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Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Defra project report IS0205

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The authors are grateful to Defra for funding this work, especially the guidance and support of Dr Donal Murphy-Bokern. The work was mainly carried out and the report was written by staff from SRI (who have since moved to Cranfield University: http://www.silsoe.cranfield.ac.uk), but the project team included the following, whose considerable inputs made the project possible:

Raymond Jones & Richard Weller (IGER), Rosie Bryson (Velcourt Ltd), Lois Philipps (Elm Farm Research Centre), Andy Whitmore, Margaret Glendining and Gordon Dailey (Rothamsted Research), Paul Cook (Rlconsulting), Nigel Penlington (MLC) and Gerry Hayman (Hayman Horticultural Consultancy).

We also note the sudden and unexpected death earlier this year of Raymond Jones, whose contribution to the project and the research community was considerable.

The editorial input of Dr David Parsons is also gratefully acknowledged.

This report describes the current state of the LCI analysis which is now being distributed to independent experts for review and assessment.

Final report to Defra on project IS0205: Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities.

Executive Summary

The research addresses key questions underpinning the development of sustainable production and consumption systems that are based on domestically produced agricultural and horticultural commodities. It quantifies the resource use and environmental burdens arising from the production of ten key commodities and delivers accessible models that enable resource use and emissions arising from various production options in England and Wales to be examined in detail. The commodities examined are: bread wheat, potatoes, oilseed rape, tomatoes, beef, pig meat, sheep meat, poultry meat, milk and eggs.

The overall research aim agreed with Defra was to model the environmental burdens and resource use involved in producing ten agricultural and horticultural commodities using the principles of Life Cycle Assessment (LCA), and to deliver these models in a user-accessible form such as *Microsoft Excel.* The specific project objectives were to identify and define the major productions systems in England and Wales and the related process flow charts, to establish the relevant mass and energy flows and other necessary data and their uncertainties, to code the LCA models in a package, such as *Microsoft Excel*, with all the main data readily accessible and published, to use the LCA model to analyse these production systems and demonstrate that the model can compare production systems and can identify high risk parts the systems, and to publish and publicise the research outputs.

All inputs into on-farm production for each commodity were traced back to primary resources such as coal, crude oil and mined ore. All activities supporting farm production, such as feed production and processing, machinery and fertiliser manufacture, fertility building and cover crops, were included. The system included soil to a nominal depth of 0.3 m. Where appropriate (tomatoes, potatoes), commodities were defined as *national baskets of products*, for example tomato types such as loose and on-the-vine tomatoes, each included as their proportion of national production. Abiotic resources used (ARU) were consolidated onto one scale based on relative scarcity. Individual emissions, such as carbon dioxide (CO_2) and nitrous oxide (N_2O), were quantified and aggregated into impacts for global warming (GWP), eutrophication (EP) and acidification (AP). Organic production systems were analysed for each commodity, as well as variations on non-organic (or contemporary conventional) production.

Interactions between inputs, outputs and emissions were represented by functional relationships derived from process models wherever possible, so that as systems are modified they respond holistically to specific changes. For example, crop yields and nitrogen supply, dairy cow diet formulation and milk yield, and grass productivity, emissions, animal grazing and fertiliser applications are functionally related. Process simulation models were also used to derive the long term outcomes of nitrate leaching, soil, crop type and nitrogen supply.

Results

Care is needed in comparing commodities as they have different nutritional properties and fill different roles for consumers. The results for plant commodities are shown in Table I, and those for animal commodities in Table II.

Table I The main burdens and resources used arising from the production of field and protected crops in the current national proportions of production systems (with the current organic share shown in parenthesis.

Impacts & resources used per t	Bread wheat (0.7%)	Oilseed rape (0%)	Potatoes (1%)	Tomatoes (3.6%)
Primary energy used, GJ	2.5	5.4	1.4	130
GWP_{100}, t CO_2 (1)	0.80	1.7	0.24	9.4
Eutrophication potential, kg PO_4^{3-}	3.1	8.4	1.3	1.5
Acidification potential , kg SO_2	3.2	9.2	2.2	12
Pesticides used, dose-ha	2.0	4.5	0.6	0.5
Abiotic resource used, kg antimony (2)	1.5	2.9	0.9	100
Land use (Grade 3a), ha	0.15	0.33	0.030	0.0030
Irrigation water, m^3			21	39

(1) GWP_{100} uses factors to project global warming potential over 100 years. (2) ARU antimony is the element used to scale disparate entities.

The relationship between energy use and global warming gas emissions in agriculture contrasts with most other industries. N_2O from the nitrogen cycle dominates GWP from field crops, contributing about 80% in wheat production (both organic and non-organic). In addition, methane from livestock production, particularly from beef, sheep meat and milk, is a global warming gas emission not related to energy use.

About 97% of the energy used in tomato production is for heating and lighting to extend the growing season Because energy use is almost identical for all tomato production systems per unit area, the highest yielding tomatoes (non-organic, loose, classic or beefsteak) incur lower burdens than all other types of tomato.

Table II The main burdens and resources used in animal production in the current national proportions of production systems (with the current organic share shown in parenthesis).

Impacts & resources used per t of carcass, per 20,000 eggs (about 1 t) or per $10m^3$ milk (about 1 t dm)	Beef (0.8%)	Pig meat (0.6%)	Poultry meat (0.5%)	Sheep meat (1%)	Eggs, (1%)	Milk, (1%)
Primary energy used, GJ	28	17	12	23	14	25
GWP_{100}, t CO_2	16	6.4	4.6	17	5.5	10.6
Eutrophication potential, kg PO_4^{3-}	158	100	49	200	77	64
Acidification potential, kg SO_2	471	394	173	380	306	163
Pesticides used, dose ha	7.1	8.8	7.7	3.0	7.7	3.5
Abiotic resource use, kg antimony	36	35	30	27	38	28
Land use (1)						
Grade 2, ha	0.04			0.05		0.22
Grade 3a, ha	0.79	0.74	0.64	0.49	0.67	0.98
Grade 3b, ha	0.83			0.48		
Grade 4, ha	0.67			0.38		

(1): Grazing animals use a combination of land types from hill to lowland. Land use for arable feed crops was normalised at grade 3a.

On the livestock side, poultry meat production appears, however, the most environmentally efficient, followed by pig meat and sheep meat (primarily lamb) with beef the least efficient. This results from several factors, including: the very low overheads of poultry breeding stock (*c*. 250 progeny per hen each year *vs* one calf per cow); very efficient feed conversion; high daily weight gain of poultry (made possible by genetic selection and improved dietary understanding).

Poultry and pigs consume high value feeds and effectively live on arable land, as their nutritional needs are overwhelmingly met by arable crops (produced both here and overseas). Ruminants can digest cellulose and so make good use of grass, both upland and lowland. Much of the land in the UK is not suitable for arable crops, but is highly suited to grass. One environmental disadvantage, however, is that ruminants emit more enteric methane. This contributes to the ratios of GWP produced to primary energy consumed, being about 50% higher for ruminant than pig or poultry meats.

Unlike most of industry and domestic activity, the GWP from agriculture (excluding protected cropping) is dominated by N_2O, not by CO_2 from fuel use. N_2O contributes about 80% to GWP in wheat production (both organic and non-organic). The N_2O contribution falls to about 50% for potatoes as much fossil energy goes into cold storage. Because the underlying driver is the nitrogen cycle, the GWP of crop production is relatively similar across contrasting productions systems, including organic. In contrast, CO_2 from the use of natural gas and electricity in tomato production is the dominant contribution to GWP.

The balance of global warming gas emissions and fossil fuel consumption is thus quite different from most industries. In agriculture, N_2O dominates, with substantial contributions too from methane. Consequently, a carbon footprint inadequately describes agriculture; it has a *carbon-nitrogen footprint*. Indeed, the nitrogen fluxes in agriculture (and other types of land) also contribute to eutrophication and acidification. The majority of environmental burdens arising from the production of agricultural food commodities arise either directly or indirectly from the nitrogen cycle and its modification, in organic and non-organic systems.

Analyses of organic and non-organic production

About 27% less energy was used for organic wheat production compared with non-organic, but there was little difference in the case of potatoes. The large reduction in energy used by avoiding synthetic N production is offset by lower organic yields and higher inputs into field work. GWP is only 2-7% less for organic than non-organic field crops, reflecting the need for N supply to equal N take-off and the consequent emissions to the environment as nitrous oxide to air and nitrate to water.

Most organic animal production reduces primary energy use by 15% to 40%, but organic poultry meat and egg production increase energy use by 30% and 15% respectively. The benefits of the lower energy needs of organic feeds is over-ridden by lower bird performance. More of the other environmental burdens were larger from organic production, but abiotic resource use was mostly lower (except for poultry meat and eggs) and most pig meat burdens were lower. GWP from organic production ranged from 42% less for sheep meat to 45% more for poultry meat.

Land use was always higher in organic systems (with lower yields and overheads for fertility building and cover crops), ranging from 65% more for milk and meat to 160% for potatoes and 200% more for bread wheat, but the latter is a special case as only part of a crop meets the specified bread-making protein concentration.

Organic tomato yields are 75% of non-organic. Thus, the lowest yielding organic, on-the-vine, specialist tomatoes incur about six times the burden of non-organic, loose classic.

Other analyses showed that:
1. Breeding a new variety of wheat that increases yield by 20% could reduce energy use by 9%.
2. The choice of indoor or outdoor sow housing has a negligible effect on pig meat burdens.
3. Free range (non-organic) poultry increases energy use for meat by 20% and for eggs by 15%, compared with all housed production.
4. If beef production were to based 100% on beef cows (*i.e*. no calves from the dairy herd), energy use would increase by 50%.
5. Tomato burdens can be reduced by 70% if the proportion of CHP used is increased nationally to 100% from the current 25%.

The analyses were assembled in *Microsoft Excel* spreadsheets. These allow users to change key variables such as: the balance of organic and non-organic production at a national scale; N supply to crops; balance of housing types in animal production; use of Combined Heat and Power systems (CHP) in greenhouses. Alternative systems can thus be examined in detail. Default values representing the current balance of production methods in England and Wales for all commodities are included, *e.g*. national proportions of main production systems and sub-systems; fertiliser application rates.

Model access and future developments
The LCA model will be made available on the Cranfield University website at: http://www.silsoe.cranfield.ac.uk (then search for *IS0205* and *LCA*). Users will be supplied with updates and invited to participate in a workshop. Development of the modelling continues under project IS0222. The main activities include: development of versions suitable for analysis at both farm and regional levels; inclusion of new commodities, such as sugar beet; and analysing the national basket of food commodities. The latter implies accounting for interactions between commodity production systems (for example, crop rotations) and considering land availability. The current model is a life cycle inventory of commodity production and this will be progressed to produce a life cycle assessment, for example viewing the relative importance of the burdens of producing commodities.

Conclusions
1. Nitrous oxide (N_2O) is the single largest contributor to global warming potential (GWP) for all commodities except tomatoes, exceeding 80% in some cases.
2. Organic field crops and animal products generally consume less primary energy than non-organic counterparts owing to the use of legumes to fix N rather than fuel to make synthetic fertilisers. Poultry meat and eggs are exceptions, resulting from the very high efficiency of feed conversion in the non-organic sector.
3. The relative burdens of GWP, acidification potential (AP) and eutrophication potential (EP) between organic and non-organic field-based commodities are more complex than energy and organic production often incurs greater burdens.
4. More land is always required for organic production (65% to 200% extra).
5. All arable crops incur smaller burdens per t than meats, but all commodities have different nutritional properties and energy requirements beyond the farm, so care must be taken in comparisons.

6. Ruminant meats incur more burdens than pig or poultry meats, but ruminants can derive nutrition from land that is unsuitable for the arable crops that pigs and poultry must eat.
7. Heating and lighting dominate the burdens of tomato production; but maximising the national use of CHP could reduce the primary energy consumption by about 70%.
8. Non-organic, loose classic tomatoes incur the least burdens and they increase progressively and definably towards organic, on-the-vine specialist types.
9. The model has been used to inform other research projects and is well placed to analyse variations in existing production systems as well as being readily developed for new systems or commodities.
10. The model can be accessed via the Cranfield University web site at www.cranfield.ac.uk (then search for *IS0205* and *LCA*).

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1 Introduction

This is the report of a project to develop a tool to analyse and compare the environmental impacts of alternative methods of production of major agricultural commodities. A comparison of production methods requires a procedure that provides an objective and systematic calculation of the primary energy, material consumption and environmental burdens associated with the production of each commodity. Life Cycle Assessment (LCA) provides such a method and was used.

The objectives of the project were:

1. To develop, and later realise, a conceptual model to quantify the environmental burdens and resource use associated with the production of agricultural and horticultural commodities using the principles of Life Cycle Assessment (LCA).
2. To identify and classify the major typical production systems in England and Wales for the commodities specified and definea production process flow chartfor each system.
3. To establish the mass and energy flows for each commodity and other necessary input data for the working LCA model, ensure that the sources and derivation are clearly identified and the uncertainties quantified.
4. To code the LCA model in a package, such as *Microsoft Excel,* with all the main data readily accessible.
5. To use the LCA model to analyse these production systems and demonstrate that the model can compare production systems and can identify high risk parts the systems (so called hot spots).
6. To publish and publicise the working LCA model.

The analysis determines the environmental burdens per unit of ten commodities at the national level (England & Wales, Table 1). The analysis ends at the farm gate.

Table 1 The commodities and standard quantities analysed in this project

Field crops	Quantity	Animal products	Quantity
Bread wheat	1 t	Milk	10,000 l *
Potatoes	1 t	Eggs	20,000 *
Oilseed (rape)	1 t	**Meat**	
		Beef	1 t carcaseweight
Protected crop		Pigmeat	1 t carcaseweight
Tomatoes	1 t	Sheep meat	1 t carcaseweight
		Poultry meat	1 t carcaseweight

* 20,000 eggs weigh approximately 1 t. 10,000 litres milk contains approximately 1 t dry matter.

Agricultural commodities are produced using a range of production systems and in various forms in order to satisfy consumer demand. Geographical location, land use, soil type, specialised markets and support mechanisms all influence individual production systems. Depending on the production system, the burdens will be influenced by factors such as type of fertiliser and pesticide used, frequency and nature of cultivations, type of crop rotation, stocking density and yield. Future changes, from whatever cause, will alter the production systems in use. The approach that was taken endeavours to account forall these factors.

While it is possible to construct an LCA model using simply average values, it does not allow exploration of alternative production systems. Many terms are highly interactive and are much better described with functional relationships. As an example, the yield of wheat and its protein concentration respond to nitrogen supply. Increasing nitrogen fertiliser (an increased input burden) generally increases yield and protein concentration (useful outputs). Thus there is a trade-off between increasing burdens and outputs.

For arable systems, important aspects that users may wish to consider include:

- The proportion of organic versus non-organic crop husbandry
- The use of reduced cultivation methods (to save energy use)
- The reduction in N application rate (potentially to reduce N emissions)
- The use of urea rather than ammonium nitrate fertiliser (effect on N emissions)
- The increases in crop yields due to technology (increased environmental efficiency)
- Improved varieties (reduced surplus N use, reduced pesticide use)
- The incorporation of straw (or use as animal bedding or fuel)
- The type of soil on which the crop is grown (to optimise yields and emissions)
- Use of irrigation for potatoes (to reduce water use)
- Main crop versus early potatoes

For tomato production:

- The proportion of organic versus non-organic crop husbandry
- Types of tomato grown (*e.g.* classic, loose, on the vine, cherry)
- The proportion of nutrient film production (*vs* rockwool)
- The use of combined heat and power systems (CHP)

For livestock systems:

- The proportion of organic versus conventional animal husbandry
- Fecundity of dams
- Longevity of dams
- Feed conversion ratios
- Liveweight gain, milk yield or egg production
- Forage requirements (grazing and conserved)
- Feed sources
- Housing systems
- Location (upland, lowland etc) for sheep

These defined the variables of major importance in producing the LCA model, to ensure appropriate responses.

The report is divided into a description of the methods used followed by results and discussion. The first section of the methods describes the details of life cycle assessment as applied to agriculture and is followed by a description of the analysis of wheat as the major field crop and the modifications necessary to model other field crops. The next sections describe the methods used for analysing livestock systems, tomato systems and finally the capital items (buildings and machinery) used by all the systems.

2 Methods

2.1 *Outline of LCA Principles*

Error! Objects cannot be created from editing field codes.

Figure 1 Example of the LCA approach showing the system boundary

LCA analyses production systems systematically to account for all inputs and outputs that cross a specified system boundary (Figure 1). The useful output is termed the functional unit, which must be of a defined quantity and quality, for example 1t breadmaking wheat. There may be co-products or waste products like straw, together with emissions to the environment, for example nitrate (NO_3^-) to water and nitrous oxide (N_2O) to the air. All inputs are traced back to primary resources, for example electricity is generated from primary fuels like coal, oil and uranium. Ammonium based fertilisers use methane as a feedstock and source of energy. Phosphate (P) and potassium (K) fertilisers require energy for extraction from the ground, processing, packing and delivery. Tractors and other machinery require steel, plastic, and other materials for their manufacture, all of which incur energy costs, in addition to their direct use of diesel. The minerals, energy and other natural resources so used are all included in an LCA. Allowances should also be made for making the plant used in industrial processes (factory or power station) as well as the energy used directly.

2.1.1 Agriculturally specific aspects of LCA

Agriculture has particular features that are not relevant to the LCA of industrial processes. The main one is land itself and the soil. Farming systems must be considered in the long term to avoid illusory benefits. LCA requires the soil nutritional status to remain the same (over the course of a crop rotation). So, nitrogen (N), P and K inputs and outputs must balance. Omitting nitrogen fertiliser for one year may have a small effect on a conventional crop, but would have a much larger effect over many years as soil reserves are depleted. After one year, yields will only be slightly reduced owing to the soil fertility from previous seasons – the old system. The crop will, however, remove more nitrogen from the soil than enters the system as applied nitrogen. Over several years, the soil will reach a new steady state where the input and output of nitrogen become equal – and the yield stabilises at a new lower level. This is the true yield of the new system, which must be used in the LCA. Estimating long term nitrogen balances requires simulation models to project how practices would cause leaching and denitrification without soil nitrogen accumulating or being depleted. One consequence of this is that the estimates of leaching are often higher than the current actual ones, as current practices often appear to cause increases in soil organic nitrogen, which may not get microbially degraded and hence reach the environment for many years. A similar process applies to straw incorporation and soil carbon. Also weed accumulation over a rotation must be prevented by sufficient herbicide or cultivation.

Agricultural land is of varying quality, for example soil texture, rainfall potential and altitude. Models are thus needed to adjust yields according to land type for both arable and grassland. These must also reflect emissions such as leaching and denitrification. Long term data are needed for major inputs, such as fertiliser and lime use, pesticide use and grain drying energy requirement to avoid the normal variability of weather from year to year on activities.

While it is possible to consider arable crops in relative isolation, this is not true for animal production. In the simplest cases of eggs, pig and poultry meat production, there are typically breeding nuclei, from which secondary herds or flocks are derived, and these feed replacement genetic material into the commercial sector. Within the commercial sectors, several housing and rearing systems co-exist, each with its own characteristics. Changing the proportions of one part can have several interacting effects on other production areas. The situation with ruminant production (sheep meat and beef) is yet more complex. These may be reared in geographically diverse areas (such as hill, uplands and lowlands) and with a complex network of genetic flow. Beef animals are also partly derived from the dairy sector. Apart from these features, ruminants interact with the grassland that supports them.

In addition, all livestock consume concentrates (*e.g.* wheat, soya, barley, maize, oil seed cake). These are grown on arable land and contribute to the total land requirements for livestock. Some are imported from overseas and their production and transport burdens must be estimated in addition to domestically produced feeds. Forages are also conserved as winter feed for ruminants (mainly grass andmaize silage).

Livestock produce manure, which when it is applied to agricultural land promotes crop or grass growth. It contains plant nutrients and thus displace the burdens of manufacturing these nutrients which is a benefit to animal production systems, making due allowances for the likely effectiveness of use. Manure storage and spreading, on the other hand, is a burden incurred by the animal production system.

Livestock, like crops, respond to different levels of nutrition. For many meat and egg production systems, a single level can be assumed, but for example in dairying, the diet (and associated management intensity) influences not only milk production but also longevity, fecundity and methane emissions. A model combining these factors allows exploration of production systems.

Product quality is an important consideration, especially when dealing with biological materials. At the simplest end, meat is quantified as the edible carcass weight, as used in statistics produced by the Meat and Livestock Commission (MLC). This includes bones, fat, lean and skin in some cases. Milk is defined as the quantity of the fat-corrected product. Oilseed is simply that harvested, but wheat must reach a technical specification of breadmaking quality: 13.5% crude protein for conventional production. What does not reach this will end up as non-bread milling wheat or feed wheat. Tomatoes and potatoes cannot be specified as a single product as they are produced as diverse products to satisfy consumer demand, *e.g.* classic and cherry tomatoes, first early and maincrop potatoes. Each product has its own burdens and the functional unit of the commodity is instead defined as a 1 tonne basket consisting of a proportion of each product according to currentnational consumption.

The system boundary of this study was specified as *the farm gate*. Some assumptions were needed to handle this equitably. It was assumed that the burdens of grain drying occurred inside the farm as did potato cooling and storage. These are required to keep the products stable. Tomato and egg packaging was assumed to be outside the gate, even though it may be economically linked to production, but it was considered to be part of distribution. The killing out percentage of carcasses is used to obtain the edible carcass weights of animals, but slaughtering and transport to slaughterhouses is not included. Milk cooling on the farm is also included, but not pasteurisation.

A potential credit to the burdens arises from the consumption of considerable quantities of carbon dioxide by crops (and emission of oxygen). However, when the crops are consumed the same quantity is released to the atmosphere and conventionally it is ignored. However, if one was to consider the nation's net imports and exports of carbon dioxide due to the consumption of food by the population, then this becomes an important benefit to agriculture compared with importing the same amount of food. Similarly the collection of energy from the sun is ignored, although it varies with crop type and yield and the zero option of no agriculture collects no energy from the sun.

2.1.2 Allocation of burdens to co-products

Some crops and animals produce more than one useful output, for example grain and straw from cereals or oil and meal from rape. Although the latter is produced beyond the farm gate, we need to analyse it because rapeseed meal is used as an animal feed. Growing the crop incurs a set of burdens and these must be allocated equitably to the co-products. In some cases, a functional approach could be used, for example based on nitrogen or energy distribution between products, but the mainapproach we used was by economic value.

2.1.3 Separation of crops and animals

Although there are substantial interactions between animal and crop production, there is a need to separate them to determine the burdens of production of each commodity. Animals consume arable crops (and forages) and produce manure, which can fertilise grassland or arable land. Crops were analysed without manure. The benefits of the manure are credited to the animals in terms of displaced production and application of fertilisers. Summing a representative set of commodities will result in the same burdens as if the production systems were analysed as one integrated entity.

2.1.4 Organic production systems

The terms "conventional" and "non-organic" tend to be used synonymously. Non-organic is probably more descriptive, but "conventional" when used in this report, implies the aggregation of contemporary non-organic practices. The organic sector is currently relatively small (although parts are growing rapidly). Table 2 shows the current proportion of organic production of the major commodities, and shows that the non-organic sector clearly dominates throughout.

There may be many philosophical differences in outlook between organic and non-organic farmers, but there are only a few major differences that characterise the systems differently in LCA terms. The main one is fertilisation, in that organic farming does not use synthetically produced ammonium nitrate or urea (very energy intensive) or chemically processed P and K. Organic farming uses P and most K as directly extracted minerals, whereas P is commonly used as triple or single super-phosphate in the non-organic sector, because of the better availability of the nutrients in these forms. N is by far the biggest difference, however, with organic N being derived by N fixation through clover-grass leys. Cover crops are used much more in the organic sector between cash crops with a major aim of reducing N losses.

Table 2 Current proportions of organic commodity production

Commodity	Proportion, %
Bread wheat	0.7
Potatoes	1
Oilseed rape	0
Tomatoes	4
Milk	1
Eggs	1
Beef	0.8
Pigmeat	0.6
Sheep meat	1
Poultry meat	0.5

Pesticide use in the organic sector is minimal, with no herbicides used and fungicides effectively limited to a derogation to spray for potato blight using copper based products.

Potato tops are removed by mowing or flaming rather than spraying with desiccants. Organic farming places much more reliance on rotations and mechanical methods to control weeds. Ploughing is the dominant form of primary cultivation, although undersowing is often practised to provide control of weeds and other pests.

There are some systematic overheads associated with organic crop production in fertility building and cover crops. A clover-grass ley is energy-free in terms of nitrogen application because of fixing nitrogen itself, but it requires some maintenance (typically chain harrowing and /or cutting) and stops the land itself being used for growing cash crops, so inflating the land requirement for organic cash crops. Cover crops are normally ploughed in, and so cannot be harvested. The seeds must be grown elsewhere on land dedicated to the purpose and then supplied to the farm. In total, three crops are sown, but not harvested: the ley, and two years of rye. We estimate how much extra land is used to produce these seeds.

Livestock and manure are frequently an integral part of an organic cropping system. However the approach taken in the analysis was that the basic comparison between crops should be in stockless rotations because this determines the requirements for the crops and assesses their burdens more exactly and comparably. The fertiliser value of manure then becomes a reduction in fertility-building cropping required and hence land use of an organic arable crop, which is an environmental credit to the organic livestock. Note that the burdens of a whole farm, which are the sum of the burdens of the individual enterprises according to their proportions on the farm, are not affected by the choice of separation.

Organic soils used for crop production are likely to contain systematically more organic matter (and hence C) than comparable soils used as non-organic arable land without leys. Some benefits of soils with higher organic matter content will appear in terms of actual yields recorded, so are implied as given by this study. Other potential benefits are not included. We have not found adequate data on cultivation energy to allow for this. There may be some effect on rain-driven soil erosion, but, this is likely to apply to light, steep fields and we propose that this should be considered at more local level. Soil C sequestration is enhanced through the use of leys, which is normal practice in the organic sector. There is no reason to expect this to differ significantly in non-organic farming using leys, but it is likely to be systematically higher than in soils using cropping without leys.

2.1.5 Aggregation of burdens

The use of resources and emissions to the environment are collectively termed environmental burdens. Environmental impacts are a consequence of particular burdens. For example nitrate leaching is a burden, while the consequent eutrophication is an impact. Emissions to the environment, whether from farms, industrial processes or transport, are initially quantified by individual chemical species. Several of these are aggregated into environmentally functional groups of which the major ones that we use are:

Global warming potential (GWP_{100}): GWP is calculated using timescales of 20, 100 and 500 years, but we report the 100 year one in the "headline values". The main agricultural sources are nitrous oxide (N_2O) and methane (CH_4) together with carbon dioxide (CO_2) from fossil fuel. It is quantified in terms of CO_2 equivalents (Table 3).

Table 3 Global Warming Potential (GWP) factors for major gases using the IPCC (2001) climate change values.

