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LIFE CYCLE ASSESSMENT (LCA) OF DOMESTIC VS. IMPORTED VEGETABLES.
Case studies on broccoli, salad crops and green beans

Authors:
Llorenç Milà i Canals, Ivan Muñoz, Almudena Hospido, Katharina Plassmann, Sarah McLaren

Project Coordinator:
Gareth Edwards-Jones

Project Manager:
Barry Hounsome

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This report is one of the outcomes of a Rural Economy and Land Use (RELU, http://www.relu.ac.uk) programme funded project RES-224-25-0044 (http://www.bangor.ac.uk/relu): 'Comparative assessment of environmental, community and nutritional impacts of consuming fruit and vegetables produced locally and overseas'. Llorenç Milà i Canals acknowledges GIRO CT (http://www.giroct.net) for its logistical support during editing of the report. Sarah McLaren's involvement in the last two years of the project was funded through the New Zealand Foundation for Research, Science and Technology programme 'Building Capacity for Sustainable Development: the Enabling Research' (C09X0310).

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ABOUT THE AUTHORS

Dr Llorenç Milà i Canals was the main researcher for the LCA studies of this project, at the Centre for Environmental Strategy, University of Surrey (UK) between November 2004 and December 2007. After a brief period working as a *Ramón y Cajal* fellow in GIRO CT (http://www.giroct.net) in early 2008, he is currently life cycle assessment manager within Unilever's Safety & Environment Assurance Centre (SEAC, http://seac.unilever.com).

Dr Ivan Muñoz was contracted as a Research Fellow at the Centre for Environmental Strategy, University of Surrey (UK), from July to October 2007 to work within the RELU project. His main task was to model the retail to grave life cycle stages of vegetables. He is currently a *Juan de la Cierva* fellow at the Department of Hydrogeology and Analytical Chemistry, University of Almeria (Spain).

Dr Almudena Hospido visited the Centre for Environmental Strategy, University of Surrey (UK) with a grant from *Fundacion Caixa Galicia*, from November 2005 to August 2006 to work on the enabling technologies for out of season lettuce production in the UK. She is currently *Isidro Parga Pondal* fellow at the Department of Chemical Engineering, University of Santiago de Compostela (Spain).

Dr Katharina Plassmann is a research fellow at Bangor University (UK), and completed the LCA modelling of the Kenyan farms after Dr Milà i Canals left the project.

Dr Sarah J McLaren was the lead researcher for this project within the Centre for Environmental Strategy, University of Surrey (UK). She moved to New Zealand in December 2005 and is currently Research Leader at Landcare Research.

EXECUTIVE SUMMARY

The RELU[1]-funded project 'Comparative Assessment of Environmental, Community and Nutritional Impacts of Consuming Vegetables Produced Locally and Overseas' (http://www.bangor.ac.uk/relu/) aimed to validate, from a wide range of disciplines, the advantages or otherwise of eating locally produced vegetables. In other words, it addressed the question 'Which is best; to produce vegetables in the UK, or to import produce from overseas?'. To answer this question a range of characteristic vegetables produced in the UK, Spain, Uganda and Kenya were compared considering aspects such as environment, economy, consumer perception, nutrition and community.

This report presents the Life Cycle Assessment (LCA) studies that have been performed as part of the project to compare the environmental impacts generated for the delivery to UK consumers of vegetables produced in different countries. It presents detailed results for three case studies, each one focusing on a vegetable produced in different countries:

- Brassicas (broccoli) from the UK and Spain
- Salad crops (lettuce) from the UK, Spain and Uganda
- Legumes (green beans) from the UK, Uganda and Kenya.

The results provide insights into the environmental hotspots in the life cycle of the assessed vegetables, as well as the comparative environmental impacts of different supply options. The study specifically addresses the seasonality of fresh vegetables, and compares produce that may be on the market shelves at the same time of the year. In addition, it explores the variation of environmental impacts associated with the same or similar products through the year.

One of the main outcomes of this study is the confirmation that working with 'food miles' as an indicator of environmental impacts for food products is potentially misleading: imported produce may have lower environmental impacts than domestic produce supplied off-season through increased storage and/or production using enabling technologies such as heated and lit glasshouses. On the other hand, produce imported by air has higher environmental impacts than off-season domestic produce (at least in the case of lettuce and green beans), although for certain impact indicators such as land use, water use and pesticide use the result are not so clear-cut. However, at the same time it should be noted that LCA results only deal with environmental impacts; other important aspects - such as farmers' health and effects on the local economy – have been considered in the project but are not reported here.

There is considerable variation in the results from different farms producing the same product. This suggests that any single figure defining a crop (e.g. a value for the 'carbon footprint' of 1 kg green beans) is bound with significant uncertainty. Post-farm stages, and particularly home storage and cooking, have been shown to contribute significantly to the final impacts. Variations in these stages have not been modelled in detail, but are likely to be very significant due to variable consumer behaviour (e.g. cooking for more or less time, with different kitchen appliances, etc.). This is particularly true for products that are often cooked (i.e. not so relevant for products that are eaten raw, such as lettuce). Indeed, the home stage may dominate the results in the case of cooked vegetables.

This study has shown a novel approach to addressing land use impacts beyond the inventory indicator "m^2year of occupied land." Soil Organic Carbon (SOC) has been used as an indicator of soil quality, and potential changes to SOC linked to different land uses have been compiled along the whole life cycle of the products assessed. The results show that, contrary to common assumptions in several life cycle impact assessment methods, life cycle stages other than cropping may dominate the impacts related to land use, even if cropping still dominates the amount of m^2year.

Another novel approach in this study relates to inclusion of food consumption and excretion in the life cycle model. This stage has commonly been neglected in food LCA studies, but has been shown to be significant particularly in terms of water eutrophication and water use.

[1] The Rural Economy and Land Use Programme (RELU) aims to advance understanding of the challenges faced by rural areas in the UK by funding interdisciplinary research projects (http://www.relu.ac.uk).

1 INTRODUCTION. GOAL AND SCOPE DEFINITION

According to Hospido *et al.* (in preparation)

> *"Patterns of food production, distribution and consumption have undergone major transformations over the past half century. One of the consequences of these changes is that consumers have become used to a continuously increasing range of produce, regardless of the location and timing of its production. Year-round supply of fresh produce reflects supermarkets' sourcing strategies and perceived consumer demands: according to recent research[2], over 70% of consumers in UK urban areas expect to be able to purchase fresh vegetables and salad items at any time of the year."*

Research to compare localised and globalised food supply (Blanke and Burdick, 2005; Jungbluth and Demmeler, 2005; Schlich and Fleissner, 2005; Milà i Canals *et al.*, 2007a; Sim *et al.*, 2007; Edwards-Jones *et al.*, 2008) has contributed to debate around the 'food miles' concept, i.e. 'the distance food travels, from the farm to consumer' (Smith *et al.*, 2005). A more recent debate related to this issue spins around the concept of carbon footprint, which some actors suggest using as carbon label of products. Words of caution have already been expressed in relation to the difficulties of assigning greenhouse gas emissions to specific foodstuffs (Edwards-Jones *et al.* 2007; 2008; Milà i Canals and Sim, 2007). Within this framework, a RELU[3]-funded project[4] has investigated the advantages or otherwise of eating locally produced vegetables, addressing the question 'Which is best; to produce vegetables in the UK, or to import produce from overseas?'. To answer this question a range of characteristic vegetables produced in the UK, Spain, Uganda and Kenya are compared considering aspects such as environment, economy, consumer perception, nutrition and community. Spain was chosen because of its importance in terms of vegetables exports to the UK; Uganda and Kenya are representative for the African developing countries with an increasing share of British produce imports.

This report presents the Life Cycle Assessment (LCA) studies that have been performed as part of the project to compare the environmental impacts generated for the delivery to UK consumers of vegetables produced in different countries. It offers results for three case studies, each one focusing on a vegetable produced in different countries:

- Brassicas (broccoli) from the UK and Spain
- Salad crops (lettuce) from the UK, Spain and Uganda
- Legumes (green beans) from the UK, Uganda and Kenya

This introduction explains the methodology followed in the study, Life Cycle Assessment (LCA) and several considerations with respect to the goal and scope of the study that are common for the 3 case studies. The following chapters describe the LCA studies for the 3 case studies (Chapter 2 on broccoli; Chapter 3 on salad crops; Chapter 4 on legumes) following the remaining LCA main phases: description of the studied system and the data sources used for the Life Cycle Inventory (LCI); results of the main environmental impacts from the Life Cycle Impact Assessment (LCIA); and interpretation of the main conclusions and opportunities for improvement derived from each case study. Finally, Chapter 5 offers some general conclusions from the project, with especial attention to the relevance for the debates on food miles and carbon footprints/labels.

1.1 What is Life Cycle Assessment (LCA)?

LCA is a systems analysis tool that provides information on the environmental effects of a product from its cradle (acquisition of raw materials) to its grave (waste management). It gathers information on all the inputs and outputs to and from a product system, and assesses the potential environmental impacts associated with these inputs and outputs.

[2] Barry Hounsome, Bangor University, personal communication November 2006.
[3] The Rural Economy and Land Use Programme (RELU) aims to advance understanding of the challenges faced by rural areas in the UK by funding interdisciplinary research projects (http://www.relu.ac.uk).
[4] Comparative Assessment of Environmental, Community and Nutritional Impacts of Consuming Vegetables Produced Locally and Overseas (http://www.bangor.ac.uk/relu/).

ISO[5] has developed standards for the LCA methodology, in order to ensure transparency and consistency in its application. With its comprehensive view of the product's life cycle stages and environmental impacts (including global warming, effects on ecosystems, toxicity, depletion of resources, etc.), LCA helps in providing an accurate picture of the environmental trade-offs between different product options or technologies. Figure 1-1 details the four main phases of an LCA study, with a short description of what is included in each one.

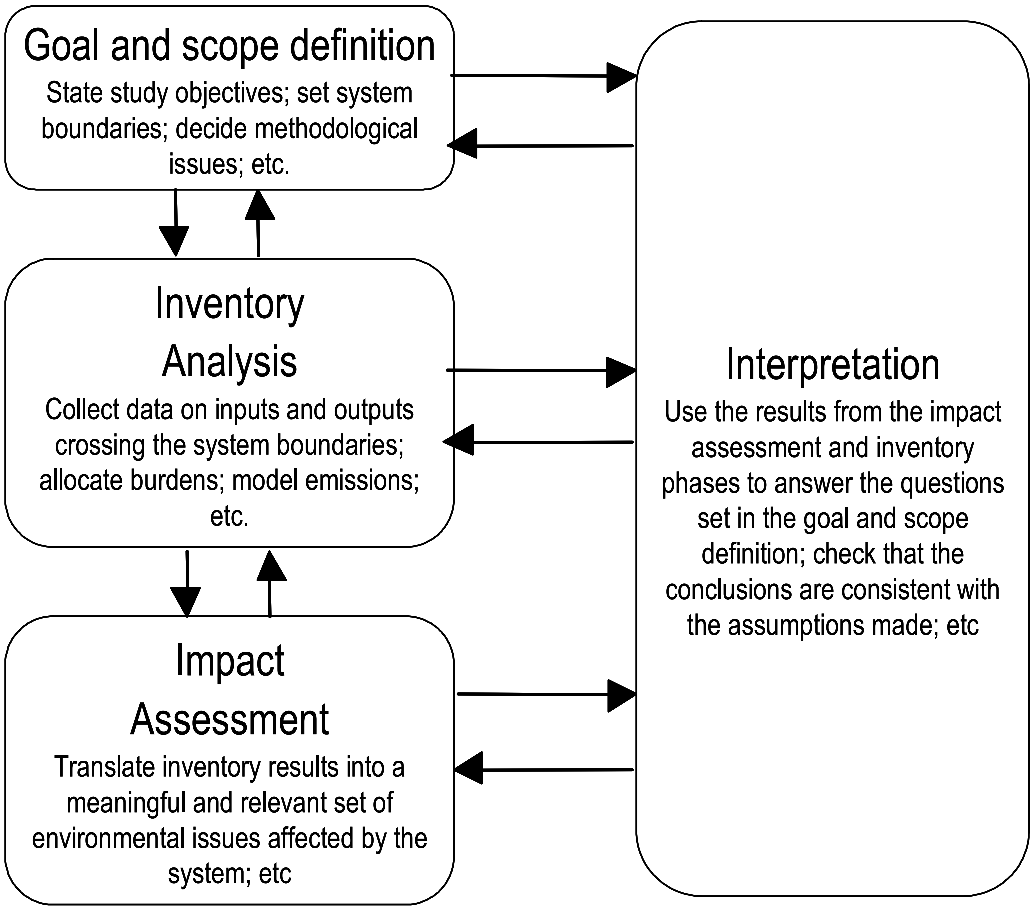

Figure 1-1: Main phases in the Life Cycle Assessment Framework. Adapted from ISO 14044:2006

1.2 LCA in this RELU Project

The scope of the LCA studies for this RELU project includes the assessment of vegetable production and delivery to UK consumers, as well as food storage, preparation and consumption at home. Different levels of detail are required for the data collected, according to the goals of the study, with site-specific data for the studied farms, national statistics for food retail and literature data for the production of ancillary products (fertilisers; pesticides; fuels; farm machinery; electricity; etc.). In Figure 1-2 the processes included in the LCA studies are shown.

[5] ISO 14044.

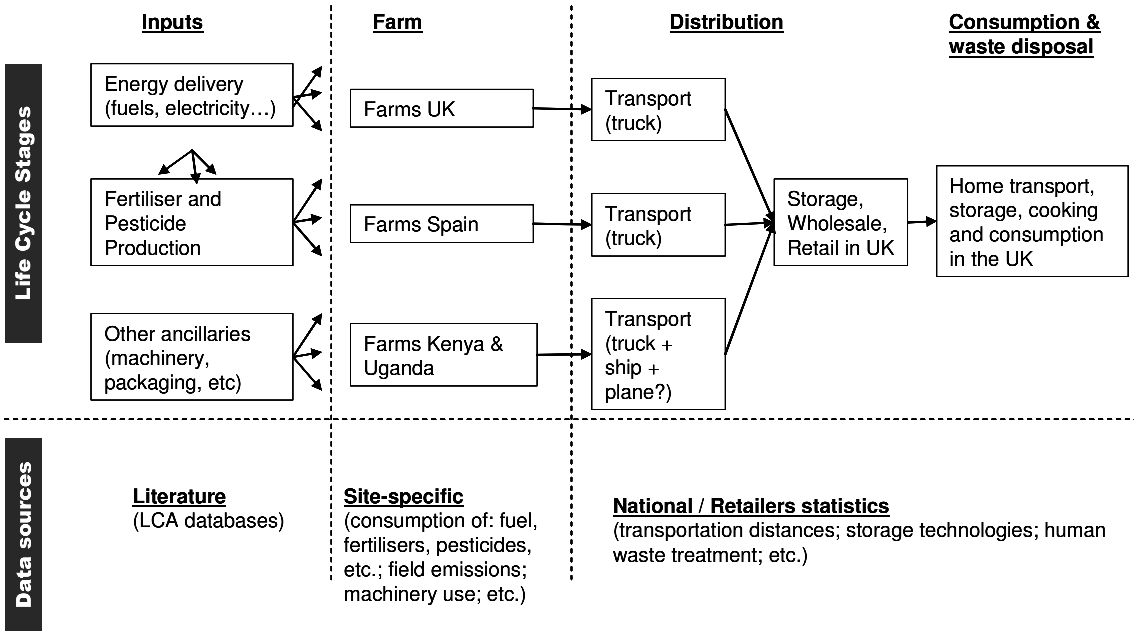

Figure 1-2: Life cycle stages investigated in the RELU project

1.3 Goals

The overall research question for this project concerns the benefits or otherwise of increasing local production for local consumption of vegetables in the UK. The overall purpose of the LCA studies is to investigate the environmental impacts associated with different systems for vegetable production, in order to understand more about the effects of increasing local production for local consumption of vegetables. More specific objectives include:

1. Determining which life cycle stages of selected vegetables contribute the greatest environmental impacts.
2. Comparing UK and overseas production of selected vegetables that are consumed in the UK.
3. Investigating whether differences in production practices between farms are more significant than differences between countries.

This report focuses on LCA studies for specific crops on specific farms. It is not necessarily representative of average crop production, and care should be taken not to draw too general conclusions from this study.

1.4 Functional unit

The functional unit is the reference measure to which the environmental burdens are expressed. It can be defined in three different ways in order to address the objectives listed above:

1. "Consumption of x kg of a vegetable" (where the quantity can be defined according to a typical portion on the plate, or any other quantity that seems appropriate).
2. "Provision of a portion of vegetables at various points in the year" (where the selected vegetables are regarded as substitutable, e.g. lettuce or chicory, beans/peas or broccoli).
3. "Consumption of x mg protein/Vitamin C/other nutrient" where the nutrient or vitamin may be provided by alternative foods.

