants, such as sheep and cattle, which produces significant quantities of methane (Olesen et al. 2006).

Growth of crops to feed livestock is another major source of greenhouse gas emissions. Around 37% of global cereal production and 34% of arable land is used to provide animal feed (FAO 2006) and so meat, egg and milk production also contributes to the release of nitrous oxide and other gases as described above. A further consideration is the efficiency with which animal feed is converted to meat. A large proportion of animal feed is respired or accumulates in non-edible parts of the animal. In the case of cattle, up to 10kg of cereal may be required per kg of meat produced and so cattle farming can represent a significant demand for land and resources (Garnett 2009). Substantial differences exist between the different forms of livestock production in terms of net energy and protein feed requirements per kg meat produced. Increasing and volatile fossil fuel prices, unless mitigated, could drive both reductions in meat demand due to increased prices, but also switching to lower energy intensity, higher efficiency, forms of meat production, possibly favouring mono-gastric rather than ruminant supply chains.

2.3 Indirect Emissions

On a global scale, 75% of anthropogenic greenhouse gas emissions are the result of fossil fuel combustion. The remaining 25% are primarily the result of land use change (Snyder et al. 2009; Le Quéré. 2009). However, land also continues to be a net sink for carbon, absorbing about 29% of total emissions, with the oceans taking up a further 26%. The balance, about 45%, accrues to the atmosphere (Le Quéré. 2009).

Deforestation involves the removal of large aboveground biomass stocks, which represented an important carbon sink during the 20th century (Bondeau et al. 2007). Belowground biomass is lost as woody root systems are replaced by the smaller, finer roots of grasses and crop plants. Disturbance during cultivation breaks down soil organic matter and accelerates decomposition, leading to further losses of soil carbon and, consequently, carbon dioxide emissions (IPCC 2006). The soil organic carbon content of temperate arable, grassland, and woodland soils are of the order of 80, 100, and 130 t C ha^{-1} respectively (Bradley et al. 2005). It is thought that between 50 and 100 years are required for soil carbon content to reach a new equilibrium following land use change (Falloon et al. 2004; King et al. 2005) and so this form of disturbance leads to a long-term source of carbon dioxide. It is generally assumed that there is little difference in soil carbon between annual and perennial food crops, including fruit orchards and plantation crops (IPCC 2006). However, detailed information is lacking and further research is needed to determine the real effects of perennial crops on emissions from soils.

Deforestation in the Brazilian Amazon basin to provide land for cattle ranching and soybean cultivation for animal feed accounts for a loss of 19,400 km^2 of rainforest each year. This alone accounts for 2% of global anthropogenic greenhouse gas emissions. Whilst complex interlinkages and causality chains exist as drivers for deforestation, much of the soybean grown in Brazil is exported for use as animal feed in Europe, Asia, the USA and Russia. Soybean expansion is more closely associated with Amazonian deforestation than the expansion of other crops (Volpi 2010). Overall, 7% of anthropogenic emissions, totalling 2.4Pg of carbon dioxide per year, are estimated to be the result of livestock-induced land use change (Garnett 2009). Consequently, livestock farming is a major cause of land use change. Use of former forest land for cattle ranching represents a direct land use change; use of the land to grow feed for livestock overseas represents a major indirect land use change. Each process results in further greenhouse gas emissions.

3 Has agricultural productivity been affected by changes in energy prices?

Fossil energy prices directly affect the costs of tillage and fertilisers and indirectly affect almost all aspects of agricultural production, through to the prices of food seen by the end consumer. The previous sections of this paper have outlined the different energy inputs and greenhouse gas emissions (energy and non-energy related) of a range of agricultural production pathways for the major food commodities. The results strongly suggest that the production costs of some agricultural commodities will be more sensitive to changing fossil fuel prices than others and that the options for mitigating the risks of fossil energy prices will also differ between those chains. This section assesses the trends in the price of oil, natural gas and coal over the last four decades and uses differences between projections for future oil prices to 2030 as a proxy for overall fossil fuel price volatility in this period.

3.1 Historic changes in fossil energy prices

Historic trends in the spot prices of oil, natural gas and coal show that throughout the 1980s and most of the 1990s, spot prices remained below US$4 per GJ, with coal staying below US$ 2/GJ until the turn of the millennium (Figure 7). In fact, until 1995 fossil fuel prices were converging around US$2/GJ, making electricity production in particular, more attractive from natural gas than from coal because of the greater flexibility, decreased capital costs and modularity of natural-gas-fired power stations. Since 1995, prices have increased, first for oil, then for gas and finally followed by coal. By 2007, prices for oil and natural gas had more than quadrupled whilst for coal they had nearly trebled. Since then, as a result of recession and also from increased investment in new supply and refining capacity, prices have fallen sharply but more recently, since the beginning of 2009, have started increasing again, particularly for oil, although not yet to the levels seen in 2007 (US EIA 2009; BP 2009; IEA 2009).

[INSERT FIGURE 7 HERE]

In part, increasing supplies are a result of the deployment of new technologies, allowing hitherto inaccessible fossil fuel resources such as oil shale, tar sands or ‘tight’ gas reserves to be exploited. It is also a result of conventional supplies becoming constrained and the resulting increase in prices making previously too expensive reserves possible to access profitably. As shown in Figure 5, all agricultural commodities in the UK simultaneously use all forms of fossil-derived energy and some renewables too. A major question remains, as to whether increasing overall prices and increasing volatility in those prices will drive further diversity in energy supply resources, or reductions in overall energy intensity or even in the total supply of agricultural products.

3.2 Projected fossil energy prices

As a result of real and perceived constraints to conventional fossil fuel supplies, in particular oil and natural gas, robust predictions for prices more than a few years forward are not available and the uncertainties associated with projections to 2030 are so great that the US Energy Information Administration currently uses three scenarios for oil price projections that range from US$50 to US$200 per barrel (Figure 8).

[INSERT FIGURE 8 HERE]

For natural gas, the dominant energy feedstock for nitrogen fertiliser production, the recent development of new drilling techniques has released very substantial quantities of so-called ‘tight’ or ‘shale’ gas, reducing the price of natural gas in the US from around US$13 per MBTU in 2008 to less than US$5 per MBTU in early 2010 (The Economist, 2010) or from US$12.7 to US$ 4.3 per GJ. If tight gas is found elsewhere in substantial volumes, as seems possible, then the historic link between oil and gas prices will be broken, with oil prices likely to increase significantly and gas remaining competitive with coal.

If bioenergy, particularly biodiesel and biogas, becomes cheaper than the direct fossil fuel inputs into agriculture, primarily diesel, then a rapid switch to on-farm bioenergy is likely to occur where rotary power, transport and thermal processing are required. Whilst the complexity of the interactions between conventional agricultural feedstocks for food and their use for energy, when coupled to global oil markets makes this price threshold difficult to estimate, it is likely to be around US$ 70 to 100 per barrel oil equivalent but may be lower for large scale commercial production facilities.

Whether this switch to bioenergy production is competitive or synergistic with food production will mainly depend on: the strength of the linkage between energy and food prices, the rate of increase of demand for bioenergy feedstocks as commodity crops, the impact from increased investment from bioenergy and the resultant increase in yields of both conventional crops (food and fuel) and advanced lignocellulosic crops, and, the availability of new land or recovered degraded or abandoned land.

4 Policies to reduce GHG emissions from the food sector

The impact of climate change on agricultural production is still uncertain. However, reports of the potential outcomes for agriculture are well documented (AEA 2007). Farmers in general face the looming spectre of climate change at two levels; firstly, by having to adapt existing practices to cope with the outcomes of climate change (i.e. changing weather patterns; water availability; changing patterns of pests, disease and thermal stress in livestock) and secondly, by addressing those farming activities which are contributing factors to increased GHG emissions.

Whilst it is likely that farmers will readily adopt measures which will benefit their productivity and financial outcomes, adopting practices at cost to farming businesses is more likely to require policy intervention. Developing mechanisms to improve GHG abatement in the agricultural sector is complex, not least because policy mechanisms are often devised through different departmental policy-making regimes.

Within the EU Climate and Energy Package (2008), the agricultural industry is not part of one of the main components, the European Emissions Trading Scheme (EU ETS 2009). Agriculture, as a non-EU ETS sector is charged with reducing emissions to 10% below 2005 levels by 2020, and it is anticipated that this will be through binding national targets. In the policy context, the farming industry faces many challenges before carbon trading as an economic strategy becomes a reality.

The UK Government published its low carbon transition plan in 2009 **(**http://www.theccc.org.uk/carbon-budgets). The Plan's main points for ***agriculture*** are:

- Encourage English farmers to take action themselves to reduce emissions to at least 6% lower than currently predicted by 2020, through more efficient use of fertiliser, and better management of livestock and manure.
- Review voluntary progress in 2012, to decide whether further Government intervention is necessary. The Government will publish options for such intervention in Spring 2010.
- Ensure comprehensive advice programmes are available to support farmers in achieving this aim, to reduce their emissions from energy use, and to save money in the process.
- Research better ways of measuring, reporting and verifying agricultural emissions.
- Encourage private funding for woodland creation to increase forest carbon uptake.
- Provide support for anaerobic digestion, a technology that turns waste and manure into renewable energy via biogas.
- Reduce the amount of waste sent to landfills, and better capture of landfill emissions.