Substance	GWP 20 years, [kg CO_2-equiv]	GWP 100 years, [kg CO_2-equiv]	GWP 500 years, [kg CO_2-equiv]
CO_2	1	1	1
CH_4	62	23	7
N_2O	275	296	156

N_2O-N	432	465	245

Eutrophication potential (EP): The main agricultural sources are nitrate (NO_3) and phosphate (PO_4) leaching to water and ammonia (NH_3) emissions to air. It is quantified in terms of phosphate equivalents: 1kg NO_3-N and NH_3-N are equivalent to 0.44 and 0.43kg PO_4 respectively.

Acidification potential (AP): The main agricultural source is ammonia emissions, together with sulphur dioxide (SO_2) from fossil fuel combustion. Ammonia contributes despite being alkaline. When deposited or in the atmosphere, it is oxidised to nitric acid. It is quantified in terms of SO_2 equivalents: 1kg NH_3-N is equivalent to 2.3kg SO_2.

Abiotic resource use (ARU): The use of natural resources was aggregated using the method of the Institute of Environmental Sciences (CML) at Leiden University (http://www.leidenuniv.nl/interfac/cml/ssp/index.html). Their data put many elements and natural resources onto a common scale that is related to the scarcity of the resources. It is quantified in terms of the mass of the element antimony (Sb), which was an arbitrary choice. Their data includes most metals, many minerals, fossil fuels and uranium for nuclear power.

Primary energy use: The major agricultural fuels include diesel, electricity and gas. These are all quantified in terms of the primary energy needed for extraction and supply of fuels (otherwise known as energy carriers). The primary fuels are coal, natural gas, oil and uranium (nuclear electricity). They are quantified as MJ primary energy which varies from about 1.1 MJ natural gas per MJ available process energy to 3.6 MJ primary energy per MJ of electricity. A proportion of electricity is produced by renewable sources such as wind and hydro-power, which account for 3.6% and 8% for UK and European electricity respectively.

Land use for crop production is reported assuming average yields for Grade 3a land (Bibby *et al.*, 1969). Yields for were scaled up or down using linear coefficients derived from Moxey *et al.*, (1995) for other land grades (Table 4) and required land use per one tonne of crop is one of these grades. However for animal grazing systems, owing to the network of rearing systems, land use is calculated as a proportion of each grade of land.

Table 4 Factors used to scale yields on different grades of agricultural land

Grade	Scaling Factor
2	0.88
3a	1.00
3b	1.08
4	1.12

2.1.6 Data sources

There are established inventories and factors for many industrial processes and impacts. These were used in the present study, together with some established agricultural ones and new ones that we developed. While some values can be satisfactorily described by constants, many cannot and must be described by functional relationships. Typical examples are: yields in response to N in synthetic fertiliser or manure; leaching from soil in response to N application rate, crop yield, soil type and rainfall; milk yield and nutrients in diet. Specific examples are included as needed.

Data were obtained from disparate sources. Much data on farm management, productivity and typical inputs were required, for example average N application rates, fecundity of sows, average potato yields. These were taken from standard texts, such as: Nix (2002-2005), Agro Business Consultants (2002-2005), Lampkin *et al.* (2002-2005), MLC yearbooks for pigs, sheep and beef, websites of organisations such as the MDC, Defra statistics from the June census, the Soil Association's annual reports, HGCA and the Potato Marketing Council reports.

Values for fertiliser use and manure compositions also came from Defra's RB209 (MAFF, 2000) and the Surveys of British Fertiliser Practice (Defra, 2001-2005), pesticide use came from the annual pesticide surveys. Gaseous emissions of ammonia, nitrous oxide and methane came mainly from the UK national inventories, which also supplied some activity data (*e.g.* proportion of manures spread on arable and grassland). Chemical composition of crops came mainly from the UK tables of feed composition (MAFF, 1992), Ewing (1998) and McCance (2002).

Apart from these standard sources, production data came from within the expertise of the project team. Commercial confidentiality precludes defining all such sources. Data also came from the scientific and popular literature as well as websites, such as those of the Feed Manufactures Association, Soil Management Initiative, Defra, and the United States Department of Agriculture. We developed our own inventory of materials and processes for the project. This was based on some of the data sources above, together with inputs from an EU harmonisation study (Audsley *et al.*, 1997) and the *Ecoinvent* LCA data source (provided under the *SimaPro* platform). *Ecoinvent* is commercially sensitive so specific data have been masked in the working model.

2.2 *Bread wheat production*

2.2.1 Summary of activities causing agricultural burdens

The main sources of agricultural burdens for field crop production are:

- Field diesel for cultivation, chemical and manure applications, irrigation and harvesting
- Machinery manufacture
- Producing fertiliser and pesticides
- Drying and cooling direct energy
- Direct soil-crop emissions to air and water (nitrate, nitrous oxide and ammonia)
- Construction of buildings
- Land use per t production

All except the last involve energy and abiotic resource use and involve some gaseous and aquatic emissions.

These apply in general to all crops, whether produced non-organically or organically, but with clear differences between crops and systems, for example potatoes are deep ploughed (never direct drilled), while conventional N comes from synthetic fertiliser and organic N from grass-clover leys and legumes. The same set of activities applies to grassland, whether grazed or used for forage conservation. So, the same list applies to feed production for livestock

2.2.2 Field operations

All arable crops are grown in a similar way, with attendant burdens resulting from:

1. Seed bed establishment
2. Crop protection (weeds and diseases)
3. Fertilisation
4. Harvesting
5. Crop storage (including drying or cooling)

Three alternative methods for planting crops were considered, namely plough-based, reduced cultivation and direct drill. Following the example of Chamen & Audsley (1993), the operations required to produce each crop were divided into:

- Pre-plough, such as subsoil which is carried out some years only
- Primary cultivation
    a. Plough followed by a rolling operation for winter crops. It is possible to use a combined operation of plough and press wheel, but with similar total power demand.
    b. Reduced cultivation such as discing or power harrowing, again followed by rolling
    c. None
- Secondary cultivation or seedbed preparation
    a. Power harrow operation, particularly on heavy land
    b. Discing or tining, particularly on light land

  Following Chamen & Audsley (1993), it is assumed that heavy land requires both a and b, medium land required two passes of b and light land required one pass of b. Combining this operation with the drilling operation in order to save labour, does not change the energy required for the operation.
- Planting – either a conventional or direct drill
- Crop protection – the number of passes depends on the system, with more weed control being required with less cultivation.
- Fertilising – the level of fertiliser depends on the yield expected, the desire to promote nitrogen content for bread quality, and the nitrogen carry-over from previous crops. Urea is less efficient due to greater ammonia losses and thus a higher application rate is required than with ammonium nitrate fertiliser.
- Harvest – if the straw is not being baled, then the combine harvester will also chop the straw (using more energy for this).
- Post harvest – baling and carting the straw

2.2.3 Fuel use for farm operations and machinery burdens

All farm operations require a certain amount of energy. Thus, for example, ploughing (turning over one hectare of soil to a depth of 0.2 m) requires a certain energy input, MJ/ha. This energy is independent of the tractor power. In general, a tractor that is twice the power will be approximately twice the weight, have twice the width of implement, etc so that rolling resistance, traction, etc will be the same.

Energy is represented by fuel use by a tractor. Table 5 shows data obtained from commercial farms on fuel use for operations, representing typical modern work rates and equipment. The data on ploughing illustrate the point that the fuel use is not a function of the size of tractor or implement.

Table 5 Work rates and fuel use for field operations obtained from commercial farms

Tractor power, kW	Implement	ha/h	Litres per 12h day	Litres/ha
336	12 furrow plough	2.5	850	28.3
	7 legged sub-soiling	3	840	23.3
	Disc & pack (5.5 m)	4.5	540	10.0
	Disc (5.5m)	5	420	7.0
	Drill (6 m)	4.2	420	8.3

194	5 furrow plough	0.84	250	24.8
130	12 t trailer		110	
	6.6 m rolls	5	130	2.2
	Sub-soiling tramlines	5	200	3.3
	4 m Power harrow	1.16	250	17.9
243	Harvest: OSR, peas, beans	2.54	500	17.9
	Harvest: barley/wheat	2.27	500	20.0
114	Spraying	10	220	1.8

Table 6 collates data from a number of sources on energy use for farm operations. There are wide differences, giving a coefficient of variation of about 40% in most cases. Energy use is a function of the soil type and Chamen & Audsley (1993) derived methods to calculate the work rate of operations as a function of the tractor power and soil type. The effect is biggest for cultivation activities, since more work is done to the soil, while surface activities like combining are unaffected. Average specific energy values (Table 7) (assumed to represent a loam soil) were thus adjusted by coefficients to compensate (Table 8).

Table 6 Direct energy use as diesel in field operations, MJ/ha as primary energy.

Activity	Sources	Mean	CoV, %
Ploughing	9	942	32
Sub-soiling - All field	3	752	29
Rotary cultivations	5	603	24
Heavy discs	7	506	53
Power harrow	6	641	23
Rolling	3	139	43
Grain drilling standalone	8	206	30
Potato planting	4	796	85
Ridging potatoes	2	634	96
Spraying	5	56	26
Potato harvesting	3	2112	66
Mowing	5	163	54
Forage harvesting	2	344	77
Transport as MJ/t	1	15	15

(Data sources included Witney (1988), Audsley (2002), Cope (1997, SRI pers. comm..), Koga *et al.* (2003), Smith (1993), Chamen *et al.* (1996), Bridges & Smith (1979), Bailey *et al.* (2003), Anon (via Audsley pers. comm.), Sijtsma *et al.* (1998), SRI farm data and commercial farms (this study).)

Table 7 Energy used in field operations, expressed as MJ/ha of primary energy. All tillage is for working loam soils.

Activity		Total energy, MJ/ha	Proportion as Field Diesel, %
General Cultivations	Sub-soiling	1,061	78
	Sub-soiling tramlines	176	74
	Plough (200 mm)	1,350	76
	Power harrow	913	77
	Rotary cultivator (4 m)	914	72
	Disc & pack	586	66
	Discing	784	71
	Spring tine harrows / weeding	300	75
	Conventional Drill	280	74
	Combined harrow & drill	1,218	75

	Direct drill	372	73
	Rolling (Cambridge rolls)	248	61
Spraying and fertilising	Spraying, (self propelled)	114	54
	Disk fertiliser broadcasting	105	78
	Lime spreading	336	70
	Muck spreader	1259	37
Grain Harvesting	Combine harvester with straw chopping	1,134	69
	Combine harvester without straw chopping	1,096	68
	Grain carting (yield dependent, 8 t/ha)	399	29
Potato cultivation	Plough (250 mm)	1,688	76
	Potato destoner	3,082	81
	Potato ridger	860	81
	Potato planter	1,116	78
	Potato harvester	3,142	74
Forage conservation	Mower	198	90
	Mower-conditioner	299	90
	Tedder / Rake	183	97
	Forage harvester	1,392	88
	Baling	298	77

Table 8 Factors to adjust cultivation energies from average values for loam soils

Activity	Clay factor	Sand factor
Ploughing	1.7	0.6
Disc & pack	2	1
Cambridge Rolls	1	1
Power harrow *	1.7	
Conventional Drill	1	1

* In the context of plough based cultivation, power harrowing was only used with clay soils.

In organic cultivations, seedbed establishment uses ploughing as the norm. Reduced tillage and direct drilling are much less applicable than in the non-organic sector because pesticides are not normally used. Some crops in rotations are, however, undersown. In defining the tillage requirements, additional light cultivations for weed control are used in organic for weed and disease control. Typical pesticide applications were assumed in the non-organic sector to achieve the same ends together with rotational control.

In both organic and non-organic crop production, rotations, tillage and spray use were defined that would achieve technically sustainable yields. The arbitrary removal of, for example, a spray application or weed control cultivation step might incur no yield loss in one year, but would progressively lead to long-term yield loss.

2.2.4 Crop yield and response to nitrogen

The effects of fertiliser nitrogen on crop yield and protein content were examined using data from Rothamsted's Broadbalk plots from 1991-2000, which used N application rates ranging from 0 to 288 kg N/ha. This dataset is very useful as the fertiliser treatments have been applied for many years, so that true long term effects can be seen (Figure 2).

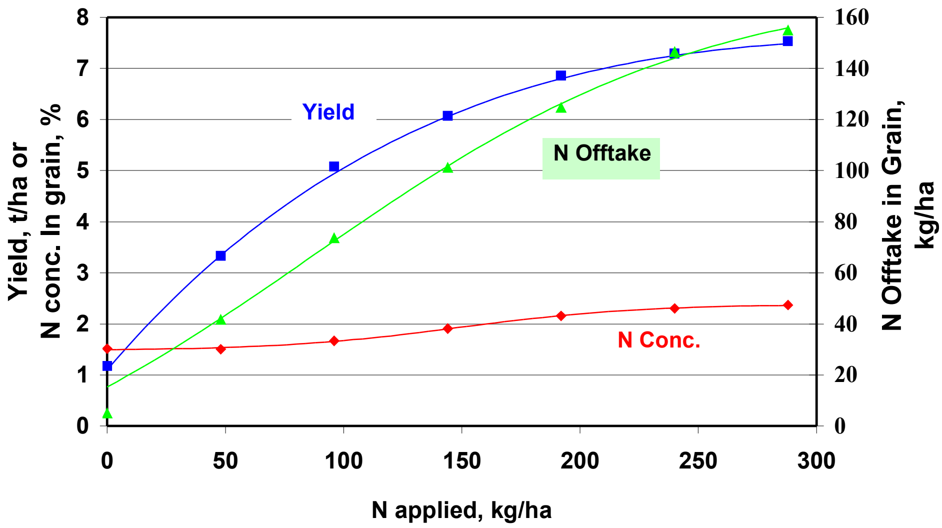

Figure 2 Grain yield, N concentration in grain and N offtake from continuous winter wheat grown on Broadbalk plots at Rothamsted 1991-2000

The data clearly show that applied N increases the grain N (and hence protein) concentration, the grain yield and grain N offtake. Yield (Y) is well characterised by a standard form of linear-exponential curve: $Y = a - b\exp(-cN) - dN$. The nitrogen offtake in grain is characterised by a logistic growth curve: $Y = a + b/(1+\exp(-c(N-d)))$. The same forms of equation applied to straw, although the change in N concentration was less pronounced. The fitted values are shown in Table 9. The grain N concentration was calculated indirectly from the nitrogen offtake and yield.

Table 9 Fitted parameters for relating bread wheat crop yield to nitrogen fertiliser application (in kg/ha)

Parameter	Grain yield, t/ha	Straw yield, t/ha	Grain N offtake, kg/ha
a	453.7	461.6	-37.35
b	452.6	460.8	204.9
c	0.000626	0.000333	0.0131
d	0.237	0.135	83.64

The Broadbalk data were for one type of wheat on one specific soil and are assumed to be for an average variety of wheat. Further adjustments were needed to allow for differences between bread and feed wheat protein concentrations and the effect of soil type on yield. The varieties chosen by farmers when growing for breadmaking are NABIM class 1 or 2. For feed they are likely to be class 3 or 4 which have higher yields (104% versus 99% of the control). Organic farmers (with lower soil nitrogen supply) need to choose the highest protein varieties to be able to achieve over 12% crude protein with any reliability and often grow spring wheat, which has a higher protein concentration, but is lower yielding. Using data from the NIAB Recommended List, the values of the yield and protein concentration were adjusted by the difference from the average of non-organic breadmaking, organic breadmaking and feed wheat varieties.
Yields were adjusted according to soil texture, using coefficients derived in the Silsoe Farm Model (Audsley 1981). These vary between crops, but average wheat yields on clay soils are 104% of those from loams and those from sandy soils are 76% of those from loams. Only these three main soil textures were used and the national distributions (along with rainfall) were those established in the study *Environmental Benchmarks of Arable Farming*. (Defra project ES0112, Williams *et al.*, 2004a).

Another soil interaction is between sub-soiling and yield. We assumed that if sub-soiling is too infrequent on some soils (one third of all), there is a yield loss. This happens when the interval (i) exceeds i_0 years. Below this interval, there is no yield loss or gain. The yield loss (l) is assumed to reach a maximum of l_{max} after a great time. The formula used for intervals above i_0 years is thus: $l = l_{\max} - s/i$, where s is a parameter. When the yield loss is zero, $i = i_0$ and so $l_{\max} = s/i_0$ and hence $s = i_0 l_{\max}$ When $i < i_0, l = 0$. We assumed a maximum yield loss of l_{max} =10%, with i_0 =3 years.

For non-organic wheat, the yield responses were further adjusted so that the national average yield (on the national distribution of soils) was obtained by using the national average N fertiliser rate.

For organic wheat, the average organic yield was used to determine the nitrogen supply that would give that yield. This was then used to determine the protein content adjusted for high protein varieties. A similar response curve for applied N from organic materials such as compost was also derived.

These relationships provide a model that can calculate national wheat yields in response to changes in major factors like soil type, wheat type and N application rate.

2.2.4.1 Determination of breadmakingquality

Not all wheat intended for breadmaking achieves the quality required. HGCA (2003) reported a survey of samples of grain after harvest. For Hereward, the protein concentrations was typically 1%<11.3%, 21%<13.5%, 71%<15.5% and 6%>15.5%, suggesting a normal distribution of protein concentrations. Both the Hereward data above and Broadbalk data suggested a standard deviation of about 1% in protein concentration. Data on organic breadmaking wheat varieties shows a standard deviation of 0.66% protein, with a mean of 12.5%. It was decided to use a standard deviation of 0.6% to calculate the proportion of crop that met the breadmaking protein criteria of 13.5% for non-organic and 12.5% for organic from the mean protein concentration achieved by different systems.

Furthermore, 5% of the NABIM 1 and 2 variety samples in the UK failed to meet the breadmaking quality criteria of Hagberg Index and specific weight, although 98% met the protein requirement. Typical reasons can be a laid crop or poor weather at harvest time. So, a further quality factor was needed to represent this, which was a constant of 4.4%, which resulted in 95% of the non-organicaly grown bread wheat being suitable for breadmaking.

Wheat that is grown for breadmaking, but fails the grade becomes feed (or non-bread milling) wheat. The burdens were allocated between the bread and feed fractions according to their economic value. Let V_F be the relative value of the feed grain and W_B and W_F be the t/ha respectively of bread and feed wheat portions, then the burden allocated to bread wheat is $G^* W_B / (W_B + v_F W_F)$. An alternative would be to use the avoided burdens approach and deduct the burdens from producing that quantity of feed wheat from the total burdens for bread wheat. However, the difference is small.

2.2.4.2 Allocation of burdens between grain and to straw

Grain is harvesting by a combine harvester, but straw may be harvested or incorporated. If harvested, additional burdens are incurred by the straw baler, but the actual combine energy is reduced slightly as a straw chopper is not required. Thus one can calculate the burden attributable to the grain.

The total burdens of producing grain and straw are: $T = H + (1 - p_s)I + p_s B + D$

Then the burden allocated to grain is: $G^* = (H + I)\ \ (Y_g / (Y_g + v_s p_s Y_s)) + D$, and the burden allocated to straw is: $S^* = \frac{(H+I)\,(v_s p_s Y_s)}{(Y_g + v_s p_s Y_s)} + p_s(B-I)$,

where H is the vector of burdens of producing grain up to the end of combine harvesting per ha, I is the vector of burdens of chopping for incorporation for all straw produced, D is the vector of burdens of drying and storage of grain, B is the vector of straw baling burdens for all straw produced, p_s is the proportion of straw baled and harvested, Y_g is the net yield of grain per ha at standard DM content, Y_s is the yield of straw per ha (whether harvested or not) at standard DM content, and v_s is the relative value of the straw *prior to baling* versus the grain, typically 0.05.

2.2.5 Nutrient inputs and crop protection

Nutrient inputs to a crop can be divided into readily mobile (nitrogen) and non-mobile (all others). Non-mobile nutrients do not need to be applied annually. Mobile nutrients are applied annually to ensure that as far as possible they are used by the crop and not lost. In a non-organic system, the level of nitrogen input to a crop is typically adjusted to be greater than the expected offtake by the crop, based largely on economic considerations. Data on the actual level of nitrogen input to crops were taken largely from the Survey of British Fertiliser Practice (Anon, 2000-2005). For scenarios where the N offtake of the crop is increased (eg increased yield or protein content), it is assumed that the N fertiliser input will be increased by the same amount.

For all other nutrients, farmers normally aim to apply quantities to maintain soil fertility levels which are checked and corrected over several years in response to soil tests. The input required to maintain a constant level of the main nutrients is therefore calculated by mass balance and it is assumed that this amount and its associated burdens are applied to the crop. One exception is potatoes when P is applied in excess of crop demand owing to the economic response. The surplus P thus displaced the P fertiliser requirement of other crops in proportion to the areas grown.

Table 10 Main burdens for producing, packing and delivering fertilisers.

Item	Unit	Primary Energy, MJ	GWP_{100}, [kg CO_2 equiv.]	EP, [g PO_4^{3-} equiv.]	AP, [g SO_2 equiv.]	ARU, [g Sb equiv.]	N_2O-N, to air, g
Ammonium nitrate (AN) as N	kg N as N	41	7.2	0.50	4.7	23	9.4
Urea (UN) as N	kg N as N	49	3.5	0.54	5.3	23	0.025
Calcium ammonium nitrate (CAN) as N	kg N as N	43	7.4	0.55	5.3	21	9.4
Ammonium sulphate (AN) as N	kg N as N	42	3.0	0.52	5.3	20	0.022
Mean N fertiliser for grassland as N	kg N as N	42	6.8	0.50	4.8	23	8.3
Triple super phosphate as P	kg P as P	19	1.2	0.74	8.1	15	0.012
Single super phosphate as P	kg P as P	13	0.60	0.57	6.6	16	0.0094
Rock P from 25% P_2O_5 Tunisian	kg P as P	15	1.1	0.97	13	17	0.012
Mean P fertiliser for grassland as P	kg P as P	18	1.2	0.74	8.0	15	0.012
K fertiliser as K	kg K as K	5.7	0.53	0.30	7.2	3.9	0.0056
Rock K as K	kg K as K	15	0.86	1.40	8.8	17	0.0094
Gypsum as S (quarried)	kg S as S	5.50	0.35	0.58	3.7	5.9	0.0031
Gypsum as S from FDG	kg S as S	1.90	0.11	0.14	0.9	4.2	0.0020
Gypsum as S (Mixed)	kg S as S	3.70	0.23	0.36	2.3	5.0	0.0025
Limestone as rock	kg product	0.90	0.06	0.10	0.6	0.9	0.0005
Limestone as CaO	kg CaO	1.6	0.11	0.18	1.2	1.7	0.0010
Limestone as Ca	kg Ca	2.3	0.15	0.26	1.6	2.4	0.0014
Total for burnt lime (or chalk) as 90% CaO product	kg product	6.0	0.16	0.14	1.7	3.6	0.0014
Burnt lime (or chalk) as CaO	kg CaO	6.1	0.16	0.14	1.7	3.7	0.0014
Burnt lime (or chalk) as Ca	kg Ca	8.5	0.23	0.20	2.4	5.1	0.0020
Weighted lime usage as product	kg product	3.4	0.19	0.31	2.1	3.2	0.0017
Weighted lime usage as CaO	kg CaO	2.3	0.12	0.18	1.2	2.0	0.0010

Weighted lime usage as Ca	kg Ca	3.2	0.16	0.25	1.7	2.8	0.0015
Sulphuric acid as a desiccant	kg	0.40	-0.13	0.06	0.6	1.0	-0.0008
Pesticide – dose ha	Dose ha	100	8.0	15	96	47	0.011

The burdens for producing, packing and delivering fertilisers (Table 10) were derived from several sources including: Audsley *et al.* (1997), Jenssen and Kongshaug (2003), Stout (1990), Shreve (1967), Sheldrick and Steier (1979), Reinhardt *et al.* (1991), Patyk and Reinhardt (1997), Patyk (1996), Mudahar and Hignett (1982, 1987a, 1987b), Mortimer *et al.* (2003), Martin and Shock (1989), Leach (1976), Helsel (1992), Goulding and Annis (1998), Elsayed *et al.* (2003), Elsayed and Mortimer (2001), Weidema *et al.* (1995), http://www.pda.org.uk/leaflets/23/no23-page3.htm, http://www.gct.com.tn/english/wcpg.htm and http://www.mining-technology.com/project_printable.asp?ProjectID=1198. The main burdens related to energy use (*e.g.* energy in the Haber process for converting N_2 to NH_3 or quarrying and transporting minerals), but one specific extra term is needed: N_2O from nitric acid production. This is used for ammonium nitrate (AN) and calcium ammonium nitrate (CAN). Fertilisers are sold in a considerable variety of formulations, but we divided them into the principal component parts.

Three minerals for use in organic systems are included: rock P, rock K and lime. These are extracted with minimal processing (quarrying and grinding being essential). We assumed that no burnt lime was used in the organic sector, and the lime used in the non-organic sector includes the small proportion recorded in the Fertiliser Survey.

Chalmers (2001) reported the proportion of each major crop receiving manure (Table 11). The organic matter gradually becomes available to future crops at a rate of 10% per year and displaces the need for some of the artificial fertiliser. If we assume that the target crop occurs every 4 years and that otherwise the crop is a winter cereal, then we can estimate the proportion of the manure nitrogen becoming available to the different crops as fertiliser:

$$N_c = (r_c U + 0.1 r_c G/(1-0.9^4))/H_c$$

$$N_w = (r_w U + 0.1 r_w G + \sum r_c G(1-0.1/(1-0.9^4)))/H_w$$

where N is the total nitrogen available as fertiliser to the crop (kg/ha)

subscript c is the crop other than winter cereals and w is winter cereals

U and G are the masses of manure nitrogen available nationally as UAN[(1)] (kg) and organic N (kg) respectively, (UAN[(1)] is the total of uric acid-N (from poultry manure) and total ammoniacal N (TAN) after storage and spreading losses have been accounted for.) U and G have values of 21128 t and 101981 t respectively.

r is the proportion of manure received,

H is the cropped area (ha),

Table 11 Proportions of cropped non-organic arable land receiving manure applications

Areas	Cropped areas in England, kha	Proportion receiving manure, %	Proportion of manure received, %	Plant available N, kg/ha
Potatoes	112	36	4.8	22
Winter cereals & OSR	2,596	12	37.0	16
Spring barley	291	23	8.0	14
Sugar beet	154	31	5.7	19
Forage maize	107	100	24.1	114
All other crops	673	26	20.4	15
Total arable area	3,932			

These values are reflected in the Fertiliser Survey by reductions in the amount of fertiliser applied. Chalmers showed that arable crop reductions are typically about 20 kg, which agrees with the above plant available N calculations. In terms of the LCA analysis this means that the 'normal' fertiliser level is the sum of the average from the survey and the value in the table. Forage maize values in the Fertiliser Survey show a very wide variation in rates from very low to 180 kg N/ha with a mean of 70. Thus the above result is not out of keeping with the values reported. The manure and hence animals are allocated the corresponding benefit.

The level of crop protection applied is taken from Pesticide Survey data (Garthwaite *et al.*, 2000-2004), cross referenced with data from commercial farms. The number of applications is taken as the number of doses applied to each crop and an average energy (and hence burden) was derived from Audsley *et al*. (1997).