The data collected in this project may be expressed using all these functional units for the analysis. Different reference units are used through the report to express the results (e.g. 1 ha of field for the cropping stage; 1 tonne or 1 kg of produce through processing; 1 kg of produce at home; etc.). Factors for the translation into other functional units are given when relevant.

1.5 System boundaries

The first objective (Section 1.3) set for the study suggests that the system boundaries should include all life cycle stages ("cradle to grave") for the food items. In other words, the study should extend from production of fertilisers and pesticides, through farming, distribution, home preparation and consumption, and on to sewage treatment after consumption and digestion, including all the food waste generated through these stages.

The other objectives (Section 1.3) require comparative analysis between alternative food items and/or production practices on different farms; for this type of analysis, it is only necessary to study the systems up to the retail life cycle stage ("cradle to retail"). This is because the subsequent life cycle stages do not constitute a difference between the alternative systems[6]. However, the relative importance of the post-distribution stages in the overall life cycle of vegetables needs to be illustrated in order to answer the first goal of the study.

The present report describes the whole life cycle of vegetables, from the cradle to the grave. The stages *"from the cradle to the central depot"* (i.e. including from the production of agro-chemicals to the regional distribution centre (RDC), with the food ready for distribution to retailers) are described for each specific case study (Chapters 2-4). The stages "retail to plate" (i.e. including all the transport steps from the supermarket to home, energy use during retail, and the home storage and cooking, including the treatment of solid waste arising from these steps) are described in detail in a separate report (Milà i Canals *et al*. 2007b). Another report details the food consumption and subsequent digestion, excretion and treatment of wastewater (Muñoz *et al*. 2007; in press).

1.6 Data quality requirements

As shown in Figure 1-2, site-specific data have been collected from farms in the UK, Spain, Kenya and Uganda. More generic data have been used for upstream production of farm inputs and downstream activities. In particular, data for the production of ancillary materials and machinery has been obtained from existing databases, as described in the relevant sections. The main LCA database used through the project is ecoinvent 2000 (http://www.ecoinvent.ch), which is described in different reports (e.g. Frischknecht *et al*. 2004; Dones *et al*. 2004; Althaus *et al*. 2004; Nemecek *et al*. 2004; Spielmann *et al*. 2004). The ecoinvent 2000 database is sufficiently comprehensive for the type of operations involved with the food supply chain. The adaptation of such datasets to the requirements of this project is explained in Milà i Canals *et al*. (2007b).

1.7 Life Cycle Impact Assessment

The impact assessment phase has been performed using mainly the CML 2001 method (Guinée *et al*. 2002) due to its comprehensiveness in terms of environmental issues covered and its scientific soundness. More details of the novel impact assessment methods used in this project are offered in Milà i Canals *et al*. (2007b). The following impact categories have been considered:

- Abiotic resources Depletion Potential (ADP)
- Climate change (measured as Global Warming Potential, GWP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Smog (measured as Photochemical oxidant creation potential, POFP)
- Soil quality (through evolution of soil organic matter: SOC deficit as defined in Milà i Canals *et al*. 2007c)

In addition, some environmental indicators which are especially relevant in the life cycle of food products have been assessed:

- Primary energy use (PEU, measured in MJ)

[6] It is assumed that crops produced in different countries and/or using different production practices generate the same impacts during subsequent preparation for consumption in the home, and sewage treatment. An exception would be increased wastage in the home associated with previous extended storage of some crops, but no data on the relationship between length of storage and food wastage has been found for the selected crops, and so this potential difference has been neglected.

- Land use (occupation, LU, measured in m^2year)
- Pesticide Hazard (PH, see Milà i Canals *et al*. 2007b)
- Water Use (WU, measured in litres)

1.8 Case studies

In order to address the goals of the project, case studies were assessed where the same vegetables could be grown in different countries apart from the UK. The study countries had to include a European supplier and an African one, in order to represent the main source of vegetables for the UK market (the EU) and the growing share of African countries as vegetable suppliers.

Spain was chosen as a representative European country, and several farms mainly in the region of Murcia were contacted and assessed. Murcia is the main source of many field vegetables (lettuce, broccoli, celery, cauliflower, etc.) sold in the UK during the colder months, with market shares of over 80% for many of them.
In Africa, Kenya was chosen due to its growing presence as a year-round source for vegetables. Particularly, Kenyan green beans and mange tout have featured in many media stories. Due to initial problems in accessing Kenyan data on vegetable production, Uganda was studied as a potential future supplier of vegetables to the UK. Uganda is currently not a big supplier, but it has the potential of becoming one following the path of its neighbour, Kenya.

In terms of vegetables, the chosen case studies had to illustrate alternative options for year-round supply apart from imports (Hospido *et al*. in preparation; Edwards-Jones *et al*. 2008), i.e. off-season production in protected horticulture (heated glasshouses) and extended storage (e.g. freezing). Thus, salad crops were chosen because they are grown in all countries and have traditionally been grown off-season in the UK in heated glasshouses. Spain is currently the main source of lettuce during the cold months (Hospido *et al*. in preparation), and although imports from Africa are still small in volume terms they represent a growing proportion of the market (baby leaves, bagged salads, etc.). Broccoli and green beans were chosen because they are currently sold frozen and supplied year-round, and imported from suitable countries. Again, Spain is a main source of broccoli and other brassicas, and Kenya in particular is the main exporter of green beans to the UK.

1.9 Knowledge exchange

In this RELU project, as in the RELU Programme in general, knowledge exchange amongst different actors in the food supply chain has been a key driver. In relation to this, small individualised LCA reports have been prepared for the participating farmers. In general, one report per crop and per farm has been produced. The main goal of such reports is to provide a summary of the studies in a format that:

- Allows the farmers to spot any error in the input data,
- Facilitates understanding of the LCA results for non-LCA practitioners, and
- Highlights practical implications of the study results.

The LCA reports have proven a valuable communication tool, and in several cases feedback from the farmers has led to correction of errors in the data used. In one case the LCA report has also prompted action by the farmer to reduce the environmental impacts of his production practices, using to a certain extent the improvement opportunities suggested in the report.

2 BROCCOLI

Broccoli is a member of the Cabbage family, Brassicaceae (formerly Cruciferae). It is classified as the Italica Cultivar Group of the species *Brassica oleracea*. Broccoli is also known as calabrese in certain regions of the UK. This vegetable has been assessed in two countries, namely the UK and Spain. This section describes the main features of the case studies carried out.

2.1 Study farms

A brief description of each studied farm is provided below.

2.1.1 Broccoli farms in the United Kingdom

In the UK, 2 different broccoli growers have been assessed. Both of them follow integrated pest control techniques, and in general tailor the fertiliser applications to the soil's nutrient state; the amounts of pesticides and mineral fertilisers applied are comparable from one farm to the other. None of the British broccoli farms assessed uses manure or any other organic fertiliser.

UK5 is a large farm which produces, processes and distributes directly to supermarkets many different types of vegetables, with a focus on *Brassica.* They have their own on-farm processing and packing plant, where produce is cooled and often chopped and packed, depending on the customer's requirements. During the cold months, they import broccoli (and other vegetables) mainly from Spain, and often pack it for retail. The first broccoli crop in the UK is protected from frost with a polythene fleece.

UK6 is a much smaller individual farmer, who sells his produce to collective processors who in turn sell to supermarkets. This farm plants to the lowest density observed, and obtains the lowest yield per hectare. Another particularity is that fertilisers are all applied prior to the first crop, and the second crop relies entirely on the residual levels in the soil. This has not been observed in other vegetable farms.

2.1.2 Broccoli farms in Spain

Two big broccoli producers were assessed in Spain; their main market for broccoli is the UK, although they also produce other vegetables mostly orientated to the Spanish market. Even though they both follow integrated pest control, the amounts of active ingredients used vary widely: while ES1 seldom applies more than one substance per crop (particularly in the second crop, during winter), ES2 has the highest use of pesticides reported for any vegetable in the study, on a per hectare basis. Both farms use similar amounts of manure in each crop (although in ES1 manure is only applied every other year whereas in ES2 they use manure for each crop). On the other hand, the amounts of mineral fertilisers are generally much higher in ES2 (N and P; ES1 uses much more K per hectare). The reasons given for the high amounts considered in ES2 are primarily the soil's pH: it is so basic that nutrients tend to be immobilised, and so they have to apply large quantities in acid form in order to a) saturate the soil bases and allow a fraction to be accessible to plants and b) reduce the soil's pH so the nutrients are more mobile.

Broccoli needs to be irrigated in Spain due to the low rainfall in the region. ES1 uses gravity irrigation and has higher water inputs (20% higher in the first crop and twice as much in the second) than ES2, which uses drip irrigation. ES2 is much more mechanised than ES1; actually ES2 is similar in this respect to the British farms, while ES1 uses seven times less tractor hours and also has much lower fuel consumption than all the other farms. In terms of hand labour inputs, similar amounts have been recorded for labour intensive operations in ES1 and ES2. In terms of yield per hectare, ES1 gets more crop out of the field, even though ES2 has a higher planting density; it must be highlighted, though, that ES2 has an extremely accurate recording system for audits, whereas ES1 yield was estimated.

Both farms have on-site state-of-the-art cooling and packing facilities, with the lowest energy use per kg produce in the brand new packing plant of ES2 (operational since 2007). In general, product is sold loose and transported in reusable and foldable plastic crates, but ES1 often uses cardboard boxes to send the produce to the UK; LDPE film is also common to wrap the broccoli heads individually and prevent moisture loss during transport.

2.2 System description and LCI

The life cycle of broccoli (and also of the other vegetables studied) has been divided in three main stages: cropping, processing for final fresh or frozen product, and retail to grave. The latter includes all the operations from the retail outlet until human consumption. These stages are briefly described below.

2.2.1 Cropping stage

Table 2-1 provides values for the main input and output flows considered in the case study crops. All the inputs and the crop output have been reported by the farmers, while the emissions have been calculated from the inputs and literature estimates. CO_2 input (fixed by crop) has been estimated from the crop's carbon content as explained in Milà i Canals *et al*. (2007b). The main differences described in section 2.1 can be observed in the figures of the table.

The general field operations performed in broccoli cropping include:

- *Soil management*: most farms follow a similar set of operations, with varying degrees of mechanisation but usually including at least one pass of each of the following machines: plough, power-harrow, bedformer, discs or rotovator (to incorporate crop residues), and often a subsoiler. The Spanish farms tend to perform fewer operations. Planting is done by hand. The Spanish fields are usually grazed by sheep after harvest in order to maximise their use.
- *Fertiliser use*: solid fertiliser is commonly used, although sometimes liquid preparations are preferred. In Spain, a manure spreading trailer is used to apply manure, and liquid mineral fertilisers are usually applied with irrigation water (fertirrigation).
- *Irrigation*: when drip irrigation is used, the infrastructure is installed by hand prior to planting. Only Spanish fields are irrigated.
- *Pest and disease management*: the biggest farms (UK5) use a self-propelled pesticide sprayer, which tends to do the job quicker. All other farms use conventional pesticide sprayer machines attached to a tractor. Spanish farms show the lowest (ES1) and highest (ES2) uses of active ingredients in all the farms, which is difficult to explain. ES1 justified their low use of pesticides arguing that most of the time the field is too dry for disease (fungal attack) and too cold for pests, which translates into very low pesticide requirements. However, ES2 fields are only about 100km away, and their use of pesticides is much higher.
- *Harvesting*: harvest is done by hand. When broccoli is grown to be sold as fresh produce the broccoli heads have to be picked at the right size (400-500g), and two to three passes per field are needed in order to progressively harvest the mature ones. This results in the operation being more labour-intensive than the equivalent in other vegetables (e.g. lettuce).

Table 2-1: Main input and output flows from the case study farms during broccoli cropping.

Flow	Units (/ha/crop)	UK5-1	UK5-2	UK6-1	UK6-2	ES1-1	ES1-2	ES2-1	ES2-2
INPUTS									
Occupation, arable land	m^2year	5000	5000	5000	5000	5000	5000	5000	5000
Plants (plugs)	number	44626	37460	32123	32123	40000	40000	45000	45000
CO_2 from air fixed in crop	kg CO_2	2647.6	2222.4	1627.3	1627.3	2881.7	2881.7	2522.8	2522.8
Tractor use	hours	35.8	31.0	38.2	36.7	5.7	4.5	31.7	30.7
Diesel (for field operations)	litres	302.4	122.8	124.2	118.9	68.8	53.5	362.5	350.6
Steel (spare parts replacement)	kg	0.5	0.2	2.4	2.4	1.3	0.7	1.2	1.2
Labour (labour-intensive operations)	person days	n.a	n.a.	n.a.	n.a.	38.7	38.7	43.0	43.0
Diesel (for workers' transport)	litres	n.a	n.a.	n.a.	n.a.	11.6	11.6	9.1	9.1
Plastic (fleece, mulch…)	kg	162.2	0	0	0	0	139.5	0.0	0.0
Pesticides (unspecified)	kg act. ingred.	5.0	1.1	2.0	2.2	0.4	0.4	10.2	14.8
Fertilisers									
N fertiliser	kg N	202	140.6	311.3	0	176	176	410	410
P fertiliser	kg P_2O_5	50.5	46.9	62.5	0	22.5	22.5	137	137
K fertiliser	kg K_2O	101	93.7	250	0	160.5	160.5	5	5
Manure / organic fertilisers	kg	0	0	0	0	2500	2500	2987	2987
Irrigation									
Blue water[7], surface water	m^3	0	0	0	0	1200	960	0	0
Blue water, groundwater	m^3	0	0	0	0	1800	1440	2500	1100
Infrastructure (pipes, sprinklers…)	kg	0	0	0	0	0	0	57.8	57.8
Electricity (pumps)	kWh	0	0	0	0	3300	2640	2750	1210
OUTPUTS									
Crop	kg	15619	13111	9600	9600	17000	17000	14833	14833
Soil emissions (literature)									
CO_2 from soil	kg CO_2	733.3	733.3	733.3	733.3	733.3	733.3	733.3	733.3
CH_4 from soil	kg CH_4	0.7	0.5	0.3	0.3	0.5	0.5	0.1	0.1
NH_3 from soil	kg NH_3	9.8	6.8	6.1	6.1	10.1	10.1	12.4	12.4
NO_x from soil	kg NO_x	0.7	0.4	0.5	0.5	0.3	0.3	0.7	0.7
N_2O from soil	kg N_2O	6.7	3.5	5.2	5.2	3.0	3.0	7.0	7.0
NO_3^- from soil	kg NO_3^-	33.2	33.2	33.2	33.2	33.2	33.2	33.2	33.2
PO_4^{3-} from soil	kg PO_4^{3-}	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Change in soil organic carbon (SOC)	kg C	-200	-200	-200	-200	-200	-200	-200	-200

2.2.2 Processing (fresh produce)

The post-harvest operations include basically an initial cooling to pull down the field temperature from the crop, as well as packaging (if needed), labelling, and loading the refrigerated lorries which then transport the produce to the Regional Distribution Centre (RDC). Electricity consumption for cooling has been obtained from the farmers in most situations, thanks to the fact that they have on-site cooling facilities; the only exception is UK6, and data from UK5 have been used for this farm. Electricity consumption is usually difficult to provide because meter readings refer to a whole site, which may have cooling alongside other processes (washing, processing for other vegetables, cutting, packaging…). In all cases, farmers provided their best estimate for electricity consumption values, but they should be considered with care. In any case, all the values reported per kg produce are relatively similar, which increases the confidence in the results. The values used in this study are as follows:

- UK5 (and UK6): 36.3 kWh / tonne sold produce
- ES1: 46.1 kWh / tonne sold produce
- ES2: 35.5 kWh / tonne sold produce

In terms of packaging, only ES1 and ES2 provided values for packaging materials consumed in the process. British produce has been assumed to be sold loose (which is the main format) and no consumption of packaging materials assigned to it (plastic crates for transport are reused many times). It must be highlighted that ES1 reported the use of cardboard boxes to distribute broccoli to the UK.

[7] Blue water is the volume of water in ground (aquifer) and surface water bodies abstracted for human uses (Milà i Canals *et al.* submitted).

These have a significant effect on the results, although this same effect would be seen in all other farms as well if cardboard boxes were used there.
Wastage of produce at this stage represents broccoli cuttings and pieces that are too small to be sold. Values for wastage lie around 12-14% of input, and are sent for animal feed. A mass allocation has thus been used at this stage (see Milà i Canals *et al*. 2007b, section 6).