Some policy instruments which aim to deliver greenhouse gas mitigation within the sector have been identified in a report commissioned by the UK's Department for Food and Rural Affairs (ADAS 2009). The report shows the mitigation potential by 2022 (Table 4), making comparisons to an earlier Scottish Agricultural College report (SAC 2008). The study does not include mitigation potential from biomass production, soil carbon sequestration or options for anaerobic digestion of farmyard waste and does not expand on further economic or market-based policy mechanisms (e.g. carbon trading extending to farming activities). The policy instruments identified are as follows:

- Regulatory - Cross Compliance and Nitrate Pollution Prevention Regulations (Nitrogen Vulnerable Zone (NVZ) regulations)
- Economic (voluntary participation) - Environmental Stewardship
- Voluntary - Extend Catchment Sensitive Farming (CSF), Farm Assurance Public Procurement, Voluntary Agreements and Targeted Communications.

[INSERT TABLE 4 HERE]

4.1 Indirect policy implications for agricultural emissions

Policies to reduce emissions from the fossil energy sector may impact on agriculture in two different ways. Firstly, by promoting crops which can be used as feedstocks for biofuel or bioenergy; different growing regimes and more efficient energy inputs may be adopted. Secondly, greenhouse gas emission reporting requirements which are being developed for biofuels may affect farming practices, particularly if benefits for improved emissions are transferred down the supply chain to the feedstock producers. Policies in the UK which aim to impact fossil fuel energy use and which may in-turn impact on agriculture are the Renewable Transport Fuels Obligation (RTFO), (DfT 2007) and the Renewables Obligation (RO), (DTI, 2006).

In the EU, the Climate and Energy Package (2008) committed the 27 member states to reduce CO_2 emissions by 20%, and to target a 20% share of energy supply from renewable energy, by 2020 i.e. the so-called “20-20 in 2020”. Policy instruments in the Package, which may then indirectly impact on agriculture, are the Fuels Quality Directive (EU FQD 2009) and the Renewable Energy Directive (EU RED 2009). The FQD aims to reduce harmful atmospheric emissions, including greenhouse gases and includes mandatory monitoring of life cycle greenhouse gas emissions. The RED, aims to promote renewable energies biofuels and has a component which addresses sustainability of biofuels and the land used to grow biofuel feedstocks.

In the United States, the California Environmental Protection Agency Air Resources Board (CARB) has been at the forefront of developing policy to reduce emissions from fossil energy and has developed the Low Carbon Fuels Standard (LCFS 2007). This standard is under review by a number of individual states in the US, which are also looking to adopt an emissions approach to the inclusion of biofuels in transport fuels. Nationwide in the U.S., the Environmental Protection Agency (EPA) has developed, under the Energy Independence and Security Act of 2007, a Renewable Fuel Standard Program (RFS2, 2009) which aims to increase the volume of renewable fuel in gasoline from 9 billion gallons (34 billion litres) in 2008 to 36 billion gallons (144 billion litres) by 2022.

In many ways, these policies are leading the development of methodologies which will improve energy efficiency and reduce GHG emissions across supply chains. Improving emissions and ensuring the sustainability of biofuels has led to the development of variety of policy-specific methodologies. They have also encouraged the formation of global stakeholder interactions, which address environmental, economic and social issues e.g. Roundtable on Sustainable Biofuel (RSB); Global Bioenergy Partnership (GBEP) and crop specific initiatives e. g. Roundtable on Sustainable Palm Oil (RSPO); Round Table on Responsible Soy (RTRS) and the Better Sugar Cane Initiative (BSI).

The UK's RTFO has been devised with GHG emissions monitoring and reduction as a key component and it has been necessary to stipulate methodology and processes to report GHG emissions from the individual biofuel supply chains used by obligated parties in law (RFA, 2009). The RTFO's Carbon and Sustainability methodologies cover biofuel supply chains from feedstock source, by country and by on-farm production inputs and outputs. In a biofuel supply chain, this may encourage farmers to improve management practices, providing that a share of the value or benefits feedback to farmers. Currently, Carbon and Sustainability reporting is not mandatory under the RTFO and better practices leading to improved carbon and sustainability profiles, are not rewarded. Many farmers in the UK have been encouraged by the idea of reducing on-farm diesel costs by producing their own biodiesel from oilseed rape. However, the market value of vegetable oil and costs for processing oils into biodiesel will always be calculated against fossil diesel costs for farm use (Lewis, 2009). Furthermore, farm vehicles will generally be under warranty from the vehicle manufacturer and it is unlikely that farmers would risk using out-of-spec fuel, to the detriment of these costly machines.

As noted by Monbiot (2009), addressing energy needs using on-site, renewable energy options only reduces dependence on diesel for on-farm use by a quarter. Options for farmers to use renewable energies, such as biomass or biogas for electricity and heat production are often limited to on-farm use only, as there are not the facilities or incentives to connect to the electrical grid. Allowing access to the national grid would give farmers an option to trade renewable energy under the Renewables Obligation, whereby the mandatory renewable requirement of 15% electricity by 2015, could potentially be met in part by surplus on-farm energy generation, traded as Renewable Energy Certificates (ROCs). The UK government is also reviewing opportunities for a Renewable Heat Incentive (RHI), under the Energy Act (DECC 2008), which promotes investment for biomass boilers and combined heat and power (CHP) facilities.

5 Options for agriculture to reduce its dependence on energy

5.1 Change tillage / pre-processing

Land preparation has become increasingly mechanised over the years. However, mechanical tillage systems are energy intensive and expose soil organic matter (SOM) to decomposition, leading to enhanced greenhouse gas emissions, reduced SOM concentration in soil and potentially, in short and longer term, to soil erosion and degradation. The potential for reducing the energy intensity of agricultural production by adopting alternative tillage systems may occur from decreased fuel use in mechanical operations or as the result of better long-term soil productivity.

Alternative methods of land preparation and crop establishment have been devised to reduce energy requirements and maintain good soil structure. These include, minimum tillage (min-till), conservation tillage (no tillage or min-till) and direct drilling, resulting in increased surface organic matter, from previous crops residues (soil coverage of 30%) (Van Den Bosche et al. 2009). Robertson et al. (2000), compared management techniques in a three crop rotation, over eight years in Michigan. The net changes in soil C (g m^{-2} $year^{-1}$) were for conventional tillage (plough-based tillage), 0; organic with legume cover, 8.0; low input with legume, 11 and no till, 30.

The consequences of reduced tillage on soil carbon are not straight-forward. Baker et al. (2007), concluded that the widespread view that reduced tillage favours carbon sequestration may be an artefact of sampling methodology, with reduced tillage resulting in a concentration of soil organic matter in the upper soil layer rather than a net increase throughout the soil. They did however, highlight that there were several good reasons for implementing reduced tillage practices. In contrast to Baker et al. (2007), Dawson and Smith (2007) reviewed the subject area and suggested sequestration rates of 0.2 (0–0.2) and 0.39 (0–0.4) t C ha y^{-1} for reduced tillage and no-till farming respectively.

Energy balance calculations resulting from fertiliser application are more difficult to assess, as interactions with increased soil organic matter become more complex. Studies which focus on energy inputs, attributed to soil preparation, tend to be regional and crop specific. Energy from tillage will depend on crop requirements, soil type, cultivation/climatic conditions, equipment used and engine efficiency.

A study which compares conventional and integrated farming in the UK attributed energy savings in integrated farming almost entirely to the reduction in energy required for mechanical operations (Bailey et al. 2003). The study also considered the effects on energy of multi-functional crop rotation; integrated nutrient and crop protection methods and ecological infrastructure management (i.e. field/farm boundary maintenance to promote biodiversity and reduce pollution), in integrated systems. A study for wheat grown in Iran provides a more detailed evaluation of five specific tillage regimes (Tabatabaeefar et al. 2009). The study reports the min-till system ('T5' in Figure 9) as most energy efficient, with energy for tillage accounting for 19% of the total energy vs. 32.5% for the least energy efficient ('T1'). Yield outcomes are also reported whereby the min-till system gives the second highest yield of the five systems, but in overall performance T3 is reported as being the most efficient system when taking both energy input and yield into account.

[INSERT FIGURE 9 HERE]

Soil carbon as a component of SOM, is important in carbon turnover within the carbon cycle, and in maintaining soil fertility, water and nutrient holding capacity, ecosystems functions and preventing soil degradation. Soil carbon and SOM are important in preserving soil in a productive, quality state for long term crop production (Dawson and Smith 2007). Understanding the processes of carbon interaction in soils is complex, both at local and national levels. Carbon losses from the soil organic matter pool, the effect of carbon loss on nutrient availability and crop productivity, and the subsequent outcomes for agricultural management activities are all important variables in calculating the overall carbon stocks and productivity of soils (Dawson and Smith 2007). Other farming options, such as residue mulching and the use of cover crops, aim to conserve and enhance SOM or soil carbon sequestration (Lal 2007).

The subsequent effects of nutrient availability on crop productivity vary between cropping systems (e.g. conventional or organic systems), land types, climatic conditions and time, and require further research before being fully integrated into farming systems (Kong et al. 2009). Studies carried out on sites in Belgium have been used to demonstrate nitrogen interactions under various planting regimes and to demonstrate the action of tillage on organic matter degradation and the subsequent availability of nitrogen in the nutrient pool over time (Van den Bossche et al.2009). They report higher soil organic matter, microbial biomass and enzymatic activity for conservation tillage, which increases with time. The anticipated effect is slower mineralisation or immobilisation of nitrogen, leading to enhanced soil fertility as the result of long term build up of nutrient reserves of the soil.

