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The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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Carbon footprinting and UK horticulture

Concepts and commercial relevance

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1 Introduction

Concern about climate change has stimulated interest in estimating the total amount of greenhouse gases (GHGs) emitted during the production, processing and retailing of many consumer goods, including food products. The process of estimating these emissions is termed 'carbon accounting' and the final description of emissions is termed the 'carbon footprint' (discussed further in the next section). Once the carbon footprint for a product has been estimated it is possible to use this information to inform producers, consumers and other stakeholders about the relative impacts of different products on the climate.

It is also possible to declare the carbon footprint of a product on its packaging; a so-called carbon label. When this occurs the carbon label may act in a similar way to many other product labels which assume that concerned consumers will preferentially purchase goods with attributes that they value, here a low carbon footprint. If the purchasing patterns of consumers were influenced by carbon labels then the producers with the lowest carbon footprint may be at a commercial advantage. The natural corollary of this is that these businesses would expand, while competing businesses with higher carbon labels might decline. While many in society may view such change as a positive response to the challenge of global climate change, there will inevitably be major impacts on individual businesses. For this reason it is important that individual businesses are familiar with the basics of carbon footprinting, and are aware of the impacts any carbon label may have on their future.

The purpose of this document is to provide a background in carbon footprinting to all those engaged in UK horticulture. It seeks to present the results of the latest science, as it is currently understood. In so-doing it does not seek to hide areas of poor performance in the sector, or to underplay the challenges that face particular sectors. The report is presented in the hope that the UK horticultural sector can rise to the challenge of adapting to climate change and develop 'carbon efficient' supply chains for the future.

This report is one of two reports which discuss carbon footprinting in horticultural enterprises. This report is the more technical and detailed report which aims to provide a full discussion of the issues to interested readers. The sister report provides a summary of the main issues, and aims to provide an accessible summary of the main issues to all interested parties.

The report is structured into three main sections:

Section 1 presents technical information on the methodology of carbon footprinting. It begins with some definitions of technical terms and then presents an outline of the current carbon footprinting methodology. In order to put the concepts and methodology in context, three case studies are presented on the carbon footprints of supply chains in three different sectors: cut flowers, apples and lettuce. (protected & field) The section concludes by considering some of the important practical and methodological points which come out of the case studies.

Section 2 presents data on the overall emissions from the UK horticultural sector. It then seeks to place these data in context by considering the relative importance of emissions from horticulture compared with those from other sectors of the UK economy.

Section 3 considers each of the major horticultural sectors in turn. Where possible relevant scientific studies are used to highlight areas of particular concern for each sector. Where no such studies exist some areas of likely concern are discussed. The section finishes with a summary of practices which could be adopted in order to reduce the carbon footprint of horticultural enterprises.

2 Concepts and case studies

2.1 Definitions

Carbon footprint: A carbon footprint is a measure of the impact of human activities on global warming. It is expressed in terms of the total amount of greenhouse gases (GHGs) produced. The carbon footprint of a product is the amount of GHG emission emitted during its production.

The most important GHGs in horticulture and agriculture are carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Other GHGs that also contribute to climate change, such as halocarbons, ozone and carbon monoxide, are not typically considered in carbon footprints of horticultural produce (see Appendix 1 for more details on calculating a carbon footprint).

CO_2 equivalents and global warming potential (GWP): Carbon footprints are expressed in units of CO_2 equivalents. This is because different greenhouse gases have different impacts on the atmosphere – so-called radiative forcing. The degree of radiative forcing of a GHG depends on several factors including how long they survive in the atmosphere, their current concentration in the atmosphere and their ability to capture infrared radiation. It is the ability of these gases to capture and reflect infrared radiation that brings about the change in global climate. The Global Warming Potential (GWP) is a measure of the relative radiative effects of the emissions of the various gases. The index is defined as the cumulative radiative forcing between the present and a future time horizon caused by a unit mass of gas emitted now, expressed relative to that of CO_2. It is necessary to define a time horizon because the gases have different lifetimes in the atmosphere.

Currently it is estimated that when viewed over a 100 year time horizon the impact of 1 kg of CH_4 on global warming is equivalent to that of 25 kg of CO_2, while 1 kg of N_2O is equivalent to 298 kg CO_2 (IPCC 2007). As scientific knowledge on global warming has progressed so these conversion factors have been amended over time. Previously, the Intergovernmental Panel on Climate Change (IPCC) had suggested that 1 kg of CH_4 was equivalent to 23 kg of CO_2, and 1 kg of N_2O was equivalent to 296 kg CO_2 (IPCC 2001), while before that IPCC (1995) had suggested GWP conversion factors of 21 for CH_4 and 310 kg for N_2O. This is not a problem from a scientific point of view, however some legislation and treaties may have adopted earlier IPCC conversion factors, and care should be taken to ensure equivalence in any calculations.

Carbon source: A carbon source is something that gives off GHGs (e.g. a coal power station).

Carbon sink: A carbon sink is something that locks up GHGs (e.g. a growing forest).

Carbon neutral: A system is carbon neutral when it has net zero emissions, i.e. it locks up as many GHGs (expressed as CO_2 equivalents) as it releases.

Carbon offsetting: Carbon offsetting is a way of achieving 'carbon neutrality' by purchasing a 'carbon sink' somewhere outside the defined system boundary (e.g. outside the household or business).

Emission factor: The amount of GHGs emitted during the manufacture and/or use of products are termed emission factors. These are usually expressed in terms of kg of CO_2-equivalents, but are sometimes quoted as kg of CO_2 only. If the emission factors for the manufacture, transport and use are known for a certain amount of product, and the amount of that product in a given process is also known, then the total GHG emission arising from the use of that product in that process can be estimated. This is achieved by a simple multiplication of the amount of product used by the relevant emission factors. If this process is repeated for all products relevant to that process, then the total GHG emissions for the entire process can be calculated. For example, consider a simple cropping system which involves use of machinery, fertiliser and pesticides. The GHG emissions from fertiliser use in this system can be obtained by multiplying the amount of fertiliser used by the relevant emission factors for its production, transport and on-farm use. A similar process is possible for machinery and pesticides, and the addition of GHGs emitted for each of the three inputs provides an estimate of the total GHGs emitted by the simple cropping process.

Rather confusingly, it is possible to find a range of emission factors reported for the same product, and a range of emission factors for typical horticultural inputs are provided in Table 1 and for different sorts of transport in Tables 2 and 3. One of the reasons for this variation relates to the fact that some of the emission factors are location specific. For example, if a country were to generate a large proportion of its electricity from renewable sources, such as hydroelectric or solar, then the emission factor for electricity in that country would be significantly less than for electricity production in a country with a large dependence on power generation technologies which emit large amount of GHGs, such as coal powered electricity generation. These differences in emission factors for electricity can then have knock-on effects on the carbon footprint (i.e. the embodied GHG emissions) from products. So emissions from nitrogen fertiliser produced in an economy largely dependent on renewable energy will be lower than the same fertiliser produced in a more coal dependent country.

A second reason for the variation in emission factors relates to the different methodological approaches adopted when calculating the emission factors. These tend to vary with time as methods, and system boundaries, change and also to vary a little between countries. In view of the variation in the available emission factors it would be sensible for anyone constructing a carbon footprint to utilise the variation in published emission factors to estimate best and worst case scenarios for the carbon footprint.

Table 1. Ranges of greenhouse gas emissions in kg CO_2 equivalents from the use of diesel, petrol and electricity, the production of different fertilisers, pesticides and silage wrap and following the application of nitrogen fertiliser reported in the literature. One potential problem

with these data is that the figures from different studies include different processes, e.g. production, packaging, transportation, storage and transfer, with some being more comprehensive than others, and some studies not stating exactly which processes are included. * CO_2 only. ** calculated assuming a global warming potential for N_2O of 298 over a 100 year time horizon (IPCC 2007).

Item	min	max	mid
Diesel (kg CO_2 equ l^{-1})			2.74
Petrol (kg CO_2 l^{-1}) *			2.315
Electricity (kg CO_2 kWh^{-1}) *			0.523
Fertiliser – N (kg CO_2 equ kg^{-1} N)	2.99	9.56	6.28
Fertiliser – P (kg CO_2 equ kg^{-1} P_2O_5)	0.42	1.08	0.33
Fertiliser – K (kg CO_2 kg^{-1} K) *	0.3	0.72	0.51
Pesticides (kg CO_2 equ kg^{-1} active ingredient)	3.4	34.2	18.8
Silage wrap (kg CO_2 equ kg^{-1} plastic)	1.3	1.94	1.64
Direct N_2O emissions from soil after synthetic N fertiliser or organic fertiliser application (kg CO_2 equ kg^{-1} N applied) **			4.68

Table 2. Direct emissions of CO_2 and global warming potential (GWP) of all gaseous emissions for different modes of transport. [a] Includes all direct emissions of CO_2 to provide 1 t*km (i.e. including production and delivery of fuel and capital infrastructure). [b] Includes also radiative forcing of emissions of other greenhouse gases. # It should be noted that the Royal Commission on Environmental Pollution highlights that “the total radiative forcing due to aviation is probably some three times that due to carbon dioxide emissions alone” (RCEP 2002). Source: Ecoinvent 1.2 database (Spielmann *et al.* 2004).

Transport type	kg CO_2 (direct)/t*km [a]	kg CO_2 equ (GWP)/t*km [b]
Passenger car	0.191 kg/passenger km	0.203 kg/passenger km
Van < 3.5 t	1.076	1.118
Truck, 16 t	0.304	0.316
Truck, 32 t	0.153	0.157
Plane, freight #	1.093 #	1.142
Train, freight	0.037	0.038
Transoceanic freight	0.010	0.011
Transoceanic tanker	0.005	0.005

Table 3. Range of emissions of CO_2 (not CO_2 equivalents) in kg CO_2 per tonne km for different modes of transport. Data from McKinnon (2006) and studies cited therein (study 1-7). * electric, ** diesel.

	Study 1	Study 2	Study 3	Study 4	Study 5	Study 6	Study 7
Short-haul air freight	1.42	1.58	1.925				
Long-haul air freight	0.637	0.800	0.800	0.867			
Train freight	0.02	0.033	0.017 *	0.030 *	0.038 *	0.18 *	0.035 **
Inland waterways	0.03-0.04						
Coastal shipping	0.03						

Food miles: This term is popularly used to describe the distance that food travels from farm gate to consumer and has generated considerable interest among environmental groups, academics, government, the media, and the general public (see Kelly 2004, Frith 2005, Smith *et al.* 2005, Hamilton 2006). In response to these concerns there is a growing advocacy for food systems that reduce food miles, popularly termed ‘local food’.

Life Cycle Assessment (LCA): Life Cycle Assessment (LCA) is an internationally standardised methodology which aims to quantify the environmental impacts of products on air, water and land, taking into account their entire life cycle from the extraction of raw materials, the production phase, distribution, to use and waste disposal. According to the relevant ISO standards (ISO 2006a, 2006b), LCA begins by defining the system under study, i.e. all the activities making up the supply chain, and also the functional unit, i.e. the quantitative basis on which the results are compiled and alternative systems compared, such as 1 kg of tomatoes or 1 litre orange juice. The subsequent inventory stage quantifies all resource flows into and emissions out of the system. In the impact assessment phase, the environmental effects of these resources and emissions are quantified in terms of their contribution to a recognised set of resource depletions and environmental impacts. The last phase is called interpretation: it applies the results of the impact assessment and inventory stages, and may use sensitivity and dominance analyses to investigate the significance and robustness of the results. LCA was originally designed for industrial systems and has been extensively used in this context (e.g. Rivela *et al.* 2006), but has also increasingly been used for food systems (e.g. Hospido & Sonesson 2005, Halberg 2003, Mattsson *et al.* 2001).

System boundary: The system boundary defines the extent of processes that are included in the assessment of GHG emissions. In the absence of an agreed framework for calculating a carbon footprint, there is the potential to draw the system boundary in different ways. For this reason it is important to clearly define the system boundary of concern, and to be aware of any differences in system boundary when making comparisons between similar products from different supply chains. Unfortunately, many of the studies on energy use and carbon footprints tend to utilise slightly different system boundaries, so when comparing between different production systems it is important to check the system boundaries are the same before coming to any conclusions.

System boundaries may be defined in any way that is appropriate to the analysis. When considering horticultural activities at least four system boundaries can be defined. These become successively more complex and comprehensive as the system boundary is expanded. Figure 1 shows a representation of a typical horticultural system. It shows the major processes and sub-systems constituting the overall system (e.g. fertilisation, harvesting), the flow of inputs into the system (e.g. seeds, energy) and the flow of outputs from the system (e.g. produce into the supply chain and emissions to the environment). By combining the relevant processes, inputs and outputs in different ways there are many ways to define the system of concern, as discussed below:

Consider on-farm activities only:

1. <u>Emissions from inputs only.</u> This includes emissions arising from the manufacture and distribution of inputs, and the transport of these inputs to the farm. It also includes any impacts related to the direct use of the inputs on-

farm, such as machinery and fuel use (i.e. considers emissions related to the production of fertilisers and other inputs and their transport, as well as direct use of fuel and energy on-farm).

2. Emissions from inputs and ecosystems. This includes the items in 1 above but also considers the flow of greenhouse gases into and out of soils and plants in the productive and non-productive areas of the farm, e.g. woodlands.

Consider on-farm activities plus processing, retailing and consumption:

3. Emissions from inputs only. This includes inputs and processes up to the farm gate plus transport, processing, packaging, retailing, consumption and waste disposal.
4. Emissions from inputs and ecosystems. This includes the items in 3 above but also considers the flow of greenhouse gases into and out of soils and plants in the productive and non-productive areas of the farm, e.g. woodlands.

Non-productive areas of farms as included in system boundaries 2 and 4 may form quite large areas in many horticultural systems, and these may have the potential to both release and lock-up carbon. Indeed some productive areas may also serve to lock up carbon, e.g. trees in orchards. (see sections 2.4.4 and 4.7 for further discussion on these matters).

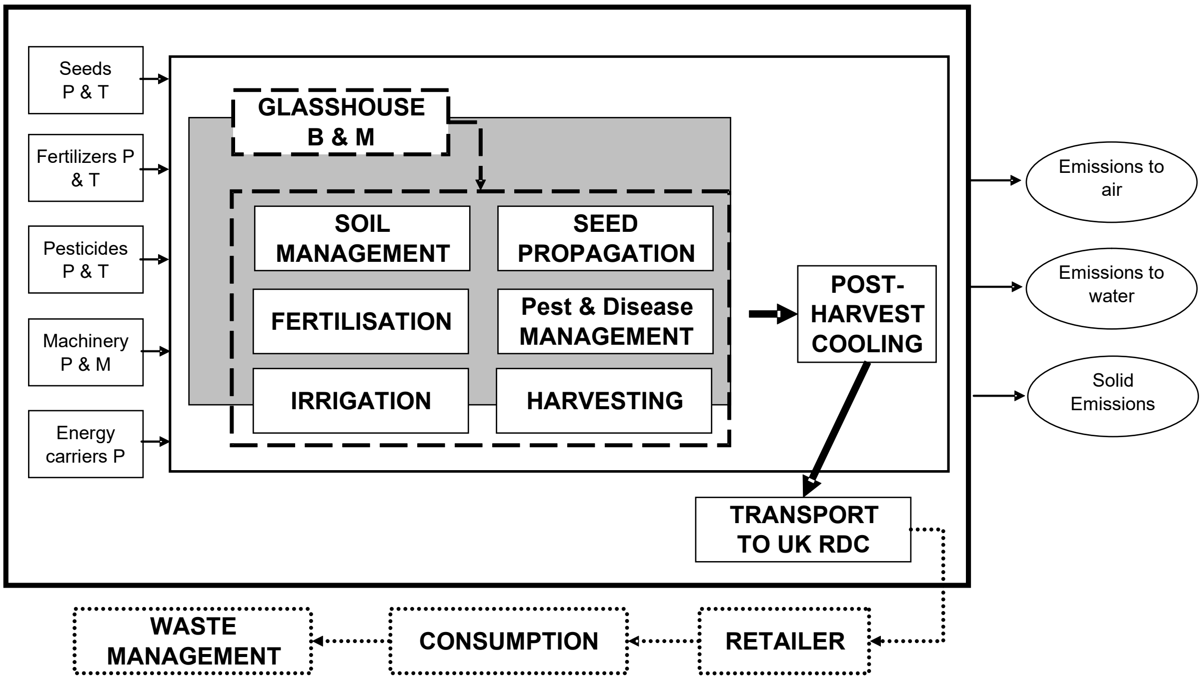

Figure 1. Example of a typical horticultural system. This shows the subsystems, the inputs, the outputs to the supply chain, and the outputs to the environment. P= production, T = transport, M = maintenance, B = building. (Hospido et al. in prep.)

2.2 Carbon footprint methodology

At the time of writing there is no single accepted method of developing the carbon footprint of a product or service. In the UK, The Carbon Trust has recently developed a draft methodology to enable calculation of the GHG emissions from an individual product across its life cycle (see http://www.carbon-label.co.uk/pdf/methodology_full.pdf). At present, it is still being developed in conjunction with BSI, but ultimately, the Carbon Trust hopes to advance the methodology to become the agreed UK standard. It would seem likely that as the importance of carbon footprinting increases then a common EU standard will be needed, and because of the international nature of many supply chains, ultimately a global standard may be desirable.

The Carbon Trust methodology includes emissions of all GHGs, each of which is converted to CO_2 equivalents. The base unit for calculations is the ‘product unit’, which defines an item as it would be purchased by the consumer, including its packaging. For services, emissions may be reported per month or year of the service provided. At least 95% of the likely life cycle GHG emissions of the product unit and all sources of emissions that contribute more than 1% of the total emissions should be included. Primary data (i.e. process-specific data collected from part or all of the supply chain) is preferable to secondary data (i.e. non-process specific data obtained from sources other than direct measurement of the supply chain being investigated).