2.2.5.1 Nutrient inputs in organic systems

The additional burdens of fertility building and cover cropping are summarised as a typical organic rotation in Table 12. Leys and cover crops increase land requirements, but provide the necessary plant nutrients. The data shows that the additional ploughing required for fertility building per cash crop is a factor of 1.25 times the non-organic crop and the additional land required is a factor of 1.525. Note that if the second clover crop was wholly or partly grazed or cut for silage, the land requirement would be lower but there would be fertility implications for the later crops in the rotation.

Table 12 Overheads of cultivation and land needs in organic crop production

Eight year stockless organic crop rotation on 1 ha	Establishment	Maintenance	Land for imported seeds, ha
Clover 1	Undersown	1 x Chain harrowing 1 x mowing	0.033
Clover 2	None	1 x Chain harrowing 1 x mowing	
Spring wheat/ potatoes	Plough based		
Forage rye	Plough based		0.033
Spring barley	Plough based		
Winter beans	Plough based		
Forage rye	Undersown		0.033
Spring oats	Plough based		
	TOTALS		
No of ploughings	5		
No of cash crops	4		
Total land use, ha	6.099		

Additional land is needed to grow seed for these crops. Rye has a typical gross yield (g) of 3.8 t/ha and the seeding rate (r) is 0.185 t/ha. So, the net land requirement for 1 t rye seed (s) is: $s = 1/(g - r)$ ha/t, or 0.277 ha/t. The seed used for forage rye is 0.16 t/ha and three crops are required (assuming the same yield for grass and clover). This is spread over four cash crops, so the seed area per ha of cash crop (a) is: $a = 0.277 * 0.16 * 3/4 = 0.033$ ha / ha and cash crop land requirements must be increased by 3.3% in addition to the ley land requirements (1 ha can supply 30 ha with seed). The establishment of grass leys in the non-organic sector was assumed to require the same land for seed production. With other seeds (*e.g.* mustard), the land requirement would still be similarly increased (and possibly with different burdens of producing the seeds).

For organic soya and maize production, the ratios are a little different, assuming the studies at Michigan State University are representative (Robertson *et al.*, 2000). In their case, no extra land was used for leys, but two winter legumes were planted for three cash crops, hence:

$$a = 0.277 * 0.185 * 2/3 = 0.034 \text{ ha / ha, or a total land inflation factor of } 3.4\%.$$

Composts are used extensively in the organic sector. The burdens of composting have two main sources: energy for collection and turning, and gases emitted during composting. A simplifying assumption was that no leaching takes place from manure heaps, but all N losses are gaseous. Energy and emissions were estimated (Table 13) using data from several sources including: UK inventories of ammonia, nitrous oxide and ammonia, the MANNER manure N support system, RB209 (MAFF, 2000) as well as Amon *et al.* (2001), Chambers (2004), Hellebrand and Kalk (2001), Hüther *et al.* (1997), Külling *et al.* (2001), Morand *et al.* (2005), Osada *et al.* (1997), Petersen *et al.* (1998), Pratt *et al.* (2002), Sneath *et al.* (2006), Sommer (2001) and Williams (1998).

Table 13 Burdens of composting residues

Item	Unit	Primary Energy, MJ	GWP_{100}, [kg CO_2 equiv.]	EP, [g PO_4^{3-} equiv.]	AP, [g SO_2 equiv.]	ARU, [g Sb equiv]	N_2O-N, to air, g
Imported compost (total FW basis & energy based only)	t	80	5.10	7.1	43	170	0.094
Compost-N (imported energy based only)	kg	8.6	0.55	0.76	4.6	18	0.010
Compost-P (imported energy based only)	kg	8.6	0.55	0.76	4.6	18	0.010
Compost-K (imported energy based only)	kg	8.6	0.55	0.76	4.6	18	0.010
Compost-S (imported energy based only)	kg	8.6	0.55	0.76	4.6	18	0.010
Cattle FYM composted - gases	kg N		4.40	68	300		3.6
Pig FYM composted - gases	kg N		1.30	570	2500		2.0
Poultry No litter FYM composted – gases	kg N		6.10	780	3400		11
Poultry With litter FYM composted – gases	kg N		4.40	620	2800		9.2

It is assumed that organic farms import compost annually into arable soils at a rate of 1.4 t/ha (Soil Association, 2003). In reality it will vary between farms, depending on the local availability, but we use the national average. The burdens of making and carrying compost (turning and transport) are debited against crops, while the fertiliser value is credited to the crop.

The N, P and K in ley and cover crops seeds must also be credited to the crop (Table 14). With other seeds (*e.g.* mustard), there are generally lower credits for N, P and K in the seeds owing to lower mass seeding rates. For the domestic rotations, rye seeds are applied twice at 0.16 t/ha and grass-clover seeds once at 0.025 t/ha for the benefit of four cash crops, thus averaging 0.086 t/ha per crop. The actual nutrient rates come from the composition with 86% DM, P and K at 0.5% of DM.

Table 14 Plant nutrient inputs from seeds of cover crops in organic rotations

Cover crop	Rye	Clover or legume for US soya and maize[1]	Grass [2]	Grass-clover ley (75% grass)	Grass-clover ley (50% grass)	Grass-clover ley (25% grass)
Composition						
Dry matter, %	87	86	86	86	86	86
Crude Protein, %	11.6	26	12	16	19	23
N, %	1.9	4.2	1.93	2.5	3.0	3.6
P, %	0.5	0.6	0.49	0.52	0.55	0.57
K, %	0.5	1.1	0.28	0.49	0.69	0.90

Seed application rate, kg/ha	160	200	25	25	25	25
No of seedings per rotation	2	2	1	1	1	1
No of cash crops per rotation	4	3	4	4	4	4
Application rate of nutrients, kg/ha cash crop						
N	1.29	4.77	0.10	0.13	0.16	0.19
P	0.35	0.69	0.026	0.028	0.029	0.031
K	0.35	1.26	0.015	0.026	0.037	0.048

1. Assumed same as peas
2. Assumed mean of rye, oats, barley and wheat (as in UK Tables on Feedingstuffs)

For the US soya and maize rotation, we assume that the seeds have the composition of peas and are sown twice at 0.2 t/ha for 3 cash crops. The same composition was assumed for clover seeds, and grass was assumed to have the same composition as the mean of major domestic cereals: wheat, barley, oats and rye. The calculations show that seeds for cover crops and the legume, used in the US are small relative to offtake, but should clearly be included. Those for grass-clover leys (and other cover crops with similar seeding rates) could be ignored without incurring great errors.

2.2.6 Grain storage

After harvest, most grain is cooled, dried and stored. Depending on the moisture content, the crop may need drying and will require input to cool the crop for storage. Grain from one month (harvest time) was assumed to be shipped from the farm and used directly, thus incurring no farm storage requirement. This it was assumed that 11/12ths of the grain was stored and, although some grain can be stored in large central facilities, this was considered to be inside the farm boundary. The building requirement was derived from the floor area needed m^2/t, $A = h/\rho$ where h is the height of a stack of grain (m) and ρ is the bulk density (t/m^3). The mean value of A is 0.41 m^2/t.

2.2.6.1 Grain drying

Grain crops are subject to moulding in storage if the grains are too moist, and so often need drying after harvest before they can be put in a store. Over the course of the harvest period the harvested moisture content will vary due to weather conditions. In a very good year, no grain will require drying. A safe moisture content is related to the equilibrium moisture content and, for cereals, a minimum of 86% dry matter (DM) content is typically required. Data on long term harvested grain DM came from the Broadbalk dataset (Figure 3). These were used to calculate the energy needed for grain drying. The drying requirements for other crops were calculated by relating their equilibrium moisture curves (Nellist, 1998) to that of wheat so that the same distribution data from Broadbalk could be used as a proxy for DM at harvesting. The results (Table 15), show that the energy needed for drying barley is similar to wheat, but considerably more is needed for rapeseed, beans and maize. Furthermore, weather clearly influences the drying requirement, with less being needed in the last 10 years. Given the changes in climate, we decided to use the 10 year dataset.

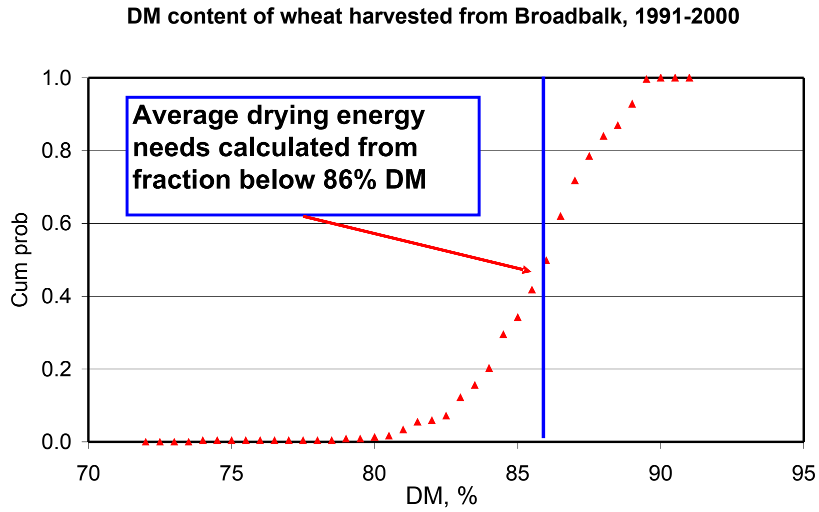

Figure 3 Cumulative probability of dry matter (DM) content of wheat harvested from Broadbalk plots at Rothamsted, 1991-2000

Table 15 Energy requirements for drying crops to achieve stable storage using three sets of data, MJ/t. Specific energy requirement for evaporating water was estimated to be 4.7 MJ/kg (McLean, 1989, Brooker *et al.*, 1993)

Years to 2001	Wheat	Barley	Rape	Beans	Maize
10	68	83	101	88	238
20	153	169	280	245	732
30	152	170	257	230	649

2.2.6.2 Grain cooling

In addition to drying and storage, some crops are cooled. Grains are cooled by ventilating with ambient air and an average value of 0.3 MJ/t was derived from data in McLean (1989) and Scotford *et al.* (1996).

2.2.7 Direct soil-crop emissions to air and water

2.2.7.1 Nitrate emissions to water

The effects of soil and rainfall on leaching (emission of nitrate to water) and denitrification (emissions of nitrogen to air) were established using the SUNDIAL simulation program from Rothamsted Research (Smith *et al.*, 1996). A range of non-organic and organic rotations were defined that contained representative crops. Simulations were run for long enough to ensure that the simulated rotations were in steady state, as indicated by the soil organic N (SON) fraction being the same at the start and end of a rotation. N inputs come from atmospheric deposition, fertiliser, fixing, seeds, returned roots, straw and haulm. N outputs come from primary crop offtake (grain, tubers), secondary crop offtake (straw), returned offtake (roots, straw and haulm), leached nitrate-N, denitrified-N and nitrogen from senescing leaves.

The rotations were simulated for nine combinations of soil type and rainfall (clay, loam and sandy soil with low, medium and high rainfall, in the context of arable crops). Crops were also grown with and without straw incorporation. Yields, which are an input to SUNDIAL, were taken from national averages or standard texts, scaled according soil type using relationships previously developed by Audsley (1981). The N fertiliser inputs for non-organic production were established from RB209 (MAFF, 2000) and use of the SUNDIAL (in the Fertiliser Recommendation System version). Individual crops were also simulated with N inputs increased or decreased by 20% from these standard values.

Rotations present interesting challenges in allocating the amount of N leached or denitrified to specific crops. The N leached is generally related to the N surplus left after a harvest, but the contributions to that surplus may have arisen from the immediate inputs of fertiliser to the crop or from mineralisation or fixation from several preceding crops. The leaching may also occur from a crop over several years in the future, albeit in diminishing amounts. The hypothesis that leaching is related to N surplus was tested at a rotational level by linearly relating the whole-rotation N-leaching to the whole-rotation N-surplus. This produced highly significant linear relationships, but these were often specific to soil or rainfall combinations and differed between rotations. Allocations were then derived for the individual crops within each rotation on the basis that the allocations should be in proportion to the surplus for each crop. The results of this analysis were combined to generate linear relationships for each crop from which denitrification or leaching could be reliably calculated for each soil-rain combination from the N surplus for that crop. These coefficients were used in conjunction with crop husbandry data to predict denitrification, leaching and senescence for any given input of N. For beans, it was concluded that denitrification and leaching losses were a constant for each combination of soil and rainfall.

For organically grown crops, an eight crop, six year stockless arable rotation was simulated with SUNDIAL, based on published data. This started with defining the crops and their typical current yields (Table 16). The crop yields (cereals, potatoes and winter beans) for these simulations were taken from Lampkin *et al.* and varied according to soil type. The initial assumption was made that these yields should be sustainable, using fixed N from a clover ley with beans in the 7th year, if it could provide sufficient N and not deplete soil reserves. Two variations of the rotations were examined in which wheat or potatoes were the principal cash crops, that is those grown after the clover ley. Preliminary runs were conducted to assess how well the rotation performed, which found that most crops could achieve their target yields, except for spring oats, which only yielded 3.0 t/ha, rather than the 3.8 t/ha that was forecast. Forage rye was used as a representative cover crop.

The N fixed was calculated by SUNDIAL as nominally 300 kg/ha over the 2 years of clover, with more fixed in the second year than first year. This was based on standard values from the literature, and agreed as a possible value with the Elm Farm Research Centre. Nitrogen fixation varies with total soil organic N: the higher this is, the less N is fixed, because more inorganic N will be available from mineralization. Total N fixed also varies with soil type. The actual values calculated by SUNDIAL for each combination of soil and rainfall type and rotation accounted for these factors.

The analysis of the outputs could not use exactly the same methods as with the non-organic rotations, because there was not a simple surplus that could be calculated for each crop (most N being fixed at the start by clover). There was also the question of how to allocate the N losses from the clover itself to a cash crop. Values for beans from non-organic rotations were used as that crop's offtake and N losses. The sum of all other losses from a rotation was then allocated to the remaining cash crops in proportion to the useful N offtake of each crop.

Table 16 Crops grown in stockless organic arable rotations that were analysed with the SUNDIAL simulation model

Crop	Yield t/ha			Sow date	Harvest date	Crop period, months
	Sand	Loam	Clay			
Clover 1	2.1	2.5	2.9	Oct Year 1	Feb Year 2	17
Clover 2	2.6	3.0	3.5	Mar Year 2	Feb Year 3	12
Spring wheat or Potatoes	4.3/ 26.6	4.5/ 28	4.7/ 29.4	Mar Year 3	Sept Year 3	7
Forage rye	4.5 -6.7	4.5 -7.0	4.0-7.4	Sept Year 3	Feb Year 4	5
Spring barley	3.3	3.5	3.7	Mar Year 4	Sept Year 4	7
Winter beans	3	3.5	4.0	Oct Year 4	Sept Year 5	12
Forage rye	4.8	5.0	5.3	Sept Year 5	Feb Year 5	5
Spring oats	2.9	3.0	3.2	Mar Year 6	Sept Year 6	7

The results of these analyses with SUNDIAL (Table 17) provided coefficients for linear equations in non-organic systems that predicted leaching and denitrification from crop type, N application rate, soil texture and rainfall. With organic systems, constants were estimated for each crop type, soil texture and rainfall combination.

Table 17 Summary of annual leaching and total denitrification for main crops as simulated with SUNDIAL under the standard (default) conditions of fertiliser application and cultivation methods for non-organic (N-org) **and organic (Org.) crop husbandry.**

		Leaching, kg NO_3-N/ha									
		Bread wheat		**Main potatoes**		**Spring barley**		**Field beans**		**WOSR**	
Soil	**Rain**	**N-org**	**Org**	**N-org**	**Org**	**N-org**	**Org**	**Org**	**N-org**	**Org**	**N-org**
Clay	Dry	37	59	25	43	17	43	18	18	32	47
Clay	Mid	41	78	29	60	22	54	30	30	36	59
Clay	Wet	46	91	30	80	14	58	40	40	42	63
Loam	Dry	39	47	31	33	15	36	14	14	40	39
Loam	Mid	43	63	32	46	14	45	25	25	39	50
Loam	Wet	46	74	32	61	13	50	34	34	43	55
Sand	Dry	60	69	42	58	21	47	38	38	54	53
Sand	Mid	60	79	41	62	19	49	42	42	52	55
Sand	Wet	62	88	35	69	16	53	47	47	64	58
		Total Denitrification, kg N/ha									
Clay	Dry	78	56	38	37	19	40	38	38	94	44
Clay	Mid	75	51	36	35	14	35	47	47	93	38
Clay	Wet	71	52	36	43	22	33	52	52	88	36
Loam	Dry	77	49	32	31	22	36	30	30	89	40
Loam	Mid	74	44	33	29	22	31	39	39	92	34
Loam	Wet	70	44	36	32	23	29	45	45	89	32
Sand	Dry	56	32	21	23	15	21	30	30	78	24
Sand	Mid	57	34	22	23	17	21	33	33	80	23
Sand	Wet	55	37	26	25	20	22	34	34	68	24

2.2.7.2 Denitrification to nitrous oxide (N_2O) using the IPCC methodology.

SUNDIAL calculates total denitrification, but the major species of concern is N_2O, given its great power in global warming. The IPCC method (IPCC, 1997), as reported in the UK GHG emission inventory (Baggott *et al.*, 2004) was largely adopted for land based emissions. It was assumed that all direct inputs of N into soil are associated with an emission of N_2O and each is associated with an emission factor. The following direct inputs are included:

1. Synthetic fertiliser
2. Biologically fixed nitrogen by legumes
3. Ploughed-in crop residues
4. Land spreading of organic fertilisers (animal manures, compost or sewage sludge)
5. Direct deposition of manures by grazing animals

In addition, two indirect emission sources are estimated:

1. Emission of N_2O from atmospheric deposition of N
2. Emission of N_2O from leaching of agricultural nitrate

Emissions of N_2O-N (kg/yr) from the application of synthetic fertiliser (O_{SN}) are given by:

$$O_{SN} = N_F(1-\lambda_e)\varepsilon_1$$

where N_F = total use of synthetic fertiliser (kg N/yr)
λ_e = fraction of synthetic fertiliser emitted as $NO_x + NH_3$
ε_1 = emission factor for direct soil emissions (0.0125 kg N_2O-N/kg N input)

Emissions of N_2O-N (kg/yr) from the biological fixation of nitrogen by crops (O_{BF}) are given by:

$$O_{BF} = 2Y_F\eta_F\varepsilon_1$$

where Y_F = production of legumes (kg dry mass/yr)
η_F = fraction of nitrogen in N fixing crop (0.03 kg N/ kg dry mass by default or actual value if known explicitly)

The factor of 2 converts the edible portion of the crop to the total biomass. The dry matter content for the crops considered is given in Table 18.

Table 18 Dry matter content and residue fraction of UK crops used for calculating N_2O emissions under IPCC

Crop Type	Dry matter content	Residue/Crop
Broad beans, green peas	0.08	1.1
Field bean, Peas(harvest dry)	0.86	1.1
Rye, mixed corn, triticale	0.855[a]	1.6
Wheat, oats	0.855[a]	1.3
Barley	0.855[a]	1.2
Oilseed rape, linseed	0.91[a]	1.2
Maize	0.50	1.0
Hops	0.20	1.2
Potatoes	0.20	0.4
Roots, onions	0.07	1.2
Brassicas	0.06	1.2
Sugar beet	0.1	0.2
Other	0.05	1.2
Phaseolus beans	0.08	1.2

a Defra (2002)

Emissions of N_2O-N (kg/yr) from ploughing in crop residues (O_{CR}) are given by:

$$O_{CR} = 2(Y_N\eta_N + Y_F\eta_F)(1-\lambda_R)\varepsilon_1$$

where Y_N = production of non-N fixing crops (kg dry mass/yr)
η_N = fraction of nitrogen in non-N fixing crops (0.015 kg N/ kg dry mass)
λ_R = fraction of crop that is removed from field as crop

Emissions of N_2O-N (kg/yr) from organic fertilisers (O_{OF}) are given by:

$$O_{OF} = \varepsilon_1\sum(N_m - N_v)$$

where N_m = total N in each type of organic fertiliser
N_v = N volatilised during storage and land spreading as N_2O-N or NH_3-N

Indirect emissions of N_2O-N (kg/yr) from the atmospheric deposition of ammonia and NO_x (O_{AD}) are estimated as:

$$O_{AD} = N_a\varepsilon_4$$

where N_a = total mass of nitrogen deposited annually (kg N/yr)
ε_4 = N deposition emission factor (0.01 kg N_2O-N/kg N_a)

Unlike IPCC, this includes all N deposited on agricultural land irrespective of its source. The estimate includes a correction to avoid double counting N_2O emitted from synthetic fertiliser use.

Indirect emissions of N_2O-N (kg/yr) from leaching (O_{LN}) are estimated as:

$$O_{LN} = N_L \varepsilon_5$$

where N_L = leached N (kg NO_3/yr), calculated explicitly.
ε_5 = N leaching/runoff factor (0.025 kg N_2O-N /kg $N_{(L)}$)

2.2.7.3 Methane oxidation by soil

A credit arises from agricultural land due to methane oxidation by methanotrophic soil bacteria. A value of 0.65 kg CH_4 ha^{-1} $year^{-1}$ for all non-organic land was established after an extensive examination of the literature (Ball *et al.* (1999), Ball *et al.* (2002), Boeckx and Van Cleemput (2001), Bronson and Mosier (1994), Dobbie *et al.* (1996), Dobbie and Smith (1996), Flessa *et al.* (1998), Freney (1997), Freibauer (2003), Goulding *et al.* (1995), Goulding *et al.* (1996), Goulding *et al.* (1998), Hutsch *et al.* (1993), Hutsch (1996), Jarvis *et al.* (1994), Mosier *et al.* (1991), Powlson *et al.* (1997), Prieme *et al.* (1997), Smith *et al.* (2000), Smith *et al.* (2003), Willison (1995), Willison (1995) and Willison *et al.* (1996)). This was arbitrarily increased by 25% for organic land on the basis that N fertiliser is not used and some work has shown inhibition of methane oxidation from this. The field evidence for more methane oxidation in organic soil was not, however, found in the literature. The extra land used for grass-clover leys in organic arable crop production is also credited with methane oxidation capacity.

2.3 *Oilseed rape production*

Oilseed rape is grown in a generally similar way to bread wheat. The main differences between the systems are listed in Table 19.

Table 19 The main features of the crop cultivation methods of principal crops studied for non-organic (N-org) **and organic (Org.) systems**

	Bread wheat		**Oilseed rape**		**Potatoes maincrop**		**Potatoes first earlies**		**Potatoes second earlies**	
	N-org	**Org**	**N-org**	**Org**	**N-org**	**Org**	**N-org**	**Org**	**N-org**	**Org**
Gross yield, t/ha	7.1	4.1	3.3	1.9	49.4	32.3	26.3	19.4	43.1	30.2
N fertiliser (synthetic), kg/ha	208	0	195	0	170	0	170	0	150	0
P fertiliser, kg/ha	18	10	18	8	110	9	10	4	17	9
K fertiliser, kg/ha	36	41	26	10	225	140	114	75	195	129
Straw/haulm incorporation, %	75	5	100	100	100	100	100	100	100	100
Seed bed preparation:										
Plough based, %	57	100	50	90	100	100	100	100	100	100
Reduced tillage, %	41	0	45	0	0	0	0	0	0	0
Direct drilling, %	2	0	5	10	0	0	0	0	0	0
Spraying:										
Active ingredients per ha	14.7	0	14.4	0	21.2	2.0	14.8	2.0	21.2	2.0
Passes per ha	5.6	0	10.6	0	12.0	2.0	8.4	2.0	12.0	2.0

The yield–nitrogen curve of each crop was modified so that the optimum fertiliser rate was equal to the fertiliser rate from the Fertiliser Survey and gave the national average yield. The resulting parameters are given in Table 20. The main differences in husbandry are that seed is more often sown by broadcasting, rather than drilling and that very little straw is harvested. An organic crop was modelled, although almost none is grown. It must be acknowledged that the comparison is thus highly speculative as there are very few data relating to organic oilseed rape. The crop parameters used were essentially scaled by the ratios of organic to non-organic wheat.

Table 20 Parameters for yield of crops versus nitrogen application

Crop	a	b	c	D	Nitrogen
Oilseed rape	203.55	-203.03	0.000614	-0.104	200
Winter barley	412.35	-411.29	0.000784	-0.270	154
Spring barley	360.07	-359.14	0.00103	-0.311	110
Potatoes-main	3061.4	-3053.5	0.000670	-1.713	220
Potatoes-1st	1628.3	-1624.1	0.000832	-1.131	170
Potatoes-2nd	2735.9	2728.9	0.000725	-1.656	200

2.4 *Potato production*

There are three main types of potato grown: maincrop, first earlies and second earlies. The main differences between the potato systems and bread wheat are listed in Table 19. The yield-nitrogen curve of each crop was modified so that the optimum fertiliser rate was equal to the fertiliser rate from the Fertiliser Survey and gave the national average yield. The resulting parameters are given in Table 20.

Earlies differ systematically from maincrop in that the crop is not stored. Yields of first earlies are about half of maincrop, while those of second earlies are about 90% of maincrop. Organic production is similar to non-organic and this is the only field crop upon which pesticides are sprayed, that is copper based products for blight control.

Potatoes tend to be grown on lighter land than cereals. Crop establishment requires deep ploughing and additional operations to destone and or ridge the crop. Harvesting inevitably requires much work to be done on soil, so it is energy intensive.

Potatoes are often irrigated, with the amount depending on the weather and soil type. Maincrop potatoes tend to need more irrigation than first earlies, which may be harvested before the summer soil water deficit sets in. A relationship for yield in terms of proportion of the area irrigated was developed. Weatherhead (1997) studied yield and water use on medium available water content (AWC) soil in the fens and showed a 25% increase where irrigation was used. Assume yield, Y increases linearly with the proportion of crops using irrigation, then

$$Y(\mu) = ((\gamma_{100} - 1)\mu + 1)Y(0)$$

where γ_{100} is the yield increase at 100% irrigation, for example 1.25

μ is the proportion of potatoes irrigated.

The current yield, Y_m and current level of irrigation μ_m is known, thus

$$Y_m = ((\gamma_{100} - 1)\mu_m + 1)Y(0)$$

Substituting for Y(0), the yield at any level of irrigation, μ, is:

$$Y(\mu) = \frac{((\gamma_{100} - 1)\mu + 1)Y_m}{((\gamma_{100} - 1)\mu_m + 1)}$$

A summary of irrigation activity (Table 21) was derived from commercial farm practice and survey data Weatherhead *et al.* (1997, 2002). The increase in yield by irrigation was derived from Weatherhead (1997) using 20 year data of yield and water use on medium AWC soil in the fens. This showed that irrigation increased yield by 25% for maincrop potatoes. In the absence of other data, this value was also used for earlies. Long term yield data were obtained from Defra, being 19.1 t/ha for earlies and 43.5 t/ha for maincrop. Care is needed in dealing with the early potato yields as the Defra statistics do not discriminate between 1st and 2nd earlies. Nix (2004, 2005) suggests yields of 44, 20 and 42 t/ha for main, 1st and 2nd earlies respectively, which are used.