Understanding the interaction between soil carbon and nitrogen also adds further complexity to determining the benefits of increasing soil carbon through changes in tillage systems. Whilst increasing fertiliser inputs may increase the soil carbon pool, the poorer GHG balance from the increased use of N fertilisers may negate the sequestration benefit. The reasons for changing agricultural activities should be clear from the outset. Is the anticipated benefit to reduce energy inputs, reduce GHG emissions, improve soil carbon sequestration or to maintain the long-term productivity of soils? Land management choices may then follow, with trade-offs expected and accepted. For example, planting marginal lands with biomass crops to improve carbon sequestration versus maximising yields on productive lands by increasing fertiliser use, or adopting min-till systems on land areas where mechanical activities are also degrading soil quality or causing soil erosion, such as on sloping sites.

5.2 Energy inputs and impacts of fertiliser use in agriculture

In addition to the direct energy inputs for tillage and harvesting, fertilisers can constitute a significant share of total energy inputs to agriculture (Figure 4) and food production, particularly for nitrogen intensive crops such as cereals. Figure 10 shows the different energy requirements for the main constituents of commercial fertilisers, using European average technologies. The main nitrogen components of fertilisers, ammonia (NH_4; 32 GJ/t), urea (22 GJ/t) and liquid UAN (urea ammonium nitrate; 22 GJ/t), are the most energy intensive to produce, whilst the P and K components all require less than 5 GJ/t to produce.

[INSERT FIGURE 10 HERE]

The energy inputs needed to produce and supply fertilisers and pesticides substantially outweigh the energy required to apply the products in the field. GHG emission factors for production, supply and use of N, P and K fertilisers, under average UK conditions, are provided in Table 5. However, for N fertilisers, the GHG emissions arise both as a result of the fossil energy inputs needed to capture and process atmospheric nitrogen, and also from complex soil-based processes that result in the production and release to the atmosphere of nitrous oxide (N_2O) in-field.

[INSERT TABLE 5 HERE]

5.2.1 Nitrogen fertilisers

The energy inputs into nitrogen fertiliser production have decreased significantly since the beginning of the last century as a result of continual technological innovation (Figure 11). GHGs emitted during its production include carbon dioxide, methane and nitrous oxide as shown in Table 6. Carbon dioxide emissions account for 98% of the GHG emissions on a mass basis, but only 33% on a global warming potential (CO_2 equivalent) basis. N_2O accounts for 0.6% of the mass of the GHG released but 65% on a CO_2 equivalent global warming potential basis.

[INSERT TABLE 6 HERE]

However, whilst ammonia production is the most energy-intensive part of the production of N fertilisers, nitric acid production causes the release of N_2O during its production. Nitric acid is needed to produce ammonium nitrate (AN) through a reaction with ammonia. The N_2O leaks to the atmosphere in the nitric acid plants and between 70 and 90% of this N_2O can be captured and catalytically destroyed. European plants are now being fitted with this nitrous oxide abatement technology and as a result overall AN GHG emissions could be reduced, by 40% overall, from 6.93 to 4.16 kg CO_2 eq/kg N.

[INSERT FIGURE 11 HERE]

5.3 Farm forestry systems (agro-forestry)

The production of woody biomass on land unsuitable for intensive arable farming or extensive grazing is widely seen as a low-energy input option, for the production of such biomass for material or energy usage. Numerous opportunities exist to integrate the production of woody biomass and agricultural crops or livestock and production and such ‘farm-forestry’ or ‘agro-forestry’ systems have been widely discussed in the literature and through the work of the Consultative Group on International Agricultural Research’s (CIGIAR) World Agroforestry Centre[1], much of which is focussed on the developing world. A recent geospatial study by Zomer et al. (2009) has shown agro-forestry to be a significant feature of agriculture in all regions of the world – see Figure 12.

[INSERT FIGURE 12 HERE]

Zomer et al. (2009) provide a cautious estimate that 17% (~ 3.8 Million km^2) of global agricultural land involves agroforestry at >30% tree cover and, potentially, this can be as high as 46% or just over 10 million km^2, at >10% or more tree coverage rates. Agro-forestry systems are found in developed as well as less developed regions.

The widespread and significant proportion of agricultural land under agro-forestry management (e.g. in Central and South America) already points to a successful form of integrated land management for both crop production and woody biomass for energy production. This indicates a capacity for agricultural land management to accommodate integrated energy production;

---

[1] see http://www.worldagroforestry.org/af/

currently, in most cases, the woody biomass is used for immediate local needs such as fuelwood for cooking. However, there is also considerable scope for more widespread introduction of tree or coppice material to agricultural land specifically to meet on-farm energy needs and, subject to transportation constraints, as an economic product for off-farm sale. For example, in the UK, a number of estates are currently using wood produced on the estate for biomass heat schemes which is encouraged under the UK's Bioenergy Capital Grant Scheme.

With combinations of increasing prices for conventional energy inputs to farming and incentives for low-carbon forms of renewable energy, farmers may be incentivised to allocate a proportion of their crop land to meet on-farm energy use, for example, for diesel fuel replacement or potentially for high-value low-carbon certified electricity, either produced on-farm or from farm-derived woody/residual feedstocks. The ability to co-produce woody biomass for heat and/or power generation at farm scale, alongside commodity crops provides a potentially attractive route to mitigating increased or volatile external energy costs (e.g. for drying, livestock management or domestic use) and potentially as a saleable commodity in its own right (biomass fuel product(s)).

Future incentivisation for farmers to minimise agricultural GHG emissions is also likely to favour greater integration of forestry and/or woody biomass cultivation on farm e.g. short rotation coppice or perennial grasses such as *Miscanthus* in UK/EU. At the individual farm level, cultivation of perennial biomass crops on a proportion of the land may provide an attractive route to 'balance' more GHG intensive cultivation activities with carbon 'credits' from enhanced C-storage in soils, via avoided emissions from displaced fossil fuel requirements or as a direct economic benefit from biomass sales at a premium due to renewable heat and power incentive value trickling down the supply chain. Recent studies by Hillier et al. (2009) have illustrated the GHG benefits associated with soil carbon storage effects for certain biomass crops and land use transition scenarios modelled in a LCA context for England and Wales. Attention is also being given to the use of biochar[2] as a potential energy source (during the charring process) and significantly as a soil-based carbon sequestration and storage approach that can also offer soil fertility benefits (Sohi et al.2008; Collison et al. 2009). Biomass supply for biochar production can be drawn from diverse sources, including woody biomass form agro-forestry systems as well as from existing UK farm biomass, such as hedgerow management (Gathorne- Hardy, pers. comm. 2009).

6 CONCLUDING REMARKS

This paper has identified that there are significant risks to future farming and yields due to increasing and increasingly volatile fossil fuel prices. Whilst it has been difficult to obtain robust projections for oil, natural gas and coal prices, it is clear that:

1. Fossil fuel prices, particularly those of oil-derived products, will increase significantly over the coming decades and will become more volatile.
2. Prices, on a unit energy basis, between oil, gas and coal are likely to diverge with the possibility of a break in the traditional linkage between gas and oil prices emerging. Unless substantive agreements emerge from the UNFCCC's inter-governmental negotiations that limit access to coal, its large and widely distributed reserves will mean that it is the least vulnerable of the fossil fuels to price increases; a switch to coal away from oil and natural gas is likely where that is possible e.g. for processing and nitrogen fertiliser production.

---

[2] Biochar is carbonised biomass or charcoal. When biomass is turned into charcoal and applied to soils it is believed to have a half-life in the soil in order of 1000 years.

3. The world's major crops are dependent on different shares of their energy inputs from oil, gas and coal. Thus relative changes in fossil fuel prices will affect each crop type differentially.

4. Major areas of concern are:

    a. Increasing oil prices will directly affect the price of diesel used for tillage, transport of crops from fields and from storage to processing and end use.

    b. Increasing natural gas prices will have the most immediate effect on nitrogen fertiliser prices.

    c. Coal is still used for nitrogen fertiliser production, particularly in China, and is likely to be least affected by worries about reserve depletion. From a GHG perspective, a switch away from oil and gas to coal, rather than to renewable, would be detrimental.

    d. Increased costs for direct and indirect energy inputs into agriculture may lead to lower yields for the world's major agriculture commodity crops. In turn, this is likely to lead to an expansion of land areas under these crops, in turn leading to increased GHG emissions, as a result of land use change, and increased prices due to less efficient production. Significant land expansion will also have detrimental effects on biodiversity and possibly on water resources.

5. Reasons for optimism:

    a. Substantial gains in efficiency of energy use and GHG emissions are possible in all areas of food and bioenergy supply chains and from both conventional and advanced supply chains.

    b. Recent policy developments for bioenergy, and in particular, biofuels, have demonstrated that the highly complex and heterogeneous systems necessary to account, monitor, reward and penalise good or bad greenhouse gas and wider sustainability criteria, are amenable to policy. It is possible, and indeed necessary, that many of the lessons learnt in developing these policies and mechanisms for biofuels, can be applied to any form of biological production including food.

c. New tools, in particular spatial zoning and land management tools, are highlighting the potential for revised management and crop choices that could allow enhanced carbon stocking and biodiversity from integrated land management and planning that couples annual and perennial agriculture.

d. The developing of novel drilling technologies that have enabled access to ‘tight’ gas reserves in the US may delay a switch to coal and reduce inflationary pressures on nitrogen fertiliser prices.

Whilst increasing fossil fuel prices could pose a major risk to agriculture, as production costs increase, and also cause increased volatility in prices between the different major agricultural commodities, there is substantial scope for technological and management innovations to occur decreasing the dependence on fossil energy supplies and in creating opportunities for new markets e.g. in renewable energy. The opportunities and threats will vary substantively between the different crops and a careful review on a crop-by-crop basis is necessary to understand and manage these threats and the risks to future production posed by increasing fossil fuel prices.