2.2.3 Processing (frozen produce)

In the case of vegetable freezing, a big freezing plant was visited and assessed. The plant processes many different vegetables, including peas, broccoli, beans, potatoes, carrots, etc. Detailed data were gathered for the operation of the whole plant, which also includes washing and packing the vegetables. Even though the data were presented in an aggregate way per kg of total processed (frozen and packed) produce, they may be considered representative of each single one.
The main flows expressed per tonne of sold produce are as follows:

- Electricity: 132.6 kWh / tonne sold produce
- Natural gas: 32.7 kWh / tonne sold produce
- Water: 10.9 m^3 / tonne sold produce
- Diesel: 0.2 litres / tonne sold produce

Each packed (sold) tonne includes ca. 2 kg plastic bags and 22.8 kg cardboard boxes. Wastage during the whole process includes 14.2% from raw to frozen (rests of pods, leaves, faulty produce, etc.) and 6.5% from frozen to packed (discarded in the colour test). Again, a mass allocation has been applied to this waste (see Milà i Canals *et al*. 2007b, section 6).

2.2.4 Retail to grave

Retail to grave stages of the broccoli life cycle include the following processes (Milà i Canals *et al*. 2007b):

- *Transport to RDC and storage*: includes the transport step from the processing plant to RDC and the energy use for cool/frozen storage. Spain-grown broccoli has been assigned an average road transport distance of 2600 km, while for broccoli grown in the UK the average distance considered is 200 km. In addition, the energy requirements for storage are higher for frozen produce.
- *Transport to retailer and storage*: similar as above, but related to the retailing step. In this case there is no difference in transport distance between frozen and fresh broccoli, but the energy requirements for frozen produce are higher than for fresh produce. Besides, the food losses are included.
- *Transport home by the consumer*: energy use due to transport by different transport modes (car, bus, cycle, and by walking), weighed according to the average UK consumer shopping patterns (Pretty *et al*. 2005).
- *Home storage*: energy use related to storage at home, allocated depending on the need to use refrigerator or freezer space.
- *Cooking*: Energy and water use related to different cooking modes (boiling, baking, frying, microwaving), taking into account the specific UK share of electric and gas cooking appliances. Average values for use of different cooking modes were not available, and a plausible mix of modes for each vegetable studied has been assumed (Milà i Canals *et al*. 2007b, section 5.2.3).
- *Liquid and solid food waste management*: wastewater from boiling is modelled as sent through the sewer to a wastewater treatment plant, while cooking waste and leftovers are sent to a landfill.
- *Human excretion and wastewater treatment*: the biochemical reactions in the human body are taken into account, giving rise to air and wastewater emissions, the latter sent to a wastewater treatment plant.

Modelling of all the above processes is described in Milà i Canals *et al*. 2007b, section 5, with the exception of human excretion, which has been subject to a more detailed study (Muñoz *et al*. 2007; Muñoz *et al*. in press). The following table shows the summary of processes involved in this life cycle stage, per kg broccoli in plate.

Table 2-2: Inventory of retail-to-grave processes.

Processes	Units	Fresh broccoli	Frozen broccoli
RDC			
Input packed broccoli to RDC	kg	1.3	1.1
Diesel for transport to RDC			
From Spain	kg	0.068	0.056
From the UK	kg	0.007	0.006
Electricity RDC storage	MJ	0.019	0.1
Retailer			
Input packed broccoli to retailer	kg	1.3	1.1
Diesel for transport to retailer	kg	0.0016	0.0013
Electricity retailer storage and display	MJ	0.21	4
Solid waste from retailer to landfill			
Broccoli	kg	0.025	0.021
LDPE packaging	kg	0.0096	0.0081
Diesel for solid waste transport	kg	0.0000306	0.0000257
Household			
Input broccoli to household	kg	1.28	1.07
Petrol for transport to household	kg	0.01	0.01
Diesel for transport to household	kg	0.002	0.002
Electricity home storage	MJ	0.16	0.59
Electricity cooking	MJ	3.9	3.9
Natural gas cooking	MJ	6.3	6.3
Tap water	L	10.2	8.60
Solid waste from household to landfill			
Broccoli	kg	0.25	0.052
LDPE packaging	kg	0.026	0.022
Diesel for solid waste transport	kg	2.40E-04	6.50E-05
Cooking wastewater to WWTP	L	10.2	8.60
Cooked broccoli (input to human excretion)	kg	1	1

2.3 LCIA results

Cradle to grave environmental impacts of broccoli supply for the British consumer are discussed in this section. Figure 2-1 and Figure 2-2 display different graphs corresponding to 6 impact categories in Figure 2-1, and 4 indicators of environmental relevance in Figure 2-2. These graphs display all the supply alternatives studied (country of origin, fresh or frozen storage), showing at the same time the contribution to the overall impact scores by the different life cycle stages: cropping, post-harvest processing, transport and retail, home storage, cooking, and waste management, and finally human excretion.

In Figure 2-1a the impact on soil quality through the entire life cycle is shown, measured as soil organic carbon deficit (Milà i Canals *et al*. 2007c). In all the broccoli production alternatives, the cropping stage causes the main contribution to the soil organic carbon deficit. Broccoli supply from UK5 appears as the one causing the lowest impact, due to a lower contribution related to transport and retail. The highest overall impact on soil quality corresponds to the UK6 broccoli, especially in the frozen scenario, due to the carbon deficit in the cropping stage, but also to frozen storage in the transport and retail stage. The impact from the latter is enhanced due to the occupation of sealed land by the RDC and the retailer, which account for ca. 7% of the impacts on soil quality.

The Abiotic Depletion Potential (ADP) is shown in Figure 2-1b. This impact category is dominated by consumption of fossil energy resources (oil, gas, coal, etc.). The most resource-intensive life cycle stage is home processing, specially cooking, due to power and gas consumption; in all alternatives, this stage is responsible for more than 50% of total resource depletion. Cropping appears to be important in the ES2 farm, and also in all alternatives the transport and retail stage, especially when the product is frozen. The lowest overall resource depletion corresponds to supply from farms UK5 and UK6 when broccoli is sold fresh.

Contribution to the Acidification Potential (AP, Figure 2-1c) is dominated by SO_x and NO_x emissions from combustion, with the exception of cropping, in which ammonia emissions from fertiliser application are very important (30-60% of the cropping score in AP). On the one hand, the highest environmental impact is related to supply from the ES2 farm, due to higher ammonia emissions from fertiliser and from higher fuel consumption. On the other hand, the lowest environmental impact corresponds to UK5 and UK6 farms when broccoli is sold fresh. Besides cropping, transport and retail, as well as home processing are relevant stages.

Eutrophication Potential (EP, Figure 2-1d) is dominated by nitrogen and phosphorus emissions to the hydrosphere, and also from NO_x emissions related to energy use. The life cycle stage causing the biggest share of eutrophication is human excretion, although home processing is as important as the latter, due to cooking wastewater treatment and organic waste landfilling; these two stages together represent from 50% to 80% of the total score. Nutrient emissions from cropping are especially relevant in the ES2 farm, where they represent around 30% of the total score, while in the remaining farms it is around 20%. The lowest overall environmental impact corresponds to the frozen alternatives, since these involve less broccoli losses in the kitchen, and thus nutrient emissions from upstream and waste-related activities are also lower; in any case, the difference from the closest fresh alternatives is only around 10% less.

The formation of photochemical oxidants (POCP, Figure 2-1e) is mostly related to air pollutants (SO_x, NO_x, VOCs, CO) related to combustion processes, and therefore to energy use. In all the alternatives, the main contributions are caused by transport and retail, home processing, and finally to cropping, which is the least important stage in all alternatives, with the exception of the ES2 farm; in the latter, the cropping stage has the highest contribution to POCP due to fertiliser production (ca. 17% of the POCP) and high fuel consumption for mechanisation (13% and 9% of the impact in the first and second crops respectively). The lowest impact, on the other hand, corresponds to the UK5 and UK6 farms in the fresh broccoli scenario.

Greenhouse gas emissions are shown in Figure 2-1f as CO_2 equivalents (Global Warming Potential, GWP). CO_2 is first taken by plants in the crop stage, leading to a temporary carbon sequestration in biomass; however this is not shown in the figure because this fixation is more than balanced by emissions at this stage. This embedded carbon is finally released to the atmosphere in several processes, namely landfilling and excretion. Most of the life cycle CO_2 emissions are related to home processing, particularly to energy use for cooking; this stage represents between 50% and 70% of the overall emissions. Cropping stage emissions are mostly relevant in the ES2 farm, due to fossil fuel use, and transport and retail are also relevant, especially when broccoli is frozen or transported from Spain. The highest overall emissions correspond to fresh broccoli supplied from the ES2 farm, as well as to frozen broccoli from UK farms.

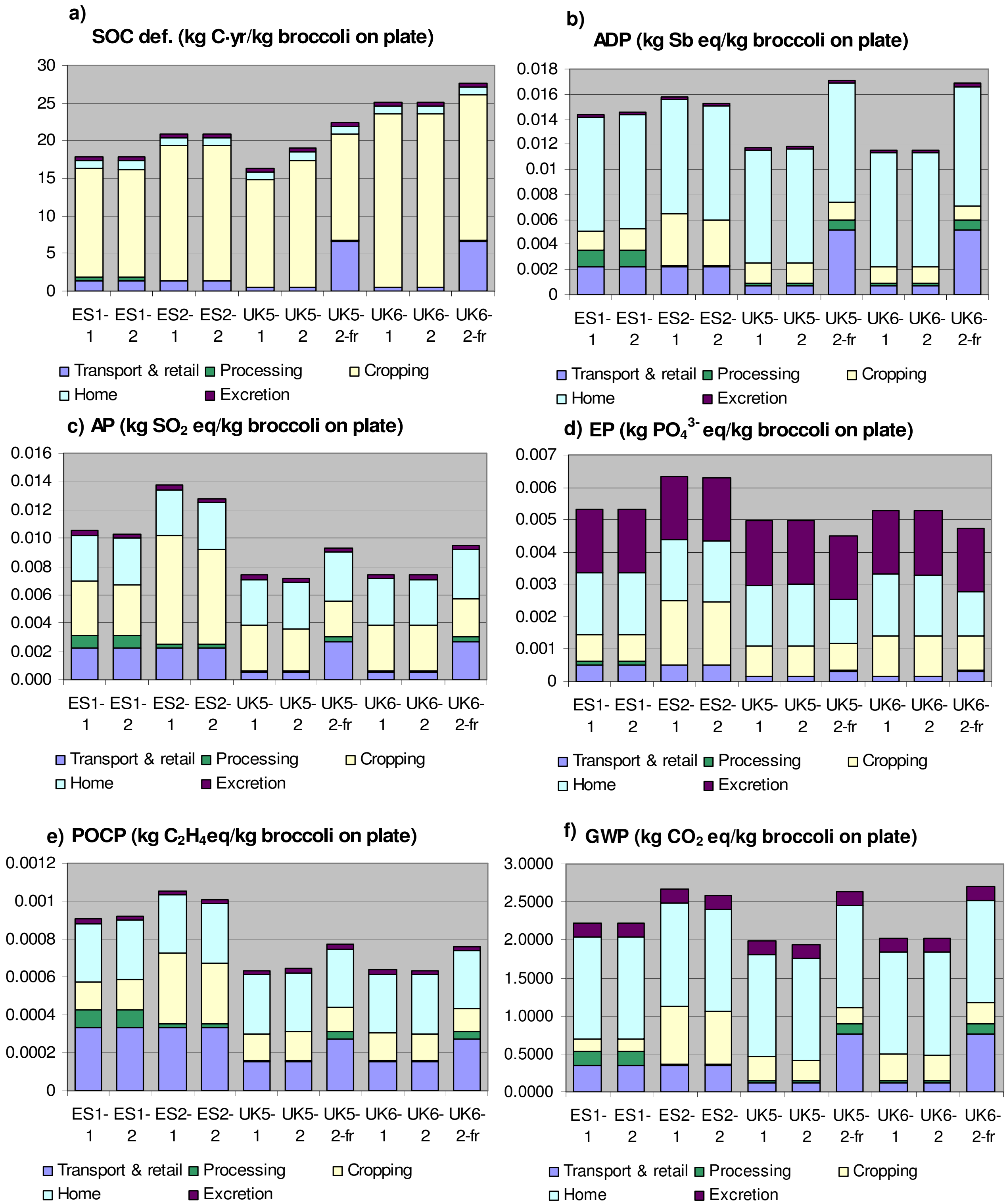

Figure 2-1: LCIA characterisation profile for UK- and Spain-grown broccoli, from cradle to grave, per kg broccoli served on plate.

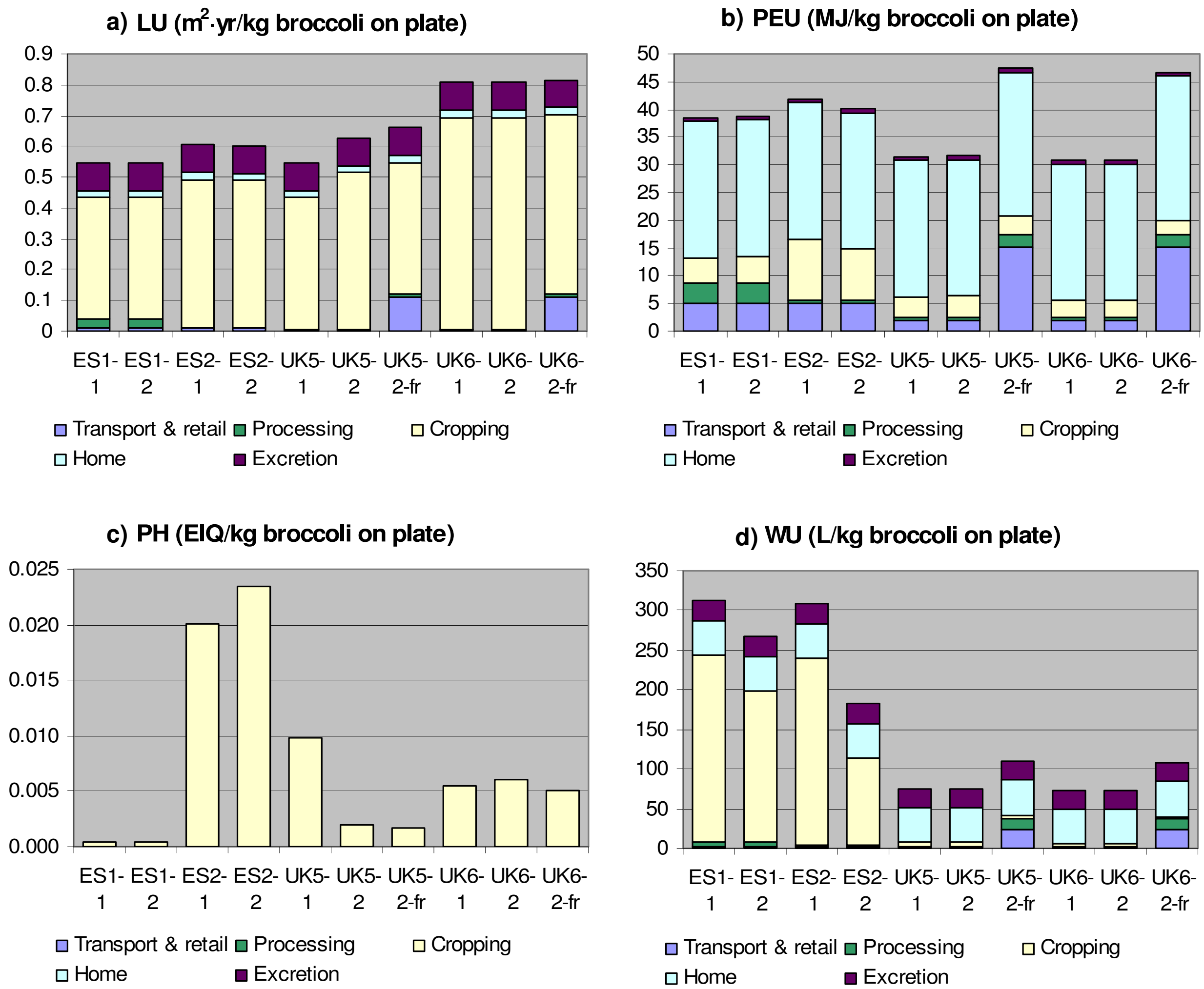

Figure 2-2: Environmental indicators for UK- and Spain-grown broccoli, from cradle to grave, per kg broccoli served on plate.

Figure 2-2 displays several environmental indicators. Primary Energy Use (PEU) is very frequently used in LCA studies. Water Use (WU) and Land Use (LU), although not so frequently used, are very relevant in this project, taking into account that agriculture is an activity with extensive use of these resources. Pesticide hazard, on the other hand, is not a typical LCA indicator, though again it is very relevant from an agricultural point of view, since pesticides are usually the main life cycle contributors to many toxicity-related impact categories (Milà i Canals *et al*. 2007b, section 7.4).