The system boundary shall include:

- extraction, growing and pre-processing of raw materials, incl. packaging
- all manufacturing processes
- lighting, refrigeration and heating of factories, warehouses and stores
- transport of raw materials, packaging materials and intermediate products
- storage and transport between place of production, storage and retail
- transport of waste and recycling materials to the point of disposal or recycling
- re-use and recycling processes
- emissions from in-use phase, e.g. cooking of food
- processes used during the disposal of the product, including recycling and emissions from waste

The system boundary shall exclude:

- manufacture of capital goods, e.g. tractors, buildings, transport equipment
- routine maintenance of machinery
- human energy inputs
- transport of employees
- transport of consumers to retail stores and transport of the produce to the consumers' homes
- the carbon which might be locked up by the productive and non-productive areas on farms
- any offsetting of emissions so as to provide information on the actual emissions associated with a product
- non-greenhouse gas emissions, biodiversity or other environmental impacts
- energy from natural sources, e.g. sunlight

The methodology comprises five major steps:

1. Analysis of the internal product data: this involves gathering detailed information on the product, e.g. raw materials required, production activities involved, waste and co-products produced, storage and transportation needs.
2. Building of a supply chain process map: the process map should include every significant process step and raw material and identify all inputs and outputs to be analysed.
3. Definition of boundary conditions and identification of data requirements
4. Collection of primary and secondary data
5. Calculation of emissions by supply chain process steps: emissions can be calculated using both energy and direct emissions data, using emission coefficients to convert into carbon equivalents.

The current methodology does not consider changes in the carbon which might be contained in vegetation or soils on farms.

2.3 Carbon labels

If an individual grower is able to produce goods which have lower GHG emissions per kg than the average grower, then that individual grower may expect to be rewarded for supplying the good demanded by consumers (and society). Rewarding the GHG efficient producer serves to simultaneously encourage innovation in the food chain, and to bring about reduced atmospheric pollution.

The development of a carbon label is potentially an excellent way to communicate the relative efficiencies of different supply chains to the consumer. If presented with a range of similar goods, each of which has a different carbon footprint, then the concerned consumer may preferentially purchase the item with the lowest footprint. This would potentially be a method to reward individual growers / farmers for their low carbon footprints. However, in order to achieve this it would be necessary to calculate the carbon footprint of each individual farm (and maybe each supply chain in which their produce is involved) – which may be a difficult task. Further, consumers could only really respond to carbon labels in this way for relatively unprocessed goods such as fruit, vegetables, primary cuts of meat and some dairy produce (e.g. liquid milk). Here the carbon label would be able to reflect the management practices on individual farms. However, for goods which utilise produce from more than one grower this becomes almost impossible (e.g. pies, pizzas, canned soup, beer).

Some companies have worked with the Carbon Trust in order to calculate the carbon footprint of their produce. Most notable at the moment are Walkers crisps (owned by PepsiCo) who display a label on their packaging which declares the grammes of CO_2 equivalents released during the production of that packet (currently 75 g for a standard 35 g packet of cheese and onion crisps, www.walkerscarbonfootprint.co.uk). Other carbon footprints have been calculated for Innocent smoothies (294 g CO_2 equivalents per 250 ml bottle of mango and passion fruit, 190 g CO_2 equivalents per 250 ml serving from a 1 litre carton, www.innocent.co.uk), and the Daily mirror newspaper (0.95 kg CO_2 per kg newspaper sold, Carbon Trust 2006a).

In order for a product to carry the label, the producing company must commit to reducing the product’s carbon footprint over a period of two years. If it fails to achieve this, the label will be withdrawn by the Carbon Trust. Recent research by those companies who have measured the carbon footprints of their products suggests that two thirds of consumers want to know the carbon footprints of products. Further, the companies who have engaged with the process so far are receiving positive consumer feedback (PepsiCo *pers comm.*).

2.4 Carbon footprints of horticultural supply chains

In order to demonstrate some of the outcomes, pitfalls and problems associated with carbon footprinting, three case studies of horticultural supply chains are presented below. These cover cut flowers, apples and lettuces. Immediately following the case studies is a discussion of the lessons that can be learnt from these early attempts to carbon footprint horticultural supply chains.

2.4.1 CASE STUDY 1: Flowers from Kenya and the Netherlands brought to the UK market place (Williams 2007)

This study estimated the carbon footprint of producing cut roses supplied to the UK market place from one company in Kenya and a separate company in the Netherlands. The supply chains differed in two significant ways:

1. Delivery from Kenya included a long flight by freight aircraft, whereas delivery from the Netherlands was by road.

2. Electricity and heat used in Kenyan greenhouses were derived from geothermal energy, while in the Netherlands heating came from burning natural gas and electricity was generated from a primary energy mix dominated by fossil fuel.

The study used a traditional LCA approach and estimated emissions of GHGs associated with the manufacture of all inputs, and their use in the supply chain. This involved tracing emissions back to primary sources of energy and material. The system boundary included production and transport up to the retail distribution centre (RDC) in Hampshire, southern England. The functional unit for the analysis was 12,000 marketable quality cut stem roses. No direct measurement of emissions occurred. Neither were data on production and management collected from direct observation, rather all data on production systems was provided to the analyst by the company and associated consultants.

The annual yields of marketable stems are 1,350,000 and 2,285,000 per ha in the Dutch and Kenyan operations respectively. The production and delivery to the RDC form Kenya incurs 68,000 MJ primary energy and emits 6,000 kg CO_2 equivalents. Delivering the same amount of flowers to the same RDC from the Dutch company incurs 550,000 MJ primary energy and emits 37,000 kg CO_2 equivalents (Table 4).

This study suggests that in the case of these two companies, it was more ‘carbon efficient’ to produce cut roses in the Kenyan company than the Dutch one. In crude terms this situation arises because the emissions related to aviation transport from Kenya to the UK are less than the emissions relating to heating and lighting the Dutch greenhouses. This example clearly shows that the simple concept of ‘food miles’ is not always a suitable indicator of the impact on global warming.

Table 4. Greenhouse gas emissions from different sections of the supply chain of roses from Kenya (K) and the Netherlands (N) to the United Kingdom. Emissions are shown as Global Warming Potential (GWP) (expressed in kg of CO_2 equivalents using the IPCC (2001) conversion factors). The emissions (kg) for the three main gases are also shown separately. Figures in parentheses are the percentage of emissions from the supply chain emitted in that sector of the chain. GWP and CO_2 emissions from Kenya include the IPCC altitude factor (adapted from Williams 2007).

Emission type	**Section of supply chain**											
	Production		Packing		Transport to airport		Transport to RDC (air)		Transport to RDC from airport		Total	
	K	N	K	N	K	N	K	N	K	N	K	N
GWP100	300 *(4)*	36,900 *(99)*	110 *(2)*	160 *(<1)*	18 *(<1)*	0	5,600 *(94)*	0	5.9 *(<0.1)*	50 *(<0.1)*	6000 *(100)*	37,000 *(100)*
CO_2	240	34,000	120	140	18	0	5,500	0	5.7	48	5,900	35,000
CH_4	1.8	91	0.0	0	0.0	0	0.9	0	0.0	0	2.8	91
N_2O	0.1	1.7	0.0	0.02	0.0	0	0.1	0	0.0	0	0.2	1.7

While this is a convincing case, there are several factors that need to be noted when considering these data. Firstly, the analysis only considered two companies, one in each country, so it is not possible to state that the data collected from these companies is representative of the two national cut rose sectors in general. Secondly, none of the data were actually collected by the analyst who undertook the carbon footprint, but were supplied by one of the companies involved and an associated consultant. Thirdly, there is no attempt to estimate any differences in emissions between seasons and/or between years, and finally the analyst himself did not see the cut roses and is not sure if they are genuinely substitutable goods (i.e. does one look and/or smell better than the other?). Therefore, while this is one of the best comparative studies available, there remain some uncertainties about its generalisability.

2.4.2 CASE STUDY 2: Apples from European and southern hemisphere countries brought to the EU marketplace (Blanke & Burdick 2005, Milà i Canals *et al.* 2007a)

In order for European grown apples to be available in European markets all year round they need to be stored for all, or part, of the year. Apples from southern hemisphere countries are imported to Europe at a time when they are in season in their own countries and out of season in Europe, e.g. from April onwards. Blanke & Burdick (2005) compared the energy required to import these fruit to Germany with that required to supply locally-grown apples.

After harvest in mid-October the German apples are stored in 300 kg boxes on-farm until the end of March in controlled atmosphere stores. In these stores oxygen is depleted to 1% O_2 and carbon dioxide enriched to 1% CO_2. In addition the temperature is held at 1°C. After storage the fruit are sold on a wholesale market. This compares to the supply chain of New Zealand (NZ) apples which are freshly harvested in March and are cooled and transported 23,000 km by ship to Antwerp. They are then transported to Germany by truck.

Blanke & Burdick (2005) calculated the primary energy requirements from crop cultivation to end user for both these supply chains for the month of April. They chose April as at this time apples from both Germany and NZ were available on the market. The energy required to ship the apples from NZ (2.5 MJ/kg) was greater than the energy used in the five months of storage in Germany (0.81 MJ/kg). However, the relative differences between the two supply chains were not that great, 5.893 MJ/kg for Germany and 7.499 MJ/kg for NZ (Table 5).

There are several important points to be made about the Blanke & Burdick (2005) study. Firstly, they did not collect any data from participants in the supply chain or make any direct measurements themselves, rather they modelled the two supply chains. Secondly, they only estimated energy and not global warming potential, and while these two variables are often correlated it may not always be so. Thirdly, they only considered the supply chains for one month of the year. This means that again it is impossible to say how representative these results are of supply chains in the two countries across the whole calendar year.

Table 5. Primary energy requirement per kg of locally-grown versus apples imported to Germany from New Zealand in the month of April (from: Blanke & Burdick 2005).

Supply chain activity – local fruit	**Energy per unit (per kg, t, km or day)**	**Primary energy requirement (MJ/kg apples)**	**Supply chain activity – import from NZ**	**Energy per unit (per kg, t, km or day)**	**Primary energy requirement (MJ/kg apples)**
Cultivation	2.8 MJ/kg	2.800	Cultivation	2.8 MJ/kg	2.100
20 km transport to Meco	3.47 MJ/t/km	0.069	40 km transport to Nelson	3.47 MJ/t/km	0.139
Initial cooling	86.3 kJ/kg	0.086	Initial cooling	86.3 kJ/kg	0.086
150 days CA storage at 1°C in Meckenheim	5.4 kJ/kg/day	0.810	23,000 km reefer Nelson to Antwerp	0.11 kJ/kg/km	2.534
			28 days cooling on board	10.8 kJ/kg/day	0.302
Packaging	650 kJ/kg	0.650	Packaging	650 kJ/kg	0.65
40 km in <28 t truck to wholesale market Rosidorf	2.32 MJ/t/km	0.093	200 km in <40 t truck to regional distribution centre	1.38 MJ/t/km	0.276
150 km <40 t truck to retail	1.38 MJ/t/km	0.207	150 km < 40 t truck to retail	1.38 MJ/t/km	0.207
Cooling on truck 95 km	0.3 MJ/t/km	0.028	Cooling on truck 175 km	0.3 MJ/km	0.055
Consumer shopping 6 km	3.83 MJ/km	1.150	Consumer shopping 6 km	3.83 MJ/km	1.150
TOTAL		5.893			7.499

However, a similar study by Milà i Canals (2007a) does examine similar supply chains across the whole calendar year. This study again considered apples from Europe and the southern hemisphere, and again analysed primary energy. However, it sought to do this over a whole calendar year. Four supply chains were analysed:

- apples grown in an EU country and eaten in the same country
- apples grown in an EU country and eaten in another EU country
- apples grown in NZ and eaten in an EU country
- apples grown in another southern hemisphere country and eaten in an EU country

The results show that transport by ship is the largest single user of energy of non-EU apples and represents 46-59% and 27-36% of possible energy use for NZ and ‘other southern hemisphere countries’ respectively. However, the most interesting part of the analysis is the relative variability in the total energy use of the alternative supply chains over the year (Figure 2). This shows that an apple produced in an EU orchard which is consumed in the same country in October uses less energy than one produced in the same orchard which is consumed in the following August, with the difference being due to the energy used in storage between October and August. Due to this energy expenditure, the total energy use of the supply chains from ‘other southern hemisphere countries’ is similar to that of the two EU supply chains during the European spring and summer. Indeed there is a suggestion that even some of the NZ supply chains may be more energy efficient than European ones during late summer in Europe. So while taken as an annual average, the consumption of EU grown apples in the EU uses less energy than consuming a NZ grown apple in the EU, the relative benefits of so doing vary with season.

This study is noteworthy not only because it consider the whole calendar year, but also because it recognised that there is variation in the supply chain in terms of on-farm productivity, loss in storage and the details of energy use at every stage in the chain. This explicit recognition of variability brings an element of realism into the analysis. However, again it is unclear how much data was collected by the research team from speaking to those involved in supply chains and how much was assumed from secondary data.

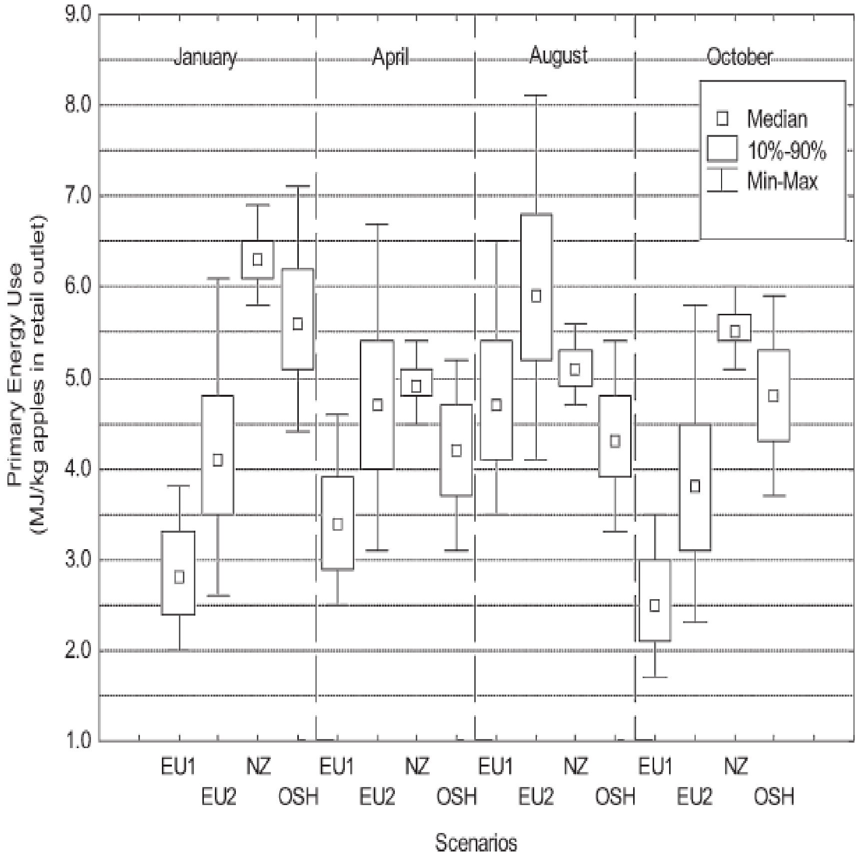

Figure 2. Primary energy use per kg of apples from European and southern hemisphere suppliers for the different seasons. EU1 indicates an apple produced in a country within the European Union (EU) and eaten in the same country. EU2 indicates an apple produced in a country within the EU and eaten in another EU country. NZ indicates an apple produced in New Zealand and eaten in an EU country. OSH indicates an apple produced in another country within the southern hemisphere, not NZ, and eaten in an EU country (Milà i Canals *et al.* 2007a).

2.4.3 CASE STUDY 3: Lettuce production in Spain and the United Kingdom for the United Kingdom market (Milà i Canals *et al.* 2007b)

In order to provide lettuce to UK consumers all year round several different supply chains have been developed. These include UK field grown lettuce in the summer, out of season protected cultivation in the UK winter and import from Spain (delivered by road). Outdoor production practices change through the seasons to respond to weather conditions; e.g. UK early crops (harvested May to mid July) are protected with fleece to prevent frost damage during the first six weeks in the field, while early

Spanish crops (planted in August-September) generally require more water for irrigation. Milà i Canals *et al*. (2007b) undertook an LCA of lettuce production from these three different supply chains. They assumed that the functional unit was 1 kg of lettuce delivered to a UK Regional Distribution Centre (RDC). Data on farm production practices, post-harvest cooling and transport to the RDC were collected directly from individual producers in the UK (three for open field: UKa, UKb and UKc; two for under-glass: UKc-In and UKd-In) and Spain (two producers: ESa and ESb). Data relate to the production of cos, iceberg and green oak leaf lettuces and fine endives, but no distinction has been made on the basis of lettuce variety or nutritional content.

Results highlighted the important contribution of fertiliser use to GWP in all supply chains. Refrigerated transport was an important contributor to GWP during transport from Spain to the UK, while energy for heating in protected cultivation dominated the results of winter production in the UK (Figure 3). Of particular note is the fact that growing and transporting lettuce from Spain in the UK winter has a lower GWP than growing the lettuce in protected environments in the UK. Also of note is that the variation in GWP between different farms in the same country.