References

ADAS. 2009. Analysis of Policy Instruments for Reducing Greenhouse Gas Emissions from Agriculture, Forestry and Land Management. RMP/5142.

AEA Energy and Environment. 2007. Adaptation to Climate Change in the Agricultural Sector. AGRI-2006-G4-05.

Audsley, E., Brander, M., Chatterton, J., Murphy-Bokern, D., Webster, C., and Williams,A.G. 2010. An assessment of greenhouse gas emissions from the UK food system and the scope for reduction by 2050: how low can we go? WWF UK and Food Climate Research Network. UK.

Bailey, A.P.; Basford, W.D.; Penlington, N.; Park, J.R.; Keatinge, J.D.H.; Rehman, T.; Tranter, R.B. and C.M. Yates, C.M. 2003. A comparison of energy use in conventional and integrated arable farming systems in the UK. –*Agr. Ecosys. Environ,* 97:241–253.

Baker, J.M., Ochsner, T.E., Venterea, R.T., and TJ Griffis, T.J. 2007. Tillage and soil carbon sequestration – what do we really know. *Agr. Ecosyst. Environ*, 118,: 1–-5.

Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W. and Gerten, D. 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Glob. Change Biol,* 13: 679-706.

BP. 2009. BP Statistical Review of World Energy June 2009. www.bp.com/statisticalreview [accessed 02dec09]

Bradley, R. I., Milne, R., Bell, J., Lilly, A., Jordan, C. and Higgins, A. 2005. A soil carbon and land use database for the United Kingdom. *Soil Use Manage.* 21: 363-369.

Collison, M., Collison, L., Sakrabani, R., Tofield, B. and Wallage, Z. 2009. Biochar and Carbon Sequestration: A Regional Perspective. A report prepared for East of England Development Agency (EEDA), DA1 Carbon Reduction Ref. No: 7049. The Low Carbon Innovation Centre, University of East Anglia, Norwich.

Crutzen, P. J., Mosier, A. R., Smith, K. A. and Winiwarter, W. 2008. N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys.* 8: 389-395.

Dawson, J. J. C. and Smith, P. 2007. Carbon losses from soil and its consequences for land use management. *Sci. Total Environ.* 382: 165-190.

DECC. 2008. Energy Act 2008. http://www.decc.gov.uk/en/content/cms/legislation/energy_act_08/energy_act_08.aspx

DfT. 2007. The Renewable Transport Fuels Obligations Order 2007. Statutory Instrument 2007 No. 3072.

DTI. 2007. The Renewables Obligation Order 2006 (Amendment) Order 2007**.** Statutory Instruments 2007 No. 1078.

Elsayed, M. A. Evans, A. & Mortimer, N. D. 2007. NF0614NFert01.xls: Selective Life Cycle Assessment for Ammonium Nitrate Fertiliser Production Using Natural Gas as a Feedstock. Defra. London. UK.

EU Climate and Energy Package. 2008. COM (2008) 30 final.

EU ETS. 2009. Directive 2009/29/EC. Official Journal of the European Union, L 140/63.

EU FQD. 2009. Directive 2009/30/EC. Official Journal of the European Union, L 140/88.

EU RED. 2009. Directive 2009/28/EC. Official Journal of the European Union, L 140/16.

FAO. 2006. Livestock in geographic transition. Chapter 2 in: Livestock's long shadow: environmental issues and options. ISBN 978-92-5-105571-7. www.virtualcentre.org. Rome, Italy.

Falloon, P., Powlson, D. and Smith, P. 2004. Managing field margins for biodiversity and carbon sequestration: a Great Britain case study. *Soil Use Manage.* 20: 240-247.

Farrell, A. 2006. Ethanol Can Contribute to Energy and Environmental Goals. *Science* 311: 506-508. DOI 10.1126/science.1121416

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N. and Snyder, P. K. 2005. Global consequences of land use. *Science* 309: 570-574.

Garnett, T. 2009. Livestock-related greenhouse gas emissions: impacts and options for policy makers. *Environ. Sci. Policy* 12: 491-503.

Gathorne-Hardy, A. 2009. Personal communication re: PhD thesis research (in progress) on 'A role for biochar in UK agriculture', Imperial College Centre for Environmental Policy, Imperial College London, UK.

Green, M.B. 1987. Energy in pesticide manufacture, distribution and use. In: Z.R. Helsel (editor) *Energy in Plant Nutrition and Pest Control*. Elsevier, Amsterdam, p.165-177.

Hazel, P. and Woods, S. 2008. Drivers of change in global agriculture. *Phil. TRans. R. Soc. B* 363, 295-515.

He, P., Zhang, W., and Zhang, F. 2009. GHG emission from nitrogen fertilizer in China: Preliminary results of FCO project. College of Resources and Environmental Sciences, China Agricultural University, Nanjing, China, Sept 21, 2009.

Hillier, J., Whittaker, C., Dailey, G., Aylott, M., Casella, E., Richter, G.M., Riche, A., Murphy, R.J., Taylor, G. and Smith, P. 2009. Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses. *GCBiology Bioenergy* 1, 267-281.

IEA. 2009. Natural Gas Market Review 2009; *Executive summary*. International Energy Agency / OECD. Paris, France. www.iea.org [accessed 30nov09]International Fertilizer Industry Association. 2009. Fertilizers, Climate Change and Enhancing Agricultural Productivity Sustainably. Paris, France, International Fertilizer Industry Association.

International Fertilizer Association. 2009.

IPCC. 2001. Technological and Economic Potential of Greenhouse Gas Emissions Reduction. MOOMAW, W., and MOREIRA, J.R. (Co-ordinating lead authors). http://www.grida.no/publications/other/ipcc_tar/

IPCC . 2006. Guidelines for National Greenhouse Gas Inventories.

IPCC . 2007. Climate Change 2007: Synthesis Report.

Jenssen, T.K. and Kongshaug, G. 2003. Energy Consumption and Greenhouse Gas Emissions in Fertiliser Production, Proceedings of the International Fertiliser Society No. 509.

Kindred, D. Mortimer, N. Sylvester-Bradley, R. Brown, G. & Woods, J. (2008). Understanding and managing uncertainties to improve biofuel GHG emissions calculations. UK Home Grown Cereals Authority (HGCA), London.

King, J. A., Bradley, R. I. and Harrison, R. 2005. Current trends of soil organic carbon in English arable soils. *Soil Use Manage.* 21: 189-195.

Kong, A.Y.Y.; Fonte, S. J.; van Kessel, C. and Six, J. 2009. Transitioning from standard to minimum tillage: Trade-offs between soil organic matter stabalization, nitrous oxide emissions, and N availability in irrigated cropping systems. *Soil Till Res*. 104: 256-262.

Konshaug, G. 1998. Energy Consumption and Greenhouse Gas Emissions in Fertiliser Production. In *Proceedings of the IFA Technical Conference in* Marrakesk, Morocco: International Fertiliser Industry Association, Paris, France.

Lal, R. 2007. Farming Carbon. Soil Till. Res. 97: 1-5

LCFS (Low Carbon Fuel Standard). 2007. Executive Order S-1-07. California Environmental Protection Agency Air Resources Board. Sacramento, California, USA.

Le Quéré, C. 2009. Recent trends in the sources and sinks of carbon dioxide. The Global Carbon Project. University of East Anglia. www.globalcarbonproject.org

Lewis, D. 2009. Biodiesel Case Studies - Logistical and Economic Issues. Royal Agricultural College and Knowledge West Report (http://www.knowledgewest.org.uk).

Macedo, I. 2008. Mitigation of GHG emissions using sugarcane bio-ethanol. Biofuels and sustainability: Brazilian perspectives. A Chatham House briefing in collaboration with the Embassy of Brazil. Held 8th October 2008. British Academy, London.

Olesen, J. E., Schelde, K., Weiske, A., Weisbjerg, M. R., Asman, W. A. H. and Djurhuus, J. 2006. Modelling greenhouse gas emissions from European conventional and organic dairy farms. *Agr. Ecosyst. Environ*. 112: 207-220.

RFA. 2009. Carbon and Sustainability Reporting Within the Renewable Transport Fuel Obligation. Technical Guidance Part 1. http://www.renewablefuelsagency.gov.uk/_db/_documents/Carbon_and_Sustainability_Guidance_Part_1.pdf

RFS2 (Renewable Fuel Standard). 2009. EPA-420-F-09-023. Office of Transportation and Air Quality, United States Environmental Protection Agency.

Robertson, G.P., Eldor, A.P., and RP Harwood, R.P. 2000. Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere. Science, 289 (15 September 2000), 1922-–1925.

SAC. 2008. UK Marginal Abatement Cost Curves for the Agriculture and Land Use, Land-Use Change and Forestry Sectors out to 2022, with Qualitative Analysis of Options to 2050. RMP4950 Final Report to the Committee on Climate Change.

Samson, R., Mani, S., Boddey, R., Sokhansanj, S., Quesada, D., Urquiaga, S., Reis, V., Ho Lem, C. 2005. The Potential of C4 Perennial Grasses for Developing a Global BIOHEAT Industry. *Crit. Rev. Plant Sci.* 24:461–495. ISSN: 0735-2689. DOI: 10.1080/07352680500316508

Snyder, C. S., Bruulsema, T. W., Jensen, T. L. and Fixen, P. E. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agr. Ecosyst. Environ.* 133: 247-266.

Sohi, S., Loez-Capel, E., Krull, E., Bol, R. 2009. Biochar's roles in soil and climate change: A review of research needs. CSIRO Land and Water Science Report 05/09, 64 pp.