LU (Figure 2-2a), measured as area·time, is clearly dominated by the cropping stage, representing between 60% and 85% of the total score. After cropping, the second life cycle stage in importance is excretion, due to the forestry related to toilet paper manufacture (estimated in the inventory as 8 g/kg consumed broccoli); this represents between 11% and 16% of the total score. It must be highlighted that no LU has been assigned to land application of sewage sludge because this process is considered as agricultural land use (i.e. land's main function is producing a crop, even if it is also used to apply waste). Finally, transport and retail, in the frozen broccoli scenarios, is responsible for 15% of land use. The highest impact, according to this indicator, is for UK6 farm, regardless of whether the product is marketed fresh or frozen, since the frozen alternative has a lower land use related to agriculture but higher LU related to energy delivery. As noted several times, UK6 reported the lowest yield per ha, which results directly in more land used to deliver the same amount of broccoli. The contribution to LU from the processing stage in ES1 comes from the use of cardboard boxes for packaging (i.e. forestry to produce paper pulp).

PEU (Figure 2-2b) is dominated in the life cycle of broccoli by the home stage, particularly by cooking, due to the relatively high amount of natural gas and electricity employed in boiling, frying, and baking. This stage represents from 50% to 80% of the energy used in the life cycle. Other relevant stages are transport and retail in the frozen scenario, and cropping in the ES2 farm. The most energy-intensive alternatives are those involving frozen broccoli, while the least energy intensive, on the other hand, are those marketing fresh broccoli from UK5 and UK6 farms. An important issue should be highlighted already at this point: PEU is often used as a proxy for environmental impacts (see e.g. Huijbregts *et al*. 2006; Milà i Canals *et al*. 2007a). However, these results show that in biotic production systems it might not be a good indicator of environmental impacts: if one considers PEU only, then an obvious conclusion would be that frozen broccoli is worse than the alternative source for winter i.e. broccoli imported from Spain. However, of all the results shown in this section frozen broccoli is only clearly the worst option for PEU, LU and ADP.

Pesticide hazard is only relevant in the cropping stage of broccoli. Although this quotient takes into account the specific hazard of different pesticides (Milà i Canals *et al*. 2007b, section 7.4), the scores obtained by the different alternatives reflect the overall amount of active ingredients used in the different farms and crops (Table 2-1). ES2-1, ES2-2, and UK5-1 involve the highest doses of pesticides, and thus a higher hazard than their counterparts. ES1-1 and ES1-2, on the other hand, have the lowest doses and hazard.

In WU (Figure 2-2d), a clear distinction has to be made between broccoli grown in Spain and broccoli grown in the UK. The former is an irrigated crop, while the latter is rain fed (and rain water use is not accounted for in the assessment). As a consequence, Spain-grown broccoli uses in the cropping stage between 100 and almost 250 L water per kg broccoli on plate, and this amount is the most important contribution in the life cycle, when compared to other processes. From cradle to grave, broccoli from Spain uses between 175 L and over 300 L per kg eaten product, while the range in the UK is 75 L to 110 L, with frozen broccoli representing the most water-consuming option in UK grown broccoli. The main contribution to WU in the broccoli of British origin is cooking (up to 60%), and excretion (up to 40%), the latter due to toilet use. It needs to be stressed again that the WU reported here is only a LCI indicator. Impact assessment of freshwater use needs to take into account the type of use (evaporative or non-evaporative) and the source of water (e.g. surface water or over abstracted aquifers?) (Milà i Canals *et al*. submitted). Milà i Canals *et al*. (in preparation) show a practical application of a novel framework for freshwater use impact assessment to the case of UK vs. Spanish broccoli.

2.4 Interpretation for year-round broccoli in the UK

LCIA and inventory results are interpreted at three levels consistently with the goals of the study (section 1.3): contribution of *life cycle stages* (where are the environmental hotspots?); *farms* (are differences between farms bigger than differences between countries?); and *fresh vs. frozen* produce (imported vs. frozen options in winter?).

2.4.1 Life cycle stages

All the life cycle stages of broccoli supply are relevant in at least one of the impact categories and environmental indicators assessed:

- The cropping stage appears as the most important life cycle stage with regard to soil quality impacts and land use, in some cases being responsible of 90% of the overall impact. It is also the most important stage for Water Use, when broccoli is grown in Spain (i.e. irrigated vs. rain fed). Emissions related to agricultural inputs, namely fertilisers and pesticides, are also very important. Ammonia and nitrate emissions from N-fertilisers are important in the Acidification and Eutrophication Potentials, respectively. The cropping stage is responsible for the use of pesticides, which dominate toxicity impacts in LCA of agricultural products.
- Post-harvest processing does not make a critical contribution to any of the impact categories and indicators assessed. However, it is not negligible, especially when broccoli is sold frozen, and also in Spanish broccoli, due to packaging production. The latter is due to a particularity of one of the Spanish farms assessed which used a relevant amount of cardboard per kg broccoli: Spanish broccoli may also be sold in reusable plastic crates and then the impacts of this stage are reduced.

- Transport and retail is an important stage in the Energy Use indicators as well as in impact categories related to energy use, such as the Abiotic Depletion, Global Warming and Photo Oxidants Creation Potentials. Two factors are dominant in this stage: first there is the Spanish origin of some broccoli alternatives, involving a road transport of 2600 km, which is responsible for almost 10% Energy Use in broccoli from ES1 and ES2. Second, there is the cold chain impact related to UK frozen broccoli; even excluding the freezing process itself, transport and retail of British frozen broccoli uses 8 times as much energy as its fresh counterpart, and almost 3 times as much as Spanish fresh broccoli, even when the latter has to be transported from Spain. It must be highlighted that the retail time is longer by definition for frozen produce, which partly explains this higher energy use.
- Home processing is the most important life cycle stage in several impact categories and indicators, such as Primary Energy Use, Global Warming and Abiotic Depletion Potentials. This life cycle stage includes refrigerator/freezer storage, cooking, solid waste disposal, and cooking wastewater treatment. From all these processes, cooking is the most important in the three indicators mentioned, while wastewater treatment and solid waste disposal are more important with regard to the Eutrophication Potential. As a consequence, energy-efficient cooking, as well as minimising food losses, should be a priority for British consumers seeking to minimise their environmental impacts. Cooking modes have not been assessed separately, but as a plausible mix. Therefore, it needs to be highlighted that the variability on environmental impacts between these cooking modes could in fact determine to a large extent the results of the LCA. I.e. it might be that the decision on boiling or roasting broccoli in the oven is the most important factor in determining the LCA results.
- Human excretion has been studied in a rather detailed way in this project. In the broccoli life cycle, this stage seems to be critical in Eutrophication Potential, due to the release of nitrogen compounds from proteins in the wastewater treatment plant. Besides, it has a remarkable contribution in land use, of up to 16%, due to toilet paper production; this contribution would increase if land application of sewage sludge was allocated some land occupation.

2.4.2 Farms

One of the factors explaining the differences between the alternatives studied for broccoli consumption is the cropping stage at different farms, with all their specific variability in terms of agricultural practices, geographical and climate constraints, etc. The main differences found, affecting performance in the LCIA results are the following:

- Concerning first and second crops in the same farm, in most cases there is not a big difference in environmental impact. The exceptions to this are Water Use in Spanish farms and Pesticide Use in ES2 and UK5. With regard to the former, the second crop uses less water than the first because the crop is in the field during a colder period of the year (e.g. January-March) with less evapo-transpiration. Concerning pesticides, their use increases in the second crop of the ES2 farm, but decreases in UK5.
- Concerning the overall performance of the different farms, the results have shown that the ES2 farm has a higher environmental impact in many categories and indicators, such as Acidification and Global Warming Potentials, and Primary Energy Use, among others. This is caused by their higher material (fertilisers, pesticides) and energy requirements (particularly fuel). On the other hand, they tend to use less water per ha than ES1 because ES2 uses drip irrigation (whereas ES1 uses gravity irrigation); this is partly cancelled by a lower yield per ha in ES2, though.
- UK6 obtains worse results than the other farms concerning the impacts on soil quality and land use. The main reason for this is the lower yield per ha in UK6, which results in the most inefficient land use.
- Finally, there is clearly a higher Water Use when broccoli is grown in Spain compared to when it is grown in the UK. There are no clear differences between the two Spanish farms in their first crop, but ES2 uses less water than ES1 in the second crop (explained above).

2.4.3 Fresh vs. frozen broccoli

One of the most interesting issues to discuss from this case study is the environmental relevance of consuming fresh or frozen broccoli. It must be highlighted once more that comparing Spanish fresh with British frozen broccoli is the relevant and fair comparison, because the two options are available

to the British consumer at the same time of the year (November to April). In fact, frozen broccoli is available year-round and so may be compared to British broccoli during summer too. When making this comparison, it must be borne in mind that there is a key assumption affecting both life cycles, namely the wastage rate at home. We have assumed a lower amount of broccoli wasted in the kitchen when it is purchased frozen than when it is fresh. Our assumption for this loss is 20% of the home input for fresh broccoli, whereas for frozen broccoli a figure of 5% is used. This parameter has a remarkable effect in the life cycle, since upstream operations for fresh broccoli must supply 1.3 kg at home, while only 1.1 kg must be supplied by the frozen broccoli supply chain. Our 20% figure, however, could be higher, according to recent surveys (WRAP 2007).
In spite of this relative advantage of frozen over fresh broccoli, the LCIA results generally show a lower environmental impact for the fresh broccoli life cycle, as it can be seen in Table 2-3, taking as reference the first crop from ES1 farm and the second crop from UK5 farm. Out of this set of 10 impact categories and environmental indicators, 6 show a worse performance in the frozen broccoli scenario when compared to the imported produce, and 8 when compared to domestic produce. Supplying the broccoli frozen involves up to a 20-50% increase in impacts, namely in energy use (the 3-fold difference in PH when compared to the Spanish crop is due to the notably low pesticide usage in ES1). In other indicators this difference is lower, but still remarkable. It must be highlighted, however, that in Eutrophication Potential frozen broccoli performs better, due to the lower food losses in the kitchen, and also in Pesticide Hazard, as a consequence of the lower amount of broccoli to be supplied. In addition, frozen broccoli performs slightly better than Spanish fresh broccoli in AP and POCP due particularly to the lower emissions during processing and transportation (POCP).

Table 2-3: Cradle to grave LCIA results for fresh and frozen broccoli from UK5 farm.

Impact category/indicator, per kg broccoli on plate	**ES1-1**	**UK5-2**	**UK5-2-fr**	**UK5-2-fr/ ES1-1**	**UK5-2-fr/ UK5-2**
	FRESH		**FROZEN**		
LU [$m^2 \cdot yr$]	5.46E-01	6.27E-01	6.63E-01	1.21	1.06
PEU [MJ]	3.85E+01	3.16E+01	4.74E+01	1.23	1.50
Pesticide Hazard [EIQ]	4.52E-04	1.97E-03	1.66E-03	3.66	0.84
SOC Deficit [kg C year]	1.78E+01	1.90E+01	2.25E+01	1.26	1.18
ADP [kg Sb-Equiv.]	1.43E-02	1.18E-02	1.71E-02	1.19	1.45
WU [L]	3.13E+02	7.51E+01	1.10E+02	0.35	1.47
AP [kg SO_2-Equiv.]	1.05E-02	7.17E-03	9.32E-03	0.89	1.30
EP [kg Phosphate-Equiv.]	5.32E-03	4.98E-03	4.49E-03	0.84	0.90
GWP [kg CO_2-Equiv.]	2.22E+00	1.94E+00	2.64E+00	1.19	1.36
POCP [kg Ethene-Equiv.]	9.04E-04	6.44E-04	7.71E-04	0.85	1.20

These results suggest that consuming frozen broccoli during the UK broccoli season involve, when compared to fresh produce, a substantial increase in environmental impact due to the energy intensity of its cold chain, in particular by increased energy use in:

- Post-harvest processing,
- Frozen storage in wholesale and retail
- Frozen storage at home

However, if frozen broccoli is considered an alternative to importing fresh broccoli from Spain, then the conclusions are not so clear-cut, and more trade-offs exist in the environmental impacts and indicators assessed.

In the present study it is assumed that defrosting is carried out at ambient temperature, and therefore no energy use must be taken into account for this concept. Nevertheless, the lower wastage rate of frozen produce means that less amount has to be grown, processed, stored, and disposed of. From a life cycle perspective, this is better in eutrophication and pesticide use terms.

As a result, the combination of consuming fresh produce in conjunction with proper “stock” management at home, in order to avoid food going off, would be the most environmentally friendly alternative for broccoli grown in the UK. In terms of year-round impacts, eating fresh produce which is in season represents the lowest environmental impacts, although winter alternatives to broccoli in the UK would need to be assessed.

3 SALAD CROPS

Lettuce (*Lactuca sativa*) has been assessed as the main crop for the salad-type crops. There are many varieties of this crop, and in some circumstances also other species have been assessed which are consumed as alternatives to lettuce, such as fine endive. This vegetable has been assessed in three countries: the UK, Spain and Uganda. This section describes the main features of the case studies carried out.

3.1 Study farms

A brief description of each studied farm is provided below.

3.1.1 Lettuce farms in the United Kingdom

In the UK, four different lettuce growers have been assessed: Two of them (*UK2* and *UK8*) grow lettuce outdoors exclusively; *UK9* grows both outdoors and indoors (although indoors production was discontinued one year after the study); and *UK10* grows indoors year-round. All of them sell most of their produce, if not all, to the large retailers in the UK. Those which do not grow crops in the cold months act as importers from other countries in those periods. Most farms grow a wide range of salad crops, only limited e.g. in the case of indoors growing to those salad types that can be grown successfully in glasshouses (fine endive; butterhead lettuce; etc.). In open-field growing, the three farms are able to get up to two crops from the same field in the warm months. *UK9* has three additional crops from the glasshouses. *UK10* reports a more intensive use of the covered land, and gets up to seven crops per year from the same field, although five have been considered as an average value. None of the British lettuce farms uses manure or any other organic fertiliser. Salad crops are very sensitive to lack of water and are thus all irrigated; water use is higher for second crops due to higher temperatures. However, the water consumptions found per hectare are very disparate between farms and no special reason has been found for this.

Farm *UK2* is a large farm, oriented mostly to the production of salad crops. Most operations are highly mechanised (around 50 tractor hours per crop), except those that can only be performed manually such as harvesting. Some hand-weeding helps reducing herbicide input. Integrated pest control is followed, and mineral fertiliser applications are tailored specifically for each field following soil analyses. A protective polythene fleece is used for early crops in order to prevent frost damage. Irrigation water comes generally from the grid. The farm has on-site facilities for cooling and packing salad crops.

Farms *UK8* and *UK9* are similar to *UK2* in terms of business orientation, if somehow smaller. The approach to nutrient management and pest control is similar, as is the level of mechanisation (30-50 tractor hours per ha per crop). There is however a trend towards having smaller and older machines in these two farms compared to the previous one (around 465 and 240 litres of diesel per crop compared to over 550 in *UK2*). They use water directly abstracted from the river, but no information was provided on amounts of irrigation water or energy use to pump it; these figures have thus been estimated. Both farms also use protective fleeces in early crops.

Farm *UK10* is special in that lettuce production is done under glass all year round. Land use efficiency is thus very high. Also the use of mineral fertilisers is lower than in other British farms. Similar to the other farm growing indoors (*UK9*), the indicators of mechanisation (tractor hours and litres of diesel) are lower in this farm.

3.1.2 Lettuce farms in Spain

Two big outdoor lettuce producers were assessed in Spain: *ES2* and *ES7*. One of them sells to major retailers in Spain and the UK, while the other sells mostly in Spanish wholesale markets. Their production techniques are quite similar, though. In general, these farms are characterised by bigger inputs of pesticides, fertilisers and water than the British counterparts. The slightly higher pesticide input is possibly due to higher pest and disease incidence, although it could also be due to some extent to routine use of certain substances. In the case of fertilisers, higher doses are applied to overcome the nutrient fixation in the basic soils of Spain (particularly in *ES2*); in addition to mineral fertilisers, significant amounts of different types of manure are applied to each crop. There seems to be a trend in the assessed Spanish farms to grow fewer plants per hectare than in the UK, although the yields tend to be even higher; this can be explained by the growing of bigger lettuce heads. Irrigation water use per hectare is often much higher than in British farms, although when expressed per kg of produce the difference is not so evident. Energy use to pump irrigation water is higher per m^3 in Spain than in the UK, due to the fact that in Spain this is often groundwater and in some occasions it must be pumped from deep aquifers (over 100m deep). It must be noted that the value used for Spanish farms (1.1 kWh electricity per m^3, compared to 0.15-0.35 kWh/m^3 in the UK) is on the high energy use side. *ES2* and *ES7* show less mechanisation than the British farms (except those that grow indoors): 22 and 15 tractor hours per crop; however, *ES2* has big tractors and its fuel consumption is in the range of some British farms (250 litres per crop, compared to ca. 150 litres in *ES7*). The lower use of tractors must be explained with high labour inputs; human labour has not been quantified in the UK and so a comparative value cannot be given. Workers' transport-related fuel consumption was quantified in the Spanish farms, but in both farms was almost negligible compared to total use by tractors (ca. 8 and 13 litres in *ES2* and *ES7* respectively). Both farms have on-site cooling facilities.

