Methodology for assessing carbon footprints of horticultural products

A study of methodological issues and solutions for the development of the Dutch carbon footprint protocol for horticultural products

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Boki Luske, Tommie Ponsioen,
and Jasper Scholten

March 2010

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Agri Information Partners

Productschap Tuinbouw

Wageningen UR For quality of life

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Preface

In 2008 and 2009 Blonk Milieu Advies (Blonk Environmental Consultants), Agro Information Partners and LEI-WUR (Agricultural Economic Research Institute) developed a methodology, a protocol and a calculation tool for assessing carbon footprints of horticultural products. The project was commissioned by Productschap Tuinbouw (Dutch Product Board for Horticulture) and Ministerie van LNV (Dutch Ministry of Agriculture). This resulted in a report including analysis and recommendations of state of the art methodologies, which was published in early 2009. However, international accessibility of the report was limited, because it was written in Dutch. Many requests to translate the report into English resulted in the present translated report.

Methodological developments in the Netherlands, in many other countries and on international level continue. For example, late 2009 Blonk Milieu Advies produced a report commissioned by Productschap Diervoeder (Dutch Product Board for Animal Feed) with recommendations to develop a protocol and tool for animal feed products. At this moment the World Resource Institute is developing a protocol for assessing carbon footprints of products and services and aims to be publish this at the end of 2010, and the ISO norms for carbon footprints will probably be updated in 2011.

Despite these developments, we expect that most of our recommendations in the present report will be valid in the future. It gives specific recommendations for the use of certain methods, where the international protocols and norms leave a large number of such decisions to the user. We also show the consequences of choosing one method rather than the others in a number of carefully selected case studies. Therefore, this report provides valuable information for assessing carbon footprints of horticultural products now and in the future.

We would like to thank Derek Middleton for his translation services. The translation of the report was financed by Productschap Tuibouw.

On behalf of the authors, Hans Blonk, Anton Kool, Boki Luske, Tommie Ponsioen, and Jasper Scholten.

March 2010

Contents

1. Introduction

At the beginning of 2007 several British retail organisations created a demand for information about carbon footprints of agricultural products (the sum of greenhouse gas emissions that can be attributed to the product) by announcing that they would introduce a carbon footprint labelling scheme for their products. This initiative led to various product-oriented studies in Great Britain and elsewhere, but it soon became clear that there was a need for a standardised calculation method. In 2007 the British Standards Institution (BSI) began developing a protocol for calculating the carbon footprints of various products and services. This protocol was published as the Publically Available Specification (PAS) 2050, in October 2008 (BSI 2008).

In the Netherlands, studies were commissioned in reaction to the preparation of PAS 2050, especially by companies that supply products to Great Britain. At the same time, the wider Dutch business community recognised the need for a well-founded calculation method. In response to these developments, the Dutch Commodity Board for Horticulture (Productschap Tuinbouw) launched a project in 2007 to develop a protocol and calculation tool for the Dutch horticultural sector to keep pace with the anticipated developments in Great Britain. The Dutch Ministry of Agriculture (Ministerie van LNV) subsequently became involved in the project as a commissioning party. After a two-year study period, the project was completed with the preparation of a protocol for the calculation of carbon footprints of horticultural products, as well as an online demonstration version of the calculation tool, which growers and traders can use to calculate the carbon footprints of their products. The protocol contains definitions of best practices (recommended methods and standardised data) for calculating the carbon footprints of horticultural products. These best practices were developed from analyses of methodological issues within the framework set by PAS 2050 and the most recent guidelines by the International Panel on Climate Change (IPCC) for use in life cycle assessments (LCAs). These issues and the methods selected for use in the best practices are described in this report.

In Chapter 2 we describe the scope of the study and the approach we took to investigate methodological issues. The methodological issues were examined from both a theoretical and a practical perspective. A large number of case studies were carried out in which the carbon footprints of horticultural products were calculated to obtain a clear picture of the methodological issues involved and the possible solutions. The formulated best practices have therefore been tested in practical situations by using practical expertise. The case studies are reported in Chapter 3. In the subsequent chapters, the various research questions are explored and state-of-the-art solutions are proposed for inclusion in the protocol for calculating the carbon footprints of horticultural products.