Tabatabaeefar, A;, Emamzadeh, H.; GhasemiVarnamkhasti, M.; Rahimizadeh, R. and Karimi, M. 2009. Comparison of energy of tillage systems in wheat production. *Energy* 34: 41–45.

The Economist. 2010. An unconventional glut. Newly economic, widely distributed sources are shifting the balance of power in the world's gas. Print edition 394(8675):1-6. March 11th 2010. London, UK.

Tilman, D. 1999. Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. PNAS 96: 5995-6000.

US EIA. 2009. International Energy Outlook, 2009. Energy Information Administration (EIA), Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC 20585. www.eia.doe.gov/oiaf/ieo/index.html. [accessed 01dec09]

Van Den Bossche, A.; De Bolle, S.; De Neve, S. and Hofman, G. 2009. Effect of tillage intensity on N mineralization of different crop residues in a temperate climate. *Soil Till. Res.* 103: 316–324

Vermeulen, G. D. and Mosquera, J. 2009. Soil, crop and emission responses to seasonal-controlled traffic in organic vegetable farming on loam soil. *Soil Till. Res.* 102: 126-134.

Volpi, G. 2010. Biofuels in Brazil and land use change. *JBMB.* In Press.

Williams, A.G., Audsley, E. & Sandars, D.L. 2006. Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Final Report to Defra on Project IS0205. London, UK.

Williams, A.G.; Pell, E.; Webb, J.; Tribe, E.; Evans, D.; Moorhouse, E.; Watkiss, P. 2009. Comparative Life Cycle Assessment of Food Commodities Procured for UK

Consumption through a Diversity of Supply Chains. Final Report to Defra on Project FO0103. London, UK.

Wood, S. and Cowie, A. 2004. A Review of Greenhouse Gas Emission Factors for Fertiliser Production. IEA Bioenergy. Paris.

Woods, J. Brown, G. Gathorne-Hardy, A. Sylvester Bradley, R. Kindred, D. & Mortimer, N. 2008. Facilitating carbon (GHG) accreditation schemes for biofuels: feedstock production. HGCA, London, UK.

Zomer RJ, Trabucco A, Coe R and Place F. 2009. Trees on Farm: Analysis of Global Extent and Geographical Patterns of Agroforestry. ICRAF Working Paper No. 89. World Agroforestry Centre. Nairobi, Kenya.

Table 1 Primary energy used in arable crop production (GJ/t). All values are for England and Wales, except soy, sugarcane and maize. (based on Williams et al. 2006)

	Primary Energy used, GJ/t		
	Non-Organic	Organic [a]	National "Basket"
Bread Wheat	2.52	2.15	
Oilseed Rape	5.32	6.00 [b]	
Potatoes (National Commodity Level)			1.39
Potatoes Main Crop	1.46	1.48	
Potatoes 1st Earlies	1.40	1.25	
Potatoes 2nd Earlies	0.79	0.75	
Feed Wheat	2.32	2.08	
Winter Barley	2.43	2.33	
Spring Barley	2.27	2.64	
Field Beans	2.51	2.44	
Soy Beans (US)	3.67	3.23	
Sugarcane (Brazil) [c]	0.21		
Maize (US) [d]	2.41		

a. Based on long term yields obtainable from stockless rotations.

b. Very little grown currently

c. Per tonne of harvested sugarcane delivered to the mill, 2005/2006: sample of 44 mills (100 M t cane / season), all in the Centre-South Brazil; data as reported by Macedo (2008).

d. Per tonne of harvested maize grain. Derived from Farrell, A. 2006.

Table 2 Energy used in animal production at the commodity level in England and Wales (derived from Cranfield LCA model. Williams et al, 2006)

Commodity	Poultry	Pig meat	Beef	Lamb meat	Milk	Eggs

Unit	1 t ecw	1 t ecw	1 t ecw	1 t ecw	m^3	1 t
Primary energy, GJ	17	23	30	22	2.7	12
Feed	71%	69%	88%	88%	71%	89%
Manure & litter	2%	1%	1%	1%	0%	-4%
Housing	1%	4%	0%	0%	3%	3%
Direct energy	25%	26%	11%	11%	26%	12%

‘ecw’ = edible carcass weight (killing out percentage * live-weight), but the energy used in slaughter is not included. 1 m^3 milk weighs almost exactly 1 t and 15,900 eggs weigh 1 t.

Table 3 Energy carriers used in animal production

	Poultry	Pig meat	Beef	Sheep meat	Milk	Eggs
Crude Oil; %	44%	36%	33%	38%	32%	41%
Natural gas; %	27%	28%	45%	46%	40%	28%
Coal; %	13%	17%	9%	7%	13%	15%
Nuclear; %	12%	15%	9%	7%	13%	12%
Renewable; %	3%	3%	3%	2%	2%	4%

Table 4: Scale of UK Agricultural Abatement Potential by 2022 by Policy Instrument (ktCO2e per year; ADAS 2009)

Policy	**SAC**	**ADAS**
Extend Coverage of NVZs to 100% farmed area	not covered	
Extend area and scope of NVZs	2,531	602
Targeted Communications	351	212
Voluntary Agreements	480	238
Farm Assurance public procurement	10	6
Cross-compliance - additional standards within existing rules	896	896
Cross-compliance – extend scope through negotiations with EU	3,420	1,491
Environmental Stewardship	647	647
Enhance CSF – to 100% farmed area	515	200
Enhance CSF – extend area and scope	648	333

Table 5: GHG emission factors for fertilisers, seeds and pesticides (Woods et al. 2008)

Agricultural Input	GHG Emissions (kg CO_2eq/kg applied)
Nitrogen fertiliser (as N)	6.69
Phosphate fertiliser (as P)	0.71
Potash fertiliser (as K)	0.46
Lime	1.80
Pesticides (as active ingredient)	5.41
Seed material	0.87

Table 6: Primary Energy Inputs and Greenhouse Gas Emissions Associated with Ammonium Nitrate Manufacture in Europe (Elsayed et al. 2007)

Nitrogen Fertiliser Manufacture	Primary Energy Inputs (MJ/kg N)	Carbon Dioxide Emissions (kg CO_2/kg N)	Methane Emissions (kg CH_4/kg N)	Nitrous Oxide Emissions (kg N_2O/kg N)	Total Greenhouse Gas Emissions (kg/kg N)
Ammonium Nitrate	40.74 ± 5.43	2.30 ± 0.26	0.012 ± 0.001	0.015	2.33
kg CO_2 eq/kg N		2.30	0.28	4.44	6.93 ± 0.26

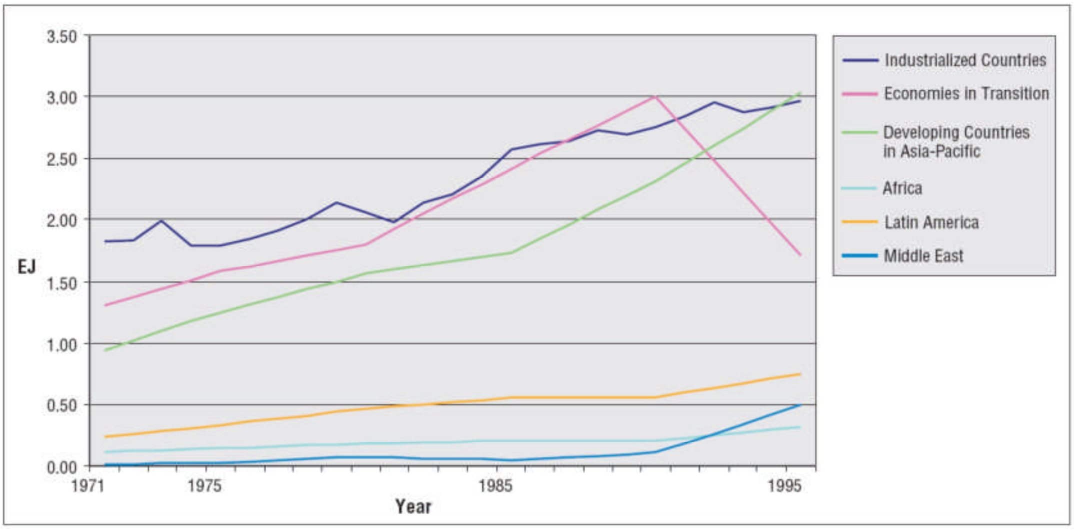


Figure 1: Primary energy use in agriculture, 1970 to 1995. (IPCC, 2001)