3.1.3 Lettuce farms in Uganda

In Uganda, three different lettuce growers were interviewed and assessed for the study. Most of them grow crops on fields recently (less than 5 years) created by slashing and often burning bits of natural forest. They all have a very low level of mechanisation, and none reported the use of mechanised machines. They all sell their produce exclusively to local markets. Different lettuce varieties are grown, and rotated with other crops (brassicas, legumes, strawberries, etc.); in general, the growing period for lettuces is 2-2.5 months, and the yields are relatively high, around 40 tonnes/ha per crop. Considering all different crops, all farmers get 2 to 4 crops/year. All operations are manual, including soil preparation; fertiliser and pesticide application. However, no quantification of labour has been possible in Uganda. This does not pose a problem for the methodology applied in these studies, because the only impacts associated to labour are those of workers' transportation, and in Uganda such transport is normally on foot or by bike (i.e. no environmental impacts associated). Farms are mostly rain fed, but all farmers bring in additional water from streams either by gravity irrigation or watering cans. Usually the same fertiliser types and pesticide ingredients are applied by most growers, but the amounts used differ widely amongst them. All growers use organic fertilisers, which vary according to the availability, and some use foliar mineral fertilisers as a complement. In this report, the data collected in Uganda for lettuce growing by different farmers have been grouped using the values considered more representative while factoring in their variability, and are not provided per farmer.

3.2 System description and LCI

The life cycle of lettuce (and also of the other vegetables studied) has been divided in three main stages: cropping, processing (cooling), and retail to grave. The latter includes all the operations from the retail outlet until human consumption. These stages are briefly described below.

3.2.1 Cropping stage

Table 3-1 provides values for the main input and output flows considered in the case study crops. All the inputs and the crop output have been reported by the farmers, while the emissions have been calculated from the inputs and literature estimates. CO_2 input (fixed by crop) has been estimated from the crop's carbon content as explained in Milà i Canals *et al.* (2007b). The main differences described in 3.1 can be observed in the figures of the table.

Table 3-1: Main input and output flows from the case study farms during lettuce cropping.

Flow	Units (/ha/crop)	UK2-1	UK2-2	UK8-1	UK8-2	UK9-1	UK9-2	UK9-IN	UK10-IN	ES2-1	ES2-2	ES7-1	ES7-2	UG
INPUTS														
Occupation, arable land	m^2year	5000	5000	5000	5000	5000	5000	3333	2000	5000	5000	5000	5000	3333
Plants (plugs)	number	56747	76836	85000	85000	100000	100000	177778	210000	60000	60000	40000	40000	120000
CO_2 from air fixed in crop	kg CO_2	1857.2	2493.4	3341.0	3341.0	1965.3	1965.3	8297.8	6002.0	4444.0	4444.0	4421.9	3684.9	5087.8
Tractor use	hours	50.8	46.2	32.4	31.4	47.4	47.4	2.9	8.6	22.4	22.4	16.5	14.5	0.0
Diesel (for field operations)	litres	591.9	560.0	470.8	460.8	238.0	238.0	96.0	56.0	251.2	251.2	155.9	143.9	0.0
Steel (spare parts replacement)	kg	3.6	3.6	7.4	7.4	18.8	18.8	35.6	0.1	1.2	1.2	1.1	1.1	n.a.
Labour (labour-intensive operations)	person days	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	39.0	39.0	27.4	27.4	n.a.
Diesel (for workers' transport)	litres	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	7.8	7.8	13.0	13.0	n.a.
Plastic (fleece, mulch…)	kg	161.5	0.0	20.0	0.0	170.0	0.0	0.0	36.8	0.0	0.0	0.0	0.0	0.0
Pesticides (unspecified)	kg act. ingred.	4.7	1.6	7.5	7.5	3.1	3.8	1.3	6.7	10.7	10.7	20.3	14.9	1.3
Natural Gas (glasshouse heating)	kWh	0.0	0.0	0.0	0.0	0.0	0.0	833333.3	143720.0	0.0	0.0	0.0	0.0	0.0
Electricity (glasshouse)	kWh	0.0	0.0	0.0	0.0	0.0	0.0	40000.0	2380.0	0.0	0.0	0.0	0.0	0.0
Fertilisers														
N fertiliser	kg N	172.5	76.5	129.8	31	123.6	123.6	119	30	559.7	559.7	154.7	159.0	0.1
P fertiliser	kg P_2O_5	58.9	0	24.7	0	30.9	30.9	113	7.5	366.4	366.4	26.5	0.0	0.0
K fertiliser	kg K_2O	117.8	0	98.8	0	30.9	30.9	0	45	0	0	22.1	0	0.0
Manure / organic fertilisers	kg	0.0	0	0	0	0.0	0.0	0	0	5301.9	5301.9	65000	65000	12500
Irrigation														
Blue water, surface water	m^3	450	600	600	1200	800.0	1200.0	760	100					31.0
Blue water, groundwater	m^3									1500.0	2700	825	2800	
Infrastructure (pipes, sprinklers…)	kg	0	0	0	0	48.8	48.8	n.a.	4.2	57.8	57.8	8.9	8.9	0.0
Electricity (pumps)	kWh	0	0	91.3	182.6	293.3	440	n.a.	165.6	1650	2970	907.5	3080	0
OUTPUTS														
Crop	kg	15446	20563	27200	27200	20000	20000	67555.6	48864.1	36100	36100	36000	30000	40800
Soil emissions (literature)														
CO_2 from soil	kg CO_2	733.3	733.3	733.3	733.3	733.3	733.3	488.9	293.3	733.3	733.3	733.3	733.3	1098.9
CH_4 from soil	kg CH_4	0.2	0.2	0.3	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.8	0.4
NH_3 from soil	kg NH_3	10.4	5.9	4.8	0.0	9.0	9.0	5.8	3.3	14.4	14.4	5.4	12.2	14.5
NO_x from soil	kg NO_x	0.4	0.2	0.2	0.1	0.2	0.2	1.6	0.1	1.0	1.0	0.4	0.2	0.8
N_2O from soil	kg N_2O	3.4	1.8	2.2	0.5	2.0	2.0	1.9	0.8	9.7	9.7	4.2	1.6	3.9
NO_3^- from soil	kg NO_3^-	33.2	33.2	33.2	33.2	33.2	33.2	22.1	13.3	33.2	33.2	33.2	33.2	22.1
PO_4^{3-} from soil	kg PO_4^{3-}	1.5	1.5	1.5	1.5	1.5	1.5	1.0	0.6	1.5	1.5	1.5	1.5	1.0
Change in soil organic carbon (SOC)	kg C	-200	-200	-200	-200	-200	-200	-133.3	-80	-200	-200	-200	-200	-300.0

The general field operations performed in lettuce cropping include:

- *Soil management*: most UK and ES farms follow a similar set of operations, with varying degrees of mechanisation but usually including at least one pass of each of the following machines: plough, power-harrow, bedformer, discs or rotovator (to incorporate crop residues), and often a subsoiler. The Spanish farms tend to perform fewer operations. In Uganda no mechanisation was observed. Planting is done by hand in Uganda, and sometimes in Spain. However, in the UK and ES this operation is often performed with a machine planter.
- *Fertiliser use*: solid fertiliser is commonly used in the UK, while liquid preparations are used in Spain through the irrigation system; very limited amounts of foliar mineral fertilisers are used in Uganda. In Spain and Uganda, animal manure or other organic fertilisers are an important (in Uganda the main) source of nutrients.
- *Irrigation*: all farms are irrigated, but in Uganda the input of blue water is minimal because farmers rely mostly on rain. When drip or spray irrigation is used, the infrastructure is applied by hand prior to planting. In Uganda fields are gravity irrigated or a watering can is used.
- *Pest and Disease management*: British and Spanish farms use self-propelled pesticide sprayers or conventional pesticide sprayer machines attached to a tractor. Spanish farms show the highest uses of active ingredients amongst all the farms. In Uganda very little amounts of pesticides are used, and these are routinely applied with manual sprayers.
- *Harvesting*: harvest is done by hand in all farms.

3.2.2 Processing (cooling)

The post-harvest operations include basically an initial cooling to pull down the field temperature from the crop, and loading the refrigerated lorries which then transport the produce to the Regional Distribution Centre (RDC). No packaging has been considered in the case of lettuce. Electricity consumption for cooling has been obtained from the farmers in most situations, thanks to the fact that they have on-site cooling facilities. In Uganda no one of the farmers assessed actually use cooling facilities; however, it has been assumed that if lettuce was to be exported then it would be cooled at some point after harvest and before being sent to the airport for transportation to the UK. Average electricity consumption from all the other (UK and ES) farms has been used for Uganda.
Electricity consumption is usually difficult to provide because meter readings refer to a whole site, which may have cooling alongside other processes (washing, processing for other vegetables, cutting, packaging…). In all cases, farmers provided their best estimate for electricity consumption values, but they should be considered with care. The same value from UK2 has been used for UK10. In any case, all the values reported per kg produce are of the same order of magnitude. The values used in this study are as follows:

- UK2 (and UK10): 49.8 kWh / tonne sold produce
- UK8: 83.9 kWh / tonne sold produce
- UK9: 53.3 kWh / tonne sold produce
- ES2: 35.5 kWh / tonne sold produce
- ES7: 62.5 kWh / tonne sold produce
- Uganda (average of the other farms): 56.2 kWh / tonne sold produce

3.2.3 Retail to grave

Retail to grave stages of the lettuce life cycle include the following processes (Milà i Canals *et al*. 2007b):

- Transport to RDC and storage: includes the transport step from the processing plant to RDC and the energy use for cool storage. Spain-grown lettuce has been assigned an average road transport distance of 2600 km, while for lettuce grown in the UK the average distance considered is 200 km. In Uganda, lettuce is first transported 70 km by mini-vans to the airport store, 6,600 km by plane to the UK and then 200 km by refrigerated truck to the British RDC.
- Transport to retailer and storage: similar as above, but related to the retailing step. The food losses at this stage are included.

- Transport home by the consumer: energy use due to transport by different transport modes (car, bus, cycle, and by walking), weighed according to the average UK consumer shopping patterns (Pretty *et al*. 2005).
- Home storage: energy use related to storage at home, allocated depending on the need to use refrigerator or freezer space; all lettuce is kept in the fridge.
- Cooking: there is no cooking in the case of lettuce.
- Liquid and solid food waste management: no wastewater is associated to the preparation of lettuce; produce gone off and leftovers are sent to a landfill.
- Human excretion and wastewater treatment: the biochemical reactions in the human body are taken into account, giving rise to air and wastewater emissions, the latter sent to a wastewater treatment plant.

Modelling of all the above processes is described in Milà i Canals *et al*. 2007b, section 5, with the exception of human excretion, which has been subject to a more detailed study (Muñoz *et al*. 2007; Muñoz *et al*. in press).

3.3 LCIA results

Cradle to grave environmental impacts of lettuce supply for the British consumer are discussed in this section. Figure 3-1 and Figure 3-2 display different graphs corresponding to 6 impact categories in Figure 3-1, and 4 indicators of environmental relevance in Figure 3-2. These graphs display all the supply alternatives studied depending on the country of origin, including the contribution to the overall impact scores by the different life cycle stages: cropping, post-harvest processing, transport and retail, home storage and waste management, and finally human excretion.

Figure 3-1a shows the impact on soil quality through the entire life cycle, measured as soil organic carbon deficit (Milà i Canals *et al*. 2007c). In all lettuce production alternatives but the Ugandan supply chain, the cropping stage causes the main contribution to the soil organic carbon deficit. In the case of Ugandan lettuce, which has the biggest contribution of all studied supply chains, the impacts on soil quality are dominated by the ‘land transformation to mineral extraction site’ related to kerosene production (used for airfreight). Indoors production in UK10 is the one causing the lowest impact, due to the most efficient use of land in cropping. The Spanish farms show a slightly lower contribution from the cropping stage due to higher LU efficiency than their British outdoor counterparts, which is counterbalanced by the higher impacts during transportation.

The Abiotic Depletion Potential (ADP) is shown in Figure 3-1b. This impact category is dominated by consumption of fossil energy resources (oil, gas, coal, etc.). The most resource-intensive life cycle stage is airfreight from Uganda, followed by heating the glasshouses in indoors cropping (UK9-IN, UK10-IN). In a much lower level, transport from Spain by truck is also relevant, but almost negligible compared to the Ugandan or heated glasshouses supply chains. The lowest overall resource depletion corresponds to in-season supply from British farms. It needs to be stressed that groundwater is not included in the ADP, while it might be relevant when it is sourced from over abstracted aquifers (Milà i Canals *et al*. submitted).

Contribution to the Acidification Potential (AP, Figure 3-1c) is dominated by SO_x and NO_x emissions from combustion, with the exception of cropping, in which ammonia emissions from fertiliser application are very important. On the one hand, the highest environmental impact is related to supply from Uganda, due to the combustion of kerosene for airfreight. On the other hand, the lowest environmental impact corresponds to UK8-2.

Eutrophication Potential (EP, Figure 3-1d) is dominated by nitrogen oxides emissions to air due to airfreight in the Ugandan supply chain. In all other alternatives, nitrogen and phosphorus emissions to the hydrosphere, and also from NO_x emissions related to energy use, dominate this impact. Apart from transport from Uganda, the life cycle stage causing the biggest share of eutrophication is human excretion. The contributions to EP do not vary widely between British and Spanish farms.

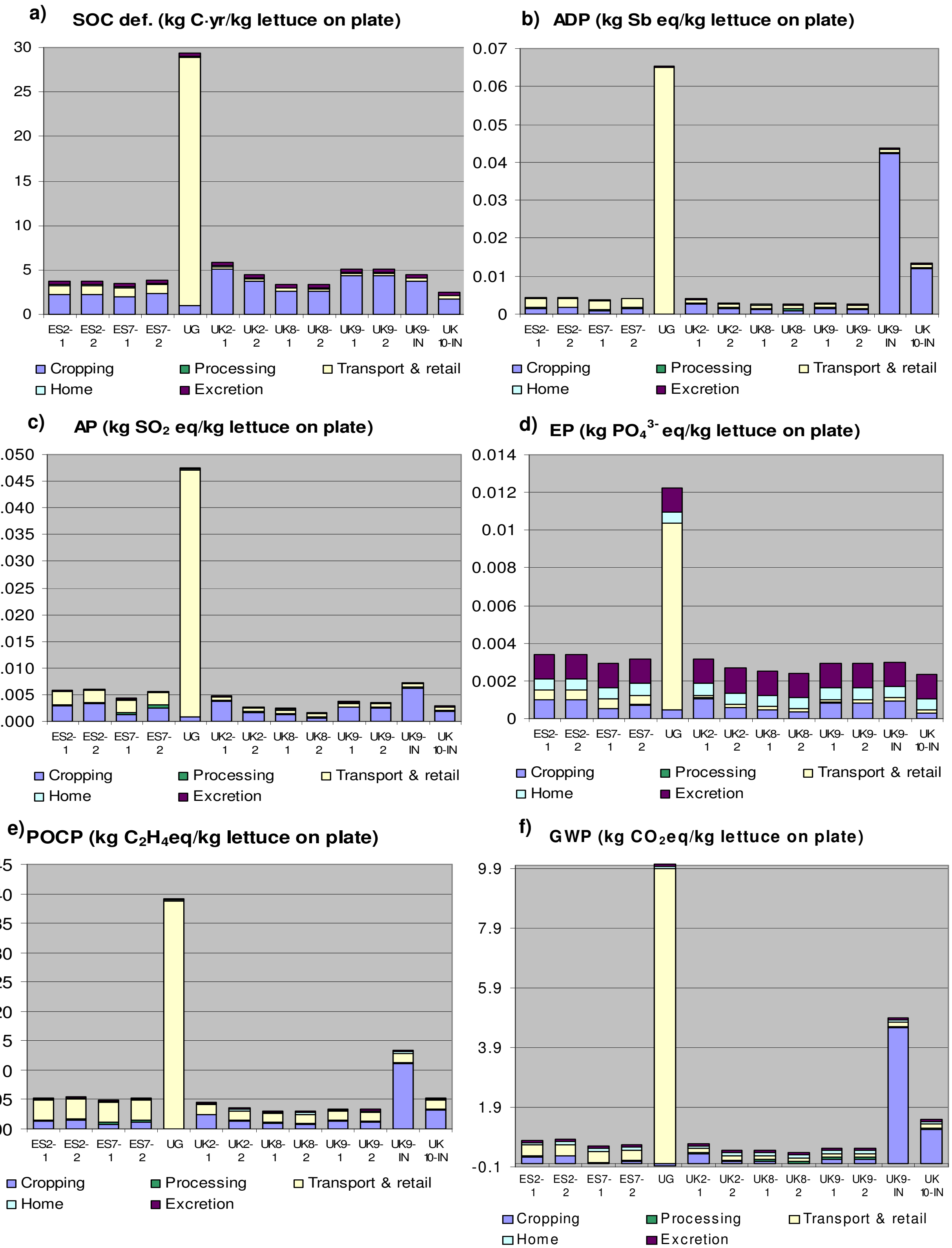

Figure 3-1: LCIA characterisation profile for UK-, Spain- and Uganda-grown lettuce, from cradle to grave, per kg lettuce served on plate.