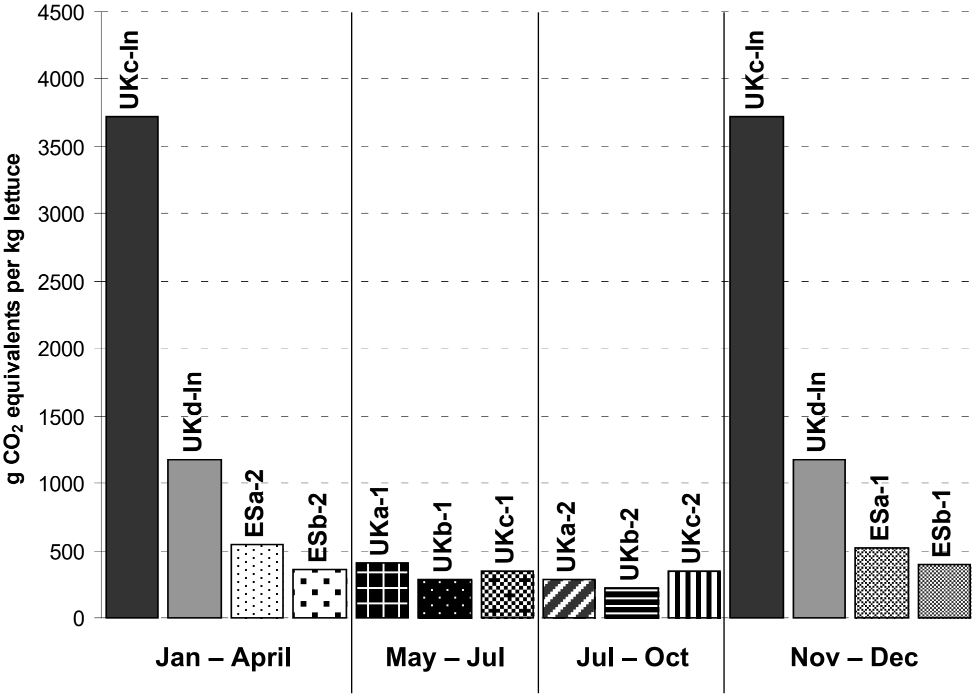

Figure 3. Comparative results for Global Warming Potential (GWP) (kg CO_2 equivalents per 1 kg of lettuce delivered to the RDC) for alternative supply chains. Each bar represents a different supply chain, where the country of origin is designated as UK for United Kingdom and ES for Spain. The individual farms are identified by the small letter (one of a, b, c); and the type of crop is designated as 1st or 2nd by 1 and 2. In: UK indoor (glasshouse) production (farms: c, d); farm c only produces indoors from September to May, but farm d produces indoors year-round. (from Milà i Canals *et al.* 2007b).

This is an interesting study as not only does it compare supply chains across the whole year, as did Milà i Canals *et al.* (2007a) for apples, but also it actually visited all the farms on several occasions and collected data on the supply chain through formal surveys with farmers and managers and from direct observation. However, while this approach offers a more realistic viewpoint of the differential impacts of alternative supply chains than does a modelling approach which uses standard databases, it is still not possible to claim that these results are statistically representative of lettuce production in Spain or the UK There is further discussion on the representativeness of these types of studies in the next section..

2.4.4 Lessons from the case studies

It is clear that the details of the methodology used to calculate the carbon footprint can have a large impact on the final outcome. In order to enable true and fair comparisons of alternative supply chains it is important that exactly the same methodology is utilised to estimate the GHG emissions from each supply chain. Key assumptions about system boundary and emission factors can have large impacts on the result. Of particular note in these early days of carbon footprinting is the absence of good data which detail the exact workings of the supply chain. For this reason it is necessary to make a whole range of assumptions about the supply chain and its relevant emissions. While there is no problem in making assumptions, it is imperative that these are stated clearly for everyone to read and understand. Failure to do this can lead to considerable misunderstanding, e.g. if a footprint considered only CO_2 emissions, rather than all GHGs, but did not state clearly that this was being done. Several other issues can also affect the outcomes of the footprinting process, as detailed below:

Baseline year(s) of data collection: The year in which the data are collected may have an impact on the footprint, particularly if that year was not typical of long term conditions. Consider for example the variation in both inputs to crops between years (e.g. more fungicides on vegetables in wet years) and differences in crop yields due to annual variation in weather.

Definition of the functional unit: LCA typically considers impacts for a well defined functional unit, e.g. 1 kg of cabbage. However, when considering emissions to and from ecosystems there may be an argument to express emissions per hectare (ha). This variation in functional unit may lead to the situation where an intensive and efficient farm system has lower GHG emissions per kg of output than a more extensive, low input-low output system, but also has greater GHG emissions per hectare. Ideally, both emissions per ha and emissions per kg would be quoted.

Representativeness: A further problem with carbon footprinting relates to making any assumption about the representativeness of a particular study and any generalisations to all supply chains in a region or country. For example, even though Milà i Canals *et al.* (2007b) measured the carbon footprints of several farms in Spain and the UK, their sample was never meant to be statistically representative of all lettuce farms in the two countries. For this reason it is not statistically valid to extrapolate the results from these study farms to the whole sector in those countries. However, regardless of how clearly scientists may make these statements, it is almost inevitable that large sectors of the media and the public will assume that these results are representative of the relevant countries, and as a result some consumers may change their purchasing behaviour.

Measurement or modelling: It is possible to utilise secondary data presented in well recognised standard sources in order to develop good models of supply chains. When used in conjunction with standard databases of emission factors, these models can then be used to estimate the carbon footprint of the supply chain. This approach has the advantage of being both relatively resource efficient and easy to undertake. Many of the large companies who are actively involved in the debate about carbon footprint methodologies favour this standardised approach. They argue that such an approach ensures that similar methodologies are applied across different supply chains. Indeed, given the enormity of the task facing a retailer who wants to carbon footprint the thousands of different goods they sell, this standardised methodology seems the only tractable way forward. However, it was apparent from the case studies that there may be large differences in the GHG emissions arising from different farms which produce similar produce. Such a pattern may also occur elsewhere in the supply chain. Any method which assumes standard emissions per kg of produce on all farms will fail to capture this variation. While this may not be important to firms such as retailers, it is important to both growers and consumers.

Greenhouse gas emissions from plants and soils: Emissions of GHGs to and from soils represent one of the major fluxes in the global carbon cycle, and through the biological and chemical processes that occur within them, agricultural soils are responsible for releasing significant amounts of GHGs into the atmosphere.

The release of CO_2 from soil occurs mainly from respiring plant roots and from soil microbes decomposing organic matter in soil (Farrar *et al.* 2003). A second GHG, N_2O, is produced naturally in soils by microorganisms through the processes of nitrification or denitrification. Nitrification is the aerobic oxidation of ammonium to nitrate; denitrification is the anaerobic reduction of nitrate to nitrogen gas. Increases in the availability of nitrogen in the soil usually lead to increases in both of these processes, so that additions of nitrogen to the soil as fertilisers, faeces, slurries, manure, ploughed in leys, arable residues etc. have the potential to increase N_2O emissions.

Major sources of emissions of the third main GHG, CH_4, are animal wastes and severely anaerobic soils (e.g. rice paddies). Although the importance of CH_4 as a GHG is relatively low in cropping and horticultural systems very large emissions can come from livestock systems, particularly those involving ruminants. This occurs as ruminants produce CH_4 through enteric fermentation in the gut, and CH_4 is also emitted from animal manure. The exact amount of CH_4 released varies with animal, type of feed and means of manure management and the IPCC provide standard equations estimating these emissions.

Soils can also be major sinks for greenhouse gases, as all crop plants sequester atmospheric CO_2 in photosynthesis. Some of this is returned to the soil when roots die and at the end of the season in crop residues left behind in the fields. Both of these are important in replenishing soil organic carbon stores. In addition, soils can also act as sinks to significant quantities of both N_2O and CH_4 (Chapuis-Lardy *et al.* 2007).

The net release of GHGs from agricultural soils is therefore a delicate balance of CO_2, N_2O and CH_4 gains and losses across an entire growing season. For this reason accurate estimates of GHG emissions from food production systems require measurements to be made over long time periods (ideally a full calendar year) on a continuous, or very regular, basis (e.g. hourly). This intensity of measurement poses severe practical challenges and is rarely undertaken. The IPCC approach to this problem was to undertake a meta-analysis of all the available experimental data and to produce standard emission factors, which describe, for example, the proportion of nitrogen fertiliser that is emitted as N_2O from crop production (Bouwman & Taylor 1996). This emission factor approach is based on a limited number of data points and is applied worldwide for agricultural soils regardless of variations in soil characteristics, land management or climate (Roelandt *et al.* 2005). This is obviously a crude approach that can have little relevance to local conditions (Smith *et al.* 2002). To address this issue, many researchers have developed mathematical modelling approaches that attempt to simulate net GHG emissions from soil at a range of temporal (days to decades) and spatial scales (field to continental level) (Vuichard *et al.* 2007). The relevance of these models to specific local conditions remains largely untested.

To date, most carbon footprints have tended to ignore emissions from the plants and soils that occur on a farm. While there may be good reasons for this, e.g. the difficulty in measuring their contribution to emissions and sequestration, plants and soils may actually represent significant resources to many growers. For example, consider an apple grower who manages an orchard of large trees with grass strips between the rows. This system probably actively locks up carbon in the trees and in the soil, and the grower may like to include this sequestration in the carbon footprint in order to offset the emissions related to other activities, such as spraying. However, current footprinting methods do not seem to enable these on-farm carbon stores to be included. A logical corollary of this would be that on-farm emissions from plants and soils should be omitted too. This would significantly reduce the footprint of those growers who use substantial amounts of nitrogen fertiliser. The major point here is that if growers are going to calculate a footprint, they need to take a consistent approach to emissions from plants and soils; and logically both emissions and sequestration should be included in any calculation.

GHGs are not the only pollutants: While the whole purpose of carbon footprinting is to estimate the impact of a process on climate change, it must be remembered that carbon emissions are not the only impact horticulture can have on the environment. In some circumstances it may be relevant to consider other environmental impacts alongside GHG emissions. A good example of this is provided by the lettuce study discussed in Case Study 3 above. Estimates of GWP of the farms clearly showed that supply chains sourcing lettuce from Spanish farms had lower GHG emissions in winter than did UK systems. However, if the impact of these systems on water pollution is measured, and expressed as eutrophication potential (calculated as kg PO_4^{3-} equivalents per 1 kg of lettuce delivered to the RDC), then a very different picture emerges (Figure 4). These data now suggest that in winter, UK supply chains have a lower eutrophication potential than Spanish ones. The lesson here is that growers who do not want to compete on the basis of their carbon footprint may want to emphasise the other environmental and ethical benefits of their produce.

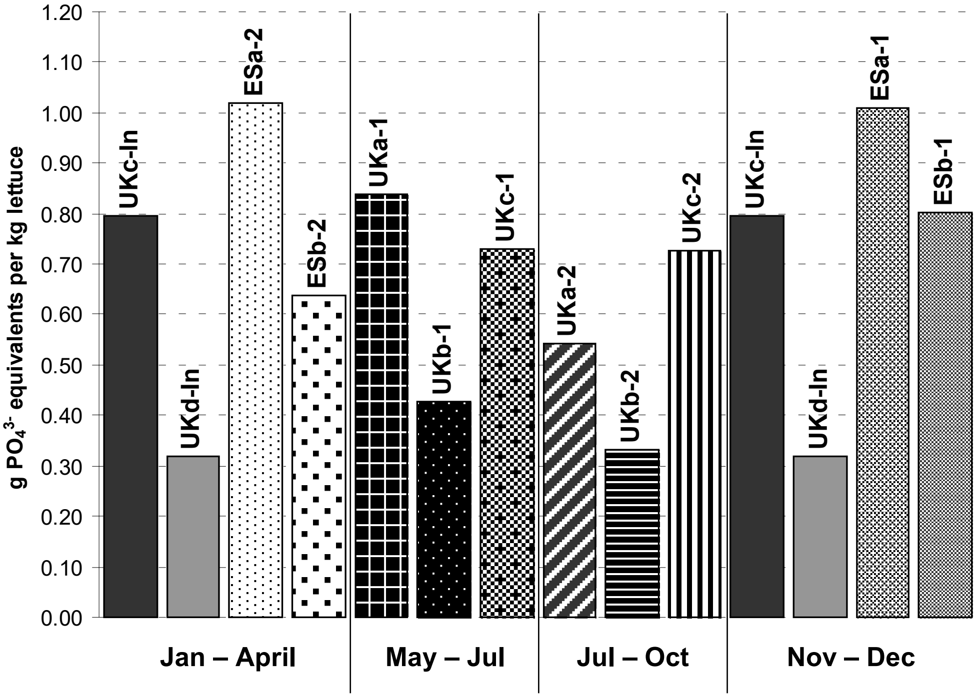

Figure 4. Comparative results for eutrophication potential (kg PO_4^{3-} equivalents per 1 kg of lettuce delivered to the RDC) for alternative supply chains. Each bar represents a different supply chain, where the country of origin is designated as UK for United Kingdom and ES for Spain. The individual farms are identified by the small letter (one of a, b, c); and the type of crop is designated as 1st or 2nd by 1 and 2. In: UK indoor (glasshouse) production (farms: c, d); farm c only produces indoors from September to May, but farm d produces indoors year-round (from Milà i Canals *et al.* 2007b).

2.5 Conclusion

Given all of the above, it is clear that carbon footprinting is a technical issue influenced by new and emerging science. There is no agreed methodology for estimating the carbon footprint of an enterprise. In addition, there is potential for commercial gains for those companies/countries which are able to demonstrate competitive advantage in terms of GHG emissions. This combination of factors offers the potential for companies to misrepresent the carbon efficiency of their produce, be this accidental or deliberate. For this reason everyone involved in developing and evaluating carbon footprints needs to ensure that the highest standards of data and analytical methods are achieved. Growers should ensure this is demanded of their competitors, and also be willing to meet the same high standards themselves.

3 Putting greenhouse gas emissions from horticulture in context

The purpose of this section is to firstly present an overview of greenhouse gas (GHG) emissions from the horticultural sector in the UK, and then to put the emissions from horticulture in a wider perspective. This is done by comparing the emissions from horticultural produce with emissions from a range of other goods and activities in the UK. Section 3 discusses sector specific issues in more detail.

3.1 Greenhouse gas emissions from UK horticulture

Horticulture accounts for about 28% of the total energy used in UK agriculture. About 35% is used by the livestock sector and 37% by the arable sector (Warwick HRI 2007). The total UK primary energy input into horticulture is split between sectors as:

- 58% to protected edible crops (20% to tomatoes)
- 33% to protected ornamentals
- 9% to field crops

Within the protected cropping sector, heating is the dominant user of energy, whilst for field vegetables it is the field operations which use most energy (Figure 5). Energy intensive edible crops include tomatoes, cucumbers, aubergines and peppers that are grown in heated greenhouses (above 18°C) with humidity and CO_2 control. Energy intensive ornamental crops include species such as chrysanthemum, begonia and poinsettia that again depend upon temperatures being above 18°C and also require humidity control, CO_2 enrichment and supplementary lighting.

Fruit and vegetables that are grown in the field within season, without heating and/or protection and do not spoil easily are the least energy and GHG intensive crops (Garnett 2006). Similarly, energy extensive ornamental crops include crops that are grown at low temperatures (below 15°C) such as summer bedding plants, summer cut flowers, hardy nursery stock etc.

Significant energy is also used beyond the farm gate, particularly in refrigeration and cooling during cold storage. Obviously, the longer food is stored (be it fresh or frozen) the greater will be the energy used. Indeed Garnett (2006) stresses the GHG intensity of fragile or highly perishable foods that are prone to spoilage which can cause a waste of the energy embedded in their production, transport and storage. Pre-prepared, trimmed or chopped food such as salad bags, fruit salads and cut pineapple are also examples of GHG intensive products.

While significant energy is used in producing and distributing food, wasted food can represent a significant waste of energy inputs used during the life cycle of a product. Garnett (2006) estimates that 25% of the total supply of fruit and vegetables goes to waste. During the production phase, some crops defined as Class II may be left to rot in the field and are therefore not utilised in the food chain (Garnett 2006). Of the fruit, vegetables and potatoes that do enter the processing sector, an estimated 12% end up as waste. In addition, about 170,000 tonnes of fruit and vegetables per year may be wasted in the retail sector (Garnett 2006). However, the greatest volume of waste occurs in consumers' homes, with 31% of consumers admitting to throwing away food because it has gone off 'always, very often or quite often' (Defra 2007).

Clearly, all the energy that has been used to bring food to consumers that is then wasted has been expended to no avail. For this reason significant savings in energy use and emissions could be achieved in supply chains that minimise waste production.

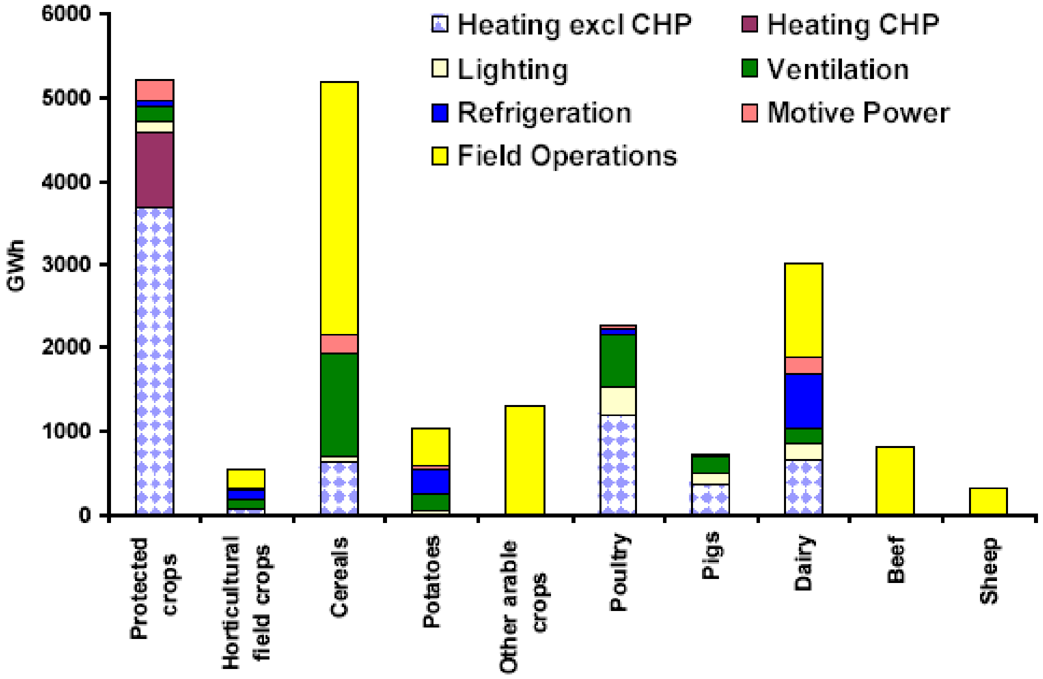

Figure 5. Direct energy expended by various sectors of agriculture in the UK by use in 2005 (from: Warwick HRI 2007).