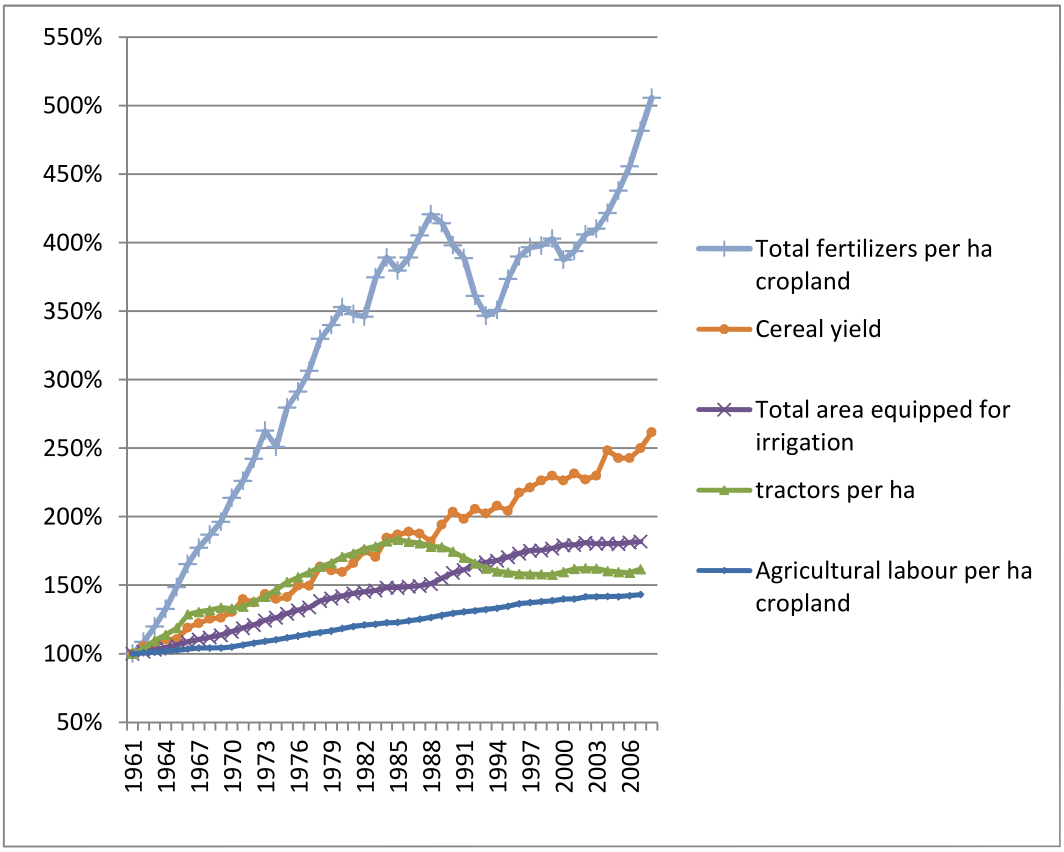


Figure 2: Global trends in the intensification of crop production (index 1961–2002/2005). Updated from Hazel & Wood (2008), based on FAOSTAT 2010.

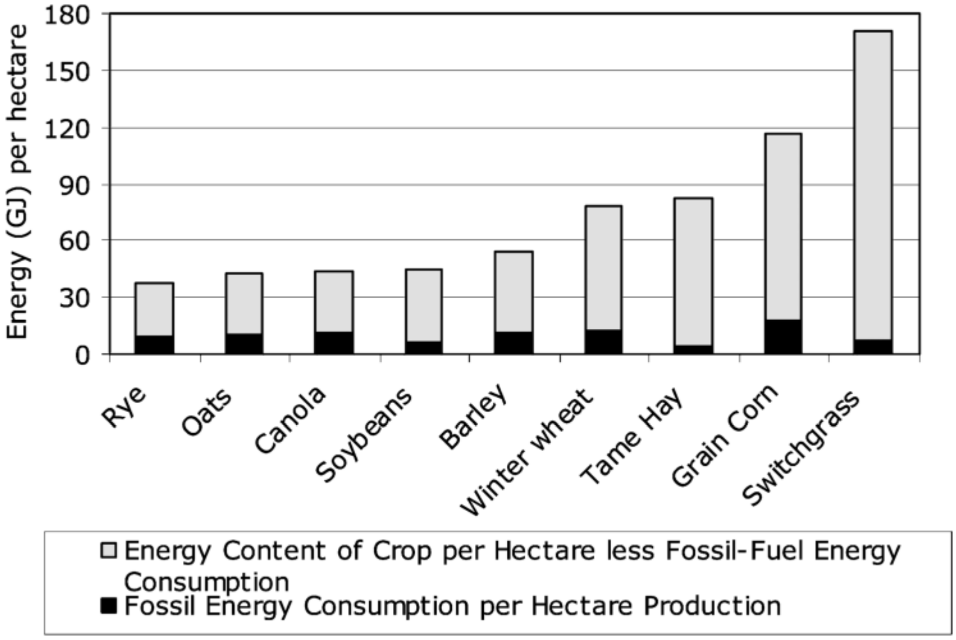


Figure 3: Solar energy collection in harvested component of crops and fossil fuel energy requirements of Canadian (Ontario) crop production, in Giga-Joules (GJ) per hectare (Samson et al. 2005).

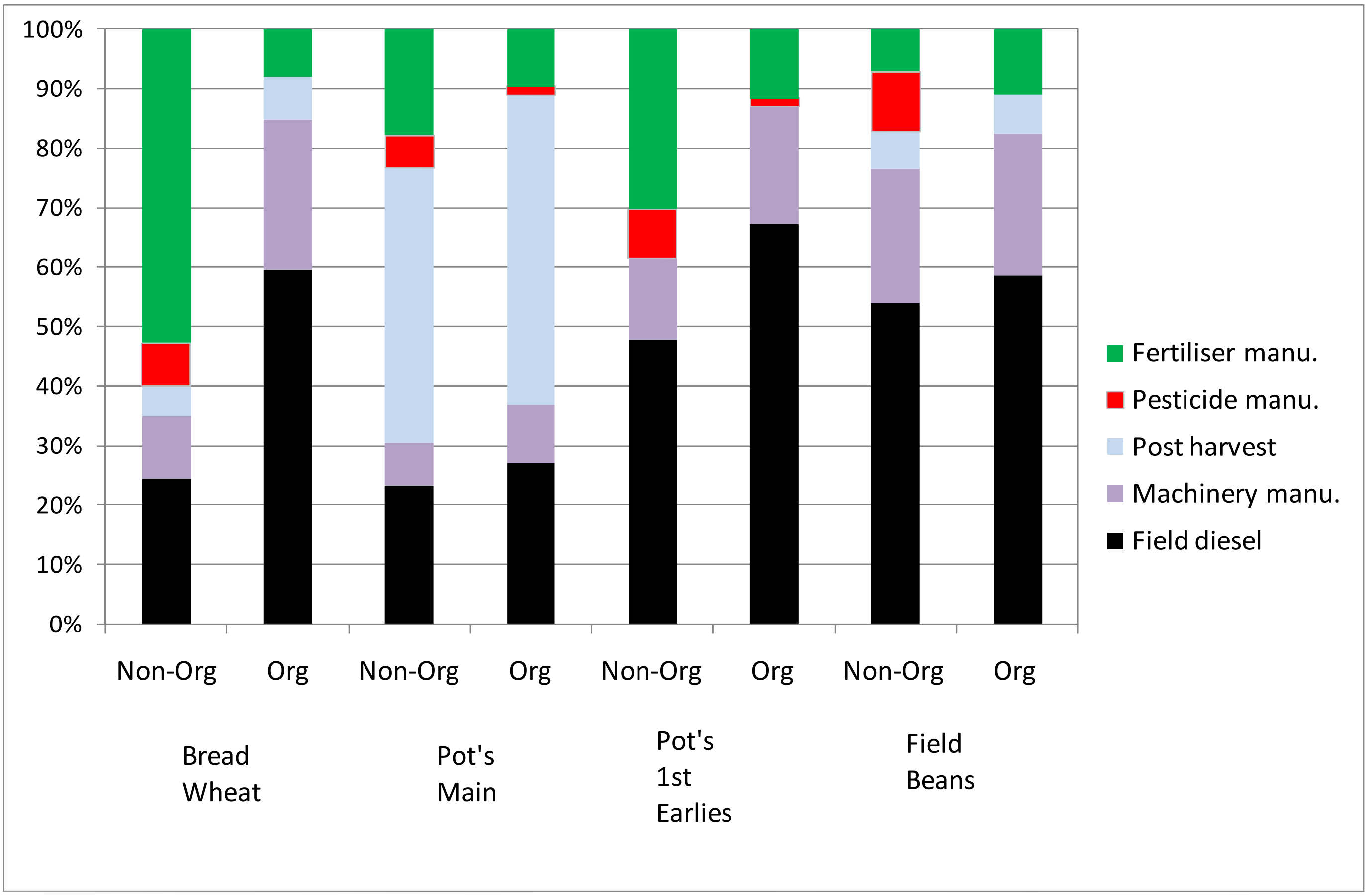


Figure 4 **Breakdown of energy used in major domestic crop production (‘Pot’s = potatoes; ‘manu’ = manufacture)**