Table 21 Mean irrigation rates, the proportions irrigated, the response to the proportion irrigated and the average yield of potato growing areas in England. (Numbers in brackets are % Coefficient of Variation)

Type of potato	Application rate, mm/year	Proportion irrigated, %	γ_{100}	Y_m
First earlies	90 (18)	40 (11)	1.25	19 (21)
Second earlies	105	48	1.25	42
Maincrop	120 (23)	56 (24)	1.25	44 (4)

Maincrop potatoes may be stored for over a year (*e.g.* Defra Statistics: http://statistics.defra.gov.uk/esg/publications/auk/2004/6-11.xls). While the domestic market for maincrop potatoes falls in the spring, some are stored for processing (chips, crisps *etc*). Most potatoes are stored in temperature controlled environments, some using just ambient ventilation, while others use refrigeration. A small proportion is stored in clamps. The distribution of store types was found from the Pesticide Usage Survey (Anderson *et al.*, 2002).

Reported values for the specific energy needs for cooling potatoes range from 63 MJ/t as electricity for ambient cooling (Anon, 1999) to refrigerated stores at 700 MJ/t (Beukema and van der Zaag, 1990). Two crucial parts of the overall estimate are how long the storage phase lasts and how full a store is. If all stores are emptied gradually, the efficiency of cooling will fall with time. An ideal approach is to empty stores in sequence so that whole stores can be switched off in turn. The actuality must lie between these extremes, and this was modelled, together with data on the distribution of store types. Using the data sources above plus commercial practice (from this project), Bishop and Maunder (1980) and British Potato Council Monthly Data, a set of values was estimated (Table 22). This included an assumption that 10% of organic maincrop is sold directly (*e.g.* vegetable boxes and farm shops). This would probably not remain valid if the organic method became the main production system rather than the niche it currently occupies, so the cooling energy was scaled in proportion to the level of organic production so that the energy demand became the same for 100% organic and non-organic.

Table 22 Energy consumption during potato storage

Item	National Total - for non-organic, %	Organic (estimated), %	Building, MJ (as primary energy)	Electricity (as primary energy), MJ	Weighted primary use, non-organic, MJ	Weighted primary use, organic, MJ
Outdoor clamps	0.2	0.7			0.0	0.0
Unventilated building	2.7	9.3	11		0.3	1.0
Ventilated building	35.8	33.2	11	224	84	78
Refrigerated building	61.3	56.8	11	929	576	534
Total	100.0	100.0			**661**	**613**

2.5 *Animal feed crop production*

Six feed crops are modelled as they are major components of animal feeds. In two cases (maize grain and soya), production is overseas. In these cases, production was modelled as closely as possible using local techniques, but transport burdens for importing were also included.

Table 23 The main features of crop cultivation methods for the feed crops studied

	Feed Wheat	Winter Barley	Spring Barley	Field Beans	Soya Beans	Maize Grain	Maize Silage

	N-org	Org	N-org	Org	N-org	Org	N-org	Org	N-org	Org	N-org	Org	N-org	Org
Gross Yield, t/ha	8.0	4.6	6.5	3.8	5.7	3.1	3.5	3.3	2.6	2.6	7.2	4.0	11.2	7.5
N fertiliser (synthetic), kg/ha	192	0	150	0	110	0	0	0	0	0	120	0	100	0
P fertiliser, kg/ha	20	11	21	11	19	9	12	13	10	11	19	7	30	19
K fertiliser, kg/ha	41	43	56	46	60	44	32	28	40	38	54	6	138	92
Straw/haulm incorporation, %	75	5	15	0	0	0	100	100	100	100	100	100	0	0
Seed bed preparation														
Sub-soiling	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	.20	0.20	0.20	0.20
Plough based, %	57	100	57	100	57	100	57	100	27	100	30	100	57	100
Reduced tillage, %	41	0	41	0	41	0	43	0	53	0	58	0	41	0
Direct drilling, %	2	0	2	0	2	0	0	0	20	0	12	0	2	0
Spraying														
Active ingredients per ha	14.7	0	14.2	0	8.1	0	10.0	0	10.6	0	2.8	0	2.5	0
Passes per ha	5.6	0	4.9	0	4.9	0	6.1	0	6.5	0	7.8	0	7.5	0

2.5.1 Feed wheat production

Feed wheat was modelled as bread wheat, except that higher yielding lower protein varieties were used. The details are shown in Table 23.

2.5.2 Barley production

Barley was modelled as bread wheat, but using appropriate parameter values for both winter and spring varieties of barley. About 70% winter barley is used for feeds and 30% of spring (the remainder being used for malting).

2.5.3 Field bean production

Field beans were modelled on wheat, but with notable differences. Crop establishment does not include direct drilling, but broadcasting followed by ploughing is the norm (to set seeds deeper than is necessary for cereals). No N fertiliser is used, beans being leguminous. The only real difference between organic and non-organic is that pesticides are not used in organic production. The yields of organic beans are normally similar to non-organic ones, but the decision was taken to increase land requirements in the same way as wheat or potatoes for the grass-clover ley. While beans do not need the ley, they are grown with it as part of a whole system. Land requirements of the other arable crops would have had to have been increased yet more.

2.5.4 Soya bean production

Soya beans were modelled in a similar way to field beans, except that direct drilling and reduced cultivation is practiced extensively on this crop. The main imports are from the USA, Brazil and Argentina. The proportions of crop establishment methods were estimated using data from the National Agriculture Statistics Service of the US Department of Agriculture (http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/#field), the European Conservation Agriculture Federation (ECAF), (http://www.ecaf.org/). Reduced tillage and direct drilling are used much more widely in the Americas than here, although much of the motivation is for water retention rather than energy saving. The summary is shown in Table 24.

Table 24 Distribution of cultivation methods used for soya and maize grown overseas

	Source of imports, %	Plough, %	Reduced tillage, %	Direct Drilling, %
Soya				
USA	70	30	58	12
Brazil	20	23	45	32
Argentina	10	16	33	51
Weighted tillage types for soya		**27**	**53**	**20**
Maize for grain (all from USA)		**30**	**58**	**12**

Yields and fertiliser requirements were obtained from USDA, Benton Jones (2003) and Michigan State University (Robertson *et al.* 2000, plus supplementary data from the university web site). Transport burdens were based on the ocean travel distances, together with assumptions about a split of internal transport in the producing countries and in Britain (Table 25).

Table 25 Distances transported (km) and methods of calculating burdens for imported feeds.

Feed	Country	Road	Rail	Ship	Proportion of soya imports
Soya, Maize	USA	300	1,000	5,120	70%
Soya (Organic from here only)	Brazil	300	1,000	8,320	20%
Soya	Argentina	300	500	10,080	10%
	Weighted mean	**300**	**1,080**	**7,478**	

2.5.5 Maize grain production

Almost all maize grain used in the UK comes from the USA. Crop production and yield data were obtained from the same sources as for soya.

2.5.6 Maize silage production

Forage maize is grown to ensile and use as cattle feed. It is grown like other arable crops, although a forage harvester is used and manure applications are normally included in the fertilisation regime. Data on crop composition and fertilisation needs were taken from Wilkinson *et al.* (1999), with the crop nutritional needs being based on manure-free soil.

2.6 *Grassland production*

Table 26 shows how various operations were combined into systems of work for grassland management. The extra field operations of rolling and forage harvesting or rolling, cutting, swathing and baling were added to calculate the burdens.

Table 26 Field operations used in grassland production systems

	Grassland agronomy	Grassland agronomy -Upland	Grass Land agronomy	Grassland harvesting	Grassland establishment	Grassland establishment	Grassland establishment	Organic grassland establishment	Organic grassland establishment	Organic grassland establishment
Seedbed cultivation Plough based - Clay					0.5			0.5		
Seedbed cultivation Plough based - Loam						0.5			0.5	0.5
Seedbed cultivation Plough based - Sand							0.5			
Seedbed cultivation Reduced tillage - Clay					0.4			0.4		
Seedbed cultivation Reduced tillage - Loam						0.4			0.4	0.4
Seedbed cultivation Reduced tillage - Sand							0.4			
Seedbed cultivation Direct drilling - Clay					0.1			0.1		
Seedbed cultivation Direct drilling - Loam						0.1			0.1	0.1

Seedbed cultivation Direct drilling - Sand							0.1			
Grass seeds (at 25 kg/ha seeding rate)					1	1	1	1	1	1
Spraying for herbicide					1	1	1			
Fertilisation	4	2			1	1	1			
Liming (once) default rate is 1/7 years					1	1	1	1	1	1
Chain harrowing	1		1							
Grass roller	1		1		1	1	1	1	1	1
Mower – conditioner				1						
Rake				1						
Forage harvesting				1						

2.6.1 Grass yield and nitrogen model

Grass yield was modelled using the grass site class system (Brockman and Gwynn, 1988). The dry matter (DM) yield (t/ha) of grass (Y_{GDM}) was related to site class (S) and N fertiliser applied (N_F, kg/ha) by regression to obtain the following expression for grazed pastures:

$$Y_{GDM} = \frac{c_S - a}{k} \ln(1 + b \cdot e^{-k(N-N_m)})$$

where c_S is a fitted parameter for each site class

$$a = 0.01485 + 0.00112c_S$$
$$k = e^{(-5.302+0.594S)}$$
b=1.5
$$N_m = 296/(1+e^{-0.836(c_S-5.15)})$$

The optimum nitrogen application (N_{opt}) for a ratio (r) of (price of grass):(cost of nitrogen) is given by:

$$N_{opt} = N_m - \ln\left[\frac{1}{b((a \cdot r)-1)}\right]/k$$

where typically r=100. The values for N_{opt} in each site class are shown in Table 27, together with the fitted parameter c_s..

Table 27 Parameter values for c_s and calculated values of N_{opt}

Site class, S	c_S	N_{opt}
7 (rough grazing)	2.00	12
6	7.55	263
5	8.40	285
4	9.52	304
3	10.55	324
2	11.81	356
1	13.51	417

In a grazing system, in addition to applied fertiliser, nitrogen is applied to the crop by the animals' excreta. This causes the organic matter to build up and cycle round the system to become available to both the crop and loss processes to air and water. In addition the sward may include clover which fixes nitrogen. The resulting system can be described by a system of equations which can be solved for a steady state.

The total nitrogen available annually to the grass crop is:

$$N_a = N_{atm} + N_c + N_f + N_s + N_e ,$$

where N_{atm} is the atmospheric nitrogen, which typically ranges from 15-35 kgN/ha,

N_c is the nitrogen fixed by the clover percentage C, which was derived from NCYCLE (Scholefield *et al*, 1991)

where $N_c = 8.6\ Cc_S / c_1$

$$C = 41.36 - 0.0128 N_f - 0.0482 N_a \quad \text{if grazed}$$

$$C = 28.2 - 0.1072 N_f \quad \text{if cut for silage}$$

N_f is the fertiliser nitrogen applied, which in a non-organic system is defined as the amount that makes the nitrogen available without atmospheric nitrogen, equal to the economic optimum. In the organic system it is zero.

N_s is the nitrogen surplus not leached or denitrified over the winter.

N_e is the nitrogen in grazed animal excrement which is not lost.

The nitrogen content of the grass is a function of the nitrogen available

$$g_N = 20.14 + 0.0136(N_a - N_{atm})$$

thus, the total nitrogen taken up by the crop is $g_N Y_{GDM}$. The balance is thus at risk of loss to air and water.

The proportion emitted to air and water is given (Sandars, 2003) by 0.45+0.08 I, where I is the soil index and the balance is N_s remains available to the crop. The proportion of this leached is 0.965-0.13 I and the balance is denitrified. This was partitioned into N_2O-N and N_2-N using the Bouwman equation for N_2O (Bouwman, 1996).

When grazing, 20% of the dry matter yield is assumed to be spoilt by trampling and defoliation and thus unavailable for consumption by the animal and returned as organic matter to the soil.

When grazing, an animal utilises on average u% of the nitrogen content and the balance is excreted. (u=5.9% for sheep, 9.6% for beef and 24% for cows). Of the excreted proportion, 70% is urine and 10% of the dung is soluble. Of this soluble N, 15% is volatised as ammonia and the balance of the N excreted becomes available over time as part of the total N available to the crop, N_e.

This system of equations is solved (iteratively) for N_a and the resulting N_f were found to be comparable with typical values of fertiliser application.

The default sources of fertility for grassland are, in the non-organic case ammonium nitrate (AN) as N, triple super phosphate as P, K fertiliser as K. In the organic case we assume that the equivalents are Clover N, Tunisian Rock P containing 25% phosphate, Rock K as K. The corresponding utilisation factors for phosphate and potash, for all classes of stock, are 0.33 and 0.1, respectively.

2.6.1.1 Calculation of sward types

A sward type, such as lowland dairy grazing, is a composite of different grass growth site classes. For each 5 km grid square in England and Wales, the percentage of each soil type is known (NSRI database) and the percentage of the land of each land use types is known (MAGIC database). Soils are classified as potentially arable, potentially grassland or unsuitable. Uses are allocated to known soil types as far as possible, with sandy soils given priority for arable, then the unsatisfied uses are allocated pro-rata to the remaining soil. Thus the area of grassland in each grid is associated with a number of soils.

Using the table of site classes (Brockman, 1995), each soil is defined as a site class based on the soil type, rainfall and altitude. Allowance is also made for northerly soils such that at the Scottish border 1 is added to the site class. The soil is also classified as lowland or upland.

The final report on Defra project IS0209 (Morris *et al*., 2005) identified the area of land used by dairy, beef and sheep in the lowlands and uplands. Using these data, dairy land was identified as the 'grass not heath' of site classes 1 to 3. Beef was then allocated to all remaining land in site classes 1-5, in the lowland and upland proportions identified by the report. Sheep was allocated similarly, but also included site class 6. The resulting total areas of land closely matched the total areas from the June census (Defra, 2004) and the report's land allocations. Regionally, the method seemed to predict too good a site class in the East and particularly South-East, for the number of animals in the census, so an additional rainfall requirement was imposed on land in the east ofthe country.

2.7 *Crop by-products and feed processing*

The main domestic by-product is straw for bedding (mainly wheat) and feed (mainly barley). Burdens for these were derived by economic allocation from the grain production burdens. Major feeds are also produced from oil-bearing crops (*e.g.* rape, soya and maize) and cereals (*e.g.* fractions of milled wheat). Much animal feed is processed in mills, with the rest being home fed, with little processing, except for crushing. Values for general feed processing on farms and in mills (rolling, flaking, pelleting etc) were derived from UKASTA data and the Ecoinvent database (Table 28).

Table 28 Energy consumption in general feed processing (not including oil extraction)

Type of feed	Primary energy, GJ/t
All feeds at mills	0.70
Domestic cereals ground on farms	0.30
Peas and beans ground on farms	0.45

Milled feeds are also transported from the point of production to the mill and out to the receiving farms. For pigs and poultry, an eastern dominance was assumed with a mean 150 km back to farms, while for cattle and sheep, a western dominance was assumed with a mean of 250 km to farms (by large lorries). Delivery to the mills was assumed to be a mean of 100 km for wheat and barley and 260 km for rape (Elsayed *et al*., 2003).

Imports of soya and maize come from several sources, with a mixture of methods (Table 25). These were weighted by the distribution of country of origin.

2.7.1 Wheatfeed

Milling wheat produces the desired main product of flour and a variety of products that can be used for animal feed: collectively wheat offals or wheatings or wheatfeed or varieties thereof. We use the term wheatfeed as it is used in the Defra feed statistics. The allocation used was by economic value. Data on the composition of milled fractions came from INABIM (1979) and Pomeranz (1988).

2.7.2 Maize partitioning

Maize grain can be split into starch, oil, gluten and minor components. Maize gluten is a major feed for cattle and is used for some other stock and is what we import. Other products from maize processing are used for feeds in the US, but these are often wet and are not suitable for export. The processing is much more intense than mere milling and involves screening, milling, steeping, centrifugation and drying stages. The main alternative products are maize starch and oil. Cederberg (1998) provided two sets of values for the partitioning of maize and the energy used (Table 29). It seems reasonable to set the gluten feed fraction as 22% of maize grain. Economic value is used in allocating the burdens.

Table 29 Mass fractions of maize during fractionation to produce maize gluten feed

Item	Source 1	Source 2

Starch	63%	61%
Maize gluten feed (22% CP)	20%	24%
Maize gluten meal (60% CP)	5%	9%
Germ meal	7%	7%
Total accounted for	95%	100%

2.7.3 Rape meal

Rapeseeds are converted into oil and meal residue, using crushing and solvent extraction. There is also a little wastage. Data on mass partitions, process energy and solvent requirements came from Elsayed *et al.* (2003). As far as we know, rape meal is not used as an organic feed.

2.7.4 Soya meal

As with rape seeds, soya beans are also split into oil, meal and a little wastage, but the hulls can also be extracted separately. Crushing and solvent extraction are also used. Allocation was also economic, using values for partitioning and prices from Cederberg (1998), Wolf and Cowan (1979) [cited by Cederberg (1998)] and some extrapolation of the extraction methodology from Elsayed *et al.* (2003). A major difference between soya and rape fractionation is that the soya meal is much more valuable that rape mean, given its very good amino acid profile and high protein concentration. Only whole soya beans are used in organic feed. It was also assumed that meal with hulls was fed to ruminants while pigs and poultry received meal without hulls.

2.8 *Tomato production*

Tomatoes require a similar set of activities to field crops, but also require heating to extend the growing season. They also need the greenhouse itself, support materials (twine and hooks) and a growing medium, *e.g.* rockwool, nutrient film or soil. Another major difference is that much more human labour is used in crop establishment, pesticide application and harvesting, so diesel use is much lower.

Some of the principles described for field crops apply to organic tomatoes, for example synthetic fertilisers and pesticides are not used for organic tomato production and soil is used. Biological pest control is used in both sectors. Nitrogen fertility is supplied from manure based products. Some materials are not used in organic production, for example twine is made from jute rather than the fossil-fuel derived polypropylene.

2.8.1 Features of protected cropping

Tomato production differs from arable cropping in that it takes place in the protected environment of glasshouses. This extends the cropping season from an unprotected one of July to October up to March to October-November. This provides a fresh salad crop for much more of the year than was previously possible and so enhances the national diet and reduces our dependency on importing alternatives. Protected cropping allows biological control of pests to be reliably deployed, so reducing the use ofsynthetic pesticides.

Glasshouses for long-season tomato production are heated and ventilated with the aim of providing an optimum microclimate for fruits to develop. Heating is most commonly by gas-fired boilers. The heat raises the temperature so that photosynthesis and hence fruit production is accelerated. Furthermore, the exhaust gas is chemically clean, containing mainly N_2, O_2, CO_2 and H_2O. The CO_2 in exhaust gas can also be fed into glasshouses to enhance photosynthesis. Modern glasshouses use a variety of control systems to optimise heat and CO_2 from boilers. Much CO_2 is thus fixed as biomass during the growing season, but this is relatively temporary and is emitted to the atmosphere following digestion by humans and disposal of residues by composting *etc*. There is also an increasing trend to replace heating from gas-fired boilers by combined heat and power generation from gas, so that electricity is produced as well as heat and CO_2. This applies to all production systems. Glasshouse production is a high input-high output system, with much higher yields per ha than from field crops, so having considerably lower land requirements.

2.8.2 Physical structure

The burdens of producing the structures of the glasshouse must be included in the analysis. The main parts are the house itself, including glass, metal frames (typically aluminium), steel boiler, possibly a generator and heating pipes; concrete for foundation, passageways etc., plastic pipes and pumps for irrigation; metal motors and links for ventilation control. These have a relatively long life span and are written off over 10 to 30 years. Other components are brought in every 1-2 years, including steel supporting hooks, supporting twine plastic sheeting, rockwool, synthetic fertilisers, pesticides and composts.

2.8.3 Tomato production systems and products

There are three main tomato production systems, two non-organic and organic, and several marketed products, which contribute to the national basket of tomatoes. The main non-organic system uses rockwool as the growing medium (94.4%) and the rest use the nutrient film technique (NFT). Both non-organic systems supply nutrients and water in a closely controlled way so that supply matches demand as exactly as possible. This eliminates leaching losses and, as long as nutrient solutions are aerobic, denitrification to N_2O should be minimised. The third system is organic, which uses soil-based production with nutrients from composted manure and other residues. The soil water relationships can be closely controlled (unlike with field crops) so that leaching and denitrification losses should be lower than from field crops.

2.8.4 Physical, chemical an biological inputs

The main glasshouse structure is the same for all production systems, but organic ones have soil, which must be cultivated and is periodically disinfected with steam to prevent disease build up. Rockwool is usually disposed of annually. Organic producers use less disposable plastic than non-organic producers do, for example twine is from imported jute rather than polypropylene. All systems use biological control, but synthetic pesticides are used in the non-organic sector and surfactants that act physically are also used in the organic sector. There is great commercial secrecy about the production of biological control agents, so that the burdens of their production are somewhat speculative. Tomatoes are required for their production, so we inflated tomato production burdens by 0.5% and included transport requirements. All systems use bees for pollination.

Tomato products can be divided in several ways, which we have simplified a little. The main type is the classic tomato, with the rest being collectively "specialist". The specialist types include: cocktail, cherry, plum (mini, midi and maxi) and beef. Any tomato may be loose or on the vine, although beef seem to be only produced loose. Beef tomatoes have similar yields to classic so that they are subsequently grouped with classic rather than the other specialist varieties. Similarly, any tomato type could be produced organically, although the current market composition is biased more towards specialist and vine types.

2.8.5 Productivity of tomato types

A critical feature of the LCA analysis is that the inputs of heat, electricity and fertilisation for each system are about the same per ha irrespective of the product grown. The yields of the tomato types differ substantially. Organic production yields about 75% of non-organic, but there is negligible difference in productivity between NFT and rockwool. The current weighted mean of specialist tomatoes yield about 50% of classic tomatoes while vine tomatoes yield about 42% of their loose equivalents. The land area required per t of the main tomato types consequently varies considerably (Table 30). Given that the main burdens for each type are related to the area-based inputs, this has a strong influence on the burdens of production.

Table 30 Land needed to grow tomato of different types of tomato, m^2/t

Product	Non-organic	Organic
Classic loose	19	25
Specialist loose	38	51
Classic vine	45	61
Specialist vine	92	122

2.9 *Buildings and machinery*

2.9.1 Machinery

Tractors, implements and other machinery are manufactured (mainly from steel and plastic), maintained and housed. The burdens of these were calculated over the typical life time of implement and tractor combinations. These depend on work rates and machinery longevity. The analysis used the method of Audsley *et al*. (1997), with data from that study, supplemented by data gathered in the present study. As with the energy input to operations, in terms of the burdens of making and maintaining machinery, operations are independent of tractor power.

Weights of tractors, ploughs and sub-soilers were found from manufacturers' data and were fitted to linear equations as:

$$W_2 = 15.2P + 2540$$
$$W_4 = 71.5P - 1420$$

where W_2 and W_4 are the weights of two and four wheeled tractors (kg) and P is the engine power in kW and:

$$W_p = 401\eta - 629$$
$$W_s = 281\eta - 24.9$$

where Wp and Ws and the weights of ploughs and sub soilers (kg) and η is the number of furrows or legs. Maximum power available from a PTO shaft (P_{max}) was related to engine power (P_e) by:

$$P_{max} = P_e\,(0.000421\,P_e + 0.735)$$

The main characteristics derived from Audsley *et al.* (1997) and using the above relationships were evaluated to give the lifespan of machinery as well as the energy needed for manufacturing, maintenance and housing (Table 31 and Table 32).

Table 31 Main characteristics of typical tractors and self-propelled machinery

Machine	Engine power, kW	Machine mass, kg	Service life, years	Units	Rate of utilisation unit/yr	Proportion of life per unit of use, %	Total primary energy for manufacturing and housing per unit of life of item, MJ
75 kW Tractor (2 WD)	75	3,680	10	h	1,000	0.010%	59
75 kW Tractor (4 WD)	75	3,940	10	h	900	0.011%	60
150 kW Tractor (4 WD)	150	9,300	10	h	700	0.014%	182
300 kW Tractor (4 WD)	300	20,000	10	h	700	0.014%	392
Combine harvester with straw chopping	150	11,500	7	ha	600	0.024%	350
Combine harvester without straw chopping	150	11,500	7	ha	600	0.024%	346
Forage harvester per ha	370	11,900	5	ha	1,818	0.011%	165
Sprayer, self propelled	114	10,300	7	ha	3,500	0.004%	53
Fore end loader, self propelled	75	4,440	7	h	1,825	0.008%	44
Potato harvester	200	4000	5	ha	500	0.007%	33
Front loader (potato harvest loading)	100	6229	5	h	1,830	0.022%	172

Table 32 Main characteristics of typical trailed and powered machinery

Machine	Machine	Service	Units	Rate of	Proportion of	Total primary energy

	mass, kg	life, years		utilisation, unit/yr	life per unit of use, %	for manufacturing and housing per unit of life of item, MJ
5 furrow plough	1,380	10	ha	83	0.120%	96
7 furrow plough	2,180	10	ha	167	0.060%	109
Subsoiler, 3 legs for tramlines	818	10	ha	500	0.020%	19
Subsoiler, 7 legs for normal cultivation	1,940	10	ha	500	0.020%	45
Heavy discs 5.5 m width	4,580	10	ha	500	0.020%	107
Light discs 5.5 m width	4,500	10	ha	500	0.020%	105
Disc & pack 5.5 m width	4,750	10	ha	500	0.020%	111
Power harrow, 4 m	2,250	4	ha	431	0.020%	52
Power harrow & packer, 4 m	2,500	4	ha	431	0.020%	58
Seedbed conditioner 6 m	1,130	10	ha	500	0.020%	26
Inter-row cultivator 6 m	1,130	10	ha	500	0.020%	26
Spring tine harrows 6 m	1,130	10	ha	500	0.020%	26
Other light cultivations 6 m	1,130	10	ha	500	0.020%	26
Cambridge rolls, 6 m	3,180	15	ha	500	0.020%	75
Rotary cultivator 4 m	1,300	7	ha	200	0.071%	108
Conventional drill 6 m	1,200	5	ha	1,000	0.020%	28
Direct drill 6 m	1,800	5	ha	1,000	0.020%	42
Combined harrow/drill 6 m	4,580	5	ha	1,000	0.020%	106
Mounted crop sprayer 24 m	1,000	7	ha	2,000	0.007%	7.6
Disk fertiliser broadcaster 12 m	200	7	ha	1,000	0.014%	3.1
Lime spreader	1,300	5	ha	1,000	0.020%	30
Baler	1,800	7	bales	1,500	0.010%	20
Potato planter	2,250	7	ha	500	0.020%	52
Potato ridger	1,130	7	ha	500	0.010%	13
Potato destoner	1,300	7	ha	500	0.029%	43
Straw chopper on combine	150	7	ha	600	0.024%	3.9
Mower, 6 m	1,290	7	ha	1,000	0.014%	20
Mower - conditioner, 6 m	1,970	7	ha	1,000	0.014%	30
Tedder 6 m	700	7	ha	2,000	0.007%	5.8
Rake 12 m	700	7	ha	1,000	0.014%	12
Transport as MJ t^{-1} ha^{-1}	30	7	ha	500	0.029%	1.0
Irrigator (fuel per mm applied)	1,000	7	m^3	22,900	0.046%	58

2.9.2 Buildings

The burdens of a representative set of farm buildings were derived from the typical material composition of building components, including steel, glass, concrete, insulation, wood plus energy for construction, demolition and maintenance. Values for these came from measurements made by the project team, Audsley *et al.* (1997), technical specifications of agricultural structures and interpretation of such data by a structural engineer from Silsoe Research Institute. Burdens of components came from proprietary software (*SimaPro*), data sheets from the Building Research Establishment (www.bre.co.uk/envprofiles/) and Audsley *et al.* (1997). The main building burdens are shown in Table 33.