The formation of photochemical oxidants (POCP, Figure 3-1e) is mostly related to air pollutants (SO_x, NO_x, VOCs, CO) related to fuel combustion and production processes, and therefore to energy use. The biggest contribution is found again with the Ugandan supply chain due to the kerosene consumption in airfreight. On the other hand, the lowest POCP corresponds to in-season supply from British farms. In the other alternatives, the main contributions are caused by heating the glasshouses (indoors production), transport and retail and cropping. Post-harvest cooling shows almost negligible impacts in all cases.

Greenhouse gas emissions are shown in Figure 3-1f as CO_2 equivalents (Global Warming Potential, GWP). CO_2 is first taken up by plants in the crop stage, leading to a temporary carbon sequestration in biomass; however this is only shown (imperceptibly) in the Ugandan supply chain, because this fixation is more than balanced by emissions at this stage in all other production systems. This embedded carbon is finally released to the atmosphere in several processes, namely landfilling and excretion. In any case, the life cycle CO_2 emissions are overruled by airfreight emissions in the Ugandan supply chain, which shows the highest GWP of all the alternatives studied. After UG, indoors production in the UK has important contributions to GWP due to the combustion of natural gas to heat the glasshouses. Contributions from outdoors production (both Spanish and British) are about two orders of magnitude lower than the Ugandan supply chain.

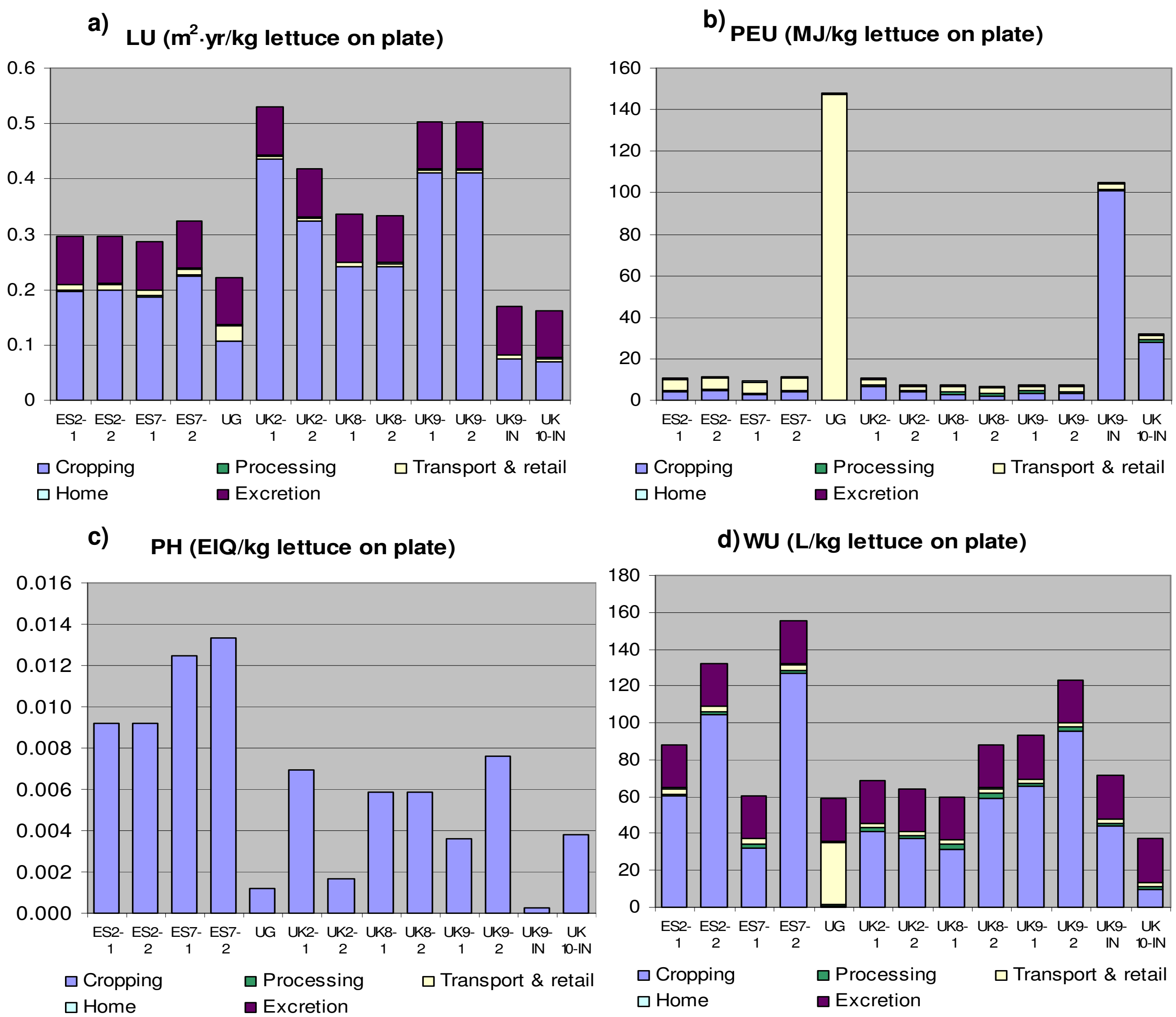

Figure 3-2: Environmental indicators for UK-, Spain- and Uganda-grown lettuce, from cradle to grave, per kg lettuce served on plate.

Figure 3-2 displays several environmental indicators. Primary Energy Use (PEU, Figure 3-2b) is very frequently used in LCA studies. Water Use (WU, Figure 3-2d) and Land Use (LU, Figure 3-2a), although not so frequently used, are very relevant in this project, taking into account that agriculture is an activity with extensive use of these resources. Pesticide hazard (PH, Figure 3-2c), on the other hand, is not a typical LCA indicator, though again it is very relevant from an agricultural point of view, since pesticides are usually the main life cycle contributors to many toxicity-related impact categories (Milà i Canals *et al*. 2007b, section 7.4).

LU (Figure 3-2a), measured as area·time, is clearly dominated by the cropping stage, representing between 42% and 82% of the total score. The figure shows a ranking of the supply chains using land in a more efficient way in the cropping stage (i.e. getting more yield per ha). After cropping, the second life cycle stage in importance is excretion, due to the forestry related to toilet paper manufacture (estimated in the inventory as 8 g/kg consumed broccoli); this represents between 16% and 39% of the total score for outdoors produced lettuce (this goes up to 50% for indoors lettuce due to the much lower LU intensity in the cropping stage). It must be highlighted that no LU has been assigned to land application of sewage sludge; because this process is considered as agricultural land use (i.e. land's main function is producing a crop, even if it is also used to apply waste). The highest land occupation corresponds to British outdoor lettuce, followed by Spanish outdoor lettuce, then Ugandan, and the lowest score is for British indoors due to the high yields obtained per ha. Comparing Figure 3-2a with Figure 3-1a demonstrates the importance of characterising land use flows beyond the LCI indicator m^2year, as suggested elsewhere (Milà i Canals *et al*. 2007d). It needs to be highlighted too that only occupation is factored in this indicator: the impacts from slashing and burning natural forest to provide horticultural land in Uganda have not been considered.

PEU (Figure 3-2b) is dominated in the life cycle of lettuce by kerosene consumption for airfreight from Uganda, as advanced previously. In fact, this indicator is a very good approximation of the ADP, shown in Figure 3-1b and discussed above. Thus, no more detailed comments will be made here on PEU. It needs to be highlighted though that in this case PEU would work relatively well as an indicator for most impacts shown in Figure 3-1 with the exception of EP, AP, and SOC deficit; when the differences in PEU are not "big enough" between alternatives, other sources of impacts than energy use nuance the contributions. Besides, the other impact indicators shown in Figure 3-2 are not correlated to PEU at all.

Pesticide hazard (Figure 3-2c) is only relevant in the cropping stage of lettuce. Although this quotient takes into account the specific hazard of different pesticides (Milà i Canals *et al*. 2007b, section 7.4), the scores obtained by the different alternatives reflect to a certain extent the overall amount of active ingredients used in the different farms and crops (Table 3-1). ES2 and ES7 report the highest doses of pesticides, and thus a higher hazard than their counterparts. It is also notable that UG and UK9-IN report the same amount of active ingredients used (Table 3-1), but the specific substances used in UK9-IN yield a relatively lower pesticide hazard.

In WU (Figure 3-2d), no clear pattern can be deducted from the graph. In general the cropping stage dominates water use, except in Uganda, where irrigation is very low and most WU is related to kerosene production. Temporal differences in cropping are clearly shown in the Spanish farms, where irrigation requirements change dramatically from the 1^{st} to the 2^{nd} crop. After cropping (or transport, in UG), the main contribution to WU comes from excretion (20-35%, up to 63% in UK10-IN), the latter due to toilet use. It needs to be stressed again that the WU reported here is only a LCI indicator. Impact assessment of freshwater use needs to take into account the type of use (evaporative or non-evaporative) and the source of water (e.g. surface water or over abstracted aquifers?) (Milà i Canals *et al*. submitted).

3.4 Interpretation for year-round lettuce in the UK

LCIA and inventory results are interpreted at three levels consistently with the goals of the study (section 1.3): contribution of *life cycle stages* (where are environmental hotspots?); *farms* (are differences between farms bigger than differences between countries?); and *indoors vs. outdoors production* (domestic vs. imported options?).

3.4.1 Life Cycle stages

Most life cycle stages of lettuce supply are relevant in at least one of the environmental impacts or indicators assessed, although the home stage only shows notable contributions in EP. Post-harvest cooling (processing) is the least significant stage and its contribution is negligible to most impacts. In order of appearance, the contributions of each stage are:

- The cropping stage is the most dominant stage in all supply chains except for the Ugandan one, where most impacts are dominated by airfreight. Cropping dominates land and freshwater use as well as pesticide related impacts. Fertiliser-related emissions contribute significantly to AP and EP.
- Post harvest processing (cooling) is negligible in most impacts and indicators assessed.
- Transport and retail dominates most impacts in the Ugandan supply chain due to the airfreight, with contributions often above 95% of the life cycle impacts. Kerosene production and combustion is responsible for the highest share of all environmental impacts and of the PEU indicator. In the other supply chains, transport and retail is less important, although it is significant particularly for the Spanish supply chains. When lettuce is imported from Spain the contributions from the cropping stage are normally lower than the British outdoors producers, but the transport by truck counterbalances this, particularly in ADP, AP, POCP and GWP, where transport and retail is responsible for 50-60%; 40-54%; 60-70%; 45-60% of the overall impact of the Spanish supply chains.
- Home is only relevant in EP due to emissions from waste landfilling.
- Human excretion has been studied in more detail than is common in LCA studies. In the life cycle of lettuce, it is relevant in EP due to the release of nitrogen compounds in the wastewater treatment plant (although this is overruled by airfreight emissions). Other notable contributions are seen in WU and LU, due to toilet flush and toilet paper use respectively.

3.4.2 Farms

The variability observed between different lettuce farms in the UK and Spain is not very big, particularly when put in perspective of the results for the Ugandan supply chain. When the attention is focused on the cropping stage only, then the variability between farms is more pronounced, particularly in the following impact categories or indicators: SOC deficit, AP, POCP, GWP, PEU, LU, PH and WU. In this case, Uganda shows generally the lowest environmental impacts in the cropping stage, due to the extremely low inputs of mechanisation, fertilisers and pesticides. The main differences found are due to the following parameters:

- Indoors vs. outdoors: clearly the production indoors requires more energy use and has more impacts related to this energy use. The big difference observed between UK9-IN and UK10-IN is possibly due to the different origin of energy use data in these two farms: in UK9 literature benchmarks have been used, whereas UK10 offered detailed meter readings (see Hospido *et al*. in preparation).
- In one same farm, first and second crops show differences in WU due to differences in the climatic conditions (e.g. in Spain this effect is more marked and second crops seem to require more water). Some farms also provided different spray records for first and second crops, due to the variation in pest and disease incidence through the year, as can be observed in Figure 3-2c. However, there is no clear pattern in terms of PH (see e.g. UK2 and UK9).
- The specific yield per ha varies widely between farms (in some cases also between 1st and 2nd crops). This has immediate effects particularly on SOC deficit and LU results. The yield in the farms assessed is grouped in countries and technologies, with UK outdoor farms reporting the lowest yields (15-30 tonnes per ha per crop); followed by the Spanish outdoor farms (30-36 tonnes per ha per crop); Uganda (40 tonnes per ha per crop); and finally indoors production in the UK (50-60 tonnes per ha per crop). This trend may actually be associated to different customer requirements in the different countries, as well as to technical possibilities: it is likely that the UK field farms are growing smaller plants, while indoors production allows higher densities and thus yields. In Spain and Uganda, bigger plants were being harvested, and the planting density was also higher than in UK outdoors production.

3.4.3 Indoors vs. outdoors production

In the lettuce case study the enabling technology allowing for off-season consumption, besides imports, is protected horticulture. The results of the study show that when compared to European imports protected horticulture in British heated glasshouses is worse in most environmental impacts and indicators (particularly ADP, GWP, POCP and PEU). In other aspects, protected horticulture seems to perform better (e.g. LU and maybe WU). However, if the alternative was African lettuce air freighted to the UK, then protected horticulture might be environmentally preferable. This is due to the impacts from kerosene production and combustion dominating the environmental profile of Ugandan lettuce.

4 LEGUMES

Green beans have been chosen as an example of legume crops. They are the unripe fruit of the common bean (*Phaseolus vulgaris*), and exist in many varieties (French beans, runner beans, etc.). This vegetable has been assessed in the UK and in two African countries: Kenya (currently the main exported of fresh green beans to the UK) and Uganda.

4.1 Study farms

A brief description of each studied farm is provided below.

4.1.1 Legume farms in the United Kingdom

In the UK, one big farm specialised in runner beans (and producing other crops) has been assessed for this study. In line with the other British farms assessed, it presents high levels of mechanisation; however, runner beans are also very labour intensive for certain operations (particularly harvesting and to a lesser extent planting). Labour is "imported" in the form of SAW: Student Agricultural Workers; these are usually students or young workers from Eastern Europe who come to work in British farms while studying English. They are lodged in on-farm facilities, and travel every day to the fields with farm buses (see Milà i Canals *et al*. 2007b, section 3.3.2). Applications of fertilisers and pesticides are tailored to the crop's needs through soil analyses and pest monitoring. Early crops (planted in March) are protected with a plastic cloche for the first weeks to prevent frost damage. Later crops (planted through the spring and summer, until June) do not require the cloche. The crop stays in the field for 3.5-4 months, but the same fields are only used once during the year. Therefore, a whole ha year has been considered per crop. The yield is ca. 12 tonnes/ha. UK11 also has its own cooling and packing plant, but this could not be assessed in the study, and therefore average values for other farms and crops had to be used.

4.1.2 Legume farms in Uganda

In Uganda, five different growers of green beans were interviewed and assessed for the study. Most of them grow crops on fields recently (less than 5 years) created by slashing and often burning bits of natural forest. They all have a very low level of mechanisation, with only two reporting the use of hired ploughs for soil preparation. Some of them sell directly to exporters who send the produce to Europe or Asia (India), but in many occasions they sell also or exclusively to local markets. Two main crops have been studied: French beans, which are often exported to Europe, have a short growing cycle (about 4 months from sowing to next crop), and a yield of ca. 9.5 tonnes/ha; and Sim beans, a local variety not so often exported, has a longer growing cycle (whole year) and a higher yield of ca. 30 tonnes/ha. This report focuses on French beans. Most operations are manual, including soil preparation; fertiliser and pesticide application. However, no quantification of labour has been possible in Uganda. This does not pose a problem for the methodology applied in these studies, because the only impacts associated to labour are those of workers' transportation, and in Uganda such transport is normally on foot or by bike (i.e. no environmental impacts associated). Most farms are rain fed and rely on the wet season's yield only; some manual watering has also been described to combat dry spells during the rainy season. Usually the same fertiliser and pesticide ingredients are applied by most growers, but the amounts used differ widely amongst them. Particularly in the case of fertilisers, the variation seems correlated with the frequency of opening new fields; i.e. growers who use more fertilisers report longer periods using the same fields, while a farmer who reported especially low fertiliser use said he'd simply open new fields more often to overcome the reduced fertility. However, this trend could not be studied in detail. In this report, the data collected in Uganda for French green beans growing by different farmers have been grouped, and are not provided per farmer.