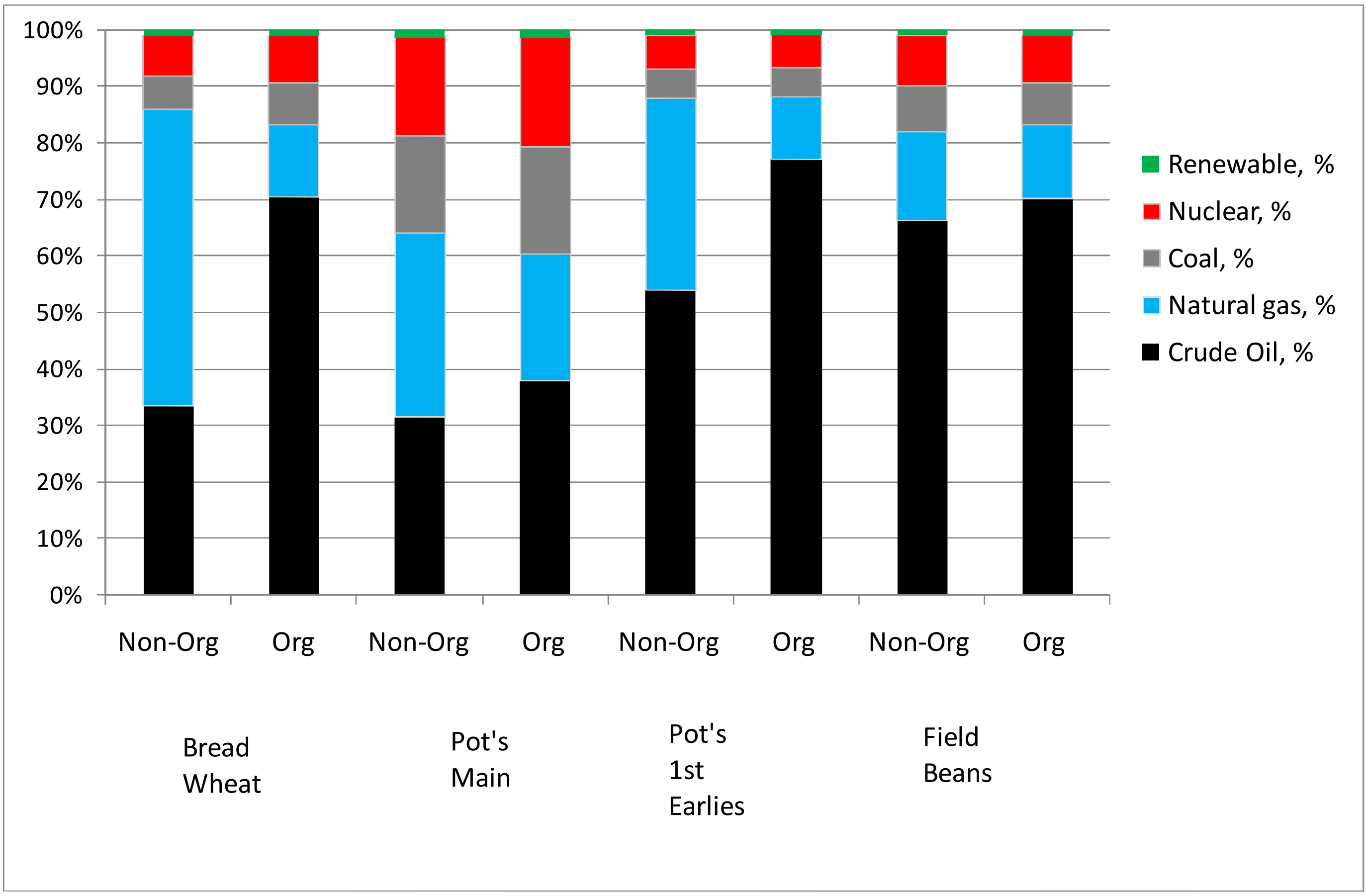


Figure 5 Distribution of energy carriers used in field crop production

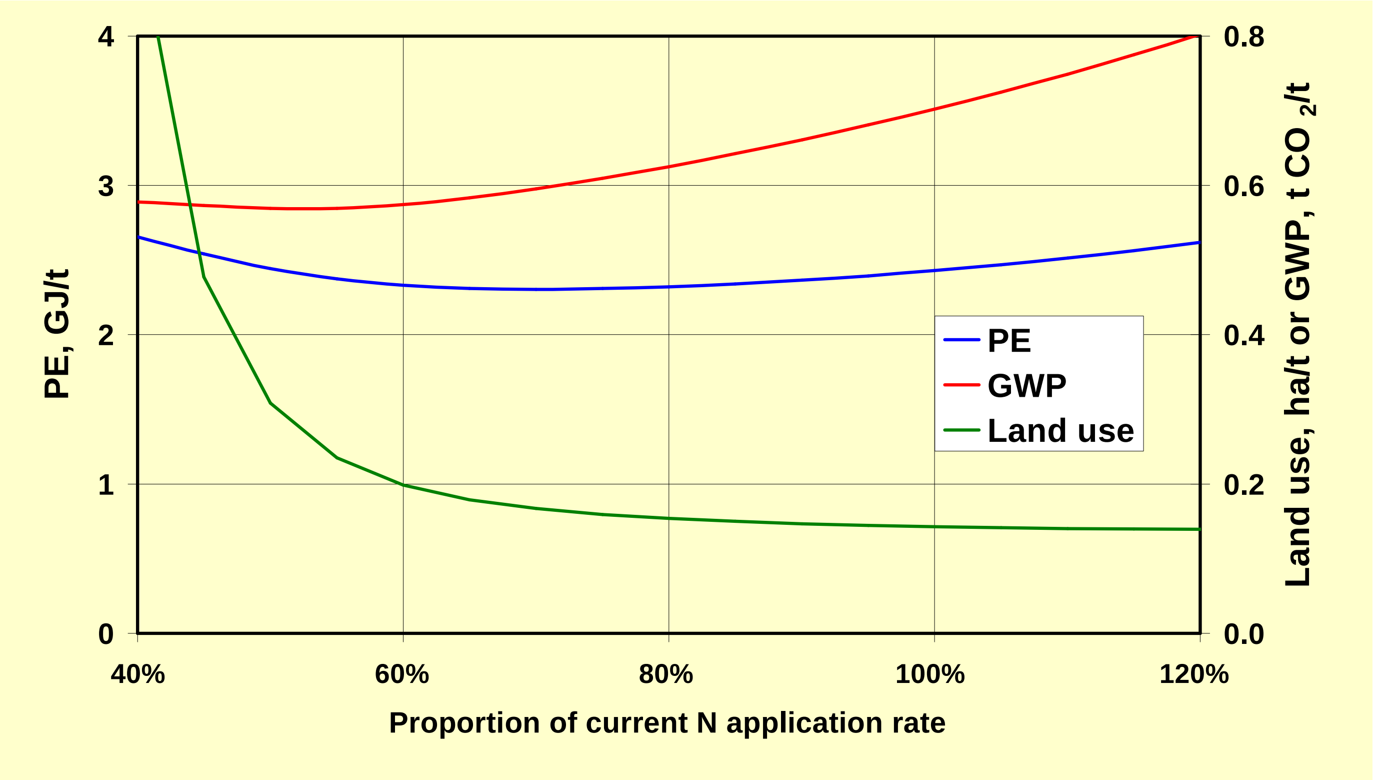
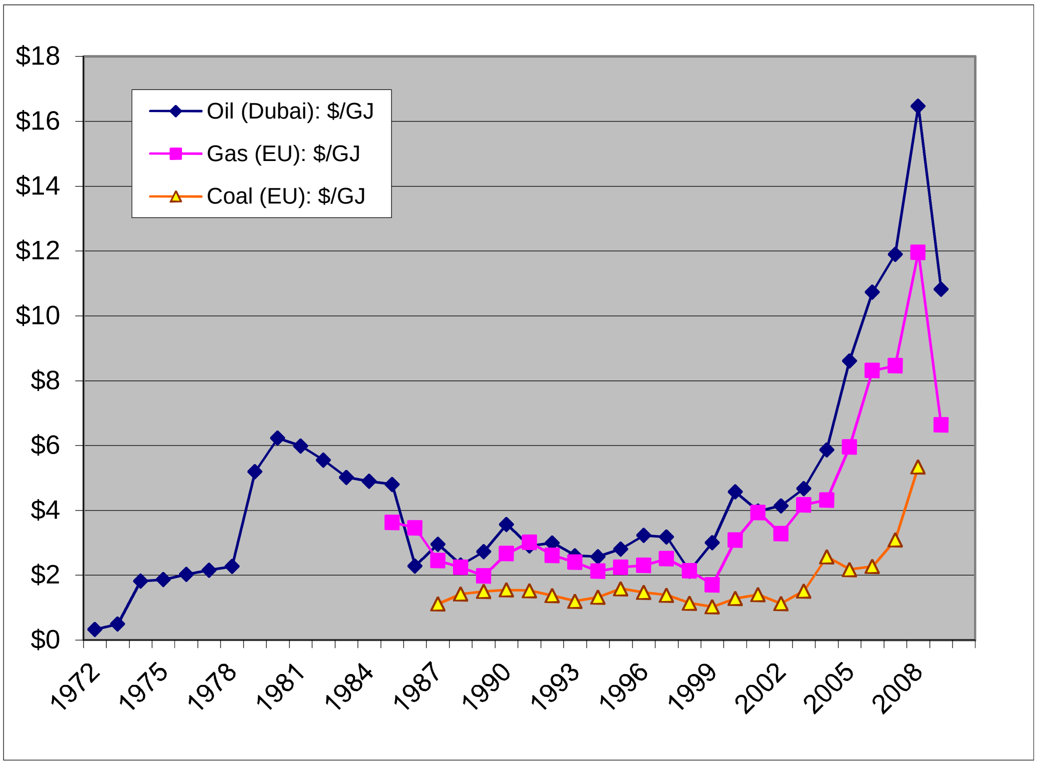