As is evident from the above discussion, many studies on horticulture report on energy use (for example, Table 6 shows estimates of primary energy inputs into some protected and field crops in the UK in 2005). This is important when considering the carbon footprint of an enterprise, as energy use is normally one of the major contributors to climate change impacts and thus can be an indicator of the extent of GHG emissions. However, in order to estimate the true carbon footprint of an enterprise, more processes and inputs as well as N_2O and CH_4 emissions need to be considered. In the only study that has attempted to estimate the GHG emissions of some of the UK's horticultural sectors, Garnett (2006) estimated that the fruit and vegetable sectors contribute about 2.5-3% of total UK GHG emissions.

In addition, Foster et al. (2006) noted that relatively few life cycle assessment studies had been completed for horticultural products. Most existing research had looked at the production phase only, and few studies covered processed foods and specific food systems in the UK. Based on the limited evidence Foster et al. (2006) noted three major points:

1. non-CO_2 global warming impacts vary widely, with N_2O emissions significant for soil grown produce
2. processing can have a considerable impact when foods are subject to major processing, e.g. tomatoes to ketchup
3. refrigeration and packaging impacts depend on whether fresh, frozen, canned etc.; packaging impacts depend on degree of end-use recycling.

Table 6. a) Primary energy inputs into horticultural protected crops. b) Primary energy inputs into horticultural field crops (from: Warwick HRI 2007).

a) protected crops

Crop	Area (ha)	Primary energy inputs (GWh/ha) Electricity	Other static	Mobile machinery	Energy use (GWh)
Edible crops					
Tomatoes	187	0.26	6.0	0.0017	1,171
Cucumbers	120	0.26	5.5	0.0017	691
Sweet peppers	59	0.26	5.5	0.0017	340
Lettuce	97	0.26	2.3	0.0017	249
Celery	26	0.26	2.3	0.0017	67
Mushrooms	11	6.8	2.0	0.0017	97
Soft fruit	194	0.26	2.3	0.0017	497
Other edibles	55	0.26	3.5	0.0017	207
TOTAL	749	-	-	-	3,318
Ornamental crops					
Cut flowers	104	0.58	4.0	0.0017	477
Pot plants	123	0.58	4.0	0.0017	564
Bedding plants	224	0.26	1.6	0.0017	417
Nursery stock	368	0.26	0.6	0.0017	317
Bulb flowers	224	0.26	0.25	0.0017	115
TOTAL	1,043	-	-	-	1,889
GRAND TOTAL	**1,792**	-	-	-	**5,207**

b) field crops

Crop	Area (ha)	Primary energy inputs (GWh/ha) Electricity	Other static	Mobile machinery	Energy use (GWh)
Field leafy salads	5,593	0.03	trace	0.0011	174
Onions	8,561	0.01	0.003	0.0016	125
Other vegetables	107,537	trace	trace	0.0016	172
Orchard & soft fruit	25,837	trace	trace	0.0003	8
Hops	1,400	trace	0.005	0.0003	7
Flower bulbs	5,726	0.0006	0.005	0.0008	37
HONS	9,519	trace	trace	0.0003	3
TOTAL	**164,173**	-	-	-	**526**

3.2 Greenhouse gas emissions from food consumption

Although there are very few studies which document the GHG emissions from the production and consumption of horticultural goods in the UK, several studies have considered GHG emissions related to all food items, and many of these have been undertaken in European countries, or at the EU scale.

For example, Tukker *et al.* (2006) considered the environmental impacts of products and services in 12 areas of consumption, including food and drink, across the European Union. The results suggested that food, drink, tobacco and narcotics consumption accounted for about 20-30% of the global warming impacts of all 12 areas of consumption analysed. The greatest contribution to the food related emissions were from meat and meat products (4-12% of GWP), followed by dairy products (2-4%). Both the categories ‘vegetables’ and ‘frozen fruit, fruit juices and vegetables’ contributed to about 0.7% of the total global warming impact of the European Union.

A similar pattern is evident from studies that estimated the GHG emissions of a range of food items consumed in York (Barrett *et al.* 2002), Sweden (Wallén *et al.* 2004) and the Netherlands (Kramer *et al.* 1999) (Tables 7-10).

The York study considered the energy required to grow, harvest, process, package and transport food items to the retailers, as well as the energy required to transport waste to landfill, process the waste on site and CH_4 emissions from the anaerobic decomposition of the organic material in the landfill. The results from the York study show that the greatest GHG emissions are from meat and dairy products (Table 7), with wine and coffee also having high emissions per kg of product consumed. Horticultural products typically had emissions three to five times lower than those of meat and dairy products. The results also showed that for every tonne of food consumed, 0.25 t of packaging is needed. As a result over 515,000 t of materials are required to provide York with 92,500 t of food and drink products.

The Swedish study understandably reports different emissions for the food items, but the trends are the same (Table 8). The greatest levels of emission are associated with cheese, coffee, frozen fish and meat. The emissions for horticultural products were between 3 and 12 times lower than these high emitting items per kg of produce. However, when these emissions were combined with the amount of each product consumed a slightly different pattern emerged. Meat products were responsible for the greatest emissions (412 kg CO_2 equivalents per capita per year out of a total of 904), and consumption of vegetables was the second highest category (83 kg CO_2 per capita per year), so while vegetables may have relatively low emissions per unit, because the large amounts that are eaten, overall their consumption has a relatively high impact (Table 9).

In the Dutch study, a similar calculation was undertaken and emissions from a variety of food products were combined with annual household expenditure on these items to reflect total GHG emissions from food consumption. The results, summarised as percentage contribution of different food categories (Table 10), again show the same pattern, with the greatest levels of emission being related to the consumption of meat and dairy products. Together these accounted for 50% of the total emissions from food related consumption, whereas fruit, potatoes & vegetables accounted for only 14.9%.

Table 7. Global warming potential (GWP) in kg CO_2 equivalents per kg of food/drink product in York (from: Barrett *et al.* 2002). For more product categories, see Barrett *et al.* (2002).

Product	**kg CO_2 equivalents per kg food**	**Product**	**kg CO_2 equivalents per kg food**
Vegetables and fruit:		*Milk and milk products:*	
Processed vegetables	3.72	Butter	17.36
Fresh fruit	3.40	Cheese (natural and processed)	13.86
Other fruit (e.g. tinned)	3.32	Cream	12.17
Fruit juices	2.43	Whole milk	3.52
Other fresh vegetables	2.33	Skimmed milk	3.77
Fresh potatoes	1.88		
Fresh green vegetables	1.67	*Meat and fish:*	
		Poultry (cooked)	26.76
		Beef and veal	19.30
		Total fish	17.23
		Mutton and lamb	13.09
		Pork/ham/bacon	13.89
		Poultry (uncooked)	10.63
Drinks:			
Spirits (e.g. Whisky)	23.22	*Other food items:*	
Wine	14.33	Chocolate confectionery	6.58
Coffee	13.62	Cakes	5.93
Tea	6.01	Margarine	3.02
Beer and lager	1.91	Bread	1.49
Mineral water	0.83	Flour	1.15

Table 8. Greenhouse gas emissions from the production, processing and distribution for food consumed in Sweden. Figures do not include home cooking (from: Wallén *et al.* 2004). For more product categories, see Wallén *et al.* (2004).

Product	**kg CO_2 equivalents per kg food**	**Product**	**kg CO_2 equivalents per kg food**
Vegetables and fruit:		*Milk and milk products:*	
Green salads	3.30	Cheese	8.00
Cucumber	3.30	Butter	0.98
Tomatoes	3.29	Milk	0.41
Other fresh vegetables	3.29		
Mashed potato powder	1.12	*Meat and fish:*	
Fruit juices and syrups	0.99	Fish, frozen and filleted	6.53
Fresh and frozen berries	0.79	Unprocessed beef (incl. bones)	6.25
Frozen potato products	0.57	Unprocessed pork (incl. bones)	6.10
Root crops	0.50	Cooking oils	3.53
Onions	0.50	Unprocessed poultry (incl. bones)	2.81
Cabbages	0.50	Unprocessed fish	2.60
Bananas	0.45		
Processed vegetables	0.30	*Other food items:*	
Other fresh fruits	0.29	Margarine	2.12
Oranges	0.25	Chocolate and sweets	1.80
Apples	0.24	Rice	1.68
Unprocessed potatoes	0.17	Buns and cakes	0.91
		Pasta	0.81
Drinks:		Plain bread	0.76
Coffee, tea and cocoa	7.96	Ice cream	0.64
Soft drinks	0.56		

Table 9. Emission of CO_2 equivalents per year per capita in Sweden for different food categories (from: Wallén *et al.* 2004).

	kg CO_2 equivalents per year per capita
Meat including meat products	412.0
Other vegetables	83.1
Milk including sour milk products	57.1
Cheese	55.2
Fish including fish products	47.8
Soft drinks	42.4
Bread	38.3
Edible fats	36.0
Eggs	27.5
Sweets	21.6
Fruit juice	19.2
Fruits and berries	18.7
Potatoes	16.4
Other cereals	7.1
Rice	6.4
Pasta	5.6
Root crops	5.6
Cream	4.0
Dried leguminous plants	0.5
Total	904.5

Table 10. Contribution of different food categories to GHG emissions in % of total CO_2 equivalents in the Netherlands, taking into account both emissions per unit (from the production of basic materials and packaging materials, transport, consumption/use and disposal) and the amount consumed (from: Kramer *et al.* 1999). Bread = breads, pastry and flour products; potatoes = potatoes, vegetables and fruit; beverages = beverages and products containing sugar (including fruit and vegetable juices); oils = oils and fats; meat = meat, meat products and fish.

Item	**% GHG emissions**
meat, meat products and fish	28.2%
dairy products	22.9%
potatoes, vegetables and fruit	14.9%
Beverages and products containing sugar	14.6%
breads, pastry and flour products	13.2%
oils and fats	3.1%
other food products	3.1%

The importance of consumption in determining the total level of emissions from a food chain is evident from work undertaken on potatoes which shows that 46% of all the energy used during their production, transport, retail and consumption comes from the cooking phase (Edwards-Jones 2006) (Figure 6). A similar, but more expansive, analysis considered only the carbon (not GHG) emissions from the different stages of the UK food chain (Figure 7). This showed that households are the greatest consumers of energy along the food chain, with cooking accounting for 48% of food related energy consumption in the home, refrigeration accounting for 33% and washing up for 19% (White 2007). Processing, farming, catering and transport all contribute significantly, while storage and retail consume much less energy. However, if all GHGs were included in these calculations, the relative importance of the different stages would change, and the relative contribution of the farming stage would increase (White 2007).

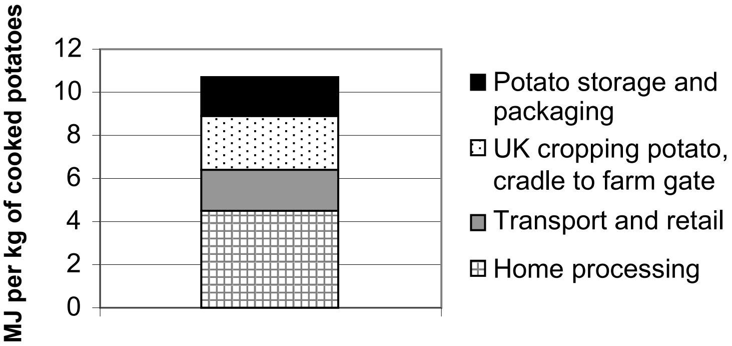

Figure 6. Energy consumption in MJ in the life cycle of 1 kg potatoes (Milo i Canals *pers comm*. cited in Edwards-Jones 2006).

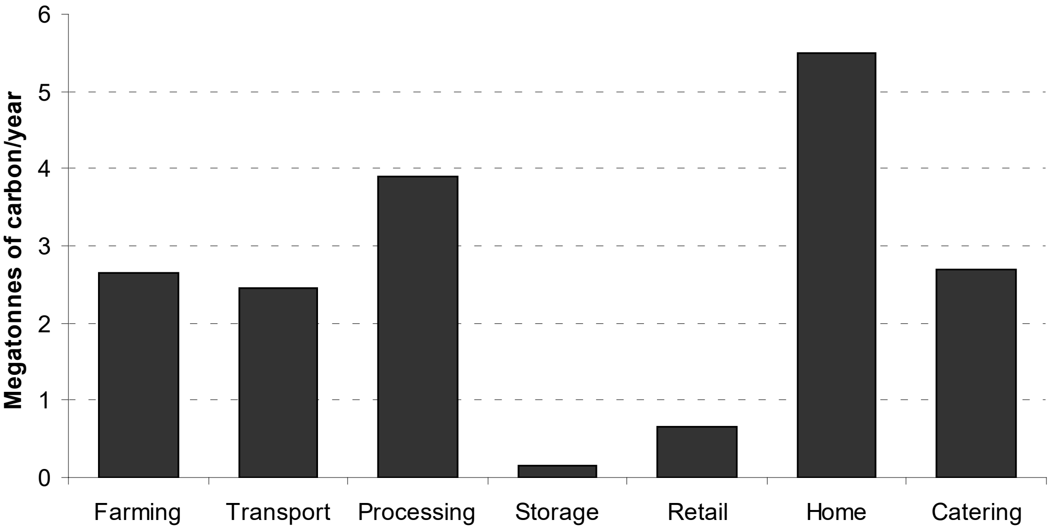

Figure 7. Carbon emissions in megatonnes of carbon per year from the different sectors of the UK food system (adapted from White 2007). This includes emissions from direct fossil energy use on-site and in the production of inputs, but excludes any embodied energy in machinery or vehicles. Also excluded are off-farm storage of fresh fruit and vegetables and food related waste management. For more information on assumptions and exclusions, see White (2007).

3.3 Emissions from horticulture in relation to other industries

3.3.1 The big picture

Although it is important for farmers and growers to try and reduce the GHG emissions from their activities, it is also important that these activities are placed in a larger context which reflects energy use and GHG emissions from other activities in both households and the wider economy.

An average household in the European Union requires 274 GJ of direct (e.g. electricity and gas) and indirect energy (i.e. energy embodied in consumer goods and services) per year (Reinders *et al.* 2003). Electricity, gas and other fuels for housing have the greatest share (35%), followed by food and drinks (18%), fuels for transport (13%), housing (9%) and other categories (Figure 8).

In a study of Dutch households Reinders *et al.* (2003) found that the consumption of food and beverages required 38 GJ per household in 1994 (15.7% of the total energy requirement). This compares to 93.2 GJ for electricity, gas and other fuels for housing; 17.3 GJ for recreation and culture and 15.7 GJ for housing and water. The categories with the lowest energy consumption were communications (1.3 GJ) and education (0.1 GJ). These results are similar to those cited in Barrett *et al.* (2002) (p. 26) which state that in York the consumption of food accounts for around 20-35% of the total energy use of a household.

However, as stated above, energy is only a rough indicator of GHG emissions. A recent study by the World Wildlife Fund suggests that consumption of food inside and outside of the home only accounts for 7% of the CO_2 emitted by the average UK household (Figure 9) (WWF 2006). The Carbon Trust (cited in Baker 2007) suggest a slightly higher figure, and they estimate that 13% of each British individual's annual carbon emissions are due to the manufacturing, transport and consumption of food and drink. However, while the figures from these studies may differ, the basic message is clear – the consumption of food and drink is responsible for a relatively small component of most people's overall CO_2 emissions.

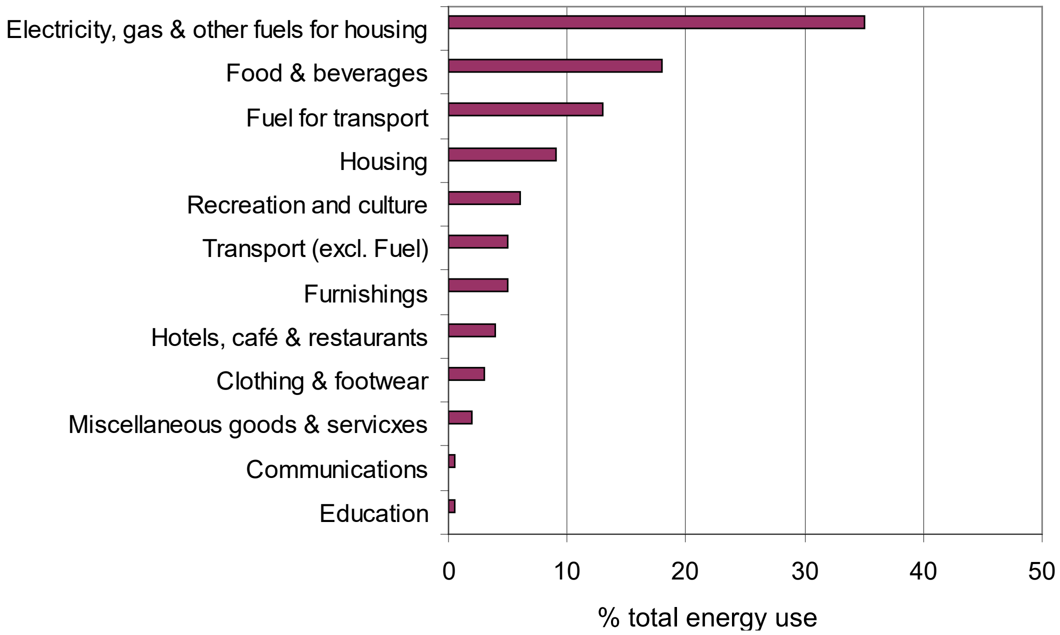

Figure 8. Relative contribution of different consumption classes to total energy use in an average household in 11 European Union member states in 1994 (redrawn from: Reinders *et al.* 2003). An average household requires 274 GJ per year. NB while these data are amongst the best currently available they were collected in the early 1990s and therefore may not be directly comparable to the current situation.