4.1.3 Legume farms in Kenya

In Kenya, one farm growing runner beans for export to the UK was assessed. The level of mechanisation was low, with planting, weeding, installation and removal of crop support, coiling and harvesting operations all being carried out manually. In the LCA, transport of workers to the farm was included. This is done mostly (89% of the workers) yb farm buses transporting 60 workers each over 10 km per day. The remaining 11% of workers travel on foot or by bike, for which no impacts have been considered. Yields amount to 38 tonness per hectare. The growing period for runner beans is 5 months; in between crops, a cover crop is planted and left in the ground for 12-15 months. New fields are planted throughout the year. Irrigation is used for 4 months per crop; however, irrigation needs vary throughout the year depending on rainfall. Fertilisation is mainly through the irrigation drench as fertigation. Lighting is applied for 10 weeks per crop.

4.2 System description and LCI

The following sections describe the operations carried out through the life cycle of green beans, divided in three main stages: cropping, processing (cooling), and retail to grave. The latter includes all the operations from the retail outlet until human consumption.

4.2.1 Cropping stage

Table 4-1 provides figures on the main input and output flows considered for the case study farms. All inputs and the crop output were obtained from the farmers, while emissions have been calculated from the inputs and literature estimates. CO_2 input (fixed by the crop) has been estimated from the crop's carbon content as explained in Milà i Canals *et al*. (2007b). The main differences described in section 3.1 can be observed in the figures of the table.

The general operations performed during the cropping stage include:

- *Soil management*: this stage is most mechanised on the UK farms, followed by Kenya and Uganda with the lowest level of mechanisation. In Kenya, many operations are carried out manually.
- *Fertiliser use*: mineral fertilisers are used in the UK and Kenya, while Ugandan farmers mainly rely on organic fertilisers (manure, compost) and supplement the crops with minor amounts of mineral fertilisers applied to foliage.
- *Irrigation*: input of irrigation water is minimal in Uganda where farmers rely mainly on rain. The greatest amount of irrigation water is used in Kenya, where river water is used. In the UK, the source of irrigation water is groundwater.
- *Pest and disease management*: the lowest amounts of pesticides are used in Uganda, followed by Kenya. UK farms use the greatest amounts of pesticides, where small differences are observed between early and late crops.
- *Harvesting*: harvesting is carried out manually on all farms.

Table 4-1: Main input and output flows from the case study farms during cropping of beans.

Flow	Units (/ha/crop)	UG	KE	UK11 early	UK11 late
INPUTS					
Occupation, arable land	m^2year	5000	10000	10000	10000
CO_2 from air fixed in crop	kg CO_2	1254	5016	1584	1584
Tractor use	hours	0.37	5.3	14.8	7.9
Diesel (for field operations)	litres	4.44	37.3	89.76	60.16
Steel (spare parts replacement)	kg	0.13	1.9	1.78	1.78
Labour (labour-intensive operations)	person days	n.a.	406	67	67
Diesel (for workers' transport)	litres	0	33.8	13.5	13.5
Plastic (fleece, mulch…)	kg	0	0	151.4	0
Pesticides (unspecified)	kg active ingredient	1.3	4.4	5.3	5.0
Fertilisers					
N fertiliser	kg N	0.05	93.2	120.1	120.1
P fertiliser	kg P_2O_5	0.04	78	0	0
K fertiliser	kg K_2O	0.04	36.8	101.3	101.3
Manure / organic fertilisers	kg	12500			
Irrigation					
Blue water, surface water	m^3	125	2251.9	0	0
Blue water, groundwater	m^3	0	0	700	300
Infrastructure (pipes, sprinklers…)	kg	0	44	8.91	8.91
Electricity (pumps)	kWh	0	1542.9	770	330
OUTPUTS					
Crop	kg	9500	38000	12000	12000
Soil emissions (literature)					
CO_2 from soil	kg CO_2	1650.2	3300.3	1466.8	1466.8
CH_4 from soil	kg CH_4	0.33	0.472	0.402	0.402
NH_3 from soil	kg NH_3	14.53	6.863	10.404	10.404
NO_x from soil	kg NO_x	0.411	0.276	0.296	0.296
N_2O from soil	kg N_2O	3.93	2.638	2.832	2.832
NO_3^- from soil	kg NO_3^-	66.43	66.43	66.43	66.43
PO_4^{3-} from soil	kg PO_4^{3-}	3.065	3.065	3.065	3.065
Change in soil organic carbon (SOC)	kg C	-450	-900	-400	-400

4.2.2 Processing (fresh produce)

The post-harvest operations include basically an initial cooling to pull down the field temperature from the crop, and loading the refrigerated lorries which then transport the produce to the Regional Distribution Centre (RDC). No packaging has been considered in the case of green beans. The farms in the UK and Kenya have on-site cooling facilities, but no data could be obtained from them; the farms in Uganda sell their produce to exporters who have cooling facilities but could not be assessed during the study (or to local markets, where no cooling is involved). Thus, average electricity consumption for cooling has been obtained from the other crops and farms studied at 56.2 kWh / tonne sold produce.

4.2.3 Processing (frozen produce)

In the case of vegetable freezing, a big freezing plant was visited and assessed. The plant processes many different vegetables, including peas, broccoli, beans, potatoes, carrots, etc. Detailed data were gathered for the operation of the whole plant, which also includes washing and packing the vegetables. Even though the data were presented in an aggregate way per kg of total processed (frozen and packed) produce, they may be considered representative of each single one.
The main flows expressed per tonne of sold produce are as follows:

- Electricity: 132.6 kWh / tonne sold produce
- Natural gas: 32.7 kWh / tonne sold produce
- Water: 10.9 m^3 / tonne sold produce

- Diesel: 0.2 litres / tonne sold produce

Each packed (sold) tonne includes ca. 2 kg plastic bags and 22.8 kg cardboard boxes. Wastage during the whole process includes 14.2% from raw to frozen (rests of pods, leaves, faulty produce, etc.) and 6.5% from frozen to packed (discarded in the colour test). Again, a mass allocation has been applied to this waste (see Milà i Canals *et al*. 2007b, section 6).

4.2.4 Retail to grave

Retail to grave stages of the green beans life cycle include the following processes (Milà i Canals *et al*. 2007b):

- Transport to RDC and storage: includes the transport step from the farm or freezing plant to RDC and the energy use for cool storage. Green beans grown in the UK have been assigned an average road transportation of 200 km. In Uganda and Kenya, green beans are first transported 70 km (by mini-vans in Uganda and refrigerated trucks in Kenya) to the airport store, 6,600 km by plane to the UK and then 200 km by refrigerated truck to the British RDC.
- Transport to retailer and storage: similar as above, but related to the retailing step. The food losses at this stage are included.
- Transport home by the consumer: energy use due to transport by different transport modes (car, bus, cycle, and by walking), weighed according to the average UK consumer shopping patterns (Pretty *et al*. 2005).
- Home storage: energy use related to storage at home, allocated depending on the need to use refrigerator or freezer space; all green beans are kept in the fridge, and 20% are home-frozen.
- Cooking: Energy and water use related to different cooking modes (boiling, baking, frying, microwaving), taking into account the specific UK share of electric and gas cooking appliances. Average values for use of different cooking modes were not available, and a plausible mix of modes for each vegetable studied has been assumed (Milà i Canals *et al*. 2007b, section 5.2.3).
- Liquid and solid food waste management: wastewater from boiling is modelled as sent through the sewer to a wastewater treatment plant, while cooking waste and leftovers are sent to a landfill.
- Human excretion and wastewater treatment: the biochemical reactions in the human body are taken into account, giving rise to air and wastewater emissions, the latter sent to a wastewater treatment plant.

Modelling of all the above processes is described in Milà i Canals *et al*. 2007b, section 5, with the exception of human excretion, which has been subject to a more detailed study (Muñoz *et al*. 2007; Muñoz *et al*. in press).

4.3 LCIA Results

This section presents the results for the cradle to grave analysis of beans produced in Kenya, Uganda and the UK and consumed in the UK. Figure 4-1 shows the results for these three countries of origin for six environmental impact categories, while Figure 4-2 illustrates four indicators of environmental relevance. The life cycle stages included are: cropping, post-harvest processing, transport and retail, home consumption and human excretion.

Figure 3-1a shows the impact on soil quality through the entire life cycle, measured as soil organic carbon deficit (Milà i Canals *et al*. 2007c). This impact is greatest for Uganda, closely followed by Kenya, while the UK grown beans have a much lower impact. The large impact for Uganda and Kenya is related to kerosene production for air freighting. In the UK, the cropping stage contributes the most to soil organic carbon deficit and is higher than in the case of Uganda and Kenya due to lower yields in the UK (only 1 crop per year considered in the UK, compared to 2 in Uganda). Frozen beans have a slightly lower impact in the cropping stage due to lower percentage of product wasted in the home stage. It should be highlighted that the impact in Uganda is probably underestimated; as mentioned in 4.1.2, most of the farmers periodically clear new pieces of forest for agriculture. This land transformation is linked to rapid degradation of SOC, but has not been yet considered due to lack of representative data (e.g. allocation of cleared forest area to cropping area).

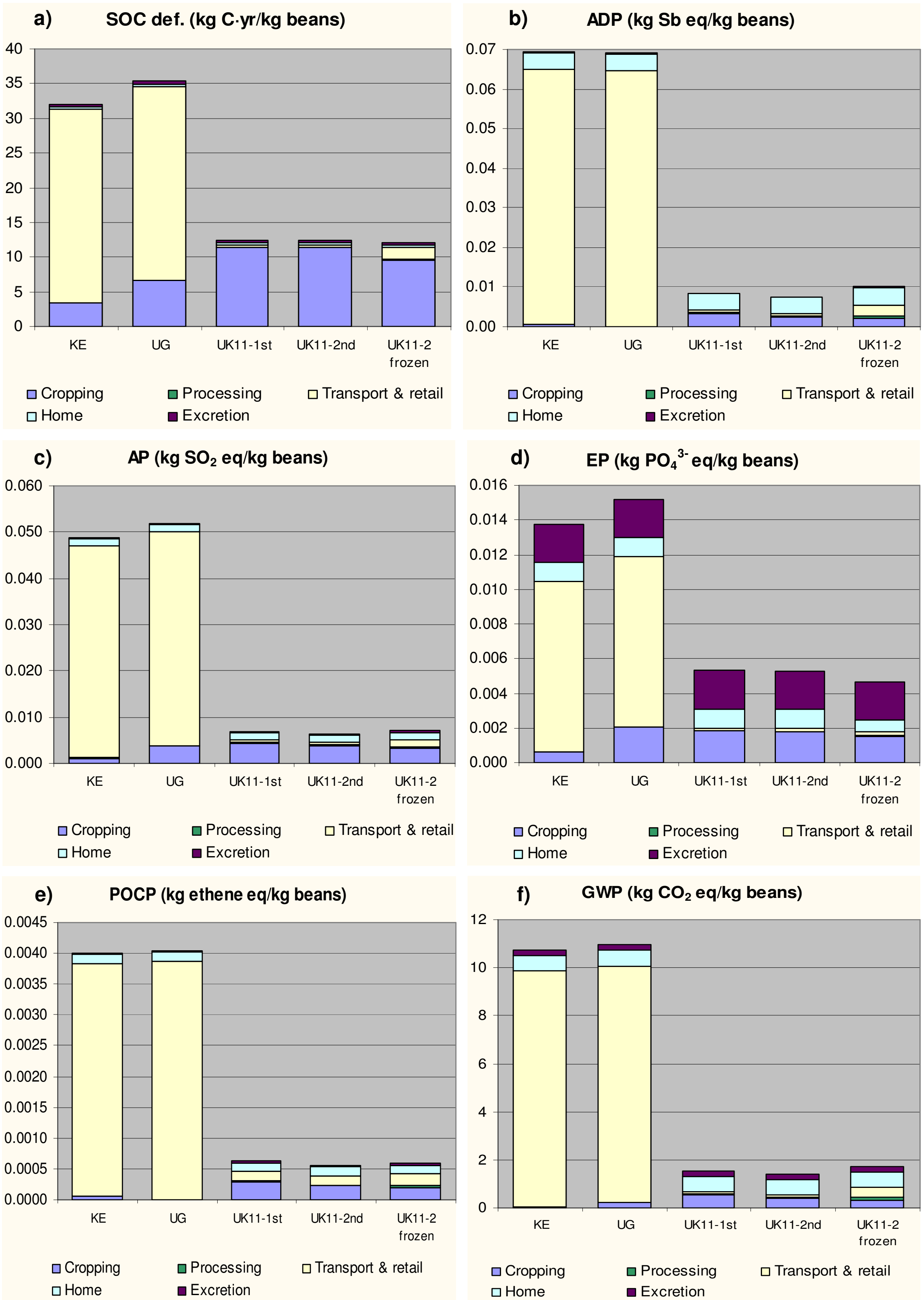

Figure 4-1: LCIA characterisation profile for UK-, Kenya- and Uganda-grown green beans, from cradle to grave, per kg beans.

Similarly, the Abiotic Depletion Potential (ADP) (Figure 4-1b) is greatest for the Ugandan and Kenyan supply chains, once again dominated by the transportation stage. This is due to the depletion of fossil fuel energy resources for air freighting. For the UK supply chains, the home stage is the greatest cause of abiotic depletion due to energy use for cooking and home storage, closely followed by the cropping stage.

The Acidification Potential (AP) (Figure 4-1c) and Eutrophication Potential (EP) (Figure 4-1d) show the same patterns, with the Ugandan and Kenyan supply chains having the greatest impact due to the combustion of kerosene for air freight and the emission of nitrous oxides respectively. For UK grown beans, the cropping stage is the main contributor to AP; this is mostly due to soil emissions from fertilisers (25% of the UK impacts), but has a relevant contribution from the air transportation of SAW (9% of total impact). In contrast to fresh UK beans, transport and retail contribute significantly for frozen UK grown beans. For all three supply chains, the contribution of human excretion to EP is significant.

The formation of photochemical oxidants (POCP) (Figure 4-1e) is dominated by the transportation stage for Uganda and Kenya due to kerosene consumption and production processes for air freighting. POCP for UK grown beans is much lower and dominated by the cropping stage for UK11-1 and UK11-2 (where air transportation of workers from Eastern Europe contributes by ca. 17%). For frozen beans, the transport and retail stage has the main impact, and contrary to fresh produce, processing is significant too.

Figure 4-1f shows the Global Warming Potential (GWP) as kg CO_2 equivalents. Similar to all other environmental impacts presented here, GWP is much greater for the African supply chains than the UK supply chains, and is dominated by the air freighting stage. Home processing is the dominant life cycle stage for the UK supply chains, followed by the cropping stage for fresh beans and the transport and retail stage for frozen produce. Again, it is worth highlighting the 9% contribution to GWP from transporting SAW to the UK farm.

Figure 4-2 illustrates the impact of the three supply chains on four environmental indicators. Primary Energy Use (PEU) (Figure 3-2b) is very frequently used in LCA studies. Water Use (WU) (Figure 3-2d) and Land Use (LU) (Figure 3-2a), although not so frequently used, are very relevant in this project, taking into account that agriculture is an activity with extensive use of these resources. Pesticide hazard (PH) (Figure 3-2c), on the other hand, is not a typical LCA indicator, though again it is very relevant from an agricultural point of view, since pesticides are usually the main life cycle contributors to many toxicity-related impact categories (Milà i Canals *et al*. 2007b, section 7.4).

Land use (LU) (Figure 4-2a), measured as area·time, is dominated by the cropping stage for all three countries of origin. The lowest LU is related to the Kenyan supply chain, followed by Uganda and the UK with the greatest LU indicator. This is explained by the differences in land use efficiency in these countries, i.e. the yield per ha, which is greatest in Kenya and lowest in the UK. Human excretion represents the second most important life cycle stage in relation to LU, which is due to forestry operations for the manufacture of toilet paper. For the UK supply chains, the transport and retail stage is important for frozen produce. It must be highlighted that no LU has been assigned to land application of sewage sludge; because this process is considered as agricultural land use (i.e. land's main function is producing a crop, even if it is also used to apply waste). Moreover, this indicator does not account for the impacts from slashing and burning natural forest to provide horticultural land in Uganda, because the land use indicator reports land occupation only (not transformation).

Primary Energy use (PEU) (Figure 4-2b) is about seven to eight times greater for the African supply chains than for fresh UK grown beans and about five times greater than frozen UK beans. For the African supply chains, PEU is dominated by transportation due to kerosene consumption for airfreight, while the UK supply chains are dominated by the home stage, with transport and retail being important for frozen beans only.