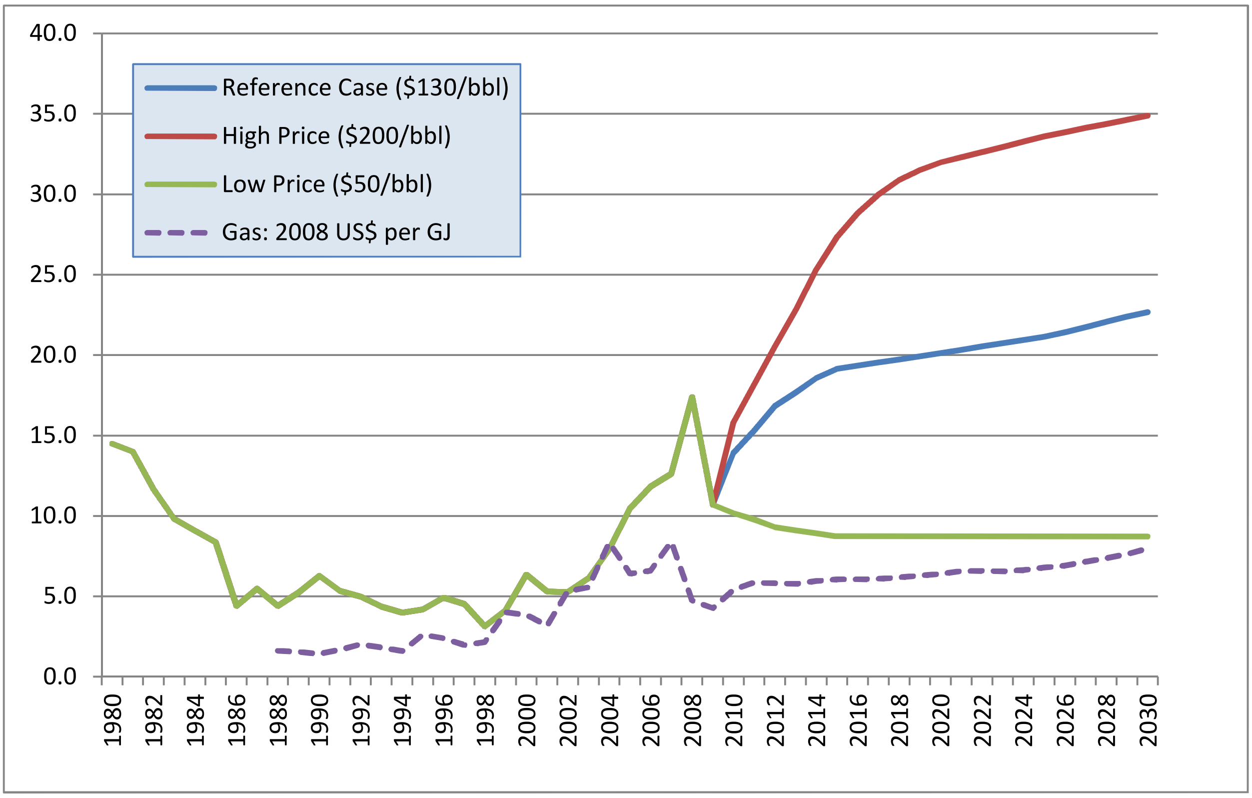
Figure 6 Effects of changing N supply on bread wheat using the Cranfield model (Williams et al. 2006; PE = Primary Energy; GWP = Global Warming Potential)



917

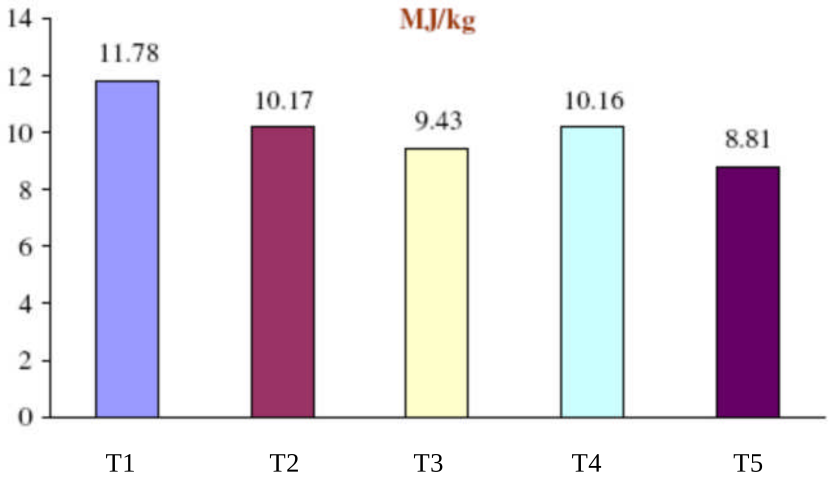
918 **Figure 7: Trends in Global oil, gas and coal spot-market prices; 1961 to 2009 (US$/GJ. BP, 2009; IEA, 2009)**

919



920

921 **Figure 8: Projected oil and gas price ranges to 2030; US$/GJ (US EIA 2009)**



T1: mold board plough+roller+drill

T2: chisel+roller+drill

T3: cyclo-tiller+roller+drill

T4: sweep+roller+drill

T5: no-till+drill

Figure 9: Energy consumed for 1 Kg wheat production in Maragheh region of Iran (Tabatabaeefar et al. 2009).

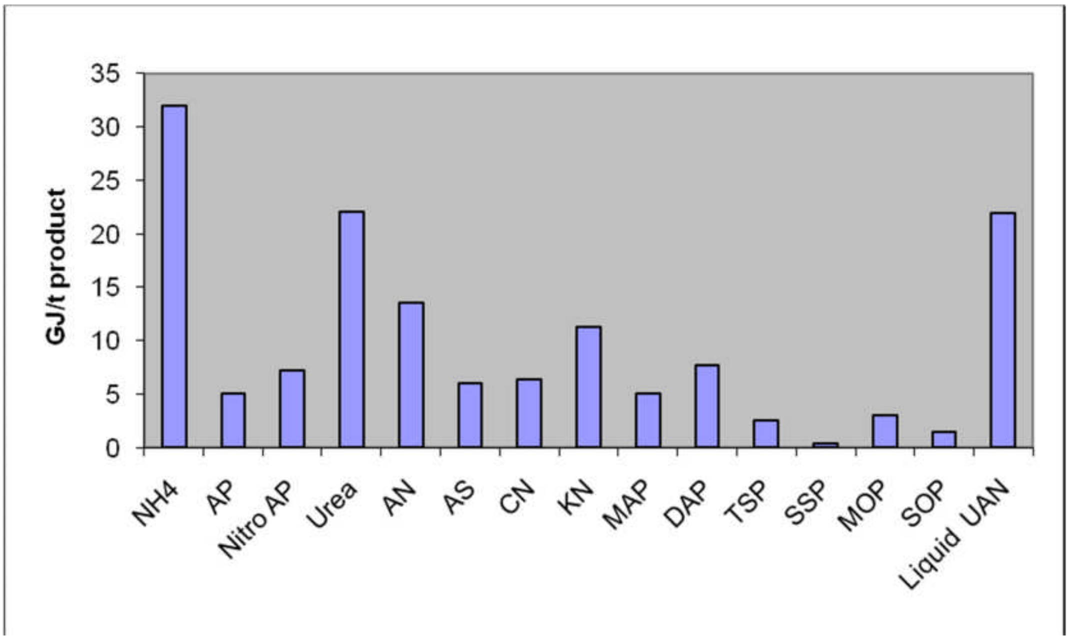


Figure 10: Energy inputs into the main fertiliser building blocks; European average technology (Jenssen and Kongshaug 2003)

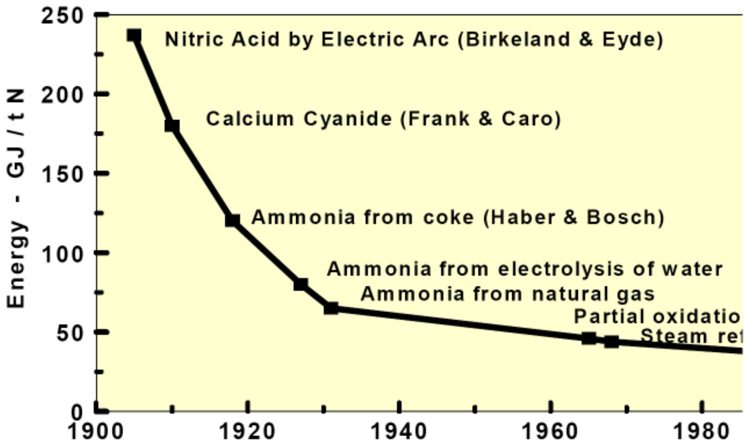


Figure 11: Historic Development of Energy for N-fixation (Kongshaug 1998)

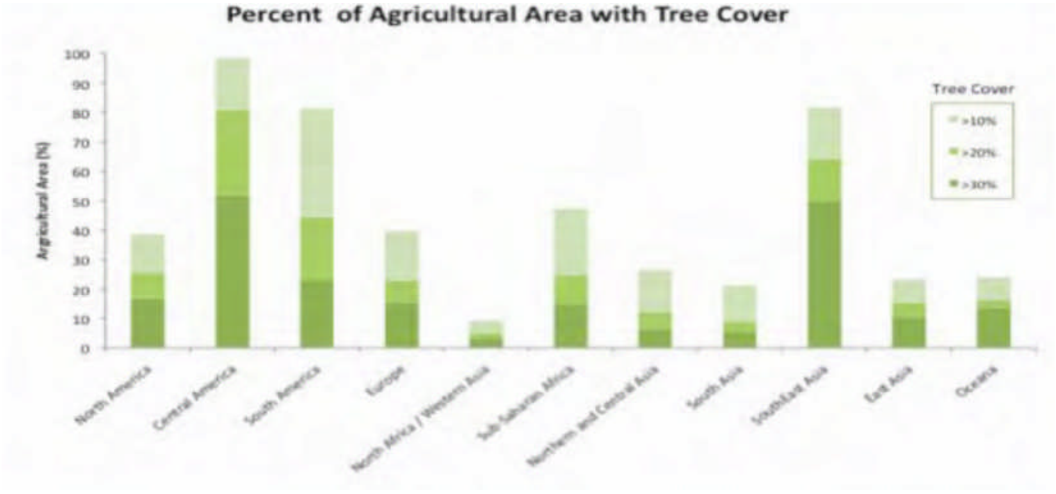


Figure 12: Percentage of world agricultural land that can be regarded as being under agro-forestry systems to varying intensities (after Zomer et al. 2009).