Table 33 Summary of total resources used in agricultural buildings (per year per m^2)

Building	Primary Energy use, MJ	GWP 100, [kg CO_2 equiv.]	EP, [kg PO_4^{3-} equiv.]	AP, [kg SO_2 equiv.]	ARU, [kg Sb equiv.]
Steel clad, concrete floor, *e.g.* grain, potato store	26	2.7	0.0024	0.014	0.65
Steel framed, fibre cement clad, concrete floor, *e.g.* grain, potato store	39	3.9	0.0030	0.019	0.62

Steel roof, earth floor, *e.g.* machinery store	17	1.4	0.0015	0.007	0.81
Broiler house, steel framed, wooden, earth floor, insulated	34	3.9	0.0051	0.030	1.15
Steel framed, Timber sided building, concrete floor, *e.g.* dairy cattle	62	7.9	0.0078	0.038	1.02
Pole barn, wood clad & steel roof	8.7	6.0	0.0027	0.021	0.14
Pig house, slatted floor	87	11	0.0095	0.062	1.30
Battery house	87	11	0.0095	0.062	1.30
Perchery / stilt	28	3.3	0.0042	0.025	0.96
Free range birds	24	2.8	0.0035	0.021	0.80
Outdoor pigs	1	0.1	0.0001	0.001	0.04
Low cost beef / sheep	10	6.1	0.0028	0.022	0.22
Greenhouse	16	1.3	0.0009	0.007	0.38

2.10 *Animal production*

Six animal commodities were studied: poultry meat, pig meat, sheep meat, beef, milk and eggs. Poultry meat was assumed to be a composite of chicken and turkey meat. The other commodities were all produced by one class or species of stock. Milk comes from dairy cattle breeds and the contribution from other species, such as goats, is assumed negligible at the national level. Similarly, all eggs are assumed to be produced by chickens. The functional units are taken as 1 t of carcass dead weight, 10 m^3 milk, or 20,000 eggs. The functional units were chosen to reflect the way that each commodity is traded, but the system boundary is the farm gate. The "Killing out Percentage" (KoP) is a factor for the conversion from liveweight to deadweight and is estimated as 47%, 55%, 70% for lamb, beef and poultry respectively; and as 72%, 75% and 77% for pigs of liveweights 76, 87 and 109 kg respectively (MLC data and http://statistics.defra.gov.uk/esg/evaluation/ofs/annexf.pdf).

In addition to field emissions there are direct and indirect emissions from the animals (indirect ones coming from manure). These are: methane (enteric and manure), nitrous oxide (manure in housing, storage and land application) and ammonia (same sources as nitrous oxide). Nitrate can also be leached from land-applied manure. Animal production also requires feed processing (on or off the farm) and some overseas imports *e.g.* whole soya beans (organic) and soya meal after oil extraction (in Britain) for non-organic. Bedding is also used, mainly straw – a co-product of cereal production.

2.10.1 Modelling the structure of the animal production industries

To model the production of livestock commodities in England and Wales, account has to be taken of the structure and diversity of the national industry. The meat-producing animal is produced by mothers who themselves have to be produced. The components of the sheep industry are spread amongst different farm types. From a farm management perspective, the industry is thus studied and reported as a set of different enterprises. These enterprise descriptions provide the essential building blocks from which we have modelled the industry. Transport steps connect some of them. Enterprise descriptions also define different ways of doing the same job.

For example, piglets for finishing can be produced from indoor or outdoor breeding units. The non-organic sheep industry has a structure that maximises hybrid vigour in the terminal generation. Pure bred hill flocks produce draft ewes that are used in the kinder uplands to produce cross breeds, which in turn supply the female breeding stock to the lowland fat lamb producers.

These different ways co-exist but the model can be used to examine the implications for the environment of changes in their proportions.

2.10.2 Animal production network structure

Changes in the proportion of any enterprise component must result in changes to the proportions of others in order to keep producing the desired amount of commodity. Establishing how much of each enterprise is required is found by solving simultaneous linear equations that describe the relationships that link the enterprises together.

The equations have the following structure. The solution is the amount, X, of each activity, i, that produces the desired massof output Z,

$$Z = \sum_{i=1}^{n} z_i X_i$$

where z_i is the output (meat, milk or eggs) of activity i, and also satisfies the set of flows between activities:

$$\sum_{i=1}^{n} c_{ij} X_i = 0, j = 1...p$$

where c_{ij} is the supply or demand of j by activity i, which describes the relationship between enterprises. Demands are negative and supplies are positive and total supply must equal total demand. For example, purebred lowland flocks produce rams, which are, in turn, demanded as terminal sires by lowland finishing flocks.

The total amount of material k flowing into the system is:

$$M_k = \sum_{i=1}^{n} m_{ik} X_i, k = 1...q$$

where m_{ik} is the flow of material k into activity i. The LCI for the system is the total of each burden l

$$B_l = \sum_{k=1}^{p} M_k b_{kl}, l = 1...r$$

where b_{kl} is the amount of burden l produced by the use or disposal of material k and M_k is the total amount of material. The LCI identifies the contribution of each material

$$B_{kl} = M_k b_{kl}$$

or activity

$$B_{il} = X_i \sum_{k=1}^{q} m_{ik} b_{kl}$$

which provides the data to enable particular "hotspots" to be identified.

Note that one of the burdens from ruminant systems is the land use is a combination of different land classes, indicating the proportion of the production which is on hills, upland or lowland. This contrasts with the field crops where land use can be any one of the land classes, the amount required being dependent on the quality of the land.

2.10.2.1 Pig meat structural model

Non-organic breeding and weaning units are modelled with indoor and outdoor options (Table 36). Finishing units are modelled as entirely housed, but three different finishing weights are modelled, 76, 87 and 109 kg liveweight. Replacements are modelled as retained females with inputs analogous to finishing. In the organic case the whole system is modelled as an outdoor combined breeding, weaning and finishing system.

The model assumes that 80% and 25% of non-organic breeding and weaning units are outdoors, respectively. The non-organic finishing units produce 75% light and 20% medium and the balance as heavy. The model assumes that 0.6% of the market is organic.

2.10.2.2 Poultry meat structural model

Three generations of breeders are required to produce the final generation; the breeding process is similar for organic and non-organic production. The final generation of non-organic chickens can be finished in housed or free range condition. For non-organic turkeys the choice is between housed, pole barns or free range. The only finishing system for organic poultry is free range.

The model (Table 38) assumes that 80% of the poultry market is derived from chickens and approximately 1% of the chicken and turkey market is organic. Free range accounts for 0.54% of non-organic production and barn production accounts for a further 15% of finished turkey production.

2.10.2.3 Eggs structural model

Like poultry production there are three generations of breeding stock, which are similar for non-organic and organic production systems. Non-organic egg layers can be housed in cages or in barns (percheries) or free range; organic can only be housed free range.

The model (Table 37) assumes that 66% of non-organic production is in caged housing and 27% is barn produced with the balance as free range production. 1% of the market is assumed to be currently organically produced.

2.10.2.4 Beef structural model

The beef industry is characterised by numerous finishing systems of various intensities, taking advantage of the different finishing characteristics of purebred dairy, crossbred dairy and suckler beef bred calves (Table 41 and Table 42). A number of intermediate grass and indoor growing stages are modelled because beef take more than one season to finish. Under lowland conditions suckler herds can be spring or autumn calving. Intensive cereal beef finishing is modelled for non-organic production.

The model assumes that 35% of beef calves originate from beef suckler herds. Of these suckler herds 33% and 33% are located in the hills and uplands respectively with 40% of the remaining lowland herds calving in the spring. Of the spring born non-organic lowland suckler calves 20% and 20% are assumed to be finished intensively as cereal beef and silage beef, respectively. Of the dairy bred calves 45% are finished in 18-20 months, 25% in 22-24 months and 15% are winter finished. 0.76% of the market is assumed to be currently organic.

2.10.2.5 Milk structural model

Milk is modelled as self-contained herds at a series of yield levels (Table 35). In the non-organic case, three yield levels are modelled for autumn and for spring calving herds. In the organic herds, we model three yield levels and an all year round calving pattern.

The model assumes that 1% of the market is currently organic. For each of the series of yield levels 25% are low, 55% are medium yielding and the balance are the highest yielding. Of the non-organic herds 80% are autumn calving and 20% of the herds have access to maize silage in their diets.

2.10.2.6 Sheep meat structural model

The non-organic sheep industry is a network of pure and cross bred flocks that come down from the hills to produce the terminal generation of fat lambs in the lowlands (Table 39 and Table 40). The organic industry is self contained.

The model assumes that 1.17% of the market is currently organic. The organic industry assumes a 50:50 split between ewes in the lowland and upland. Of the non-organic industry the model assumes that there are three upland ewes to every hill ewe and that of the surplus hill lambs 10% can be sold as finished to continental markets with the remainder being finished as stores at home. In addition 10% of all non-organic lambs can be produced intensively as early lowland lambs.

2.10.3 Animal production models

The technical performance of the livestock enterprises required data, such as values for daily liveweight gain, feed conversion ratio offspring per dam, longevity of dams, concentrate and forage requirements *etc.* The data came from the standard sources (for example Nix, ABC, MLC yearbooks). These provided constants, which are adequate for describing most current livestock production, but functional relationships (models) were also needed, for example relating energy and protein supply to milk yield and manure outputs in dairy cows, in order to allow changes within a system to be made and for all the effects to be properly quantified. This section details the models that wereused

2.10.3.1 Milk production

The following expressions were developed to give a system that is more responsive to change than one based solely on static coefficients derived from the standard sources.

Cow productive life, L is a linear function of milk yield, Y: $L = L_0 Y / Y_0$ where L_0 and Y_0 are the average life and milk yield.

Increased milk yield can be attributed to a number of factors, namely the size of cow, the feeding level and the milk productivity bred into the cow. Mature cow liveweight, W kg is defined as a function of milk yield, $W = W_0 \sqrt{Y / Y_0}$

The model produces the required number of purebred replacement female calves with a number of male calves produced. Surplus matings are crossbred to beef type bulls. The model assumes a 0.51 chance of a male calf.

Given that the total dry matter intake from forage, maize and concentrates must equal the feed intake limit and that the energy intake must equal the energy required, these two equations can be solved for the amount of forage and concentrates required in the diet of any yield of cow. The feed model is derived from the Agricultural Research Council. (1980).

Voluntary feed intake, V kg [dry matter] per year: $V = 9.125W + 0.1Y$

Metabolisable energy (ME) needs, E MJ/year: $E = (3029.5 + e_W W) + e_P + e_Y Y / 0.84$

where e_W is the ME requirement of live weight = 33.215 MJ/ kg
e_P is the ME requirement of a pregnancy = 2013.5 MJ/ year
e_Y is the ME requirement of milk = 5.16 MJ/ litre

In England the proportion of the diet which is maize is largely correlated with the yield potential of the herd. The maize in the diet is estimated as $\lambda_z = 0.001Y - 5.5$ kg DM

Solving the two equations for dry matter intake and energy, the requirement for concentrates, x_c kg DM: $x_c = (\alpha E - \beta V) / (\alpha m_c - \gamma \beta)$

where m_c is the ME of concentrates = 12.5 MJ /kg DM
$\alpha = \lambda_z (1-g)/g + s(1-g)(1-\lambda_z)/g + 1$
g is the proportion of the forage diet that is grazed = 0.6 and 0.4 for spring and autumn calving herds, respectively
s is the factor by which silage suppresses appetite = 1.2

$$\beta = m_z \lambda_z (1-g)/g + m_s (1-g)(1-\lambda_z)/g + m_g$$

m_z is the ME content of maize silage = 11 MJ/t
m_g is the ME content of grazed grass = 10 MJ/t
m_s is the ME content of grass silage = 9 MJ/t
γ is the substitution rate of concentrates for forage = 0.6

The diet responds to production requirements, which means that the properties of excreta, especially the nitrogen need to respond as well.

The dietary Crude Protein nitrogen requirement P, g/year

$$P = 31025 + 146W) + (11000 + 50Y)\kappa$$

where κ= Kjeldahl N content of protein =0.16 kg [N]/ kg [Protein]
The excreted nitrogen is X_N, g[N] / year: $X_N = P/d_p - Y\eta_Y$

where d_P is the digestibility of dietary protein = 0.6
η_Y is the nitrogen content of milk, 5.44, g [N]/ litre

As the fate of nitrogen in manure is linear with content, the correct environmental burdens can be calculated by the addition of appropriate proportions of slurry or farmyard manure using only two standard nitrogen contents of 4 and 5 kg [N]/t [fresh weight]. Thus 10t of 4kg/t plus 10 t of 5 kg/t is the same as 20t of 4.5kg/t.

The enteric methane emission factor was scaled in proportion to the forage dry matter intake.

2.10.4 Inputs to animal production

2.10.4.1 Concentrate feedstuffs

The precise mixture of ingredients varies for each concentrate fed to different classes of stock (Orr, 1995). Defra statistics (http://statistics.defra.gov.uk/esg/datasets/hstcomps.xls) show that wheat and derivatives dominate feeds blended by manufacturers (Table 34). The inclusion of six other main crops (and minerals) accounts for 84% of feed production. Diets were formulated using these feeds, assuming that the minor feeds provided similar nutritional properties for similar burdens. Further analysis of feed by IGER which included home mixing, suggested that concentrates consisted overall of: 50-60% wheat,20-30% barley and about 20% of a protein source (*e.g.* rape meal, legumes, soya or fishmeal). There are only limited data on the breakdown between animal types as much feed is mixed on farms. Furthermore, commercial feed producers maintain a high degree of confidentiality over actual ingredient mixes. We believe that the major ingredients in Table 34 cover most of the industry. Proportions between classes clearly vary, for example the IGER analysis suggested that field beans and peas were included at 8-10% in ruminant feed and barley reached 38% in beef and sheep feeds.

We aimed to include most livestock concentrates, but originally set an arbitrary threshold for inclusion of 5%. We lowered this to enable inclusion of feeds that we already modelled, *e.g.* field beans and minerals, but minor feeds like oats and some by-products were omitted. The formulation of rations was thus based on the feeds in Table 34, but the quantities were increased to cover the 16% of minor feeds not specifically modelled.

Table 34 Mean distribution of main raw feeds used by feed blenders in 2000-2004

Feed	Proportion of total, %	Burden calculation method
Wheat	25	Direct
Cereals by-products, wheat feed and other cereals by-products	21	Economic allocation from wheat and barley
Soya cake and meal	9	Direct for bean production and import

		plus economic allocation for oil extraction
Barley	6	Direct
Oilseed rape cake and meal	5	Direct for grain production plus economic allocation for oil extraction
Other oilseed cake and meal	8	Analogous to imported soya and rape
Whole and flaked maize, and maize gluten feed	5	Maize grain direct and derivatives by economic allocation from maize grains
Minerals	4	Direct
Field beans and peas	1	Direct (as beans)
Total accounted for	**84**	

Source: http://statistics.defra.gov.uk/esg/datasets/hstcomps.xls

2.10.4.2 Energy inputs

Specific data were obtained by the project team that quantified the direct energy use in intensive pig and poultry housing systems. For other cases, the whole farm energy costs (Nix, 2004) were analysed. After allowing for the energy inputs into fieldwork, which are already integral in the feed burdens, we partitioned the remainder into diesel for stock management and related activities and electricity for activities such as milking and milk refrigeration.

2.10.4.3 Animal transport

Simple assumptions were made to allow for the movement of animals between farms. Non-organic systems are widespread, and an allowance of 100 km by medium sized lorry was assumed. Organic farming systems are more widely dispersed, but more self contained, so an allowance of 200 km was assumed.

2.10.5 Emissions and manures from animal production

2.10.5.1 Direct emissions from livestock

Animals and their manures are the source of three important direct gaseous emissions: methane (CH_4), nitrous oxide (N_2O) and ammonia (NH_3). Methane is a consequence of fibre digestion in the rumen (and lower gut to a lesser extent). Emissions from the animal and from its excreta within housing systems are calculated following the methods of the national inventories for methane, ammonia and nitrous oxide.

2.10.5.2 Credit for displaced fertiliser and crops

Emissions from manure storage and land-spreading were quantified using and extension to the national inventory methods and data. The emission factors due to storage were re-estimated using new evidence from research (Williams *et al.*, 2002, Williams *et al.*, 2004a, Williams *et al.*, 2004b).

The interactions between manures, soils and crops are complex. However, in the long term all of the nutrients that are applied to the soil as manure will be accounted for as either crop products or as losses to the environment. A series of projects at SRI has studied, and developed a method of tackling this problem (Sandars *et al.*, 2003, Williams *et al.*, 2002, Williams *et al.*, 2004a, Williams *et al.*, 2004b).

After allowing for the effect of season, the proportion of the theoretically available nitrogen used to make fertiliser savings is variable. The combination of lack of knowledge of manurial nutrients, lack of respect for manure as a source of fertiliser, and a tendency to over application, lead to relatively low fertiliser saving (Scott *et al.*, 2002). In the model, we assume that 50% of the available nitrogen in pig and dairy slurries is used to save fertiliser, but for broiler litter the figure is 40% because there is more evidence of over application.

The remaining nitrogen is accounted forby several fates, which are calculated using the models. Typically, nitrous oxide losses account for 2.5% (OECD, 1991) of the nitrogen, the crops removes around 16%, and the rest is either lost as nitrate leaching (49%) or is denitrified (32.5%).

In the extreme case of non-organic outdoor pig, poultry and broiler production the same land is used for more than one season and the animals will leave the ground devoid of vegetation. We assume that none of the nitrogen in half of the excreta is available as a fertiliser saving, there being no following crop. The nitrogen cycle in these cases is complex and warrants further investigation.

With the routine use of soil testing it is safe to assume that all of the manurial potash and phosphate will, in time, be used as a source of fertility.

Ruminant manures are modelled as applied to grassland, whereas pig and poultry manure are modelled as applied to winter wheat. The model assumes that non-organically derived manures are applied to non-organic crop land. In the non-organic case the fertility in manure displaces the need for Ammonium Nitrate (AN) as N, Triple Super Phosphate as P, K fertiliser as K. In the organic case we assume that the equivalents are sacrificial legume N, Rock P from 25% Tunisian phosphate, Rock K as K. Sacrificial legume N was modelled as a sacrificial winter bean crop, expressed per kg of nitrogen fixed, which is assumed to be 40 kg N/ t.

2.10.6 Allocation of burdens in animal production

The focus of the meat production enterprises is prime meat, but meat also arises from culling breeding stock (ewes for mutton, sows, boars, dairy and beef cows, retired laying hens and broiler breeders). The quality of these meats is generally considered lower, but it is used in some catering and processed foods, which is reflected in lower prices, typically less than 25% of the value of prime meat. The basis of allocation is weight adjusted for the lower economic value. If the total meat production from a system consists of p kg prime meat with value π £/kg and c kg culled meat with value χ £/kg, then the weight adjusted meat output (w) is:

$$w = p + \frac{\chi}{\pi} c$$

This reduces the potential production of the prime meat by less than 5% in most cases.

The interaction between milk and beef is a complex one. The primary purpose of pregnancy in dairying is to initiate lactation and the secondary one is to provide female herd replacements. A consequence is the production of surplus calves that are often, but not always, taken into the beef industry. The bull used will be either a dairy or a beef bull and modern selection methods can increase the probability of a male or female calf. Purebred male dairy x dairy calves (*e.g.* Friesian-Holsteins) are often killed just after birth, but the majority of crossbred (beef x dairy) male (and some female) calves enter the beef sector. The maintenance costs and burdens of lowland suckler cows are avoided when dairy bred calves enter the beef sector.

2.10.7 Organic livestock production

Differences between organic and non-organic animal production are much more apparent between dairying systems and poultry meat production, than production systems that are more extensive such as upland sheep and beef. All monogastric organic production is free range, and with greater land requirements per head than non-organic free range, while non-organic includes free range and fully housed systems. The non-organic sector uses slurry systems and bedded housing, while bedded is the norm in organic. Until September 2005, up to 20% of feed and bedding to organic could be sourced from the non-organic sector, if organic supplies were too limited, with the bulk being organic. Now, feed and bedding should be all organic, with minor exceptions. These differences are accounted for in our analysis. Soya is used in both organic and non-organic sectors, but is used as whole beans in organic and mainly as meal, after oil extraction, in the non-organic sector. In terms of dietary composition, however, the concentrations of energy and protein are generally similar between the sectors in compounded feeds.

Outdoor organic stock are often associated with arable production. They tend to be rotated more frequently in the organic sector than non-organic, with the aim of minimising nitrogen N losses and maximising nitrogen use. This applies notably for pig and poultry production.

2.10.8 Summary of animal production data

This section summarises the data used in the animalproduction models. Milk productions is shown in Table 35, pig meat in Table 36, eggs in Table 37, poultry in Table 38, organic sheep in Table 39, non-organic sheep in Table 40, and beef in Table 41 and Table 42.

Table 35 Dairy production input data values used in the LCA model

Yield Level	Low	Average	High	Low	Average	High	Low	Average	High
	Milk herd (Organic)			Non-organic autumn calving			Non-organic spring calving		
Cow places	1	1	1	1	1	1	1	1	1
Time	52 weeks	52 weeks	52 weeks	52 weeks	52 weeks	52 weeks	52 weeks	52 weeks	52 weeks
Calving index, day	400	400	400	385	385	385	385	385	385
Productive life, lactations	5.63	4.50	3.75	4.49	3.80	3.09	4.49	3.80	3.09
Replacement heifers, head	0.162	0.203	0.243	0.211	0.249	0.307	0.211	0.249	0.307
Cow weight, kg	537	600	657	552	600	666	552	600	666
Mortalities, %	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Milk	4000	5000	6000	5500	6500	8000	5500	6500	8000
Calf mortality, %	10	10	10	10	10	10	10	10	10
Calf weight, kg	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
Female dairy calves	0.162	0.203	0.243	0.211	0.249	0.307	0.211	0.249	0.307
Male dairy calves	0.169	0.211	0.253	0.220	0.260	0.320	0.220	0.260	0.320
Female dairy X calves	0.240	0.200	0.159	0.207	0.169	0.111	0.207	0.169	0.111
Male dairy X calves	0.250	0.208	0.166	0.215	0.175	0.116	0.215	0.175	0.116
Maize prop	0	0	0	0	0.200	0.500	0	0.200	0.500
Dairy concentrates, kg DM	544	911	1312	1377	1527	1673	850	1024	1253
Grazing, kg DM	2516	2383	2478	1684	1839	2080	2842	3061	3373
Grass silage, kg DM	2516	2383	2478	2526	2207	1560	1894	1632	1124
Maize silage, kg DM				0	552	1560	0	408	1124
Excreted nitrogen, kg N	63.7	74.0	84.2	76.1	85.9	100	76.1	85.9	100
Energy diesel, MJ	475	475	475	475	475	475	475	475	475
Energy electricity, MJ	671	839	1007	923	1091	1343	923	1091	1343
Housing period	190	190	190	190	190	190	190	190	190
Grazing period	175	175	175	175	175	175	175	175	175
Straw bedding, kg	1020	1140	1249	357	388	430	357	388	430
Slurry, kg	4079	4560	4995	6963	7570	8398	6963	7570	8398
Slurry N, kg	16.6	19.3	21.9	28.7	32.5	38.3	28.7	32.5	38.3
FYM, kg	5098	5700	6244	1783	1938	2150	1783	1938	2150
FYM N, kg	13.8	16.1	18.5	6.4	7.2	8.5	6.4	7.2	8.5
Ammonia, kg [NH_3-N]	5.63	6.29	6.89	7.03	7.65	8.48	7.03	7.65	8.48
Methane, kg [CH_4]	119	126	143	101	119	150	113	132	162
Nitrous oxide, g [N_2O-N]	163	182	200	168	182	202	168	182	202

Table 36 Pig production input data values used in the LCA model

	Indoor weaners	Outdoor weaners	Indoor, light (pork)	Indoor, medium (cutter)	Indoor heavy bacon	Rearing sow replace-ments	Organic combined unit
Weaners, no	1	1	1	1	1	1	1 sow
Time, week	7.1	7.2	10.5	13.0	18.0	18.0	52.0
Start liveweight, kg	7.2	7.2	30	30	30	30	
Daily gain, kg	0.462	0.455	0.627	0.627	0.627		
Exit liveweight, kg	30	30	76	87	109	109	
Killing out, %			0.72	0.75	0.77		0.72
Transport, km	80	80					
Transport, %	0.2	0.8					
Mortality, %	0.07	0.03	0.07	0.07	0.07	0.07	0.03
Feed conversion ratio	1.77	1.65	2.74	2.74	2.74	2.74	
Concentrates, kg	40.4	37.6	126.0	156.2	216.5	216.5	
proportion housed -fully slatted	0.27	0	0.25	0.25	0.25		
proportion housed -part slatted	0.23	0	0.25	0.25	0.25		
proportion housed -loose housing	0.5	1	0.5	0.5	0.5		
Built-up area, m^2	0.03	0.04	0.18	0.25	0.38	0.31	33.3
Land area, m^2	0.04	0.65	0.24	0.32	0.49	0.40	200
Excreta, l/day	1.5		5	5	5	0.627	
Pig excreta, t	0.07		0.37	0.45	0.63		
Pig slurry, t	0.04		0.18	0.23	0.31	0.63	
Bedding straw, t	0.05	0.05	0.05	0.06	0.08	0.19	1.25
Pig FYM,t	0.09		0.23	0.28	0.39	0.82	
Outdoor pig manure before first winter, t		0.06					
Outdoor pig manure after first winter, t		0.06					7.50
Energy (diesel), kg		0.00					6.00
Energy (electricity), MJ	8.61		4.86	5.14	5.42	4.86	0.00
Casualty stock	3.85	1.71	3.45	3.95	4.87	0.98	
Weaner exiting	0.93	0.97					
Finished pigs, kg dwt			51.16	60.85	78.05	0.94	
Ammonia, kg [NH_3-N]	0.09	0.13	0.57	0.78	1.28	1.24	23.5
Methane, kg [CH_4]	0.17	0.02	0.81	1.11	1.83	2.91	7.45
Nitrous oxide g [N_2O-N]	0.5	0.5	2.0	2.7	4.5	4.5	97.3
Productive life, yrs							2.5
Sow weight							150
Culls - inedible, %							0.34
Org lactating sow concentrates, kg							700
Org dry sow concentrates, kg							750
Org weaner concentrates, kg							880
Org finisher concentrates, kg							2500
Cutters produced							12
Cutter weight, kg							83
Baconers produced							4
Baconer weight, kg							94
Baconer killing out, %							0.75