Various researchers and practitioners took part in this study. The researchers were Myrtille Danse, Rolien Wiersinga, Nico van der Velden, Jan Benninga, Rob Stokkers, Gerben Jukema and Sabine Hiller from the Agricultural Economics Research Institute (LEI-WUR) and Peter Vermeulen and Kees van Wijk from Applied Plant Research (WUR-PPO). These researchers were members of the research team and at various stages in the research project they made crucial contributions, either by providing essential data or commenting on drafts of the text. Several other people took part in expert meetings on various topics (see Appendix 1). Their contributions have also been essential for the completion of this study.

2. Scope and method

The project for calculating carbon footprints of horticultural products (the sum of greenhouse gas emissions/carbon dioxide equivalents[1] that can be attributed to the product) was carried out in response to the British initiative to develop a specification for calculating the carbon footprints of products and informing consumers of the results. The British initiative followed from the previously developed 'food miles' concept, which was based on the idea that negative environmental impacts of the transport of foodstuffs or ingredients can be avoided by using more locally produced food and ingredients. Since then, awareness has grown that the greenhouse gas emissions that can be attributed to the transportation of a product are in most cases not the key factor in determining the carbon footprint of a product. The developers of the British method (the Carbon Trust, the Department for Environment, Food and Rural Affairs and the British Standards Institution) were also well aware of this. The protocol developed by the British Standards Institution (BSI) for calculating the carbon footprints of products, PAS 2050 (BSI 2008), is based on the concept that all greenhouse gas emissions from all stages should be included in the calculation.

The PAS 2050 specification was drawn up and published during the period in which the Dutch project to develop a method for calculating the carbon footprints of horticultural products was carried out. The development of this method was informed by the concepts adhered to in the PAS 2050 specification, the general life cycle analysis (LCA) literature and the specific agricultural LCA literature. Some stages in the development of the proposed calculation methods are shown in Figure 2.1. The following four steps of the project and the results of each stage are discussed below:

- Step 1: inventory of methodological issues
- Step 2: analysis of methodological issues
- Step 3: case studies
- Step 4: synthesis

[1] Greenhouse gas emissions can be expressed in carbon dioxide equivalents. The IPCC published lists in 1996 and 2007 of greenhouse gasses and the factors to convert them to carbon dioxide equivalents, which are called global warming potential factors (GWP). There are GWP factors for the impact over 20 years and over 100 years. We use the GWP 100 year factors, conform to international standards, such as the PAS2050.