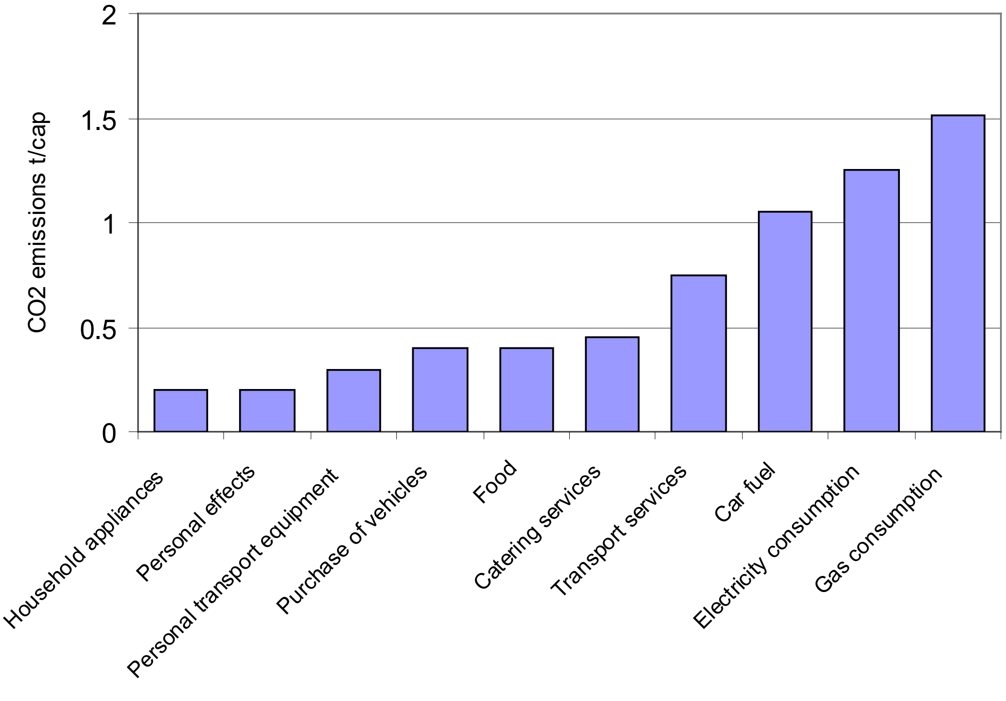

Figure 9. UK household CO_2 emissions from consumption (food and eating out account for over 7% of emissions) (redrawn from WWF-UK 2006).

3.3.2 Some specific figures

These studies on household consumption are built up from specific research on the energy use (and GHG emissions) associated with the production and use of specific goods. For example, ECCM (2000) suggest that the use of an electric kettle will on average be responsible for the emission of 0.02 tonnes of carbon per year, while a return flight from London to Paris releases 0.03 tonnes of carbon per person (Table 11).

Table 11. Estimates of carbon emissions for selected items and activities (from: ECCM 2000). For assumptions made and figures used, see ECCM (2000).

Source of emissions	Total emissions (tonnes carbon equiv)
Electric kettle, 1540 uses per year	0.02 per year
Washing machine, 8 washes per week	0.05 per year
Household refrigerator	0.03 per year
Heating and lighting a typical British home	1.64 per year
Rubbish from a typical British home	0.11 per year
Average British car	1.08 per year
Return flight London-Paris	0.03
Return flight London-New York	0.33
UK total	150 million per year
UK citizen (CO_2 only)	2.58 per year
UK citizen (all greenhouse gases)	3.43 per year

Using these types of data it is possible to make comparisons of the production and use of consumer goods and services with horticultural products. For example, the production and delivery of one Dutch grown rose to a regional delivery centre in southern England releases as much CO_2 equivalents as driving a small car (1.4 l engine) 16.9 km (Table 12). Similarly, the production of 500 g of UK tomatoes emits the same amount of CO_2 equivalents as driving a small car 25.7 km. The production of 136 kg of UK tomatoes will release the same amount of CO_2 equivalents as one passenger's return flight from London to New York (Table 13).

Some other more summary examples are shown below for information (all the assumptions and calculations are shown in Appendix 2).

- Producing 100 kg of tomatoes in the UK emits the same amount of CO_2 equivalents as does the production of 1 washing machine, or put another way 1 t of tomatoes emits the same amount of GHGs in CO_2 equivalents as does the production of 10 washing machines.

- Growing 1 ha of peas in the UK emits the same level of CO_2 equivalents as does running a 40 W light bulb 5 hours per day for 956 weeks.

- Growing 1 ha of peas in the UK emits the same level of CO_2 equivalents as does running a 60 W light bulb for 22,307 hours, i.e. 930 days or 2.6 years.

- Growing 1 kg of outdoor lettuce in the UK emits the same level of GHGs as does running a 40 W light bulb for 16 hours.

- Growing 1 kg of indoor lettuce with heating requirements in the UK emits the same level of GHGs as does running a 40 W light bulb for 125 hours.

- The production of 12,000 roses in the Netherlands which are delivered to southern England emits the same amount of GHG emissions as does the electricity use of 4.7 small offices per year.

- GHG emissions from 27.9 billion car kilometres driven in Wales in 2006 are 35 times greater than the GHG emissions from the production of the total amount of tomatoes consumed in Wales per year.

- The methane emissions from a single dairy cow have an equivalent global warming potential to the production of 0.27 t of UK tomatoes.

- The methane emissions from a single beef cow have an equivalent global warming potential to the production of 0.14 t of UK tomatoes.

- The methane emissions from a single sheep have an equivalent global warming potential to the production of 0.02 t of UK tomatoes.

- The application of nitrogen fertiliser at a rate of 200 kg N ha^{-1} $year^{-1}$ has an equivalent global warming potential to driving an average petrol car for 4,471km.

Table 12. Comparison of GHG emissions from a variety of horticultural products and emissions from the use of cars. Figures are the number of kilometres driven in different sizes of cars that cause the same amount of emissions as the horticultural product as specified. Car emissions are based on Defra (2007) figures and include CO_2 only (small petrol car: 0.1831 kg CO_2 per km, medium petrol car: 0.2162 kg CO_2 per km, large petrol car: 0.2964 kg CO_2 per km, average petrol car: 0.2095 kg CO_2 per km). GHG emissions for horticultural products are based on figures in: Williams (2007) for Dutch roses (up to the delivery to a regional distribution centre in the UK); Williams *et al.* (2006) for tomatoes (up to the farm gate); Barrett *et al.* (2002) for fresh green vegetables and fresh fruit consumed in York (all life cycle stages except consumption); Hospido *et al.* in preparation/unpublished for lettuce (up to the regional distribution centre) and Milo i canals *pers. comm.* for UK outdoor broccoli (data include production, transport, retail and consumption phases).

	Single rose from the Netherlands	**500 g UK tomatoes**	**500 g fresh green vegetables**	**500 g fresh fruit**	**kg UK outdoors lettuce**	**UK indoors lettuce (heated)**	**kg UK broccoli**
small petrol car, up to 1.4 l engine	16.9	25.7	4.6	9.3	1.8	14.3	2.6
medium petrol car, 1.4-2.0 l engine	14.3	21.7	3.9	7.9	1.5	12.1	2.2
large petrol car, above 2.0 l engine	10.4	15.9	2.8	5.7	1.1	8.80	1.6
average petrol car	14.8	22.4	4.0	8.1	1.6	12.5	2.3

Table 13. Emissions from short- and long-haul return flights and the kg of tomatoes and fresh green vegetables causing the same amount of emissions. Calculations are based on figures for CO_2 emissions per passenger km, plus an added 9% to account for non-direct routes, delays and circling (Defra 2007). GHG emissions for horticultural products are based on figures in Williams *et al.* (2006) for tomatoes (up to the farm gate) and Barrett *et al.* (2002) for fresh green vegetables (all life cycle stages except consumption).

Flight	kg CO_2 per passenger km	total emission (kg CO_2 per passenger)	kg tomatoes grown that these emissions equate to	kg fresh green vegetables these emissions equate to
Return flight London-Athens (3000 km)	0.1304	426.4	45.4	255.3
Return flight London-New York (11,130 km)	0.1056	1,281.1	136.3	767.1

4 Sector specific issues

This section highlights specific issues relating to the GHG emissions from each of the main horticultural sectors. There are limited amounts of publicly available information pertaining to many sectors. Indeed several sectors do not seem to have any analysis undertaken on the level of their GHG emissions (e.g. bulbs and outdoor flowers, mushrooms). Even when sectors have been reasonably well studied, such as for tomato production, much of the available information is very general in nature. While the publicly available data are limited, several horticultural businesses have undertaken carbon footprints of their own businesses. This type of business specific analysis will provide much higher level of information to managers than this report can achieve. Against this background this section hopes to achieve three things:

a) to provide an overview of all sectors
b) to provide generic information against which specific businesses can compare their own GHG emission data
c) to provide information to those businesses who may not have yet undertaken a carbon footprint of their activities.

4.1 Field vegetables

In contrast to most industrial and domestic activities where total GHG emissions are usually dominated by CO_2 from fossil fuel use, emissions from field based agriculture are dominated by N_2O emissions (Williams *et al.* 2006). These emissions largely arise during the manufacture of fertilisers and from direct N_2O emissions from soils after fertiliser application. For example, fertiliser use accounts for 40% and 60% of the farm stage GWP for carrots and onions grown in Sweden and 75% for onions grown in Denmark (Lagerberg Fogelberg & Carlsson-Kanyama 2006). This is an important difference to the protected crops sector, where CO_2 from the use of electricity and natural gas is the dominant GHG.

Primary energy inputs in field horticulture tend to be lower than for protected crops (Figure 5) and are dominated by the use of oil and diesel for field operations. For example, cut flowers grown outdoors generally require about 25% less energy inputs than glasshouse grown flowers (Vringer & Blok 2000).

There are relatively few case studies on energy consumption or GWP for horticultural and arable field crops in the UK. In one wide ranging study, Tzilivakis *et al.* (2005) calculated GWPs per ha for UK production as follows:

0.7 t CO_2 equivalents for peas;
3.0 t CO_2 equivalents for potatoes;
1.0-1.8 t CO_2 equivalents for sugar beet;
1.7 t CO_2 equivalents for winter wheat;
1.2 t CO_2 equivalents for oilseed rape;
0.7 t CO_2 equivalents for spring barley.

A more specific analysis of pea production suggested that the field production stage had the greatest GWP, with N_2O emissions of 0.2 kg N_2O per ha per year. Expanding the system boundary to include long storage periods in the supply chain and final consumption did not alter the overall conclusion that the field based activities had the greatest GWP in the supply chain (Foster *et al.* 2006).
However, when considering fresh carrots transport, especially consumer transport from the retail store to consumers' homes, was the main contributor to GWP. Because of this, peeled carrots have lower impacts than bunched carrots due to the lower weight being transported from shops to homes (Foster *et al.* 2006). This is similar for fresh broccoli, where the stems that are regarded as waste account for about 40% of the product, and thereby increase transport costs and related emissions. For this reason processing by industry instead of consumers reduces the amount of product that needs to be transported (Lagerberg Fogelberg & Carlsson-Kanyama 2006).

For frozen carrots, storage in distribution, retail and at home are the main stages dominating GWP. Packaging is the most important stage for canned produce (but this impact can be mitigated by recycling), while transport and packaging are most important for pouched carrots and carrots sold in laminated cartons. The GWP per 600 g serving of carrots decreases in the following order: frozen carton > frozen bag > food can (landfill) > laminate carton pouch > fresh bunched > fresh peeled (Foster *et al.* 2006).

Storage and drying or cooling is the main use of primary energy for maincrop potatoes. As second earlies are not stored while having relatively good yields their energy burden per tonne of product is much lower than for maincrops (1,510 MJ and 775 MJ per t for maincrop and second earlies respectively) (William *et al.* 2006).

Although field vegetables have been well studied when compared with other sectors, there is the potential to undertake much more research in order to increase understanding of the patterns of GHG emissions in the supply chain. Further details and examples of LCA studies and a study on energy consumption for field horticultural crops are given in the Appendix 3.

Summary/key points

- GHG emissions from field based horticulture are usually dominated by N_2O from the production and application of nitrogen fertilisers
- primary energy use is lower than for protected crops
- primary energy use is dominated by oil and diesel used for field operations; other uses of energy are for refrigeration, ventilation and heating
- storage and drying or cooling requirements may greatly increase energy use per t of product
- consumer transport of produce to their homes can represent a significant proportion of total GHG emissions
- the type of packaging can have a significant impact on GWP

4.2 Protected crops

Greenhouse horticulture emits CO_2, CH_4, N_2O and sulphur dioxide (SO_2). In contrast to field horticulture, where CH_4 and N_2O represent a significant part of total emissions, CO_2 from the use of electricity and natural gas is the single most important GHG produced by protected horticulture. Emissions of CO_2 result from the combustion of natural gas for heating and for increasing CO_2 concentrations in the greenhouse to stimulate crop growth. In Dutch greenhouse horticulture the combustion of natural gas accounts for 99% of total greenhouse gas emissions (Pluimers *et al.* 2001). In the Netherlands, total GHG emissions per hectare are more than 50 times higher for protected horticulture than field based agriculture. However, some other emissions are lower than in field agriculture, and for tomatoes grown in Sweden and the Netherlands, fertiliser use contributes only 1% and 2% respectively of glasshouse GWP (Lagerberg Fogelberg & Carlsson-Kanyama 2006).

Tomatoes, cucumbers and peppers are usually grown at higher temperatures than other edible crops, resulting in larger heating energy inputs (Warwick HRI 2007, Table 6a). In a study of British tomato production Williams *et al.* (2006) estimated the GWP from the current national basket of tomatoes at 9.4 t CO_2 equivalents per t of tomatoes, with heating and lighting dominating GWP. The types of tomatoes with the highest yields (non-organic, loose, classic or beefsteak) have lower GWPs than organic and on-the-vine tomatoes (Williams *et al.* 2006). The Williams study suggests that the current mix of organic tomato types has almost double the GWP of the conventional mix. This is because of the lower yield of organic tomatoes (75% of the conventional types) and the higher proportion of specialist and on-the-vine varieties (specialist on-the-vine varieties have five times greater GWPs than classic loose), while inputs to the production systems are very similar (Williams *et al.* 2006). Given the importance of these types of studies to the protected cropping sector it may be beneficial for further studies to be undertaken which could both serve to verify Williams' results and also highlight the impact of best practice on the carbon footprint.

For lettuce, energy inputs for heating and lighting result in significantly greater GWP for protected than field production (Milà i Canals *et al.* 2007b). For summer crops, cold storage dominates GWP, whilst for winter crops, the glasshouse stage is the dominant contributor to GWP (Hospido & Milà i Canals unpublished report) (see Case study 3 in Section 2. 4.3 for further details).

Electricity use is high for cut flowers and pot plants because of lighting to improve growth during winter and/or to regulate flowering. Although cut flowers and pot plants are also usually grown at high temperatures, energy saving screens commonly used at night reduce average heating electricity inputs. A Dutch study on cut flowers found energy requirements ranging from 3 to 195 MJ per flower depending on type of flower and month purchased (Vringer & Blok 2000). The glasshouse stage accounts for 99% of GWP for the production, packaging and transport of Dutch roses up to regional distribution centres in the UK (Williams 2007). However, innovative options for heating, such as geothermal heating can reduce emissions considerably (see Case Study 1 in Section 2. 4.1).

Table 6a shows estimates of primary energy inputs into protected crops and total energy use per crop in the UK. Appendix 3 contains details of case studies on lettuce, tomatoes, watercress, cut flowers and cut roses. Taken together these studies suggest that during the production stage of most protected crops heating and lighting are the main energy users, and generally, the glasshouse stage of the supply chain dominates GHG emissions. However, if the supply chain requires the cold storage of produce then this stage may actually produce more GHG emissions than the glass house stage. Other processes such as steam cleaning of glasshouses with disinfectants may also represent a significant use of energy, while soilless greenhouse cultivation can reduce environmental impacts due to lower inputs of fertilisers and pesticides (Mugnozza *et al.* 2007).

Summary/key points

- unlike field agriculture, GHG emissions from greenhouse horticulture are dominated by CO_2 emissions from the use of natural gas and electricity
- heating and lighting dominate energy use in protected horticulture
- crop varieties with higher yields have reduced GWPs as compared to lower yielding varieties (assuming the same level of inputs)
- if crop storage is required, this may be a significant part of total GWP
- for crops such as tomatoes, where the production stage is very energy intensive, emissions due to transport may be insignificant in comparison to the production stage.

4.3 Bulbs and outdoor flowers

No case study on bulbs and outdoor flowers was found in the scientific literature. However it appears that the primary energy inputs for bulb flowers are relatively low (Table 6). Through discussion with growers it appears that the main issues in daffodil production (as bulbs and as a flower crop) relate to the following:

- fuel use for field operations (ploughing, planting, application of pesticides, harvesting of bulbs)
- fuel use for transport of bulbs and flowers on-site
- electricity use for cold storage of cut flowers on-farm for 1-8 days at about 2°C
- electricity for forced air ventilation during bulb drying for about one week, plus possibly electricity or calor gas use to speed up the drying process
- electricity use for on-farm grading and packaging of bulbs into 25 kg units

- transport of flowers and bulbs to markets
- oil or electricity used for hot water treatment (3 hours at 44.4°C) for half of the bulbs produced during a growing cycle that are retained as planting stock
- energy used to manufacture herbicides and fungicides

Unlike field vegetables, fertiliser use does not appear to be of importance (at least for daffodils). Application rates of nitrogen are kept to a minimum because it lead to soft growth with can result in disease problems.

4.4 Hardy nursery stock

No case study on hardy nursery stock was found in the scientific literature. However it appears as though container grown nursery stock only requires low energy inputs (Warwick HRI 2007). This is because there is only little requirement for additional lighting and heating. The main uses of energy are:

- heating of areas used for propagation (a minimum of 15°C of ground heat is required for cuttings to start rooting)
- pumping of irrigation water
- potting machines
- transport of the final product to retail and customers
- transport of growing media such as peat from e.g. Ireland or Eastern European countries to the nurseries
- production of fertilisers and pesticides or biological pest control
- production of polyethylene for polytunnels (with an average life time of about 5-7 years)
- production of pots, trays, plastic bags for compost etc.
- on-site fuel use for tractors, forklifts etc.