Table 37 Egg production input data values used in the LCA model

	Free Range Layers	Organic Free Range Layers	Barn Eggs	Housed Layers	Pullets	Layer Breeders
Eggs, no/layer	289	262	288	295		295
Life, week	55	55	55	55	18	52
Layer feed, kg	49.3	49.3	47.8	44.9	6.6	44.9
Mortality	0.08	0.08	0.07	0.05	0.03	0.05
Amount of manure deposited indoors, kg $head^{-1}year^{-1}$	44.4	44.4	50.5	50.5	16.5	47.8
Proportion of manure dropped outdoors	0.12	0.12				
Amount of manure deposited outdoors, kg $head^{-1}year^{-1}$	6.1	6.1				
Proportion in non-mobile housing	0.8	0				
Proportion of housed layers with deep cages				0.753		0.753
Proportion of housed layers with belt cleaned cages				0.247		0.247
Proportion of pullets on manure based systems					0.5	
Proportion of pullets on litter based systems					0.5	
Housed area, m^2	0.12	0.12	0.12	0.18	0.03	0.18
Range area in rotation, m^2	0.85	4.23				
Total range area, m^2	4.23	4.23				
Methane kg/head	0.03	0.03	0.03	0.03	0.00	0.03
Ammonia, kg/head	0.22	0.22	0.25	0.20	0.04	0.20
Nitrous oxide, g/head	15.1	15.1	15.1	10.8	2.3	10.2

Table 38 Poultry production input data values used in the LCA model

	Broiler systems				Turkey systems			
	Breeder Systems	Free-range	Free-range -Organic	Housed	Free range	Free range - Organic	Pole-barn housed	Fully housed
Time to laying, week	18							
Finishing, day		56	82	42				
Female finishing age, week					20	20	20	8
Female finishing weight, kg					7.5	7.5	7.5	5
Male finishing age, week					20	20	20	8
Male finishing weight, kg					13.5	13.5	13.5	5
Rejects, %		1.5						
Laying, time, week	54							
Eggs laid	170							
Eggs rejected	20							
Hatching rate, %	0.85							
Chicks hatched	115							
Feed, t/1000 birds	45	5.5	8	4.6	29	29	29	14
Poult feed, t/1000 birds	6.6							
Spent broiler breeder,kg	5							
Manure, t/1000 birds	42.0	3.1	4.5	2.3	16.1	16.1	16.1	6.8
Straw, t/1000 birds		1	2	1	4	4	4	2
Finished weight, kg		2.35	3	2.54				
Mortality, %		0.05	0.05	0.04	0.05	0.05	0.04	0.04
Methane, g/head	31.6	0.7	1.4	0.6	1.2	1.2	1.2	0.2
Ammonia, g/head	203.7	7.1	13.3	5.9	11.4	11.4	11.6	2.2
Nitrous oxide, g/head	10.2	2.2	4.1	1.8	5.5	5.5	5.5	1.0

Table 39 Organic sheep production input data values used in the LCA model

	Organic production systems					
	Organic Upland Breeding Stock & Lamb Production	**Organic Lowland Lamb Production**	**Store Organic Lamb Finishing Short Keep -in situ**	**Store Organic Lamb Finishing Long Keep in situ**	**Store Organic Lamb Finishing Short Keep**	**Store Organic Lamb Finishing Long Keep**
Flock life, year	4.5	6				
Store lambs, head[30-36kg lwt]			1.03		1.03	
Store lambs, head[26-30kg lwt]				1.03		1.03
Sheep concentrates, kg		30				
Lamb concentrates, kg		15	10	24.4	10	24.4
Minerals, kg	1.8	1.6				
Barley mix, kg	18	18				
Lowland grazing, kg DM/yr		504	16	39	16	39
Upland grazing, kg DM/yr	522					
Hill stocking rate, ha/year						
Hay, kg DM	190	47				
Energy, diesel, MJ	175	142	19.5	59	19.5	59
Energy, electricity, MJ						
Mean weight, kg			33	28	33	28
Transport t.km					6.8	5.8
Implied fecundity	1.13	1.45	0	0	0	0
Dead ewes	0.04	0.03				
Culled ewes, head	0.232	0.172				
Culled rams, head	0.008	0.008				
Dead stores, head			0.03	0.03	0.03	0.03
Store lambs, 26-30 kg lwt - in situ	0.01					
Store lambs, 30-36 kg lwt - in situ	0.18	0.16				
Store lambs, 26-30 kg lwt	0					
Store lambs, 30-36 kg lwt	0.11	0.09				
Finished standard lambs (32.1-39 kg)	0.55	0.99	1	1	1	1
Wool, kg	2.91	3.12				
Nitrous oxide, g[N2O-N]	12.9	1.3	0.00494	0.0124	0.00494	0.0124
Ammonia, kg[NH3-N]	1.33	1.39	0.0913	0.228	0.0913	0.228
Methane, kg[CH4]	9.9	10.4	0.94	2.34	0.94	2.34
FYM, kg	150	150				

Table 40 Non-organic sheep production input data values used in the LCA model

	Non-organic production systems													
	Hill pure bred flocks, option 1	**Hill pure bred flocks, option 2**	**Upland pure bred flocks, option 1**	**Upland pure bred flocks, option 2**	**Upland halfbred flocks**	**Lowland pure bred flocks**	**Gimmer-ing**	**Lowland spring lamb productio n**	**Lowland early lamb productio n**	**Lowland broken mouthed ewes productio n**	**Store lamb finishing short keep -in situ**	**Store lamb finishing long keep -in situ**	**Store lamb finishing short keep**	**Store lamb finishing long keep**
Flock life, years	4	4	4.2	4.2	4.2	4.5	1	4.5	4.5	1	1	1	1	1
Rams					0.0083			0.0083	0.0083					
Draft hill ewes					0.26									
Cross breed ewe lambs							1.03							
Broken mouthed ewes with lambs										1				
Store lambs, head[30-36 kg lwt]											1.03		1.03	
Store lambs, head[26-30 kg lwt]												1.03		1.03
Gimmers								0.28	0.28					
Sheep concentrates, kg	30	30	50	50	50	53		53	53	53				
Lamb concentrates, kg						12		12	97	12	12	18	12	18
Minerals, kg														
Barley mix, kg							14							
Lowland grazing, kg DM/yr						504	457	504	502	282	16	39	16	39
Upland grazing, kg DM/yr			541	541	541									
Hill grazing, kg DM/yr	457	457												
Hay/ big bale silage, kg DM			48	48	48	190		190	190					
Energy, diesel, MJ	113	113	73	73	73	59	59	59	59	30	20	59	120	59
Energy, electricity, MJ														
Mean weight					80		40	80	80	90	33	28	33	28
Transport t.km					2.1		4.1	2.3	2.3	9.0			3.4	2.9
Outputs														
Implied fecundity	0.998	0.998	1.383	1.373	1.375	1.49		1.51	1.46	1.45	0	0	0	0
Draft hill ewes 3-5 years old, head	0.2	0.2												
Upland ram lambs, head			0.34	0										
Crossed ewe lambs, head					0.69									
Terminal sires, head						0.371								

Non-organic production systems														
	Hill pure bred flocks, option 1	**Hill pure bred flocks, option 2**	**Upland pure bred flocks, option 1**	**Upland pure bred flocks, option 2**	**Upland halfbred flocks**	**Lowland pure bred flocks**	**Gimmer-ing**	**Lowland spring lamb productio n**	**Lowland early lamb productio n**	**Lowland broken mouthed ewes productio n**	**Store lamb finishing short keep -in situ**	**Store lamb finishing long keep -in situ**	**Store lamb finishing short keep**	**Store lamb finishing long keep**
Gimmers, head							1							
Broken mouthed ewes			0.200	0.200	0.200									
Barren ewes	0.05	0.05	0.04	0.04	0.04	0.05		0.05	0.05					
Dead ewes	0.05	0.05	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02				
Culled ewes, head						0.152		0.210	0.210	0.98				
Culled rams, head	0.008	0.008	0.008	0.008	0.0083	0.008		0.0083	0.0083					
Dead stores, head											0.03	0.03	0.03	0.03
Store lambs, 26-30 kg lwt -in situ	0.06		0.0100	0.010	0.010	0.010		0.010	0	0				
Store lambs, 30-36 kg lwt -in situ	0.260		0.240	0.340	0.210	0.190		0.320	0.150	0.18				
Store lambs, 26-30 kg lwt	0.05		0.01	0.01	0	0		0.01	0	0				
Store lambs, 30-36 kg lwt	0.21		0.13	0.19	0.12	0.11		0.19	0.05	0.11				
Finished light lambs (25.5-32 kg lwt)		0.58												
Finished standard lambs (32.1-39 kg)	0.11	0.11	0.385	0.555	0.345	0.58		0.98	1.26	1.16				
Finished medium lambs (39.1-45.5 kg)											1	1	1	1
Upland ewe lambs			0.5	0.5										
Wool, kg	2.08	2.08	2.91	2.91	2.91	3.12		3.12	3.12	3.12				
N2O, g[N]	17.1	17.1	15.8	15.8	15.8	13.0	0.03	13.0	13.0	13.0	0.0049	0.0124	0.00494	0.0124
NH3, kg[N]	0.274	0.274	0.43	0.43	0.43	1.39	0.548	1.39	1.39	1.39	0.0913	0.228	0.0913	0.228
CH4, kg	9.63	9.63	10.24	10.24	10.24	10.43	5.61	10.43	10.43	10.43	0.94	2.34	0.94	2.34
FYM, kg			150	150	150	150		150	500					

Table 41 Beef production input data values used in the LCA model (Part I)

	18-20 Month beef	22-24 Month beef	Cereal Beef (continental X dairy bulls), 12-13 months	Silage beef (dairy & continental X bulls), 16-17 months	Lowland suckler herds -autumn calving	Lowland suckler herds - spring calving	Upland suckler herds -autumn calving	Upland suckler herds- spring calving	Hill suckler herds	Winter feeding spring-born suckled calves	Grass finishing spring-born suckler stores	Winter Finished Suckled Calves	Cereal Beef -spring born calves (Suckler bulls)	Silage Beef (suckler bulls and steers)
Mortality, %	0.03	0.03	0.026	0.026	0.02	0.02	0.03	0.03	0.02	0.015	0.007	0.003	0.026	0.026
Calf mortality, %														
Killing out, %	0.551	0.551	0.543	0.543							0.551	0.55	0.543	0.543
Calves born/head/yr					0.92	0.91	0.93	0.93	0.91					
Productive life, year					7.5	8	7	6.5	5.6					
Weeks	82.8	100.2	54.5	71.9	52.0	52.0	52.0	52.0	52.0	25.7	47.3	26.4	52.0	61.6
Mean transport distance, km	100	100	100	100	100	100				100	100	100	100	100
Lowland grazing kg DM	1680	3500			3920	3710					1610			
Upland grazing, kg DM							3234	2982						
Hill grazing, kg DM									3234					
Calf liveweight														
Entrance liveweight, kg/ head	45	45	45	45						275	380	365	280	280
Exit liveweight, kg /head					365	278	335	278	264	385				
Slaughter liveweight, kg/head	515	565	540	535							530	560	530	520
Milk replacer, kg	15	15	15	15										
Whole milk, l														
Calf concentrates, kg	160	160	160	160	155	85	200	100	77					
Finishing concentrates, kg	800	950									47	495		
Cow concentrates, kg					200	150	200	140	212					
Rearing concentrates, kg					690	690	80	80	90	295				
Barley ration, kg			2100	1050									1300	800
Hay, kg	30	30	90	30									90	
Silage, kg DM	1600	0	0	1600	884	884	1500	1500	1257.5	875		850	0	1050
Proportion cubicle housed	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18		0.18	0.18	0.18
Proportion loose housed	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82		0.82	0.82	0.82
Days housed	182	365	382	503	182	182	182	182	0	182		185	364	431
FYM, kg	3200	3600	2800	3200	3000	2200	2800	2400		2800	0	2400	2800	3200
Straw, kg	640	720	560	640	600	440	560	480		560		480	560	640
Livestock units, LU	0.585	0.585	0.585	0.585	1.5	1.33	1.5	1.33	1.33	0.6	0.83	0.86	0.74	0.74
Diesel, MJ	377	457	248	328	237	237	237	237	237	117	216	120	237	281
Ammonia, kg N	3.83	7.67	8.02	10.58	9.81	8.70	9.81	8.70	0.00	3.92	0.00	5.72	9.68	11.46
Nitrous oxide, kg N	0.19	0.23	0.13	0.17	0.31	0.28	0.31	0.28	0.28	0.06	0.16	0.09	0.15	0.18
Methane, kg	56.96	68.93	37.49	49.46	91.73	81.33	91.73	81.33	81.33	18.14	46.15	26.73	45.25	53.58

Table 42 Beef production input data values used in the LCA model (Part II)

	Dairy-herd bred calves 18-20 month grass finishing	Organic lowland suckler-finishing herds -spring calving	Organic upland suckler herds-spring calving	Organic hill suckler herds-spring calving	Grass finished spring-born suckler stores	Silage beef spring born calves (suckler bulls and steers
Mortality, %	0.03	0.02	0.03	0.02	0.03	0.03
Calf mortality, %		0.07	0.07			
Killing out, %	0.55	0.54			0.54	0.54
Calves born, head/yr		0.91	0.93	0.91		
Productive life, year		7.0	6.5	5.6		
Duration, week	83	52	52	52	47	62
Mean transport distance, km	200					
Lowland grazing kg DM	3168	4312			2310	4620
Upland grazing, kg DM			3360			
Hill grazing, kg DM				3360		
Calf liveweight						
Entrance liveweight, kg/head	45					
Exit liveweight, kg/head			280	264	280	280
Slaughter liveweight, kg/head	515	490			530	520
Whole milk, l	320					
Calf concentrates, kg	130	90		77		
Concentrates, kg	700			1258	250	350
Cow concentrates, kg		150	200	212		
Rearing concentrates, kg		350		90		
Hay, kg	30	150	150		50	100
Silage, kg DM		220	220		600	950
Proportion cubicle housed	0	0	0	0	0	0
Proportion loose housed	1	1	1	1	1	1
Days housed	182	182	182	0	182	431
FYM, kg	3400	4400	2400			
Straw, kg	680	880	480		0	0
LU (Cow and Calf)	0.585	1.25	1.33	1.33	0.75	0.74
Diesel, MJ	375	474	474	237	216	281
Ammonia, kg N	4.07	8.69	9.25	0.00	5.21	12.18
Nitrous oxide, kg	0.19	0.26	0.28	0.28	0.14	0.18
Methane, kg	56.96	76.44	81.33	81.33	41.71	53.58

2.11 *Implementation of the LCA model*

The relationships and data were put into Excel workbooks of three generic types. Arable crops were put into standard templates for non-organic and organic systems, with values set to zero where not required, and a home page for each crop. Common data worksheets were used wherever possible. The tomato worksheet stands alone, except for accessing common data worksheets. The commodity sheets can be interrogated using the normal Excel interface as well as through macros that allow some scenarios to be investigated. The animal worksheets each have the same philosophy, but are tailored to the specifics of the sector. A common worksheet allows for quick selection of commodities and initiates the tool that solves the simultaneous equations that define the animal production systems. These underlying sheets allow detailed examinations to be made.

In addition, a graphical interface was written in Visual Basic (VB) to allow rapid and easy interrogation of the model. Interfacing VB and Excel has presented many technical challenges and final development was postponed in favour of enhancing the underlying spreadsheets. The graphical interface (Figure 4) allows users to select values that define different production systems using a set of sliders. The default set of values are the ones that we believe best represent current practices and proportions of production systems and methods. Users can thus quickly compare current and notional future practices. The model is interactive, so that changes to livestock systems, such as reducing the proportion of sheep on the hills, cause the structure of the production network to be automatically recalculated. In addition, crops can be influenced from the animal screens, for example changing the nitrogen application rate for wheat.

All the commodities include the proportion of organic production. Typical options for field crops also include the proportions of tillage types (plough, reduced, direct drilling), N fertiliser application rate and soil texture distribution. For tomatoes, choices include the mixture of products (classic, specialist, loose, vine), production system and the amount of CHP used. For animal production, options include housing types, intensity of nutrition (for dairying), generic location for sheep production.

Figure 4 Example of screen for users to change components of production systems

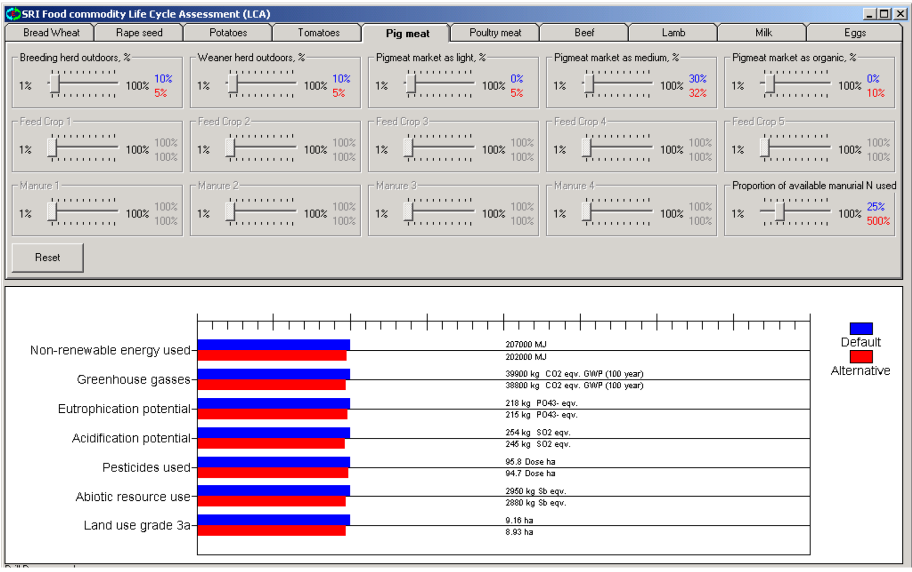

Figure 5 shows an example of the input/output section of the bread wheat spreadsheet. Cells with blue text and a yellow background are for inputting values, green text is descriptive and black text shows calculated results, with the main LCI values at the bottom. Apart from those shown on this screenshot, the LCI dataset includes about 50 values (*e.g.* water use, N_2O, GWP over 20 and 500 years) allowing for more detailed scrutiny.

Main annual cultivation methods for Bread	Proportions
Plough based	60%
Reduced tillage	35%
Direct drilling	5%
Fertilisation and yield potential	
Mineral fertilisation assumed at std av. rate	208
Proportion of N applied as urea	11%
Increase in yield of varieties	0.0%
Increase in protein content of varieties	0.0%

Harvested Outputs and properties	
Gross Grain yield (86% dry matter), t/ha	**7.72**
Protein content of grain (Dry Basis), %	13.6%
Yield of bread wheat allowing for grain of	7.1
Straw yield, t/ha	4.0
Proportion incorporated (rest is baled)	50%

Environmental burdens from the production	Bread
Conventional system	
Summarised values per t	
Energy used, MJ	2,646
Global Warming Pot'l, kg 100 year CO_2	420
Eutrophication Pot'l, kg PO_4^{3-} Equiv.	3.0
Acidification Pot'l, kg SO_2 Equiv.	2.8
Pesticides used, dose ha	1.4
Abiotic depletion, kg Antimony Equiv.	15.8
Land used	
Grade 2	0.12
Grade 3a	0.14
Grade 3b	0.15
Grade 4	0.16
N losses in detail	kg t^{-1}
NO_3^--N	4.4
N_2O-N	0.7
NH_3-N	0.7
N_2-N	4.8

Figure 5 Example of screen showing main input and output cells of the spreadsheet

Figure 6 to Figure 8 to are examples from the animal spreadsheet, showing the table allowing scenarios of pig production to be directly changed (all the others are similar), the table for changing the scenarios for the feed crops and the table of results. Note that this latter table actually has a large number of columns listing all the major environmental emissions.

Livestock Commodities	Description	Minimum	Maximum	Default Value	Altenative Value
Pig meat	Breeding herd outdoors, %	1%	100%	80%	80%
	Weaner herd outdoors, %	1%	100%	25%	25%
	Pigmeat market as light, %	1%	100%	75%	75%
	Pigmeat market as medium, %	1%	100%	20%	20%
	Pigmeat market as organic, %	1%	100%	1%	1%

Figure 6 Screeenshot showing the input cells for changing scenarios to analyse pig systems

Feed Crops			
All	Description	Value	Value
	Proportion of national area producing conventionally	99%	99%
	Proportion of conventional using plough based tillage	49%	49%
	Proportion of conventional using ploughless tillage (but not direct drilling)	45%	45%
	Variation from average mineral N application rate	134.4	134.4
	% N as Urea N	13%	13%
	% Urea as liquid	0%	0%
	Yield increase by technology (conv), %	0%	0%
	Yield increase by technology (org), %	0%	0%
	Protein conc increase of grain (conv), %	0%	0%
	Protein conc increase of grain (org), %	0%	0%
	Straw incorporated for conventional (rest baled)	70%	70%
	Straw incorporated for organic (rest baled)	58%	58%
	Affects energy of grain drying	86%	86%
	Clay soil affects yields	31%	31%
	Compost use (Organic), t/ha	1.00	1.00

Figure 7 Screenshot showing the input cells for changing scenarios to analyse feed crops

Commodity	Reference	Unit	Primary energy used, MJ	Greenhouse gases, kg CO2 eqv. GWP (500 year)	Eutrophicatio n potential, kg PO43- eqv.	Acidification potential, kg SO2 eqv.	Pesticides used, Dose ha	Abiotic resource use, kg Sb eqv.
Pig meat	1000	kg dwt	16,680	4,133	100	394	8.8	34.5
Poultry meat	1000	kg dwt	11,998	3,144	49	173.4	7.7	29.7
Beef	1000	kg dwt	27,681	8,145	158	471	7.1	36.2
Sheep meat	1000	kg dwt	23,083	8,003	200	382	3.0	27.2
Milk	10000	l	25,104	5,645	64	163.0	3.5	27.6
Eggs	20000	no	14,110	3,871	77	306.0	7.7	38.2

Figure 8 Screenshot showing the first six columns of burdens from the results table for all animal commodities

3 Results

3.1 *Arable*

Table 43 lists the basic burdens for each crop commodity as produced by present production systems. Note that each commodity stands alone. Caution is needed in comparing commodities as their nutritional, cultural and commercial properties differ. Rape incurs more burdens that wheat, but contains more protein and much more energy. Potatoes contain about 80% water (compared with wheat at 14%) and their storage is much more demanding. The main purpose of the analysis is to provide a mechanism by which the different methods of producing any one of the commodities might be compared.

The results combine the appropriate proportions of current non-organic and organic farming and different current cultivation systems. Note that the functional unit is tonnes of production, rather than tonnes of dry matter or MJ of energy produced.

Table 43 Main burdens of production of each crop commodity (per t)

Impacts & resources used	Bread wheat	Oilseed Rape	Potatoes
Primary energy used, MJ	2,460	5,390	1,390
GWP_{100}, kg 100 year CO_2 equiv.	804	1,710	235
Eutrophication Potential (EP), kg PO_4^{3-} equiv.	3.1	8.4	1.3
Acidification Potential (AP), kg SO_2 equiv.	3.2	9.2	2.2
Pesticides used, dose ha	2.0	4.5	0.6
ARU, kg antimony equiv.	1.5	2.9	0.9
Land use, ha (One of the following)			
Grade 2, ha	0.13	0.27	0.024
Grade 3a, ha	0.14	0.31	0.028
Grade 3b, ha	0.15	0.33	0.030
Grade 4, ha	0.16	0.35	0.031
N losses			
NO_3-N, kg	4.4	12.2	1.6
NH_3-N, kg	1.4	3.0	0.3
N_2O-N, kg	1.0	3.2	0.9
N_2-N, kg	7.0	27.2	1.2
Irrigation water, m^3			21

3.1.1 Bread wheat

The contrast between non-organic and organic arable crop production is well illustrated by bread wheat in Table 44. The main differences are that non-organic production uses about 50% more energy than organic, while using only a third of the land area. Although emissions per ha are sometimes lower from organic than non-organic, because yields are about halved and nitrogen building crops are needed prior to the organic wheat crop, burdens are in many cases little changed and in the case of nitrate leaching and eutrophication actually increased.

A breakdown of the use of primary energy shows that, after fertiliser production, cultivations and harvesting are the main energy consumers. Fertiliser manufacture dominates in non-organic production. In organic production, field work dominates. Operations represents about a quarter of the total energy input to non-organic wheat, with the energy use for manufacturing the equipment making up about one third of that energy input. Cultivations represent about half of the fuel use. A typical breakdown of the energy used in operations (Figure 9) shows how crop establishment dominates when using plough-based or reduced tillage. The current mean of cultivations methods for non-organic bread wheat is also shown, together with associated spraying activity (not the spray manufacturing itself). More spraying is used with reduced tillage and with direct drilling than with plough based tillage, although fertilisation remains the same. The energy used for manufacturing the equipment ranges from 26% for reduced tillage to 42% for harvesting.