Pesticide Hazard (PH) (Figure 4-2c) is only relevant for the cropping stage. Although this quotient takes into account the specific hazard of different pesticides (Milà i Canals *et al*. 2007b, section 7.4), the scores obtained by the different alternatives reflect to a certain extent the overall amount of active ingredients used on the different farms. Thus, the lower level of pesticide usage in Uganda and Kenya is reflected in a much lower PH than for the UK farms. On the UK farms, the lower amount of pesticides used for late crops leads to a reduced PH compared to early crops.

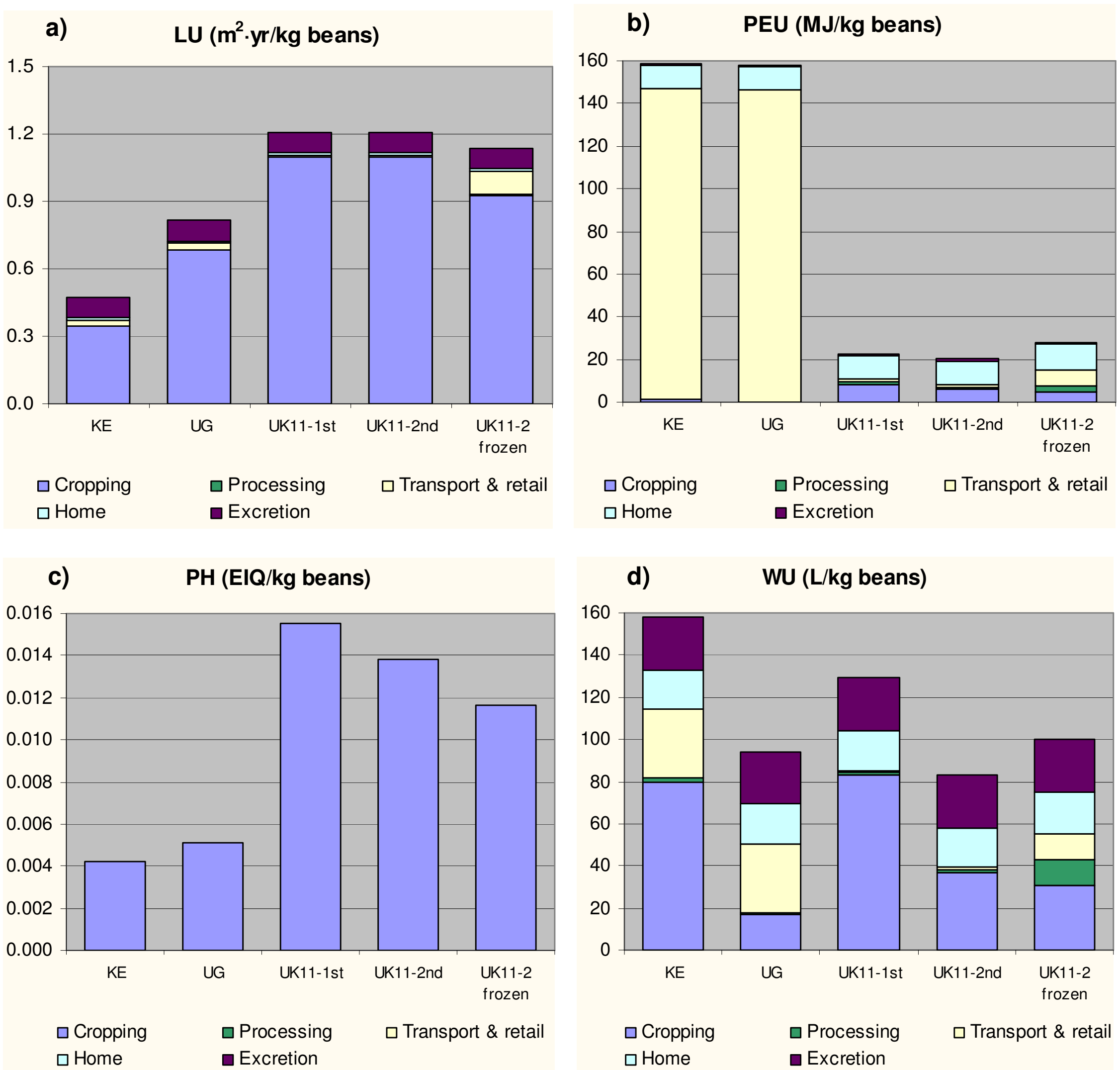

Figure 4-2: Environmental indicators for UK-, Kenya- and Uganda-grown green beans, from cradle to grave, per kg green beans.

Water Use (WU) (Figure 4-2d) is dominated by the cropping stage for Kenya and the UK and by the transport stage for Uganda. The transport stage is the second dominant stage for Kenya. For the UK supply chains, human excretion is the second dominant stage. Processing and transport and retail are important for frozen UK beans. It needs to be stressed again that the WU reported here is only a LCI indicator. Impact assessment of freshwater use needs to take into account the type of use (evaporative or non-evaporative) and the source of water (e.g. surface water or over abstracted aquifers?) (Milà i Canals *et al*. submitted).

4.4 Interpretation for year-round green beans in the UK

LCIA and inventory results are interpreted at two levels: contribution of *life cycle stages* (where are the environmental hotspots?); and *fresh vs. frozen* produce (imported vs. frozen options in winter?). As only one farm in each country was assessed, no comparison between impacts arising from different farms within the same country could be conducted.

4.4.1 Life cycle stages

Most life cycle stages of green beans supply are relevant in at least one of the environmental impacts or indicators assessed, although the processing stage is usually negligible with some importance in the frozen supply chain. In order of appearance, the contributions of each stage are:

- The cropping stage has relevant contributions to most impact categories, except those closely related to PEU in the African supply chains; in fact most impacts in the African supply chains are dominated by air freight. Cropping dominates land and freshwater use as well as pesticide related impacts. Fertiliser-related emissions contribute significantly to AP and EP.
- Post harvest processing (cooling) is negligible in most impacts and indicators assessed, with the exception of water use for the frozen supply chain.
- Transport and retail dominates most impacts in the Kenyan and Ugandan supply chains due to the airfreight, with contributions often above 95% of the life cycle impacts. Kerosene production and combustion is responsible for the highest share of all environmental impacts and of the PEU indicator. In the UK supply chains, transport and retail is less important.
- Home processes have a significant but minor contribution to energy and freshwater use, and the impacts related to energy sourcing (GWP, AP, POCP, etc.). Its contribution to EP is relatively higher due to emissions from waste landfilling.
- Human excretion has been studied in more detail than is common in LCA studies. In the life cycle of green beans, it is relevant in EP due to the release of nitrogen compounds in the wastewater treatment plant (although this is overweighed by airfreight emissions). Other notable contributions are seen in WU and LU, due to toilet flush and toilet paper use respectively.

4.4.2 Fresh vs. Frozen green beans

Table 4-2 shows a summary of all the environmental impacts and indicators, for each one of the studied systems. UK11-1 and UK11-2 supply fresh green beans in the warm months and are not 100% comparable with all other systems, which may supply produce through the year.

Table 4-2: Cradle to grave LCIA results for fresh and frozen beans.

Impact category/indicator, per kg beans on plate	KE	UG	UK11-1	UK11-2	UK11-2 frozen
LU [m^2·year]	0.48	0.82	1.21	1.21	1.14
PEU [MJ]	158.9	158.2	22.4	20.1	27.7
Pesticide Hazard [EIQ]	0.004	0.005	0.016	0.014	0.012
SOC deficit [kg C per year]	32.0	35.3	12.5	12.5	12.1
ADP [kg Sb equiv.]	0.069	0.069	0.008	0.008	0.010
WU [kg]	158.2	94.3	129.4	83.2	100.1
AP [kg SO_2 eqiv.]	0.049	0.052	0.007	0.006	0.007
EP [kg phosphate eqiv.]	0.014	0.015	0.005	0.005	0.005
GWP [kg CO_2 equiv.]	10.7	10.9	1.55	1.42	1.72
POCP [kg ethene equiv.]	0.004	0.004	0.001	0.001	0.001

For all impact categories and environmental indicators with the only exception of Land Use, Water Use and Pesticide Hazard, the African supply chains had much greater impacts per kg of beans than the UK supply chain. This was always due to the transportation over long distances by air. Differences between the first and second crop grown at the UK farm assessed proved to be negligible for all impact categories. For frozen UK beans, impacts were greater than for fresh produce for most impact categories, but much lower than for beans imported from Kenya or Uganda. On the other hand, frozen beans are related to smaller wastage of produce, and thus the impacts related to the cropping stage are reduced. This can be seen in the overall contributions to impact categories and indicators mostly affected by such stage in the UK, e.g. LU, Pesticide Hazard and SOC deficit: in these categories the overall impact from frozen produce is smaller than for fresh produce.

5 CONCLUSIONS

One of the main outcomes of this study is the confirmation that working with 'food miles' as an indicator of environmental impacts for food products is potentially misleading: imported produce may have lower environmental impacts than domestic produce supplied off-season through increased storage and/or produced using enabling technologies such as heated and lit glasshouses. Long-term storage through e.g. freezing of local produce offers a better alternative to imports than protected cultivation. After enabling technologies providing the fair domestic alternative to imports have been assessed, the discussion is not only focused on the distance any more. On the other hand, produce imported by air shows clearly higher environmental impacts than off-season domestic produce (at least in the case of lettuce and green beans), although for certain impact indicators such as land use, water use and pesticide use the result are not so clear-cut. However, it needs to be highlighted that LCA results only deal with environmental impacts, and do not address other important aspects considered in the project, such as farmers' health and effects on the local economy.

A novel approach tested in this study is the allocation of the impacts from transporting farm workers to the farm. These impacts have been shown to be negligible when considering road transport from on-farm or near-to-farm lodgement. However, the contribution of air flights for fully dedicated temporary workers (e.g. the SAW scheme) is relevant in the overall results, if not dominant, according to the LCA of green beans produced in UK11. Such impacts do not overweigh the burdens of air freight of fresh produce, but might present a comparative disadvantage against produce imported by road.

There is considerable variation in the results from different farms producing the same product. This suggests that any single figure defining a crop (e.g. a value for the 'carbon footprint' of 1 kg green beans) is bound with significant uncertainty. Post-farm stages, and particularly home storage and cooking, have shown to contribute significantly to the final impacts. Variations in these stages have not been modelled in detail, but are likely to be very high due to alternative consumer behaviour (e.g. cooking for more or less time, with different kitchen appliances, etc.). This is particularly true for products that are often cooked (i.e. not so relevant for products that are eaten raw, such as lettuce). Indeed, the home stage may dominate the results in the case of cooked vegetables. This result should demand some caution when designing and implementing carbon labelling schemes of food products.

Transport and retail dominated most impacts in the Kenyan and Ugandan supply chains due to the airfreight, with contributions often above 95% of the life cycle impacts. Kerosene production and combustion is responsible for the highest share of all environmental impacts and of the PEU indicator.

When no air freight or cooking are involved, the cropping stage dominates many environmental impacts, in particular with regard to soil quality impacts and land use. It is also the most important stage for Water Use when the crop is irrigated. Emissions related to agricultural inputs, namely fertilisers and pesticides, are important contributors to GWP, while ammonia and nitrate emissions from N-fertilisers are important in the Acidification and Eutrophication Potentials, respectively.

This study has also shown a novel approach to address land use impacts beyond the inventory indicator m^2year of occupied land. Soil Organic Carbon (SOC) has been used as an indicator of soil quality, and potential changes to SOC linked to different land uses have been compiled along the whole life cycle of the products assessed. The results show that, contrary to common assumptions in several life cycle impact assessment methods, stages different than cropping (e.g. mining for kerosene production) may dominate the <u>impacts</u> related to land use, even if cropping still dominates the amount of m^2year.

Another novel approach in this study relates to food consumption and excretion. This stage has commonly been neglected in food LCA studies, but has shown its significance particularly in terms of water eutrophication and water use.

REFERENCES

Althaus H-J, Blaser S, Classen M, Jungbluth N (2004) Life Cycle Inventories of Metals. Final report ecoinvent 2000 No. 10, Swiss Centre for Life Cycle Inventories, Duebendorf (Switzerland), for ecoinvent members only.

Dones R, Faist M, Frischknecht R, Heck T, Jungbluth N. (2004) Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries. Final report ecoinvent 2000 No. 5, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Duebendorf (Switzerland), for ecoinvent members only.

Edwards-Jones G, Koerber G, Milà i Canals L, York EH (2007): *Identifying and managing emissions from farms and food chains*. Carbon Footprint Supply Chain Summit. London (UK) 24-25 May 2007 [http://www.bangor.ac.uk/relu/documents/gejcarbonsummit.ppt]

Edwards-Jones G, Milà i Canals L, Hounsome N, Truninger M, Koerber G, Hounsome B, Cross P, York EH, Hospido A, Plassmann K, Harris IM, Edwards RT, Day GAS, Tomos AD, Cowell SJ, Jones DL (2008): *Testing the assertion that 'local food is best': the challenges of an evidence based approach*. Trends Food Sci Tech. **19** (2008) 265-274.

Frischknecht R, Althaus H J, Doka G, Dones R, Heck T, Hellweg S, Hischier R, Jungbluth N, Nemecek T, Rebitzer G, Spielmann M. 2004. *Overview and Methodology*. Final report ecoinvent 2000 No. 1, Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland. www.ecoinvent.ch

Guinée J B, Gorree M, Heijungs R, Huppes G, Kleijn R, Udo de Haes H A, Van der Voet E, Wrisberg M N. 2002. *Life Cycle Assessment. An operational guide to ISO standards.Volume 1, 2, 3*. Centre of Environmental Science, Leiden University (CML), The Netherlands.

Hospido A, Milà i Canals L, McLaren SJ, Clift R, Truninger M, Edwards-Jones G. *Environmental Consequences of Permanent Summertime: exploring the options for year-round lettuce supply to the UK*. In preparation

Huijbregts MAJ, Rombouts LJA, Hellweg S, Frischknecht R, Hendriks AJ, van de Meent D, Ragas AMJ, Reijnders L, Struijs J (2006): *Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products?* Environ Sci and Technol **40**(3) 641-648

McDevitt J, Milà i Canals L (submitted): *Life Cycle Assessment for eco-breeding: assessing the areas where plant variety development can reduce the environmental impact of porridge oats for human consumption*.

Milà i Canals L, Sim S. 2007. *How much carbon for an apple? The carbon footprint of fruit production*. The 64th National Fruit Show 2007. Handbook, pp. 24-27

Milà i Canals L, Cowell SJ, Sim S, Basson L. 2007a. *Comparing Local versus Imported Apples: A Focus on Energy Use*. Env Sci Pollut Res, **14**(5) 338-344

Milà i Canals L, Muñoz I, McLaren SJ, Brandão M 2007b. *LCA Methodology and Modelling Considerations for Vegetable production and Consumption*. CES Working Papers 02/07 Available from http://www.surrey.ac.uk/CES

Milà i Canals L, Romanyà J, Cowell SJ. 2007c. *Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in Life Cycle Assessment (LCA)*. Journal of Cleaner Production. **15** 1426-1440

Milà i Canals L, Bauer C, Depestele J, Dubreuil A, Freiermuth Knuchel R, Gaillard G, Michelsen O, Müller-Wenk R, Rydgren B (2007d): *Key elements in a framework for land use impact assessment in LCA*. Int J LCA **12**(1) 5-15

Milà i Canals L, Chenoweth J, Chapagain AK, Orr S, Antón A, Clift R (Submitted) *Assessing Freshwater Use Impacts in LCA Part I: Inventory Modelling and Characterisation Factors for the Main Impact Pathways*. Int J Life Cycle Ass

Milà i Canals L, Chapagain AK, Orr S, Chenoweth J (In preparation): *Assessing Freshwater Use Impacts in LCA Part II: Case study for broccoli production in the UK and Spain*. Int J Life Cycle Ass

Muñoz I, Milà i Canals L, Clift R, Doka G. 2007. *A Simple Model to Include Human Excretion and Wastewater Treatment in Life Cycle Assessment of Food Products*. CES Working Papers 01/07 Available from http://www.surrey.ac.uk/CES

Muñoz I, Milà i Canals L, Clift R. (in press). *Consider a spherical man - A simple model to include human excretion in Life Cycle Assessment of Food products*. Journal of Industrial Ecology. Accepted

Nemecek T, Heil A, Huguenin O, Meier S, Erzinger S, Blaser S, Dux D, Zimmermann A (2004*): Life Cycle Inventories of Agricultural Production Systems.* Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf (Switzerland)

Pretty JN, Ball AS, Lang T, Morison JIL (2005): Farm costs and food miles: An assessment of the full cost of the UK weekly food basket. Food Policy **30** 1-19

Spielmann M, Kägi T, Tietje O. (2004) *Life Cycle Inventories of Transport Services.* Final report ecoinvent 2000 No. 14, Swiss Centre for Life Cycle Inventories, Duebendorf (Switzerland), for ecoinvent members only

WRAP (2007): *Understanding Food Waste.* Research Summary. Available from www.wrap.org.uk

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