Rising fuel costs may impact the hardy nursery stock sector more than other sectors because of the bulkiness of the final products, as well as through increased costs for the delivery of large amounts of compost/growing media.

Environmental impacts other than climate change and GHG emissions from this sector include the consumption of significant amounts of water and peat. Although some growers mix peat with other materials, e.g. barks, peat remains the main growing medium used by the industry. Some growers collect run-off rain water to reduce water use from the mains, while others recycle used water.

4.5 Mushrooms

No case study on mushrooms was found in the scientific literature. However some available data suggests that compared with other edible crops they have relatively large energy inputs per ha (Table 6a). Discussion with growers suggests that the main energy uses in mushroom growing appear to be:

- electricity for cooling to prevent temperatures in the compost from rising too high
- air conditioning including computer control of CO_2 levels, humidity and temperature to remove the amount of CO_2 and water vapour produced
- cleaning after each crop cycle with steamed water

- cold storage of produce
- production of spawn which involves autoclaving at high temperatures
- transport of spawn in cooled vehicles that is imported from Ireland, France and the Netherlands in the absence of any British producers

Large quantities of compost are being used by the mushroom industry, which means that transport of compost to and from the farms will have a significant share of total GHG emissions. Compost may be made of straw, chicken manure and other ingredients; although the straw and manure may be regarded as by-products of cereal and meat production, significant GHG emissions will have resulted from the production of these materials. The use of peat for casing represents another environmental concern, both in terms of the destruction of peat moors and of the transport distances from its source (e.g. Baltic States) to the farm.

4.6 Soft fruit

Only one case study on energy consumption of soft fruit was available in the scientific literature (Defra 2005), this related to strawberries. Energy use and GWP were found to be amongst the largest environmental impacts of strawberry production, with ecotoxicity, water use and visual impact also significant. The study highlighted a great variability of energy inputs between different strawberry production systems (between 15.8 and 168.3 GJ per ha).

Strawberries have relatively low nitrogen requirements, so that unlike field horticulture where the greatest energy inputs may result from fertiliser manufacture, the main use of energy for strawberries is associated with the production of soil fumigants, irrigation pipe and the plastic used for polytunnels and mulch. Energy inputs are reduced in soil grown systems with second or third crops, as the energy inputs associated with bed preparation, fumigation and mulch are shared between additional crops. Energy associated with crop nutrition is greater in container than soil grown systems. There is a potential to reduce emissions throughout the sector by more efficient use of sprays and fertilisers, power and machinery.r

Because container grown systems require greater inputs of nitrogen than other systems, their GWP per ha is higher. GHG emissions per ha are lowest in soil grown systems without protection or fumigation; however, greater yields in coir systems may result in lower GWP per tonne produce than some soil grown systems. Unfortunately the recent loss of chemicals for disease management is encouraging greater use of peat bags, which in turn may be serving to increase GHG emissions from the sector.

4.7 Tree fruit

While some crops, such as apples have been well studies, others such as nuts and stone fruit have not been studied at all. (For a detailed description of case studies on apple production, see section 2.4.2 and Appendix 3). These studies suggest that areas of likely concern in relation to GHG emissions are:

- fertiliser use, which may contribute significantly to GWP through the emission of GHGs during production and N_2O emissions after application
- pesticide production contributes to GWP but usage varies between crops; for example, susceptible fruit (e.g. Cox apples) receive an average of 18 sprays comprising 35 products and 38 active substances (Garthwaite *et al.* 2000), and stone fruits receive less than pome fruits (Garthwaite *et al.* 2000)
- mechanisation of field operations (especially harvesting) was found to be the dominant cause of energy consumption in New Zealand apple orchards (64-71%) (Milà i Canals *et al.* 2006)
- machinery production and fertiliser manufacture also represent major energy inputs in New Zealand apple orchards (Milà i Canals *et al.* 2006)
- emissions related to energy consumption and fertiliser use dominate GWP in New Zealand apple orchards (Milà i Canals *et al.* 2006)
- packaging and cold storage can represent significant uses of energy (Blanke & Burdick 2005)
- loss of produce during storage increases energy used and GHG emissions per unit product sold

Some recent work on orchards in Hereford demonstrates the potential for orchard systems to act as substantial stores of carbon (Bangor University unpubl.). A comparison of seven orchards showed that the amount of carbon stored in the ecosystem (soil and trees) varied between 50 and 190 t of carbon per ha (Figure 10). Orchard management was related to the amount of carbon stored in the system with the highest carbon content being found in an old traditional orchard. Generally older orchards had more carbon stored both in the soil and in the tree biomass than younger orchards.

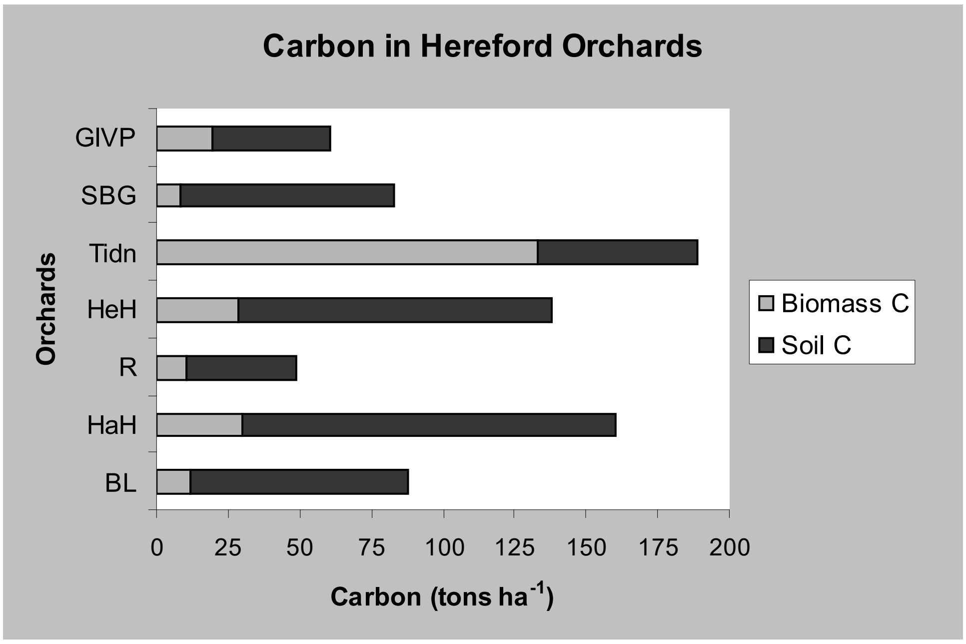

Figure 10. Carbon storage in seven orchards in Hereford in t ha^{-1}. The letters on the y-axis represent the names of different orchards. (from: unpublished report undertaken by Bangor University for Bulmer Foundation).

4.8 Best practice and mitigation opportunities

Because of rising energy costs, the protected horticulture sector and other agricultural sectors have already implemented many measures for energy saving, resulting in a 36% reduction in specific energy use since 1985 (Garnett 2006). For example, British tomato growers reduced their energy use by 25-30% between 1985 and 1995, when most of the greenhouses were converted to natural gas (Smith *et al.* 2005). However, additional savings of up to 10% might be achieved by more widespread uptake of existing technologies and good management (Garnett 2006). Benchmarking of energy use can help to identify energy saving opportunities and regular monitoring of energy use can help adopt energy efficiency measures. General measures to increase energy efficiency include regular maintenance of equipment (savings of up to 10%), regular collection and monitoring of energy use data and the use of renewable energy (Warwick HRI 2007).

Examples of best practice already widely applied in the protected crops sector include:

- heating of protected crops is mainly by large, centralised, fossil-fuel fired boilers, while direct-fire heaters burning gas, LPG, kerosene or gas oil are only found in older and/or less sophisticated greenhouses
- older, steam based systems have now largely been replaced by low temperature hot water systems (maximum 90°C)
- use of computer and microprocessor based climate control systems to optimise energy use/application of IT
- installation of Combined Heat and Power (CHP) energy generation
- Use of themal screens
- Waste heat/sourcing partnerships

4.8.1 Field based horticulture

Some potential mitigation measures and their payback periods are shown in Table 14. Energy saving and GHG mitigation measures in field operations and bed preparation include (Warwick HRI 2007):

- replacement of old machinery with newer, more efficient models
- fuel savings can be made by careful selection of cultivation methods, organisation of cultivation or using reduced tillage methods
- use of GPS and precision farming methods
- correct tractor ballasting, tyre selection and implement matching
- adoption of correct driving techniques
- do not exceed crop nitrogen requirements
- accurate timing of nitrogen fertiliser applications to minimise leaching losses
- do not spread manure at inappropriate times, i.e. when there is little crop requirement (too late in the season or when there is no crop to utilise the added nitrogen)

Generally, only 55-70% of the nitrogen applied to the soil is taken up by crops (MAFF 2000). Nitrogen that is not taken up by the crop may enter the atmosphere as N_2O, cause eutrophication as nitrate or acidification as ammonia. As the production and application of nitrogen fertilisers, together with N_2O emissions resulting from nitrogen applications, are a major contributor GHG emissions from field based horticulture, management practices that increase the fraction of applied nitrogen that is actually taken up by plants would help reduce GHG emissions. This will require greater precision in timing and placement of nitrogen fertiliser.

Table 14. Measures for energy and carbon savings in field based horticulture (total energy use: 526 GWh) and length of the payback period for the, with the year 2005 as the base year (from: Warwick HRI 2007). Percentage savings refer to the total used in the sector in the UK.

Energy-saving measure	Potential energy savings	C savings (1,000 tonnes)	Payback period (years)
Store insulation, optimised storage	9 GWh 2%	0.5	2-5
Improved field heat removal	15 GWh 3%	0.7	2-5
Optimisation of field operations	15 GWh 3%	1	0-2

4.8.2 Protected horticulture

Energy saving and GHG reducing measures in greenhouses include (Warwick HRI 2007):

- optimisation of heat storage to minimise heat loss (correct sizing, adequate insulation)
- improved boiler design by fine-tuning of combustion efficiency through adjusting the fuel/air mix and boiler control (e.g. use of variable speed drives on the boiler fan motor),
- replacement of older boilers with newer, more efficient models
- matching boiler capacity to demand
- use of multiple boilers and smaller, more localised heating systems allowing to turn off heating for specific production areas at times of no heat demand and reducing energy losses from pipework
- improving the overall efficiency of gas-fuelled boilers by using flue-gas condensers
- use of modern thermal screens to reduce heat transmission losses in greenhouses by up to 40%; the latest materials reduce heat losses, maximise light transmission (up to 88% diffuse light, 80% direct light) and fold away in such a way as to cause minimal crop shading
- replacement of damaged or missing pipe insulation and flanges, valves etc. in pipe heat distribution systems
- a reduction of air leakage through glass, framework joints, poorly fitted ventilators and doors can decrease the heat demand of a greenhouse by 12% per year
- climate control systems can significantly reduce energy consumption
- more energy efficient humidity control systems are being developed at present
- use of CHP
- recycling of polyethylene for polytunnels and mulches

Table 15 shows typical energy consumption for protected edible crops and ornamental crops as well as reductions that can be achieved by following best practice measures. Tables 16 and 17 list options for the reduction of energy use and

CO_2 and N_2O emissions in protected horticulture. Table 18 estimates potential energy savings and carbon emission savings from a variety of mitigation measures, as well as payback periods and potential barriers to the uptake of these measures in the UK protected crops sector.

Table 15. Energy use benchmarks: average values for energy consumption in protected greenhouse horticulture in kWh m^{-2} (Carbon Trust 2004).

	Edible crops				**Ornamental crops**			
	Intensive		Extensive		Intensive		Extensive	
	Heat	Electricity	Heat	Electricity	Heat	Electricity	Heat	Electricity
Best practice	520	10	225	8	350	60	155	8
Typical	675	15	250	12	450	60	175	12

Table 16. Energy saving technologies and potential for the protected horticultural sector (from: Biffaward 2002).

Energy conservation measure	**Potential energy reduction**
Efficient light sources	80-85%
Variable-speed motor drives (pumping and irrigation)	40%
Combined heat and power	30%
Heat pumps for heating	30%
More efficient greenhouse design	25%
Thermal storage	20%
Improved greenhouse heating controls	15%
Boiler flu gas condensers	15%
Decentralised boiler plant	15%
Monitoring and targeting, energy awareness training	5%
High-efficiency motors for various motor applications	2%

Table 17. Options to reduce farm level abiogenic emissions of CO_2 and NO_x that result from the combustion of natural gas in Dutch tomato cultivation and their technical potentials to reduce emissions (from: Pluimers *et al.* 2001).

Reduction options	**Reduction of CO_2 [a]**	**Reduction of NO_x [a]**
Condensers: single, retour and combi	4-12%	4-12%
Screens: fixed, movable and double	8-25%	8-25%
Wall insulation: wall screens, double glass and coated glass	0.5-8%	0.5-8%
Roof insulation: double and coated glass	20-35%	20-35%
Alternative CO_2 application: heat buffer or pure CO_2	10%	10%
Alternative gas combustion: low NO_x burner	0%	40%

Temperature management: climate computer, decrease of average temperature and temperature integration	7-16%	7-16%
Greenhouse construction: better insulation	1-2%	1-2%

[a] Technical potential to reduce emissions on the farm level as a percentage of the emissions in the unabated situation.

Table 18. Measures for energy and carbon savings in protected horticulture (total energy use: 5,207 GWh), length of the payback period for the grower and potential barriers to the adoption of these measures, with the year 2005 as the base year (from: Warwick HRI 2007). Percentage savings refer to the total used in the sector.

Energy-saving measure	Potential energy savings	C savings (1,000 tonnes)	Payback period (years)	Barriers to take-up
Monitoring and benchmarking	520 GWh 10%	30	0-2	Sub-metering needed. Communal action needed.
Improved greenhouse cladding and reduced air leakage	230 GWh 4%	13	2-5	Investment in new glasshouses
Decentralised boiler plant	230 GWh 4%	13	2-5	High capital cost. Cultural resistance.
Improved boiler design (including flue gas condensers)	230 GWh 4%	13	2-5	High capital cost. Only practical with gas, and where low grade heat can be utilised.
Thermal screens	240 GWh 5%	14	2-5	High capital cost. Cultural resistance in edibles sector.
Correct insulation and sizing of thermal stores	240 GWh 5%	14	2-5	
Temperature integration and climate control	800 GWh 15%	45	2-5	Technology transfer needed. Worry about losing control! Research gaps.
CHP installation	1,050 GWh 20%	60	5-10	High capital cost. Electricity requirements have to be high or there is export potential (local infrastructure needed).
High efficiency lighting	15 GWh 0.2%	0.7	2-5	High capital cost. Research gaps.
Improved motive power application	30 GWh 0.6%	1.4	0-2	Research gaps. Technology transfer needed.

4.8.3 Options for increased energy efficiency during different production stages

Nonhebel (2006) concluded that the non-agricultural stages of the food chain have the largest impact on the GHG emissions related to food. Consequently, it is important to increase energy efficiency and implement other GHG reduction measures along the whole food chain, not just the production stage. Some opportunities for achieving reductions include:

Energy saving measures in crop drying and storage:

- adequately insulate all controlled temperature and controlled atmosphere stores

- improve humidity control

Refrigeration and cooling systems:

- size components carefully according to their intended use and function
- the condenser needs to be placed correctly and maintained properly
- coils must be kept free of debris and dirt
- refrigerant levels must be as prescribed and monitored annually by engineers
- improved airflow through stores ensuring that refrigerated air reaches the entire crop results in energy savings
- combining conventional refrigeration and ambient cooling can reduce operational hours and allow a reduction in the size of the refrigeration components
- better insulation of stores and reduced air leakage allow energy savings
- possible energy savings from replacing old and inefficient equipments: 20-50%
- store foods at a temperature no lower than necessary
- keep air circulation to the minimum needed
- minimise pressure drops in pipes
- when buying new equipment, buy the most efficient equipment available
- maintain equipment to minimise leakages and inefficiencies
- use better insulation, more efficient motors, automated closing doors
- energy savings for refrigeration in supermarkets could be achieved by covering currently open cabinets
- implement novel technologies such as combined heat, power and refrigeration (so-called trigeneration plants).

Lighting:

- use of more energy efficient lamps
- use of timers, light sensors and proximity sensors to ensure lighting is only used when needed
- conversion to discharge lighting, including fluorescent
- fluorescent lighting provides more energy-efficient day length control than tungsten bulbs
- alternative light sources based on light emitting diodes may enable energy savings
- lamps specifically for plant lighting with high outputs of photosynthetically active radiation and lamps with slower reductions in light output with age are being developed

Motive power:

- use of high-efficiency motors in new motive applications
- pressure linked variable speed drive technology can help reduce energy use by circulation pumps used for irrigation and for heating in greenhouses

Energy savings during transport can be achieved by:

- better fleet management
- fuel efficient driving
- use of more aerodynamic vehicles
- more efficient planning of routes and loads
- better time management
- use of cleaner fuels

Plant breeding:

- may help reduce waste by producing new varieties that are less prone to spoilage and/or help reduce energy use in storage

- plant breeds that use nitrogen fertilisers more efficiently can help reduce application rates and thus GHG emissions (as well as other environmental impacts such as water pollution)
- plant breeds that extend the UK growing season could help reduce imports

A reduction in food waste could be achieved through behavioural changes because:

- supermarkets' and consumers' expectations of continuous supplies lead to overproduction and waste
- most waste is produced in the consumers' homes

Other waste reduction options:

- use of biodegradable mulch films
- a reduction of product wastage at all stages of the supply chain
- re-use of pots, trays etc.

Consumers:

- use of more energy efficient kitchen appliances, e.g. refrigerators
- use of renewable energy sources
- increased consumption of field grown rather than greenhouse grown produce
- decreased consumption of meat and dairy products

4.8.4 Use of synergies between different crops

Synergies between different crops might be exploited more in order to reduce energy use and GHG emissions. For example, tomatoes are grown using CO_2 fertilisation at high temperatures, while mushrooms give off large amounts of CO_2 and heat as a waste product. Anaerobic digestion of organic materials such as slurry, green waste and waste food can be used to produce biogas to power CHP units for electricity generation.