Table 44 Burdens of producing bread wheat non- organically and organically (per t produced)

Impacts & resources used	Non-organic	Organic
Primary Energy used, MJ	2,460	1,740
GWP_{100}, kg 100 year CO_2 equiv.	804	786
Eutrophication Potential (EP), kg PO_4^{3-} equiv.	3.1	9.3
Acidification Potential (AP), kg SO_2 equiv.	3.2	3.4
Pesticides used, dose	2.0	0.0
ARU, kg antimony equiv.	1.5	1.3
Land use grade 3a ha	0.14	0.44
N losses		
NO_3^--N kg	4.3	18.3
NH_3-N kg	1.4	1.5
N_2O-N kg	1.0	0.9
N_2-N kg	7.0	12.4
Primary Energy Usage Proportions		
Field work: Cultivation	19%	60%
Field work: Spraying	3%	0%
Field work: Fertiliser Application	3%	3%
Field work: Harvesting	8%	21%
Crop storage & drying or cooling	5%	8%
Pesticide manufacture	8%	0%
Fertiliser manufacture	53%	9%
Contributors to GWP_{100}		
CO_2	18%	14%
CH_4	1%	-1%
N_2O (direct)	75%	60%
N_2O (via nitrate)	6%	27%

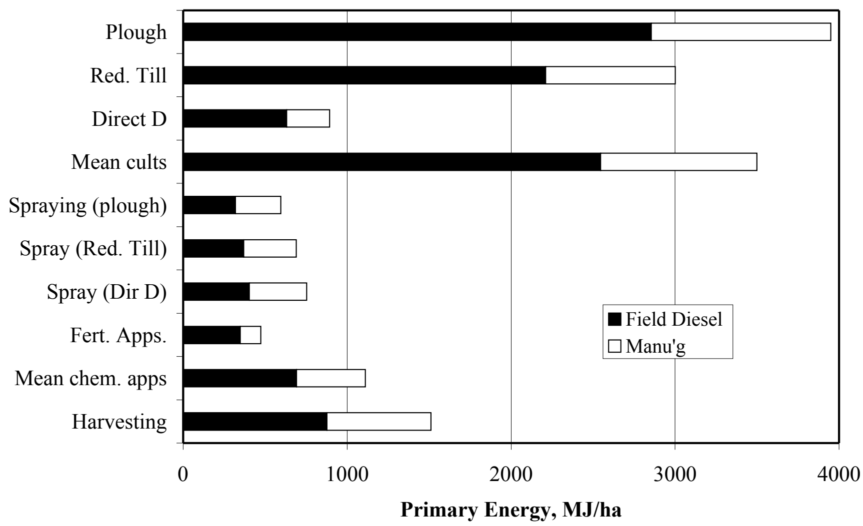

Figure 9 Typical breakdown of energy use in arable field operations

In this example, field work at 6,100 MJ/ha represents 35% of total energy used (17,700 MJ/ha). The remainder comprises crop cooling, storage and drying (5%), pesticide manufacture (8%) and the dominating term of fertiliser manufacture at 52%. The field energy expended in all combinable crops is generally similar, although energy for fertiliser manufacture clearly changes between crops, with beans having the lowest requirement as no N is applied. Buildings contribute little to the overall production burdens. In animal production, the energy flow that is embedded in the feed greatly outweighs that of the building itself. In contrast, grain storage occupies a relatively large area and once filled, the store cannot be readily used for another purpose, so these burdens are relatively higher, but are still small compared with production itself.

However primary energy is only a minor contributor to global warming as in arable agriculture the main contributor is the N_2O-N emissions which are 80% of the cause because they are 400 times more potent than CO_2. Nitrous oxide is emitted as a by-product of the nitrogen cycle in the soil as nitrogen is transformed between organic matter, ammonia and nitrate. The standard IPCC estimate is 1.25% of the N fertility and thus as much is generated per tonne by organic as non-organic.

Scenarios
Table 45 shows the use of the model to investigate the impact of some scenarios of bread wheat production. Since non-organic represents 99% of the production, any effects on organic production are masked.

- Currently 20% of the fertiliser applied to bread wheat is urea. If this is increased to 100%, the primary energy use is increased due to losses of ammonia which also increase acidification potential.
- If energy input to cultivations is reduced by changing from about 50% ploughing and reduced cultivations to 50% reduced cultivation and 50% direct drilling, there is only a small reduction in primaryenergy use.
- If the fertiliser input is reduced to 75% of its current level, this has the effect of reducing both yield and protein content so that more land is required to produce the bread wheat and all burdens are increased.
- If the crop is grown on mainly the heaviest soils, this has the effect of reducing all burdens, which is largely a reflection of the increased yields.
- If plant breeding provided varieties with 1% higher protein, there is no direct environmental benefit since a corresponding additional N input is required **per tonne.** However a greater proportion of the UK wheat could then be used,replacing the need for imports.
- If breeding provides varieties with 20% higher yield and the same protein content, there is a significant reduction in all burdens, even though there is a 20% increase in nitrogen fertiliser used. Note that in breeding terms, there is a negative correlation between increased yield and increased protein.

Table 45 Effects of some scenarios on the burdens of bread wheat production (per t)

Impacts & resources used	Original	All urea	Reduced cults	75% Nfert	90% clay	+1% protein	+20% yield
Primary Energy used, MJ	2,460	2,570	2,330	2,670	2,350	2,550	2,230
GWP_{100}, kg 100 year CO_2 equiv.	804	711	808	872	743	843	735
EP, kg PO_4^{3-} equiv.	3.1	4.0	3.2	4.0	2.7	3.2	2.6
AP, kg SO_2 equiv.	3.2	9.2	3.1	3.5	3.0	3.4	2.9
Pesticides used, dose ha	2.0	2.0	2.3	2.1	1.8	2.0	1.6
ARU, kg antimony equiv.	1.5	1.4	1.4	1.6	1.4	1.5	1.4
Land use grade 3a ha	0.143	0.146	0.146	0.159	0.147	0.142	0.119
N losses							
NO_3^--N kg	4.4	3.9	4.5	6.1	3.7	4.6	3.5
N_2O-N kg	1.4	1.2	1.4	1.5	1.3	1.5	1.3
NH_3-N kg	1.0	3.6	1.0	1.1	0.9	1.1	0.9
N_2-N kg	7.0	6.1	7.2	9.6	6.6	7.3	5.6

3.1.2 Oilseed rape

Table 46 shows a breakdown of the comparison between organic and non-organic production systems. The results show the same effects as wheat. In absolute terms the values are higher than wheat due to the lower yield in tonnes of a higher energy crop.

Table 46 Burdens of producing oilseed rape non- organically and organically (per t)

Impacts & resources used	Non-organic	Organic
Primary Energy used, MJ	5,390	4,020
GWP_{100}, kg 100 year CO_2 equiv.	1,710	1,620
EP, kg PO_4^{3-} equiv.	8.4	14.8
AP, kg SO_2 equiv.	9.2	5.7
Pesticides used, dose ha	4.5	0.0
ARU, kg antimony equiv.	3.3	2.9
Land use grade 3a ha	0.309	0.845
N losses		
NO_3^--N kg	12.2	28.5
NH_3-N kg	3.0	3.0
N_2O-N kg	3.2	1.2
N_2-N kg	27.2	18.6
Primary Energy usage proportions		
Field work: Cultivation	20%	53%
Field work: Spraying	7%	0%
Field work: Fertiliser application	3%	2%
Field work: Harvesting	7%	17%
Crop storage & drying or cooling	3%	4%
Pesticide manufacture	8%	0%
Fertiliser manufacture	52%	23%
Contributors to GWP_{100}		
CO_2	16%	19%
CH_4	-1%	1%
N_2O (direct)	64%	72%
N_2O (via nitrate)	21%	8%

3.1.3 Potatoes

Table 47 shows a breakdown of the comparison between organic and non-organic potato production systems. In contrast to oilseed rape, potato yields are very high, being 80% water, and thus burdens per tonne are much lower. One might expect burdens to be a factor of about 10 less than those of oilseed rape therefore those that are, are do not require further explanation. The main difference is seen in crop storage. A large component is for cooling the potatoes through to May (a typical storage period). As it is a fresh crop rather than a dry crop, storage requires cooling and refrigeration and this is a considerable energy burden amounting to 50% of the total primary energy input.

This is illustrated in Table 48 as the difference between second early and maincrop potatoes, which have a similar yield but second earlies are not stored. This has to be compared with the early crop which is of course also not stored and has burdens about twice that of the later crop. Although irrigation is lower per hectare, per tonne it is a similar level. Early potatoes have particularly high on nitrate leaching because they are fertilised at a similar level, with reduced yield, therefore leaving a greater residue of nitrogen in the soil. As the crop is harvested in June/July, there is the opportunity to make use of this fertiliser with a following crop, but we have not included this.

Table 47 Burdens of producing potatoes produced non-organically and organically (per t)

Impacts & resources used	Non-organic	Organic
Primary Energy used, MJ	1,260	1,280

GWP_{100}, kg 100 year CO_2 equiv.	215	199
EP, kg PO_4^{3-} equiv.	1.1	1.2
AP, kg SO_2 equiv.	1.9	0.8
Pesticides used, dose ha	0.5	0.1
ARU, kg antimony equiv.	0.9	1.1
Land use grade 3a ha	0.022	0.058
N losses		
NO_3^--N kg	1.39	2.04
NH_3-N kg	0.30	0.27
N_2O-N kg	0.70	0.06
N_2-N kg	0.98	0.88
Irrigation water, m^3	17.4	3.9
Primary Energy Usage Proportions		
Field diesel	28%	35%
Machinery manufacture	8%	13%
Crop storage & drying or cooling	36%	40%
Pesticide manufacture	3.9%	0.8%
Fertiliser manufacture	24%	11%
Contributors to GWP_{100}		
CO_2	45%	49%
CH_4	2%	1%
N_2O (direct)	48%	42%
N_2O (via nitrate)	4%	7%

Table 48 Comparison of the burdens of producing early, second early and maincrop potatoes (per t)

Impacts & resources used	Maincrop	Second earlies	Earlies
Primary Energy used, MJ	1,510	775	1,220
GWP_{100}, kg 100 year CO_2 equiv.	208	178	318
EP, kg PO_4^{3-} equiv.	0.8	1.0	2.6
AP, kg SO_2 equiv.	2.0	2.1	2.8
Pesticides used, dose ha	0.5	0.6	0.7
ARU, kg antimony equiv.	1.1	0.4	0.6
Land use grade 3a ha	0.022	0.025	0.043
N losses			
NO_3^--N kg	0.7	0.9	3.9
NH_3-N kg	0.3	0.3	0.5
N_2O-N kg	0.8	0.9	1.1
N_2-N kg	0.7	0.8	2.5
Irrigation water, m^3	16.6	14.4	17.7
Primary Energy Usage Proportions			
Field work	28%	61%	61%
Crop storage & drying or cooling	49%	0%	0%
Pesticide manufacture	4%	8%	6%
Fertiliser manufacture	19%	31%	33%

Table 49 shows the effects of the use of irrigation on maincrop potato production. The main burden of energy use is barely affected, while land use and other burdens fall as yields increase. Note that the model takes into account the fact that the fertiliser requirement changes due to the changed yield with irrigation, so per tonne of production there is little change in fertiliser use.

Table 49 Effects of irrigation on potato production (per t). The current value for non-organic production is 50%

Impacts & resources used	Irrigation at 0% of total area	Irrigation at 100% of total area
Primary energy used, MJ	1,480	1,540
GWP_{100}, kg 100 year CO_2 equiv.	211	206
EP, kg PO_4^{3-} equiv.	0.9	0.8
AP, kg SO_2 equiv.	2.2	2.0
Pesticides used, dose ha	0.6	0.5
ARU, kg antimony equiv.	1.1	1.1
Land use grade 3a ha	0.025	0.020
N losses		
NO_3-N, kg	0.8	0.7
NH_3-N, kg	0.3	0.3
N_2O-N, kg	0.9	0.7
N_2-N, kg	0.7	0.6
Irrigation water, m^3	0	27.0

3.1.4 Feed crops, including imported crops

Table 50 lists the same burdens for the feed crops that are used by the livestock models in calculating the burdens of meat production. It is notable that the two highest users of primary energy are the protein crops which fix their own nitrogen. Because they have a high protein content, they also have low yields and therefore the field work energy becomes more important per tonne.

Some major feeds are produced by extensive processing after the actual crop production. Five were modelled, of which only wheatfeed was grown organically (Table 51) There is a notable contrast between soya, which has its protein content increased by a relatively intensive process that also produces a high value product (oil), and wheatfeed where the feed is a cheap by-product of a relative low input process. Transport and processing burdens for soya are about the same, while wheatfeed milling incurs about 9 times the burdens of transport.

Table 50 Main environmental burdens of production of each feed crop (per t)

Impacts & resources used	Feed wheat	Winter barley	Spring barley	Field beans	Soya beans	Grain maize	Forage maize
Primary Energy used, MJ	2,260	2,410	2,380	2,470	3,010	1,970	1,880
GWP_{100}, kg 100 year CO_2 equiv.	731	726	710	1,010	1,300	650	577
EP, kg PO_4^{3-} equiv.	3.0	2.5	2.3	5.9	7.3	2.8	1.6
AP, kg SO_2 equiv.	2.8	2.9	2.3	4.8	6.4	1.6	1.8
Pesticides used, dose ha	1.9	2.2	1.4	2.9	4.4	0.4	0.2
ARU, kg antimony equiv.	1.4	1.4	1.5	1.4	1.7	1.3	1.5
Land use grade 3a ha	0.130	0.160	0.182	0.303	0.422	0.141	0.090

Impacts & resources used	Feed wheat	Winter barley	Spring barley	Field beans	Soya beans	Grain maize	Forage maize
N losses							
NO_3-N, kg	4.4	2.9	2.5	8.4	9.8	4.3	1.9
NH_3-N, kg	1.3	1.2	1.2	1.9	2.4	1.1	1.0
N_2O-N, kg	0.9	0.8	0.5	1.4	1.9	0.4	0.4
N_2-N, kg	6.9	5.6	2.9	11.5	14.0	4.3	1.9
Primary Energy Usage Proportions							
Field work: Cultivation	20%	21%	22%	45%	39%	22%	18%
Field work: Spraying	4%	4%	4%	8%	10%	6%	4%
Field work: Fertiliser application	3%	3%	3%	6%	7%	3%	2%
Field work: Harvesting	9%	10%	11%	17%	17%	11%	9%
Crop storage & drying or cooling	6%	6%	12%	6%	5%	1%	2%
Pesticide manufacture	8%	9%	6%	12%	15%	8%	4%
Fertiliser manufacture	51%	47%	41%	6%	6%	49%	61%
Contributors to GWP_{100}							
CO_2	19%	20%	20%	14%	13%	18%	20%
CH_4	1%	1%	1%	0%	0%	0%	1%
N_2O (direct)	74%	75%	75%	77%	79%	74%	76%
N_2O (via nitrate)	7%	5%	4%	10%	9%	8%	4%

Table 51 Total burdens of processed animal feeds, including field production, processing, import and delivery transport (per t)

Impacts & resources used	Wheat-feed (N-org)	Wheat-feed (Org)	Maize gluten feed	Soya meal (no hulls)	Soya meal (with hulls)	Rape meal
Primary Energy used, MJ	795	576	3790	6630	5990	3450
GWP_{100}, kg 100 year CO_2 equiv.	128	108	338	944	853	550
EP, kg PO_4^{3-} equiv.	0.9	1.9	1.1	7.5	6.8	3.9
AP, kg SO_2 equiv.	0.82	0.73	1.2	8.5	7.7	4.6
Pesticides used, dose ha	0.45	0.00	0.15	4.5	4.1	2.1
ARU, kg antimony equiv.	0.51	0.43	2.3	6.7	6.1	2.1
Land use grade 3a ha	0.032	0.083	0.055	0.424	0.384	0.144
N losses						
NO_3-N, kg	1.3	3.6	1.7	9.8	8.9	5.7
NH_3-N, kg	0.2	0.2	0.1	2.0	1.8	1.5
N_2O-N, kg	0.3	0.3	0.4	2.5	2.2	1.4
N_2-N, kg	2	2	2	14	13	13

3.2 *Animal products*

The animal products (Table 52) tend to show an effect of the different genetic capacities for meat production, with highly selected broilers having a very high feed conversion ratio and daily liveweight gain, together with low breeding overheads. These are in contrast to beef, where a calf also requires a cow to be fed. It should be remembered that the nutritional values of the meats will differ, so that a simple comparison of meat types may be misleading. Cattle and sheep are, of course, produced on land that is unsuitable for producing poultry feed.

Table 52 Main burdens of animal products (from current national balance of systems) per functional unit produced (1 t dead weight, 20,000 eggs, and 10,000 l milk)

Impacts & resources used	Beef	Pig Meat	Poultry Meat	Sheep Meat	Eggs	Milk
Primary energy used, MJ	27,700	16,700	12,000	23,100	14,100	25,100
GWP_{100}, kg 100 year CO_2 equiv.	15,800	6,350	4,580	17,400	5,540	10,600
EP, kg PO_4^{3-} equiv.	158	100	49	200	77	64
AP, kg SO_2 equiv.	471	394	173	380	306	163
Pesticides used, dose ha	7.1	8.8	7.7	3.0	7.7	3.5
ARU, kg antimony equiv.	36	35	30	27	38	28
Land use (Note 1)						
Grade 2, ha	0.04	0.00	0.00	0.05	0.00	0.22
Grade 3a, ha	0.79	0.74	0.64	0.49	0.67	0.98
Grade 3b, ha	0.83	0.00	0.00	0.48	0.00	0.00
Grade 4, ha	0.67	0.00	0.00	0.38	0.00	0.00
N losses						
NO_3-N, kg	149	48	30	287	36	72
NH_3-N, kg	119	97	40	106	79	40
N_2O-N, kg	11	6.4	6.3	9.0	7.0	7.1

Note 1: Land use for grazing animals comprises a combination of land types from hill to lowland. Land use for arable feed crops consists of land of one of the types. In the above table, arable land use is taken as all grade 3a.

3.2.1 Beef

Table 53 shows that 41% of the energy burden comes from the production of grass and a similar amount comes from the production of various concentrate feeds for beef. Manure represents a negative energy burden as it replaces fertiliser, but the emissions from manure and slurry mean that other burdens are positive.

Table 53: Distribution of burdens of beef production (per t)

Impacts & resources used	Grass	Concen-trates	Manure	Other
Primary energy used, MJ	41%	50%	-1%	10%
GWP_{100}, kg 100 year CO_2 equiv.	21%	27%	6%	46%
EP, kg PO_4^{3-} equiv.	48%	7%	36%	9%
AP, kg SO_2 equiv.	26%	4%	57%	13%
Pesticides used, dose ha	0%	97%	0%	3%
ARU, kg antimony equiv.	25%	72%	-1%	4%

The scenarios examined in Table 54 show that with beef there is a substantial difference between non-organic and organic production in the energy use, reflecting the difference between organic and non-organic grass. The former is assumed to include substantial amounts of clover, whereas non-organic grassland is assumed to have none due to the use of fertiliser discouraging the growth of clover. This is very much a worst case assumption and it is likely that up to 10% clover is possible versus up to 40% in the organic case. Note however that all other burdens from organic production increase including land use by 80% and a trebling of nitrate leaching.

Three alternative scenarios are shown. The first considers producing all the calves by suckler cows rather than a proportion being by-products of the dairy industry. This is increasingly likely with developments such as sexed semen. The maintenance costs of lowland suckler cows are saved when dairy bred calves enter the beef sector. This change increases all burdens by 40% to 60%.

The last two scenarios consider the alternatives of beef produced either on the lowlands or not on the lowlands. The results are similar which is a reflection of the poor land classes used in the lowlands for beef production. The model might need to be revised to consider the impacts if better lowland were used.

Table 54 Comparison burdens of production of some alternative beef systems (per t)

Impacts & resources used	Non-organic	Organic	100% suckler	Lowland	Hill & upland
Primary energy used, MJ	27,800	18,100	40,700	26,800	29,700
GWP_{100}, kg 100 year CO_2 equiv.	15,800	18,200	25,300	15,600	16,400
EP, kg PO_4^{3-} equiv.	157	326	257	153	169
AP, kg SO_2 equiv.	469	711	708	452	510
Pesticides used, dose ha	7.2	0.0	7.3	6.7	8.0
ARU, kg antimony equiv.	36	31	51	34	41
Land use, ha	2.3	4.21	3.85	2.28	2.41
N losses					
NO_3^--N, kg	147	427	269	146	156
NH_3-N, kg	119	180	178	114	130
N_2O-N, kg	10.9	11.8	15.9	10.7	11.3

3.2.2 Pig meat

Table 55 shows the differences between non-organic and organic pig systems. Unlike other commodities, pig meat shows reductions of all burdens from organic production, but uses considerably more land for the production of feed. Three alternative systems are compared. Finishing pigs at a heavier weight shows a slight reduction in burdens, mainly as a result of reducing the overheads of breeding piglets. The breeding herd being indoors or outdoors makes only a small difference to the burdens.

Table 55 Comparison burdens of production of some alternative pig meat systems (per t)

Impacts & resources used	Non-organic	Organic	Heavier finishing	Indoor breeding	Outdoor breeding
Primary energy used, MJ	16,700	14,500	15,500	16,700	16,700
GWP_{100}, kg 100 year CO_2 equiv.	6,360	5,640	6,080	6,420	6,330
EP, kg PO_4^{3-} equiv.	100	57	97	119	95
AP, kg SO_2 equiv.	395	129	391	507	362
Pesticides used, dose ha	8.8	0.0	8.2	8.6	8.8
ARU, kg antimony equiv.	35	33	33	40	33
Land use, ha	0.74	1.28	0.69	0.73	0.75
N losses					
NO_3^--N, kg	48	71	43	40	51
NH_3-N, kg	98	40	98	119	91
N_2O-N, kg	6.4	6.8	5.9	6.1	6.5

3.2.3 Poultry meat

Table 56 shows the difference between organic and non-organic poultry meat production. Unlike pig meat, organic poultry has a higher food conversion ratio and a longer growing period for the heavier chickens that are produced, resulting in a net increase in energy requirement for organic poultry meat production. The scenario of increasing the proportion of free-range chickens (in the non-organic sector) to 100% increases energy use and most burdens by about 20%, but still less than organic.

Table 56 Comparison burdens of production of some alternative poultry meat systems (per t)

Impacts & resources used	Non-organic	Organic	Free-range (non-organic)
Primary energy used, MJ	12,000	15,800	14,500
GWP_{100}, kg 100 year CO_2 equiv.	4,570	6,680	5,480
EP, kg PO_4^{3-} equiv.	49	86	63
AP, kg SO_2 equiv.	173	264	230
Pesticides used, dose ha	7.7	0.6	8.8
ARU, kg antimony equiv.	29	99	75
Land use, ha	0.64	1.40	0.73
N losses			
NO_3^--N, kg	30	75	37
NH_3-N, kg	40	60	53
N_2O-N, kg	6.3	9.3	7.6

3.2.4 Sheep meat

Table 57 shows the reduction in energy use with organic sheep meat production. As with beef, a considerable proportion of this reduction is due to the assumption of a large clover proportion in the grass, whereas, with non-organic production, the worst case assumption is made of no clover. Some of the other burdens, however, do not show a reduction.

One alternative scenario considered is to increase the value of mutton. At present, a ewe is valued at £35 and this is used to allocate the burdens between prime lamb meat and mutton. If the value of mutton is increased to £100 (the relative value that consumers ascribe to lamb meat and mutton), there is a reduction in burdens of about 15%.

Table 57 Comparison burdens of production of some alternative sheep meat systems (per t)

Impacts & resources used	Non-organic	Organic	Higher valuation of mutton
Primary energy used, MJ	23,100	18,400	19,400
GWP_{100}, kg 100 year CO_2 equiv.	17,500	10,100	14,600
EP, kg PO_4^{3-} equiv.	195	594	168
AP, kg SO_2 equiv.	368	1,511	321
Pesticides used, dose ha	3.0	0.0	2.5
ARU, kg antimony equiv.	27	19	23
Land use, ha	1.38	3.12	1.18
N losses			
NO_3^--N, kg	282	700	242
NH_3-N, kg	100	618	89
N_2O-N, kg	8.9	13.4	7.6

3.2.5 Eggs

Table 58 shows that organic egg production needs 14% more energy than non-organic and increases most environmental burdens by 10% to 33% (except pesticides), but the land area needed more than doubles. Comparing non-organic systems, keeping 100% hens caged incurs 15% less energy than 100% free range, with similar differences for most other burdens, although abiotic resource is 10% higher forcaged birds and land use 25%less.

Table 58 Comparison burdens of production of some alternative egg production systems (per 20,000 eggs)

Impacts & resources used	Non-organic	Organic	100% cage, non-organic	100% free-range, non-organic
Primary energy used, MJ	14,100	16,100	13,600	15,400
GWP_{100}, kg 100 year CO_2 equiv.	5,530	7,000	5,250	6,180
EP, kg PO_4^{3-} equiv.	77	102	75	80
AP, kg SO_2 equiv.	306	344	300	312
Pesticides used, dose ha	7.8	0.1	7.2	8.7
ARU, kg antimony equiv.	38	43	39	35
Land use, ha	0.66	1.48	0.63	0.78
N losses				
NO_3^--N, kg	36	78	35	39
NH_3-N, kg	79	88	77	81
N_2O-N, kg	7.0	9.0	6.6	7.9

3.2.6 Milk

Table 59 shows the reduction in energy burdens from organic farming, but all other burdens increase, particularly the doubling of land use with the consequent effect on nitrate leaching. Three alternative scenarios are also shown. In the first scenario, maize silage is increased to represent 50% of the bulk fodder, replacing grass and grass silage. There is a generally small change in burdens. The second scenario considers increasing the milk yield profile of low, medium and high yielders in the national herd from 25:55:20 to 0:40:60. This results in small decreases in most burdens of 2% to 5%, with greater milk producing efficiency being partly offset by less longevity in higher producing cows. Changing from 80% to 20% autumn calving herds (*i.e.* more summer milk) reduces energy needs and GWP by about 5%, but nitrate leaching and hence eutrophication potential increased by 8% and 3% respectively.

Table 59 Comparison burdens of production of some alternative milk production systems (per 10,000 l milk)

Impacts & resources used	Non-organic	Organic	More fodder as maize	60% High yielders	20% autumn calving
Primary energy used, MJ	25,200	15,600	23,600	24,200	23,400
GWP_{100}, kg 100 year CO_2 equiv.	10,600	12,300	9,800	10,200	10,300
EP, kg PO_4^{3-} equiv.	63	103	61	60	65
AP, kg SO_2 equiv.	162	264	164	159	159
Pesticides used, dose ha	3.5	0.0	2.8	3.4	2.9
ARU, kg antimony equiv.	28	14	24	27	25
Land use, ha	1.19	1.98	1.18	1.14	1.21
N losses					
NO_3^--N, kg	71	117	65	65	77
NH_3-N, kg	40	63	41	39	39
N_2O-N, kg	7.1	7.6	6.3	6.6	6.6

3.3 *Tomatoes*

3.3.1 Main burdens

The main burdens were calculated from producing the current national basket of tomatoes, the conditions of which are summarised in Table 60. An important systematic difference between the organic and non-organic sectors is that the organic sector favours both more specialist varieties and more on-the-vine (across the types). Combined heat and power (CHP) can theoretically be used in any production system and we have assumed an equal distribution of its use throughout.

Tomato production is a high input and high output system, with much higher yields per has than normal arable crops. Overall, however, the use of fuel for extending the season does result in substantially higher burdens per t than for arable crops.

Table 60 Summary of conditions used for producing the current national basket of tomatoes

Item	Proportion, %
CHP (same for all systems)	25
Organic by mass (*v.* non-organic)	3.6
Non-organic as NFT by mass (*v.* rockwool)	100
Non-organic crop as classic (*v.* specialist)	80
Non-organic crop as loose(*v.* on the vine)	80
Organic crop as classic (v. specialist)	43
Organic crop as loose(v. on the vine)	57

Table 61 Burdens of producing 1 t of the current national basket of tomatoes

Impacts & resources used	
Primary Energy used, GJ	125
GWP_{100}, kg 100 year CO_2 equiv.	9.4
EP, kg PO_4^{3-} equiv.	1.5
AP, kg SO_2 equiv.	12
Pesticides used, dose ha	0.5
ARU, kg antimony equiv.	100
Land used, m^2	30
Water, m^3	39

3.3.2 Benefits of CHP

Unlike field crops, the distribution of energy and GWP burdens are clearly dominated by the main heating and lighting inputs from natural gas and electricity (Table 62). Some values for heating and electricity are greater than 100% as the credits from CHP offset these as negative values. The same general trends apply to most burdens, although fertilisation and direct crop emissions contribute disproportionately highly to eutrophication potential and the greenhouse structure itself to abiotic resource use.

Table 62 Proportions of the main burdens attributable to each aspect of production with CHP, per t weighted production

Item	Primary Energy	GWP_{100}	EP	AP	Abiotic resource use
Heating & electricity	105%	102%	86%	101%	77%
Fertilisation	0.55%	0.85%	9%	6%	0.4%
Chemical crop protection	0.02%	0.02%	0.2%	0.2%	0.1%
Biological crop protection	0.21%	0.20%	0.2%	0.2%	0.2%
Annual materials	1.03%	0.60%	2.0%	2.9%	1.9%
Construction of greenhouse	0.87%	1.03%	4.0%	4.2%	26%
Seedling production	0.3%	0.3%	0.3%	0.3%	0.2%
Waste disposal and compost credits	0.01%	0.01%	0.05%	0.05%	0.02%
Direct crop emissions of N and P	0.00%	0.36%	7.6%	0.1%	0.0%
CHP credit	-7.9%	-5.3%	-9.3%	-15%	-5.7%
Total	**100%**	**100%**	**100%**	**100%**	**100%**

With the main burden being from heating and lighting, the potential benefits of CHP were explored by setting the national proportions to 0 and 100%. The results (Table 63) show that 70% of primary energy consumption could be saved with complete national implementation of CHP. The effects on other burdens are even more dramatic, with both eutrophication and acidification potentials becoming negative.

Table 63 Effects of changing the national proportions of CHP on main burdens, with current production systems

Burden	25% (current CHP)	0% CHP	100% CHP
Primary Energy used, GJ	125	111	37
GWP_{100}, kg 100 year CO_2 equiv.	9.4	8.1	6.7
EP, kg PO_4^{3-} equiv.	1.5	1.4	-0.06
AP, kg SO_2 equiv.	12.3	11.8	-10.4
Pesticides used, dose ha	0.5	0.5	0.5
ARU, kg antimony equiv.	99	91	48
Land used, m^2	30	30	30
Water, m^3	39	39	39

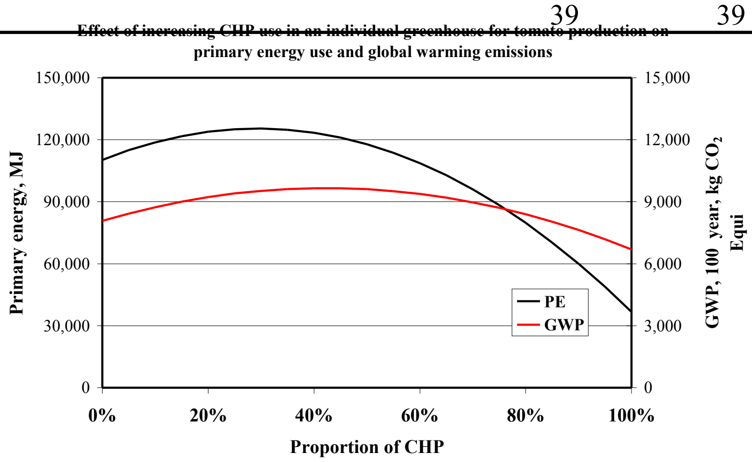

Figure 10 Effect of increasing CHP use in tomato production on primary energy use and global warming emissions, per t tomato production

Implementation within a greenhouse presents an interesting picture. The effects are curvilinear with the peak burdens occurring between 20% and 45% CHP (Figure 10 and Figure 11). Burdens increase as more gas is needed for CHP and the benefits of exporting electricity are not reached until a suitable threshold is reached.

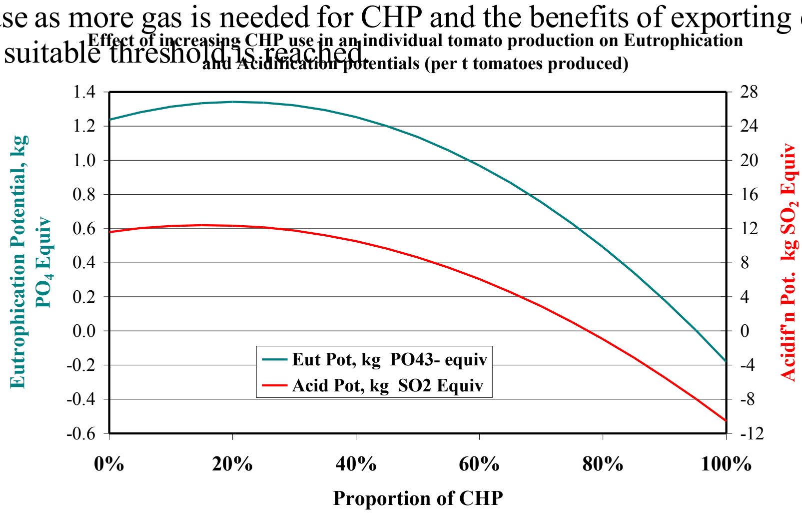

Figure 11 Effect of increasing CHP use in tomato production on eutrophication and acidification potentials, per t tomatoes produced

3.3.3 Effects of growing different tomato types

Because the inputs to the greenhouse remain very similar, irrespective of the type of tomato grown, the burdens per type of tomato grown depend very much on their yield. This was explored in various scenarios (Table 64). These show that organic production with the current organic mixture of tomato types has nearly twice as high burdens as non-organic production with the current conventional mixture of tomato types. This results from both the lower yields of organic tomatoes (75% of equivalent non-organic types) and the higher proportion of specialist and on-the-vine that are produced organically, which are also intrinsically lower yielding. The relative differences between the two non-organic systems of rockwool and NFT are trivial in comparison. Changing the proportions of tomatoes grown organically to be that of the current non-organic mix, reduces the organic burdens to being about 30% more than non-organic. This is further highlighted by comparing the burdens of producing individual tomato types (Table 64). This shows the burdens increase nearly five-fold (in any production system) moving from loose classic to specialist on-the-vine. These are further increased by going over to organic from non-organic.

Table 64 Burdens of producing different types of tomatoes by different methods

Burden	All organic (current mix)	All non-organic (current mix)	All NFT (current mix)	All rockwool (current mix)	All organic (current *conventional* mix)
Primary Energy used, GJ	229	122	121	122	159
GWP_{100}, kg 100 year CO_2 equiv.	17.5	9.14	9.09	9.15	12.2
EP, kg PO_4^{3-} equiv.	5.5	1.3	1.2	1.3	3.8
AP, kg SO_2 equiv.	34.6	11.5	11.3	11.5	24.1
Pesticides used, dose ha	0.3	0.5	0.5	0.5	0.2
ARU, kg antimony equiv.	181	96	96	97	126
Land used, m^2	55	29	29	29	39
Water, m^3	49	38	22	39	34

Table 65 Burdens of producing different types of tomatoes

	Classic loose	Classic on-vine	Specialist loose	Specialist on-vine	Specialist on-vine organic
	Non-organic				
Primary Energy used, MJ	79	188	159	380	505
GWP_{100}, kg 100 year CO_2 equiv.	5.9	14.1	11.9	28.5	38.6
EP, kg PO_4^{3-} equiv.	0.8	1.8	1.6	3.7	12.1
AP, kg SO_2 equiv.	7.3	17.5	14.8	35.4	76.3
Pesticides used, dose ha	0.3	0.7	0.6	1.5	0.6
ARU, kg antimony equiv.	62	148	125	299	398
Land used, m^2	19	45	38	92	122
Water, m^3	14	34	29	69	107

Of course, organic production does not incur as much pesticide use as non-organic production. The small amount recorded has a physical rather than physiological effect.

4 Discussion

4.1 *Arable*

The results from arable crop production show a general trend for organic production to be less energy demanding per functional unit produced than non-organic. This is mainly due to not using synthetic nitrogen fertiliser, which has a high energy requirement, although this has reduced over the years. The reliance of nitrogen fixing by legumes in organic systems clearly reduces energy demand, but the throughput of nitrogen is limited, so restricting yields and / or protein concentration in crops like wheat. The organic system also has high losses of nitrogen leached as NO_3^- and volatilised as N_2 and N_2O. This is partly because the soil has to contain high levels of nitrogen and more than one year's leaching occurs percash crop.

Organic cropping uses the plough as the principal primary cultivation tool for the crops studied. Undersowing is also practiced, but the overall effect of using cover crops and the plough is for the direct energy consumption per ha to be generally higher in organic than non-organic cropping. With the lower yields of organic production, this field consumption of fuel largely offsets the saving from not using fuel for fertiliser manufacture.

The land use for organic cropping is based on stockless rotations so that all the land used for N fixing was included in the land's requirements for the cash and feed crops. There is some dual use of such land in practice, although if there is too much offtake (for example by grazing animals or conserved forage), then the nutrients available for subsequent arable crops will be reduced. The arable (and animal) systems were analysed using a steady state analysis in which no long term accumulation or depletion of plant nutrients was allowed to occur. Thus all offtake had to be replaced by imports (for P & K) or fixing and import of N. It is quite plausible that many farmers are actually over-or under-supplying nutrients, so that, for example, organic farmers (especially early in conversion) may be depleting soil P and K until new equilibria are established. If our estimates of P & K imports seem high, this may be the reason. The long term steady state analysis does imply that some practices are technically unsustainable.

Wheat was analysed by Audsley *et al*. (1997) in a pan-European project. They calculated energy consumption for wheat with 12% CP to be 3.3 GJ/t for 8 t/ha non-organic production and 2.8 GJ/t for 4 t/ha organic wheat. We found rather lower values for bread wheat at 2.5 and 1.7 GJ/t, but of a similar magnitude. The Danish food LCA database (http://www.lcafood.dk/) has similar values for some aspects of wheat production, although the main contrast is that they have a much lower GWP and land use from organic wheat production. Our study calculates the burdens per tonne of wheat that reaches the bread quality threshold, which, especially for organic production, gives higher values than burdens pertonne of crop yield (Table 66).

Table 66 Comparison of wheat production burdens between this study and in Denmark

Impact category	Non-organic		Organic	
	DK	This study	DK	This study
GWP	710	804	280	786
Acidification	5.3	3.2	4.5	3.4
Land use, ha	0.15	0.14	0.22	0.44

Generally good agreement was also found between potato and rape production in the Danish LCA work and ours (Table 67). The comparison shows second early potatoes because the Danish inventory did not include storage.

A large amount of energy is used for storing maincrop potatoes, which comes from mainly electricity consumption. While we have endeavoured to represent the industry practice fairly, there is a need for more activity data on contemporary practice.

Table 67 Comparison of potato and rape production burdens between our study and in Denmark

Impact category	Non-organic potatoes		Non-organic rape	
	DK	This study	DK	This study
GWP	160	178	1,510	1,710
Acidification	1.16	1	11.8	9.2
Land use, ha	0.031	0.025	0.35	0.31

Röver *et al.* (2000) compared primary energy consumption from non-organic and organic production in Germany (Table 68). Values from this study presented are bread wheat and second early potatoes (no storage required). Agreement between the two studies is good overall. The main difference is that our value for organic rape is substantially higher than theirs, but we acknowledge that our estimates for organic rape yields are based on the relative yields of organic and non-organic wheat. Very little organic rape is, however, grown in Britain.

Table 68 Comparison of primary energy consumption (GJ/t) between arable production in Germany and this study.

	Non-organic		Organic	
Crop	Germany	This study	Germany	This study
Wheat	2.4	2.5	1.5	1.7
Rape	6.0	5.4	2.5	4.0
Potatoes	0.63	0.65	0.58	0.65

There is thus reasonably close agreement between the values from the present study and those conducted elsewhere. It supports confidence in our results, but also has highlighted some differences. Whether these are because of geography and farming methods or simply the assumptions made requires more detailed investigation.

Pig feed production in Brittany (by non-organic methods) was examined in an LCA study by van der Werf *et al.* (2005). The mean of piglet, sow and finishing feeds were compared (Table 69). All results were generally similar, except GWP, which was almost twice as high in this study than in the Brittany one. Land use was identical.

Table 69 Comparison of pig feed (1 t) production between this study and in Brittany

	Brittany mean	This study mean
Primary energy used, GJ	3.7	3.4
GWP_{100}, kg 100 year CO_2 equiv.	0.53	1.1
EP, kg PO_4^{3-} equiv.	4.4	3.4
AP, kg SO_2 equiv.	4.6	4.8
Land use (grade 3a in this study), ha	0.17	0.17

4.2 *Animal products*

Cederberg (1998) compared organic and non-organic milk production in Sweden on 2 individual farms. Compared with ours (Table 70), Swedish production consumes more energy but creates similar GWP. Other values are all in the same order of magnitude. The lower energy land use in Britain suggests greater efficiency than in Sweden, probably enabled by geographic differences.

Table 70 Comparison of milk production systems in this study and Sweden (per 1,000 l milk)

	Non-organic		Organic	
Impacts & resources used	Sweden	This study	Sweden	This study
Primary Energy used, GJ	3.6	2.5	2.5	1.6
GWP_{100}, t 100 year CO_2 equiv.	1.1	1.1	0.95	1.2
AP, kg SO_2 equiv.	18	16	16	26
Land use, ha	0.19	0.12	0.35	0.20

N losses				
NO_3^--N, kg	3.6	7.1	4.9	12
NH_3-N, kg	7.0	4.0	6.1	6.3
N_2O-N, kg	0.36	0.71	0.30	0.76

Subak (1999) calculated GWP from beef cattle in US feedlots and assuming 55% recovery of liveweight as edible carcass, this equated to 14.5 t CO_2 equivalent per t beef. Cederberg (2002) calculated a value of 17 t CO_2 equivalent per t beef for animals produced by home feed growing and mixing. Both are similar to our values.

It is apparent that the ruminant products produce larger burdens than pig and poultry meat. This partly results from the much higher daily gains and better feed conversion ratios found in the mono-gastrics. It also stems from much greater fecundity of sows and hens, so that breeding overheads are lower. Non-ruminant pigs and poultry effectively live on arable land. Ruminants, however, permit animal production on land that is unsuitable for arable crop production, since they can digest cellulose, albeit with enteric emissions of methane which increase the ratio of GWP / Energy to about 0.3 versus 0.2 for mono-gastrics. Ruminants can also make good use of some arable by-products, such as barley straw as feed and straw as bedding (later returned as manure). This clearly imposes limits on the potential substitution of any animal commodity for another. Also, one should remember the close association of beef to milk production.

4.3 *Tomatoes*

Tomato production is clearly much more energy demanding than other crops. That is the price for obtaining a greatly extended supply of fresh salad food. It is also the exception in this study in that organic production is more energy consuming per tonne owing to the lower yields from similar energy consumption.

Although outside the system boundary, there may be significant differences in the fate of tomatoes post-production. The more specialist (and organic) are increasingly expensive in cash terms and there are probably also greater expectations about taste. Consumers are likely to be less wasteful of more expensive varieties, so that the relative burdens of the consumed fruits should be closer than that based on just production alone. There may also be systematic differences in the quantities of fruit types bought directly by end-consumers and the catering industry that could also affect the final burdens of productions and consumption. It would be very interesting to have these effects quantified.

Increasing the use of CHP could reduce the burdens. Other possibilities are:

- Decoupling heat and CO_2 supply: Heat and CO_2 are currently normally supplied from one source, so that the supply rate tends to be a compromise. If an alternative source of CO_2 were available, de-coupling, with more targeted supply rates could be achieved. The best source of CO_2 is biogenic, *e.g.* from the fermentation industries.
- Using only waste heat without CO_2 enrichment: This would provide one method of enhancing growth, with a low environmental (and presumably economic) cost, but would reduce productivity per unit area. Relocation is also implied.
- Reduced heat input: One option is to use heat only in the winter months. It would reduce the heat requirement and productivity and possibly hasten the end of the season. The exact balance could be environmentally favourable or not. It requires careful analysis.
- Short season cropping: Greatly limiting heat input would return the growing season to the summer months and so make the UK produced tomato supply much more seasonal, but less reliant on fossil fuel. It would be much less productive and increase the seasonality of labour requirement, with generally negative effects on employment and

cost. The ultimate environmental effects would depend on the balance of imported alternatives (from where and how produced) as well as any change in consumer preferences.

We do not yet have sufficiently detailed data on all aspects of production to be able to analyse all the possible options in great detail. This results from the main sources being commercial data in which some items, like green waste, would not be measured with scientific accuracy and others could be restricted for commercial reasons. Average data on items like fertiliser use and green waste tend to mask actual differences between specific production methods and varieties. For example, a house may contain several types of tomato, each with different nutritional needs. There are other possible outcomes from the use of CHP in that the balance of available heat and CO_2 differ from boiler heating. There may be effects on productivity that have not been adequately described. Without sufficiently detailed data, we cannot model all options as closely as could be wished.

4.4 *A carbon-nitrogen footprint for agriculture.*

Unlike most of industry and domestic activity, the GWP from arable cropping is dominated by N_2O, not by CO_2 from fuel use. N_2O contributes about 80% to GWP in wheat production (both organic and non-organic). The N_2O contribution falls to about 50% for potatoes as much fossil energy goes into cold storage. A similar pattern occurs with animal production as they live on crops. Another consequence is that the GWP of organic crop production is little lower than from non-organic cropping. In contrast, CO_2 from the use of natural gas and electricity in tomato production is the dominant contribution to GWP.

The balance of global warming gas emissions and fossil fuel consumption is thus quite different from most industries. Most industries consume energy (most from fossil C-based fuel) and thus emit CO_2 as the main gas contributing to global warming. The *carbon footprint* is thus a reasonable shorthand for both the consumption of C-based resources and the emission of CO_2. In agriculture, N_2O dominates, with substantial contributions too from methane. Consequently, a carbon footprint inadequately describes agriculture; it has a *carbon-nitrogen footprint*. Indeed, the nitrogen fluxes in agriculture (and other types of land) also contribute to eutrophication and acidification.

Others have noted the dominance of N_2O in GWP. Robertson *et al.* (2000) compared arable cropping systems of wheat, maize and soya in a rotation (and other land management options). They found that the contribution of N_2O (by field measurement) to GWP was 45% for plough-based conventional tillage, 46% for direct drilling and 80% for organic. These do not include soil carbon, which was not included in our study. In the present study, N_2O contributed to between 75% and 84% of GWP for these crops grown non-organically and 60% to 88% organically. Robertson *et al.* (2000) did not, however conduct a full LCA, so sources like secondary N_2O from leaching were not included and it is unclear if direct N_2O emissions from fertiliser manufacturing were included or not, but both studies show the prominence of N_2O.

N_2O emissions from land are the probably least well understood agricultural emission and thus the prominence of N_2O makes calculation of the GWP more uncertain than from other industries (especially those with easy to measure emission outlets), They are also more uncertain than the other environmental emissions from agriculture. This reinforces the need to improve the understanding of N_2O emissions. We used the IPCC methodology and there are other methods that could be justly used, for example the DNDC simulation model (Li *et al.*, 1992). Broad agreement would be anticipated, but there could be substantial differences between particular features.

Agriculture contributes 7% of aggregated greenhouse gases in the national inventory (Baggott *et al.*, 2004). Agriculture, however, dominates ammonia emissions and nitrate leaching and these both contribute to eutrophication and ammonia to acidification. The agricultural carbon-nitrogen footprint thus affects three major areas of environmental pollution.

4.5 *Uncertainties*

Measurements of major terms used in this study (*e.g.* pollutants and energy use on farms or in manufacturing) are all associated with errors. This can be very small in well-defined situations, but those to do with agriculture are inherently more variable. Measurements of individual emissions may have coefficients of variation, CV, (standard deviation divided by the mean) of as much as 70% (*e.g.* for N_2O). The errors in national inventories of gaseous emissions from agriculture are typically about 30%. The errors in a whole farm model (which included field operations; profitability; emissions of ammonia, methane, nitrous oxide and nitrate; and soil P balance) were in the range of 10% to 34% (Williams *et al.*, 2004b), with most the emissions at about 32%.

Aggregating components reduces uncertainty. For example, summing three uncorrelated components of equal magnitude, each with a CV of 35%, results in an overall uncertainty of 20%. Multiplying increases uncertainty and multiplying the same three terms results in an overall uncertainty of 61%. The LCA model includes both additive and multiplicative terms. A reasonable estimate of the uncertainty associated with any calculated burden is 30%.

Major factors (in addition to N_2O) are N fertilisers, fuel and yield. Energies for ammonium nitrate production in the literature range from 38 to 51 MJ/[kg N], with values generally decreasing with time. We have used 41 MJ/[kg N]. Changing the estimate by 3 MJ/[kg N] corresponds to energy use changing by 67 MJ / [t bread wheat] or 3%. Fuel use estimates have been shown to have a typical coefficient of variation of 40%. This corresponds to 220 MJ / [t bread wheat] or 9%. An error of 0.5 t/ha in yield corresponds to 161 MJ / [t bread wheat] or 6%. Nitrate leaching was estimated using models which demand that all the nitrogen be accounted for. While this ensures that the surplus of intake over offtake is correct, the balance of emissions could be incorrect.

The component ruminant rearing systems are taken from a number of sources to represent the major structure of the industries. It is acknowledged however that there are a very large number of ways used to rear beef and sheep, often making use of otherwise waste products. There is therefore still a need to examine further their uses of feed sources and their consequent use of energy.

Data on national fertiliser use on grassland is aggregated and a model was created to estimate the use on different land types by different animal systems. Further work is needed to ensure this model accurately represents the different systems and correctly predicts N emissions.

Despite the effects of uncertainty on the absolute accuracy of the LCA model, it is relatively accurate at performing comparative analyses. Uncertainty is highly correlated between scenarios, thus comparative differences are largely a consequence of differences between systems.

5 Publicising and using the model

5.1 *Publicising the model*

A user workshop was held at which the interface and models were presented. It generated considerable interest from a number of parties and allowed the proposed approach of the interface to be tested. It generated incisive questions for the team as well as guidance on the type of studies that user might wish to undertake with the model. Several requests for working copies of the model followed.

Descriptions of the model and preliminary outputs were put on the SRI website. This provided us with more feedback, thus indicating that it had been accessed. It was later mounted on the Cranfield University website at: http://www.silsoe.cranfield.ac.uk/ (then search for IS*0205* and *LCA*).

Presentations about the work were also given at conferences including: the Soil Association Annual Conference, the Agricultural Research Modellers' Group and the European Society for Operational Research, as well as at university seminars and to visitors.

The model has been used to inform other Defra-funded research projects and is well placed to analyse variations in existing production systems. It can also be readily developed to analyse new production systems or commodities. For example, sugar beet would be based on potatoes or farmed deer on sheep or beef.

6 Further Work

Further work is required and much should be achievable in the Defra-funded project IS0222 (*Underpinning the delivery of computer based environmental Life Cycle Assessment (LCA) of agriculture*), which is already underway. The objectives relating to model development are shown below, with limited descriptions.

1. Further development and delivery of the Defra life-cycle inventory of the production of agricultural commodities
   1.1. User testing
   1.2. Overcoming problems found in the tool
   1.3. Development of the tool to meet users' desired enhancements
   1.4. Addition of other commodities
2. Development of a UK food basket version of the LCI tool
   This objective will seek to integrate the individual commodity analyses to a single UK food analysis which will explicitly consider the interactions between them.
3. Development of a farm-level version of the LCI tool
4. Disaggregation of the LCI tool to analyse production on a regional basis
5. Development of a life cycle assessment to follow from the inventory
   This objective will add an impact assessment section to the LCI tool to enable users to study the comparative importance of the identified burdens.

Particular areas that have come to light since the writing of the project objectives for the Defra-funded project IS0222 include soil carbon loss from imported feeds, like Brazilian soya or palm oil residues, and overall soil carbon balances in domestic agriculture; use of , by-products or waste products from the food industry. Also, given the great importance of nitrous oxide on GWP, consideration should be given to alternative calculation methods for emissions from soils.

7 Conclusions

7.1 *The models*

- A procedure to calculate the burdens of production for current and future combinations of production systems, using the principles of life cycle assessment (LCA) was constructed for ten agricultural and horticultural commodities in England and Wales
- The modelling system allows users to compare different production systems by varying the proportions of the components within them, for example to study an increased proportion of higher yielding dairy cows.
- The models calculate all resource burdens back to primary units (*e.g.* energy as crude oil in the ground) and include all significant inputs and processes from phosphate rock quarrying to animal feedproduction, imports, processing and delivery.
- Emissions to the environment are aggregated as functional burdens, *e.g.* global warning potential (GWP) over a 100 year time frame, acidification (equated to sulphur dioxide), eutrophication (equated to phosphate) and abiotic resource used scaled in relation to the element antimony .
- Individual emissions are also accessible to allow more detailed analysis.
- Detailed breakdowns of components such as the energy of different arable operations or the components of animal production are available.
- Alternative grades of land use for arable crops are modelled, based on linear scaling of the grade 3a land class. In contrast, geographical data was used to estimate the entire range of land grades that are currently used for different grassland systems, such as upland sheep grazing.
- Animal production is modelled as a network so that changes to one part, *e.g.* upland sheep, are systematically reflected in another, *e.g.* lowland sheep.
- All analyses include organic and non-organic (or contemporary conventional) production systems, which may each have several sub-systems.
- All production was analysed using a long-term, steady-state approach to ensure that no depletion or accumulation of plant nutrients occurred.

7.2 *The results*

- Organic field crops and animal products mostly consume less primary energy than non-organic counterparts owing to the use of legumes to fix N rather than fuel to make synthetic fertilisers. Poultry meat and eggs are exceptions, resulting from the high overall efficiency of feed conversion in the non-organic sector.
- The relative burdens of GWP, acidification and eutrophication between organic and non-organic field-based commodities are more complex than energy. Organic production often results in increased burdens, from factors such as N leaching and N_2O emissions from clover leys and lower yields.
- N_2O is the single largest contributor to GWP for all commodities except tomatoes, exceeding 80% in several cases. It is also the emission about which there is the least understanding about its reliable quantification.
- The lower yields and fertility building requirement of organic production mean that more land is *always* required for organic production, ranging between 65% and 200% extra.

- Ruminant meats produce more burdens than pig or poultry meats, but ruminants can derive nutrition from land that is unsuitable for the arable crops that pigs and poultry must eat.
- Heating and lighting dominate the burdens of tomato production, but increasing the national use of combined heat and power (CHP) could reduce the primary energy consumption by about 70%.
- Unlike field crops, organic tomatoes always incur more burdens (except pesticide use) than non-organic counterparts because yields are lower, but the inputs are almost the same per unit area.
- Smaller and on-the-vine tomato types also incur definably more burdens of production than loose and larger ones (classic and beefsteak).
- The LCA model generally agrees with reported studies. Where substantial differences exist, it is not clear whether these stem from different assumptions in methods or the actuality of production in different geographic areas.

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This final report on IS0205 updates and extends the draft report submitted to Defra on 7th December 2005 on the closure of Silsoe Research Institute. It includes additional sub-models developed as part of the on-going project IS0222.
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