5 Closing remarks and a suggested position

1. The science and practice of measuring the carbon footprints of horticultural production systems are currently in their infancy, but there will be rapid development in methods over the coming years. Of particular note is the drive from the Carbon Trust with BSI and others to develop a standardised method for developing a carbon footprint. However, given the international nature of many supply chains it seems unlikely that standardisation of methods at the UK level will be sufficient to ensure comparability between analyses. Rather it seems likely that an EU, and maybe globally, agreed methodology will be needed. This will take several years to develop and agree, and in the mean time there is ample opportunity for businesses to measure their carbon footprint and use this to improve their competitiveness. This may involve real efforts to reduce GHG emissions and / or the use of the footprint results to gain marketing advantage. Evidence suggests that there may be 'first mover' advantage in utilising a carbon label for marketing purposes (cf Walkers crisps). If businesses wish to seek such an advantage then they need to be confident that their carbon footprinting method and results are robust. In order to achieve this they need to use the best available methodology and to be totally transparent in their assumptions.

2. The status of carbon stocks and GHG fluxes into and out of ecosystems in carbon accounting remain unclear. For some sectors such as tree crops, the production system itself may act as a significant carbon sink. Over time the commercial importance of these stores may become more important, especially if carbon trading is enabled between businesses (as planned for The Netherlands). Further research is needed in quantifying these stocks and fluxes, and in estimating their potential financial significance in any carbon trading scheme.

3. The information discussed in this report clearly shows that the overall carbon footprint of a business (and the supply chains it supports) is not necessarily dominated by emissions related to transport. These can be significant (see examples in Sims 2007), but it is also evident that the nature of the production process can have major impacts on the carbon footprint. Indeed in some cases efficiencies in the supply chain may compensate for the emissions related to long distance travel (e.g. cut roses from Kenya discussed in Case Study 1). So it is probably wrong to assume that local produce necessarily has a lower carbon footprint than non-local produce.

4. It is unclear how consumers will respond to the introduction of carbon labels on horticultural produce. If faced with two similar products, say tomatoes, then environmentally aware consumers may preferentially choose the tomato with the lowest carbon footprint. However, it is unclear at what level consumers would make such a decision. Would they choose the produce with the lowest carbon footprint regardless of the exact nature of the tomato (i.e. not differentiate between loose tomatoes, tomatoes on the vine and cherry tomatoes) or would they assume these products to be different? If the latter, then any choice would be made between products within each class of tomato (i.e. between different types of loose tomato or tomato on the vine). In the latter situation the practicalities of seasonality and supply chains means that in reality on any one shopping event there may be very little choice between similar produce available to most consumers, and so the impact of the label may be minimal.

5. Some consumers may respond to carbon labels by boycotting certain produce which they deem to have unacceptably large carbon emissions. So rather than choose between cherry tomatoes from different supply chains, certain consumers may choose not to buy any cherry tomatoes at all. If consumers were logical in their choice of food items to boycott, then based on the data shown earlier processed dairy products, alcoholic drinks and coffee may be the first items to be boycotted. However, consumers are rarely rational in their behaviour, and their choices may be heavily influenced by pressure groups, the media and / or specific marketing campaigns. For this reason the horticultural industry in general may wish to stress the relatively low levels of GHG emissions from horticultural produce compared to other food items.

6. There is a moral obligation on the horticultural industry to reduce the carbon footprint of its products. However, it seems only reasonable that any such reductions are mirrored in other industrial sectors. The majority of household emissions arise from energy use and transport, and there is a clear need for the relevant industrial sectors to reduce emissions from these activities. Similarly there is a need for consumers to engage in behavioural change to reduce their emissions from these activities. The horticultural sector may

wish to stress the importance of these actions in mitigating the impacts of climate change.

7. Each sector could engage in mitigation activities in order to reduce GHG emissions. However, many of these raise challenges of some kind (e.g. need for financial investment in capital, increased labour, increased variable costs, adoption of unfamiliar technology). Because of this individual businesses may only adopt mitigation activities when they expect a positive cost/benefit ratio from the action. However, just because businesses have not adopted mitigation strategies in the past, it does not mean that they will not adopt it in the future. Increases in the price of energy and other inputs, may render investment decisions financially rational in the future, even though they were not rational in the past. Similarly the emergence of new technology, a carbon tax, and/or the activities of competitors may stimulate changes in many businesses. As mitigation activities are adopted, so the GHG emissions of any given product should decrease. Such reductions will probably occur across many businesses in each sector, in the UK and beyond. For this reason any significant commercial advantage may accrue to early adopters of mitigation technology (the so-called ‘first movers’).

8. When the carbon footprint of a product is expressed as kg of CO_2 kg-equivalent per kg of product, one method of reducing the footprint is to increase the level of production per kg of GHG emitted. This philosophy encourages greater levels of productivity and in many cases an agenda of intensification. It may be commercially rational for any one business to respond to the pressures of carbon accounting in this way. However, if all businesses responded in a similar manner and this resulted in greatly increased supply of any one product then the approach would not be sustainable at the sector level (unless consumption increased to match the increased supply). Sector level sustainability could only be achieved if supply stayed in balance with demand. If this was important then it may be better to think about increasing carbon efficiency of current production levels, rather than seeking carbon economies of scale from increased outputs. Due to the commercial nature of the sectors, it seems unlikely that there would be an agreement to achieve carbon efficiencies at current levels of production, and so greater levels of intensification may be expected in the future. While this intensification may be driven by environmental needs (i.e. the need to reduce GHG emissions per kg of product), care must be taken to ensure it does not have other unwanted environmental impacts.

9. There are relatively few studies on the carbon footprint of horticultural products. While some sectors such as apples are relatively well studied, other such as mushrooms and bulbs and outdoor flowers are severely under researched. These knowledge gaps need to be filled, however the relevant balance of public and privately funded research is unclear. The advantage of publicly funded research is that the results are publicly available, and can be used to inform a wide range of stakeholders. The disadvantages of publicly available research are twofold. Firstly commercial sensitivities may preclude a complete analysis of the production system (or supply chain). Second, commercial data become available to potential competitors and customers (e.g. retail multiples). If the sector as a whole is to progress then some balance between these types of study must be found whereby business can learn from each other, without losing commercial advantage (i.e a database of anonymous results from businesses).

Position statement

Given all of the information presented in this report it is suggested that the horticultural sector adopts the following position on carbon accounting and the development of carbon footprints:

Given all of the information presented in the following review it is suggested that the horticultural sector adopts the following position on carbon accounting and the development of carbon footprints:

1. Welcome initiatives to reduce the greenhouse gas emissions (GHG) from horticultural activities.

2. Acknowledge that the horticultural industry has an obligation to reduce GHG emissions, and is happy to work with all stakeholders in order to achieve reductions.

3. Promote the environmental benefits of eating fruit and vegetables when they are in season and work with stakeholders to reduce the environmental impact of providing produce out of season.

4. Stress that the burden of reducing GHG emissions should fall equally on all industrial sectors. Horticulture should not be expected to make proportionately greater reductions than other industrial sectors.

5. Ensure that innovation in the food chain is encouraged by incentivising individual growers to reduce their carbon footprint.

6. Ensure the individual situation of growers is recognised in any carbon footprint of a supply chain. This is essential if the good practice undertaken by individual growers is to be recognised by customers. The use of sector level average data will serve to mask good practice, and will not adequately reward innovation in the food chain.

7. Encourage all stakeholders who discuss carbon footprinting to clearly state the system boundary used and the units of measurement, i.e. energy use, emissions of CO2, or emissions of all GHGs expressed as CO2 equivalents.

8. Ensure that best scientific practice is adopted when constructing a carbon label, and be willing to adapt methods over time as new scientific findings enhance understanding of GHG emissions.

9. Do not claim that any carbon footprints are representative of production in specific regions or countries unless a statistically valid sample has been conducted.

10. When communicating with the public about GHG reduction in general all stakeholders should clearly state the proportion of household emissions that derive from different activities (i.e. household heating, electricity use, transport, consumer goods, food and beverages). (Stakeholders may be Government, pressure groups or the media).

11. Ensure that when communicating with the public on GHG reduction from food systems all stakeholders (including Government, pressure groups and the media) should clearly state the level of GHG emissions from a typical range of food items (e.g. red meat, poultry, processed dairy, wine, coffee, bread & flour, fresh fruit and vegetables, frozen fish and frozen vegetables).

12. When communicating with the public about GHG reduction in food systems all stakeholders should should clearly state the level of food wastage at each stage of the food chain (processing, retail, consumption) as this represents a significant amount of GHG emissions that could be avoided. (Stakeholders may be Government, pressure groups or the media).

13. Recognise that the carbon footprint is only one element of a sustainable business. A truly sustainable business can only be achieved by balancing a wide range of environmental, social and financial factors.

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7. Appendix

Appendix 1 How to develop a carbon footprint: field horticulture as an example

Data collection
Detailed information on inputs to and outputs from the system needs to be gathered according to the system boundary chosen. For horticultural enterprises, this may include:

On-farm inputs and processes

Farm details
Produce sold (kg produce year^{-1}) or per ha?
Seeds
Compost/potting media
Farm area (ha)
Area of non-productive land on farm (ha)
Storage facilities
Ploughing
Ploughing in of crop residues
Capital inputs

Energy use
Diesel use (including diesel used by contractors) (l year^{-1})
Petrol use (l year^{-1})
Electricity use (kWh year^{-1}) –(preferably broken down into the uses by use in each subsystem (e.g. heating in greenhouse, cooling in storage, lighting in greenhouse, pumping, irrigation, ventilation, cooling etc.). This helps to identify reduction opportunities.

Fertiliser
Nitrogen (kg N year^{-1})
Phosphorus (kg P year^{-1})
Potassium (kg K year^{-1})
Organic nitrogen (kg N year^{-1})
Other e.g. trace elements

Pesticides
Herbicide (l or kg year^{-1})
Insecticide (l year^{-1})
Fungicides (l or kg year^{-1})

Waste
On-farm plastic waste (e.g. greenhouse, polytunnel, mulch and crop cover films, seed trays and pots, fertiliser bags, seed bags and pesticide containers)

Inputs and processes beyond the farm gate

Transport
Diesel use (including diesel used by contractors) (l $year^{-1}$)
Petrol use (l $year^{-1}$)
Distance moved (km $year^{-1}$)
Amount of produce moved (t $year^{-1}$)

Storage
Electricity use (kWh $year^{-1}$)
Capital inputs

Packaging
Electricity use (kWh $year^{-1}$)
Plastic and other materials used.
Capital inputs

Retail
Electricity use (kWh $year^{-1}$)
Capital inputs

Household phase
Electricity use (kWh $year^{-1}$)
Capital inputs

Waste
Packaging waste
Capital inputs

Defining the system boundary
See section 2.1.

Calculation of GHG emissions
Once the amounts of the different inputs are obtained, GHG emissions can be calculated by multiplying by the relevant emission factors if available (see Tables 1-3).

In addition to the inputs considered above, another important source of GHGs on a field based horticultural farm is the emission of nitrous oxides (N_2O) from fertilised soils. An increase in available nitrogen through the application of inorganic and organic fertilisers usually results in increased N_2O emissions. The internationally agreed default emission factor for N_2O emissions from N inputs is 0.01 kg N_2O-N kg^{-1} N (uncertainty range: 0.003-0.03 kg N_2O-N kg^{-1} N) (IPCC 2006). Indirect N_2O emissions from the soil to which nitrogen is applied occur through volatilization and leaching. For equations that can be used to calculate these emissions, see IPCC (2001).

Methane emissions relating to agriculture and horticulture are of importance in a worldwide context. In countries such as the UK, however, they are minor because there is no anaerobic rice cultivation, which is a major source worldwide, and little horticultural production on wet soils (e.g. moors), and methane emissions from farmed organic are negligible (Kasimir-Klemedtsson *et al.* 1997).

Appendix 2 Assumptions and calculations for the examples presented in Section 3.3.2

1. *Producing 100 kg of tomatoes in the UK emits the same amount of CO_2 equivalents as does the production of 1 washing machine, or put another way 1 t of tomatoes emits the same amount of GHGs in CO_2 equivalents as does the production of 10 washing machines.*

The production of a washing machine emits 954.4 kg CO_2 equivalents (Barrett *et al.* 2002). The production of 1 t of tomatoes in the UK emits 9.4 t of CO_2 equivalents up to the farm gate (or 1 kg of tomatoes emits 9.4 kg of CO_2 equivalents) (Williams *et al.* 2006).

➔ 954.4 kg CO_2 equivalents / 9.4 kg of CO_2 equivalents per kg tomatoes = 101.5 kg tomatoes
or:
➔ 1 t of tomatoes emits 9.4 t of CO_2 equivalents; the production of 10 washing machines emits 10 * 954.4 = 9,544 kg CO_2 equivalents = 9.5 t CO_2 equivalents

2. *Growing 1 ha of peas in the UK emits the same level of CO_2 equivalents as does running a 40 W light bulb 5 hours per day for 956 weeks.*

Running a 40 W light bulb for 5 hours uses 0.2 kWh of electricity. Running a light bulb for 5 hours per day for a week uses 1.4 kWh. 1 kWh emits 0.523 kg CO_2 (Defra 2007) (note that this is CO_2 only, not CO_2 equivalents). This means that running a 40 W light bulb for 5 hours per day for one week emits 0.7322 kg CO_2.

Growing 1 ha of peas in the UK emits 700 kg CO_2 equivalents (Tzilivakis *et al.* 2005).

➔ 700 kg CO_2 equivalents per ha peas / 0.7322 kg CO_2 per week = 956 weeks of running a 40 W light bulb for 5 hours a day per ha peas grown in the UK

3. *Growing 1 ha of peas in the UK emits the same level of CO_2 equivalents as does running a 60 W light bulb for 22,307 hours, i.e. 930 days or 2.6 years.*

1 kWh emits 0.523 kg CO_2 (Defra 2007) (note that this is CO_2 only, not CO_2 equivalents). Running a 60 W light bulb uses 0.06 kW. Growing 1 ha of peas in the UK emits 700 kg CO_2 equivalents (Tzilivakis *et al.* 2005).

➔ 700 kg CO_2 equivalents per ha peas / (0.06 kW * 0.523 kg CO_2 per kWh) = 22,307 h

4. *Growing 1 kg of outdoor lettuce in the UK emits the same level of GHGs as does running a 40 W light bulb for 16 hours.*

The production of 1 kg of British outdoors lettuce emits 0.33 kg CO_2 equivalents (Hospido *et al.* in preparation). 1 kWh emits 0.523 kg CO_2 (Defra 2007) (note that this is CO_2 only, not CO_2 equivalents). Running a 40 W light bulb uses 0.04 kW.

➔ 0.33 kg CO_2 equivalents per kg outdoor lettuce / (0.04 kW * 0.523 kg CO_2 per kWh) = 16 h

5. *Growing 1 kg of indoor lettuce with heating requirements in the UK emits the same level of GHGs as does running a 40 W light bulb for 125 hours.*

The production of 1 kg of British indoors lettuce with heating requirements emits 2.62 kg CO_2 equivalents (Hospido *et al.* in preparation). 1 kWh emits 0.523 kg CO_2 (Defra 2007) (note that this is CO_2 only, not CO_2 equivalents). Running a 40 W light bulb uses 0.04 kW.

➔ 2.62 kg CO_2 equivalents per kg indoor lettuce / (0.04 kW * 0.523 kg CO_2 per kWh) = 125 h

6. *The production of 12,000 roses in the Netherlands which are delivered to southern England emits the same amount of GHG emissions as does the electricity use of 4.7 small offices per year.*

The production of 12,000 stems of marketable quality roses in the Netherlands and subsequent delivery to a retail distribution centre in the UK emits 37,110 kg CO_2 equivalents (Williams 2007). A typical small office uses 15,000 kWh of electricity per year (Carbon Trust 2006b). 1 kWh emits 0.523 kg CO_2 (Defra 2007) (note that this is CO_2 only, not CO_2 equivalents).

This means that a typical small office emits 15,000 kWh * 0.523 kg CO_2 per kWh = 7,845 kg CO_2 per year.

➔ 37,110 kg CO_2 equivalents per 12,000 roses / 7,845 kg CO_2 per office per year = 4.7 offices

7. *GHG emissions from 27.85 billion car kilometres driven in Wales in 2006 are 35 times greater than the GHG emissions from the production of the total amount of tomatoes consumed in Wales per year.*

An average petrol car emits 0.2095 kg CO_2 per km driven (Defra 2007) (note that this is CO_2 only, not CO_2 equivalents). In 2006, 27.85 billion car km were driven in Wales (www.statswales.wales.gov.uk). Total emissions from the 27.85 billion car km driven in Wales in 2006 are: 27.85 billion car km * 0.2095 kg CO_2 per km = 5,834,575 t CO_2.

The production of 1 t of tomatoes in the UK emits 9.4 t of CO_2 equivalents up to the farm gate (Williams *et al.* 2006). In Wales, 17,685 t of tomatoes are consumed per year (Plassmann & Edwards-Jones 2007). The production of this amount of tomatoes emits: 17,685 t of tomatoes * 9.4 t CO_2 equivalents per t tomato = 166,239 t CO_2 equivalents.

➔ 5,834,575 t CO_2 emissions from cars / 166,239 t CO_2 equivalent emissions from tomato production = 35

8. *The methane emissions from a single dairy cow have an equivalent global warming potential to the production of 0.27 t of UK tomatoes*

A dairy cow emits 109 kg CH_4 per year (IPCC 2001). Expressed as CO_2 equivalents, this is 109 kg CH_4 * 23 (IPCC 2001) = 2,507 kg CO_2 equivalents per dairy cow per year.

The production of 1 t of tomatoes in the UK emits 9.4 t of CO_2 equivalents up to the farm gate (Williams *et al.* 2006).

➔ 2,507 kg CO_2 equivalents per dairy cow per year / 9.4 kg of CO_2 equivalents per kg of tomatoes = 266.7 kg tomatoes = 0.27 t tomatoes

9. *The methane emissions from a single beef cow have an equivalent global warming potential to the production of 0.14 t of UK tomatoes.*

A beef cow emits 57 kg CH_4 per year (IPCC 2001). Expressed as CO_2 equivalents, this is 57 kg CH_4 * 23 (IPCC 2001) = 1,311 kg CO_2 equivalents per beef cow per year.

The production of 1 t of tomatoes in the UK emits 9.4 t of CO_2 equivalents up to the farm gate (Williams *et al.* 2006).

➔ 1,311 kg CO_2 equivalents per beef cow per year / 9.4 kg of CO_2 equivalents per kg of tomatoes = 139.5 kg tomatoes = 0.14 t tomatoes

10. *The methane emissions from a single sheep have an equivalent global warming potential to the production of 0.02 t of UK tomatoes.*

A sheep emits 8 kg CH_4 per year (IPCC 2001). Expressed as CO_2 equivalents, this is 8 kg CH_4 * 23 (IPCC 2001) = 184 kg CO_2 equivalents per sheep per year.

The production of 1 t of tomatoes in the UK emits 9.4 t of CO_2 equivalents up to the farm gate (Williams *et al.* 2006).

➔ 184 kg CO_2 equivalents per sheep per year / 9.4 kg of CO_2 equivalents per kg of tomatoes = 19.6 kg tomatoes = 0.02 t tomatoes

11. *The application of nitrogen fertiliser at a rate of 200 kg N ha^{-1} $year^{-1}$ has an equivalent global warming potential to driving an average petrol car for 4,471 km.*

The emission factor for N_2O emissions from nitrogen fertiliser inputs is 0.01 kg N_2O-N kg^{-1} N (IPCC 2006). This means that the application of 200 kg N ha^{-1} $year^{-1}$ leads to the direct emission of 2.00 kg N_2O-N ha^{-1} $year^{-1}$. To convert N_2O-N to N_2O, this figure is multiplied by 44/28, resulting in 3.1 kg N_2O ha^{-1} $year^{-1}$, which is 3.1 kg N_2O ha^{-1} $year^{-1}$ * 298 (IPCC 2007) = 936.6 kg CO_2 equivalents ha^{-1} $year^{-1}$.

An average petrol car emits 0.2095 kg CO_2 per km driven (Defra 2007) (note that this is CO_2 only, not CO_2 equivalents).

➔ 936.6 kg CO_2 equivalents ha^{-1} $year^{-1}$ / 0.2095 kg CO_2 per km driven = 4,470.5 km

Appendix 3 Examples of LCA studies

Appendix 3.1 Field vegetables

Runner beans (Sims et al. 2007):

Aim
- to estimate the environmental impacts of runner beans imported into the UK from Kenya or Guatemala or grown and consumed in the UK and assess the relative importance of the transport stage

System boundary/method used
- life cycle assessment up to the delivery to UK consolidation points (i.e. including agrochemical production, growing, harvesting, packaging material manufacture, grading, storage and packing as well as transport of inputs to the farm and transport of produce to and from airports up to the UK consolidation point
- soil is excluded from the system boundary
- full crop rotations are not considered
- capital inputs were excluded

Key findings in relation to carbon
- global warming is the most important environmental impact of Kenyan and Guatemalan imported beans
- global warming potentials sourced from Kenya or Guatemala are 20-26 times greater than for UK beans, which is mainly due to emissions from air transport

Other findings
- marine aquatic ecotoxicity is the most important environmental impact from the UK supply chain (due to electricity use for growing, harvesting, grading, storage and packing)

Potential problems/limitations
- the UK results relate to produce grown in season only; for out-of-season production in greenhouses or longer storage periods, the results may be very different
- soil emissions are excluded although the may represent a major GHG source

Potatoes (Williams et al. 2006):

Aim
- to quantify the environmental burden and resource use for UK grown potatoes

System boundary/method used
- life cycle assessment up to the farm gate
- storage and cooling are included in the system boundary

Key findings in relation to carbon
- the global warming potential is 208 kg CO_2 equivalents per t for maincrop potatoes, 178 kg CO_2 equivalents per t for second earlies and 318 kg CO_2 equivalents per t for earlies
- for maincrop potatoes, crop storage and drying or cooling represents the main use of energy (49%), followed by field work (28%), fertiliser manufacture (19%) and pesticide manufacture (4%)
- for second earlies, field work accounts for 61% of primary energy use, fertiliser manufacture for 31% and pesticide manufacture for 8%
- for earlies, field work accounts for 61% of primary energy use, fertiliser manufacture for 33% and pesticide manufacture for 6%
- because second earlies are not stored while having similar yields as maincrop potatoes, energy burdens are lower (1510 MJ of primary energy used per t maincrop potatoes, 775 MJ per t second earlies)

- irrigation increases yields while having only a negligible impact on total energy use, so that the global warming potential per t potatoes decreases slightly
- direct N_2O and CO_2 have similar contributions to the overall global warming potential (48% and 45% respectively for non-organic potatoes; 49% and 42% respectively for organic potatoes)

Other findings

- early potatoes are particularly high on nitrate leaching because of similar levels of fertilisation as maincrop and second earlies but lower yields

Potential problems/limitations

- methodology not transparent

Peas (Tzilivakis et al. 2005):

Aim

- to calculate the global warming potential and other environmental impacts for peas and other crops

System boundary/method used

- total energy consumption was calculated for each activity from seed bed preparation and planting to transport of the crops to the factory, including energy inputs for the manufacture and application of inputs and the maintenance of machinery
- emissions CO_2, N_2O and CH_4 are included

Key findings in relation to carbon

- energy inputs and global warming potential for producing peas are 6.7 GJ per ha and 0.7 t CO_2 equivalents per ha respectively
- this compares to 3.0 t CO_2 equivalents per ha for potatoes, 1.0-1.8 for sugar beet, 1.7 for winter wheat, 1.2 for oilseed rape and 0.7 for spring barley
- N_2O losses amount to 0.2 kg N_2O per ha per year for peas, 1.1-2.9 for potatoes, 0.5 for sugar beet, 0.3-0.9 for winter wheat, 0.7-0.8 for oilseed rape and 0.5-0.8 for spring barley

Other findings

- pesticide ecotoxicity was assessed by calculating an average ecotoxicity score; for peas, this was 75, for potatoes 230, for sugar beet 26-67, for winter wheat 35, for oilseed rape 85 and for spring barley 30

Potential problems/limitations

- impacts on biodiversity, loss of nutrients via surface run-off or soil quality were excluded

Lettuce (Hospido et al. in preparation):

Aim

- to compare the environmental impact of lettuce production in the UK and Spain for consumption in the UK

System boundary/method used

- life cycle assessment up to UK regional distribution centres
- the system boundary includes all farm operations (soil management, fertiliser use, planting, pest and disease management, irrigation, harvesting and post-harvest cooling) and farm machinery
- the functional unit is 1 kg of lettuce delivered to a UK regional distribution centre
- emissions CO_2, N_2O and CH_4 are included

Key findings in relation to carbon

- outdoor production in the UK: fertiliser use (manufacture and direct N_2O emissions) dominates GWP (27.6%), followed by soil management (21.8%)

- outdoor production in Spain: transportation from Spain to the UK dominates GWP (42.5%), followed by fertiliser use (29.5%)
- differences between farms of the same country can be as big as differences between countries

Other findings

- fertiliser use dominates acidification and eutrophication potential for UK outdoor production

Appendix 3.2 Protected crops

Watercress (Sims et al. 2007):

Aim

- to estimate the environmental impacts of watercress imported into the UK from the USA or grown and consumed in the UK

System boundary/method used

- life cycle assessment up to the delivery to UK consolidation points (i.e. including agrochemical production, growing, harvesting, packaging material manufacture, grading, storage and packing as well as transport of inputs to the farm and transport of produce to and from airports up to the UK consolidation point, plus waste disposal)
- soil is excluded from the system boundary
- full crop rotations are not considered
- production of farm machinery was included

Key findings in relation to carbon

- watercress imported from the USA may have an up to 15 times greater global warming potential than UK grown watercress
- transport of watercress from the USA causes 89% of the global warming potential
- for the UK supply chain, global warming potential is the third dominant impact and is mainly due to electricity consumption during packaging

Other findings

- abiotic depletion is the most important environmental impact from UK grown watercress
- acidification is the second most important impact for both systems
- organically produced UK watercress has a better overall environmental performance than conventionally produced watercress

Potential problems/limitations

- the UK results relate to produce grown in season only; for out-of-season production in greenhouses or longer storage periods, the results may be very different
- soil emissions are excluded although the may represent a major GHG source

Tomatoes (Williams et al. 2006):

Aim

- to quantify the environmental burden and resource use for UK grown tomatoes

System boundary/method used

- life cycle assessment up to the farm gate
- packaging is not included

Key findings in relation to carbon

- the global warming potential is 9.4 t CO_2 equivalents per t tomatoes
- heating and lighting dominate the environmental impacts of tomato production

- maximising the use of CHP across the UK could reduce primary energy consumption by about 70%
- non-organic, loose tomatoes have the lowest environmental impact; organic, on-the-vine tomatoes have the greatest environmental impact
- organic production is more energy intensive due to lower yields at similar energy consumption
- although yields per ha are much higher than for most arable crops, the use of fuel for greenhouse production results in substantially higher environmental burdens than for arable crops
- unlike many arable crops where N_2O emissions usually dominate global warming potential, CO_2 from electricity use dominates the global warming potential for tomatoes

Other findings
- for all environmental impact categories, heating and lighting is the main burden; for abiotic resource use, construction of the greenhouse is the second most important impact; for eutrophication, fertilisation and direct crop emissions have the second and third largest impact

Potential problems/limitations
- methodology not transparent

Protected lettuce (Hospido & Milà i Canals, unpublished report):

Aim
- to quantify the environmental burden and resource use for summer and winter protected lettuce for a particular business

System boundary/method used
- life cycle assessment up to the farm gate, i.e. including the production of farm inputs, production and on-farm storage or packaging
- the global warming potential includes CO_2, N_2O and CH_4

Key findings in relation to carbon
- for winter crops, the glasshouse stage (glasshouse building, maintenance, electricity, natural gas) dominates GWP
- for summer crops, cold storage dominates GWP
- CO_2 has the greatest contribution to GWP (90% for winter crops and 80% for summer crops)
- heating dominates energy use for winter crops and harvesting and cold storage dominate for summer crops

Other findings
- for winter crops, heating dominates the emissions of acidifying substances, for summer crops, harvesting and cooling dominate
- eutrophication through nutrient emissions is mainly due to heating for winter crops and fertiliser use for summer crops

Potential problems/limitations
- field emissions were not measured but calculated using literature values

Lettuce (Milà i Canals et al. 2007b):

Aim
- to compare the environmental impacts of out-of-season lettuce production in heated glasshouses in the UK with outdoor winter production in Spain

System boundary/methodology
- LCA methodology

- the system boundary extends from plant propagation to regional distribution centre (including all farm operations, field emissions, post-harvest cooling and transport, but excluding packaging production)

Key findings in relation to carbon

- primary energy use from indoor production much greater than from outdoor production both for UK and Spanish produce, mainly due to heating and to a lesser extent lighting
- out of season production in the UK has higher energy use and global warming potential than lettuce imported from Spain
- lettuce imported from Spain during the winter has a similar global warming potential to lettuce in the field during the UK summer
- about 40-50% of the global warming potential of Spanish lettuce is due to transport to the UK

Other findings

- water use is greater in Spanish and British outdoor production than British indoor production systems

Potential problems/limitations

- differences between farms within the same country can be as large as between countries

Cut roses (Williams 2007):

Aim

- to compare energy inputs and global warming potential of cut roses for the British market produced in Kenya and the Netherlands

System boundary/method used

- life cycle analysis up to delivery to the retail distribution centre in Hampshire
- 12,000 marketable quality cut stem roses as functional unit
- capital inputs (at least vehicles) included
- emissions CO_2, N_2O and CH_4 are included

Key findings in relation to carbon

- the main energy input in the Dutch production system are 800,000 m^3 of natural gas and 1,200 MWh of electricity per ha
- primary energy use for the production of 12,000 cut roses is 68,000 MJ in Kenya and 550,000 MJ in the Netherlands
- the Kenyan operation uses about 8 times less primary energy and 20 times less fossil energy than the Dutch system analysed; the Kenyan system analysed sources most of its electricity from geothermal generation
- for Kenyan roses, 61% of primary energy use are due to the production stage, 3% for packaging and 36% for transport
- for Dutch roses, over 99% of primary energy is used during the production stage
- for Kenyan roses, the GWP is dominated by air freight (81% of total GWP) (total GWP: 2,100 kg CO_2 equivalents excluding the IPCC altitude factor correcting for the effect of high altitude CO_2 emissions on the atmosphere, 6,000 including the IPCC altitude factor)
- for Dutch roses, the GWP is dominated by the production stage (total GWP: 37,110 kg CO_2 equivalents, production stage GWP: 36,900 kg CO_2 equivalents)
- for both production systems, CO_2 dominates the GWP, with only small contributions from N_2O and CH_4
- an increase in the use of renewable energy, improved management and the development of higher-yielding varieties may decrease the GWP from the Dutch production system

- annual yields of marketable stems are 1,350,000 in the Netherlands and 2,285,000 in Kenya

Potential problems/limitations

- only two specific producers were analysed which may not be representative and renders generalisations difficult
- values used to calculate CO_2 emissions from geothermal energy were world averages, not Kenya specific for lack of data
- less actual data was available for the Dutch than the Kenyan enterprise
- the errors associated with the results are estimated to be ±30%

Cut flowers (Vringer & Blok 2000):

Aim

- to examine how household primary energy requirements can be reduced for decorative and gift functions provided by cut flowers in the Netherlands

System boundary/method used

- hybrid energy analysis method

Key findings in relation to carbon

- energy requirements range from 3 to 195 MJ per flower depending on type of flower and month purchased (see Table 19)
- flowers grown outdoors generally require about 25% of the energy consumed by glasshouse grown flowers
- energy reductions can be achieved by: buying more cut flowers in summer and less in winter; buying less energy intensive species; buying bulbs instead of bulbous cut flowers; buying indoor plants instead of cut flowers
- flowers grown in warmer countries can be grown using less energy; e.g. roses grown in Israel, Morocco and Spain require about 10% less energy than in the Netherlands, including the energy required for air freight (about 1 MJ per flower), and flowers from Kenya require about 85% less than Dutch roses (2-3 MJ per flower)

Potential problems/limitations

- methodology not transparent

Table 19. Energy requirement per flower for some species (from: Vringer & Blok 2000).

Type of flower	Energy requirement in MJ per flower
Chrysanthemum	12.5
Amaryllis	10.7
Rose	9.5
Lily	8.1
Freesia	6.5
Carnation	4.9
Iris	4.5
Tulip	4.0
Daffodil	3.6
Sword lily	3.0

Appendix 3.3 Tree fruit

Apples (Milà i Canals et al. 2007a):

Aim

- to compare the primary energy use for apples produced in different countries and consumed in Europe

System boundary/methodology

- primary energy use was calculated as an indicator for environmental impacts

- the system boundary included cultivation, storage and delivery to a European shop, while post-retail stages were excluded (cradle to retail)

Key findings in relation to carbon

- during the European autumn and winter energy consumption is generally greater for apples imported from the Southern hemisphere than for European apples consumed in Europe
- truck transport can contribute significantly to primary energy consumption depending on country of origin, which means that if apples are imported from one European country to another, energy costs may not be much lower than for apples imported from the Southern hemisphere
- transportation by ship is the largest single use of primary energy for non-European apples

Potential problems/limitations

- the study only looked at primary energy use
- the variability in data (e.g. in yields per ha between farms, countries and years) makes general conclusions difficult
- a more comprehensive comparison of local vs imported apples could include other environmental issues such as eutrophication, as well as quality of apples and economic implications
- an extension of the system boundary to post-retail stages may show a greater impact of these than energy use during cultivation and transportation and country of origin

Apples (Blanke & Burdick 2005):

Aim

- to compare the energy required for apples imported from New Zealand or grown in Germany and consumed in Germany

System boundary/methodology

- primary energy requirements were calculated from crop cultivation to end user for apples on sale in April
- energy requirements were calculated including fuel, pesticides and fertiliser; grading; cooling after harvest; storage; packaging; transport by truck and reefer; and fuel used for consumer shopping

Key findings in relation to carbon

- energy requirements for imported apples were 27% greater than for locally grown apples, even including five months of storage
- primary energy requirements for local fruit were estimated at 5.893 MJ per kg apples and at 7.499 MJ per kg apples for imported fruit

Potential problems/limitations

- this study only looked at primary energy requirements which does not represent all environmental issues and GHG sources
- no mention is made of the inclusion of GHG emissions from soils (mainly N_2O after fertiliser application)

Apples (Sims et al. 2007):

Aim

- to estimate the environmental impacts of Royal gala apples imported into the UK from Italy, Chile or Brazil or grown and consumed in the UK and to assess whether it is more environmentally beneficial to store UK grown apples for ten months to negate the need to import

System boundary/method used

- life cycle assessment up to the delivery to UK consolidation points (i.e. including agrochemical production, growing, harvesting, packaging material

manufacture, grading, storage and packing as well as transport of inputs to the farm and transport of produce to and from airports up to the UK consolidation point)
- soil is excluded from the system boundary
- full crop rotations are not considered
- capital inputs were excluded

Key findings in relation to carbon
- transport is significant for apples imported from the Southern hemisphere
- global warming is significant mainly for imported apples
- transport accounts for 72% and 90% of the global warming potential for Chilean and Brazilian apples respectively; for UK apples this figure is 6-21%
- for Italian apples, agrochemical use accounts for 49% and transport accounts for 30% of the global warming potential
- storing UK grown apples for ten months of the year to maintain year round supply instead of importing incur about half of the global warming potential as importing from Southern hemisphere countries

Other findings
- the quality of apples stored in the UK for ten months will be lower than that of fresher imported apples

Potential problems/limitations
- the UK results relate to produce grown in season only; for longer storage periods, the results may be very different
- soil emissions are excluded although the may represent a major GHG source