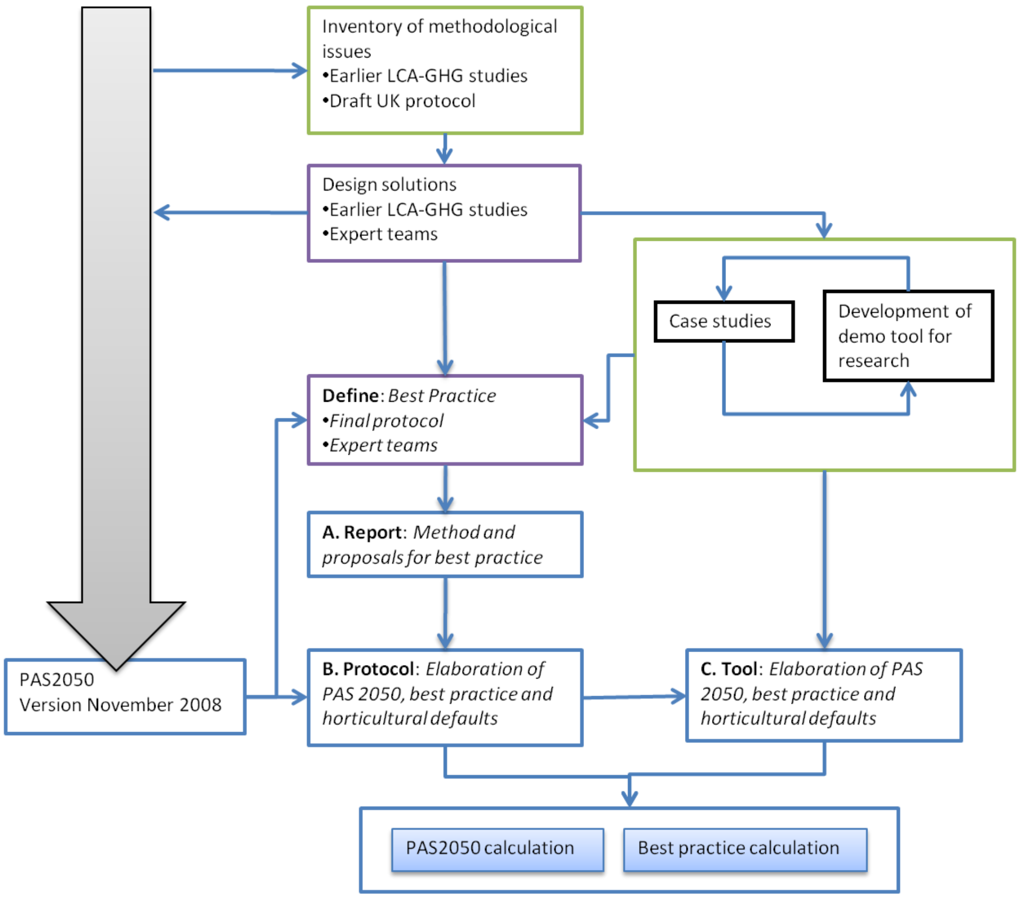

Figure 2.1 Diagram showing the stages in the research project

Step 1: Inventory of methodological issues

The first step was to draw up an inventory of the methodological issues that are relevant for the calculation of the carbon footprints of horticultural products. This was based on previously acquired knowledge and experience relating to the calculation of carbon footprints of horticultural and arable products.[2] In addition, a first draft of the PAS 2050 became available in 2007. Based on these sources, we identified a number of methodological issues that we expected to make a considerable contribution to the carbon footprint of horticultural products and for which it is important to formulate clear-cut calculation rules.

Step 2: Analysis of methodological issues

In the second step several tentative solutions to methodological issues were defined. These solutions were based on various LCA protocols (the ISO 14040 series, the Dutch handbook on LCA, Guinee 2002, and the

[2] Between 200 and 2007, Blonk Milieu Advies carried out supply chain analyses of a large number of fresh and processed horticultural and arable products in varying degrees of detail (Blonk 2000 and 2001; Blonk and Arts 2005; Blonk *et al.* 2007). In addition, several important projects were carried out at the end of the 1990s for the development of an LCA knowledge infrastructure for agriculture and foodstuffs (Wegener Sleeswijk *et al.* 1996; Blonk *et al.* 1997; Audsley *et al.* 1998). The Dutch and Danish LCA handbooks, as well as the ISO standards, were important sources of information for the LCA methodology. We also referred to a few recent English studies (including Cranfield 2006) and made use of international databases, such as Ecoinvent and articles published in the International Journal of Lifecycle Assessment.

EPLCA initiative), combined with proposals and methods from research on agricultural greenhouse gas emissions[3]. The solutions can be divided into three categories: 1) this is how it *should* be done, 2) this is how it *may/can* be done, 3) this is how it *could* be done. In the first category, there is a consensus on the approach and the calculation rules are clear cut. In the other two categories, LCA methodology does not give a definitive answer, but does describe alternative calculation procedures. An example of this is allocation in cases involving co-production: how do you allocate the upstream greenhouse gas emissions between the different co-products that are made in a single process and from a single raw material? There is a high degree of consensus about the various options available for doing this and a preferred sequence of options is even given in ISO 14040. The options were compared and evaluated for their applicability to horticulture. The third category comprises issues for which the LCA methodology gives no clear indication of how they should be tackled. For these issues, proposals have been made on the basis of scientific research into greenhouse gas emissions that are related to agriculture. They include the calculation of nitrous oxide (N_2O) emissions arising from fertilisation and the allocation of emissions to crops in a cropping plan (crop rotation). These are situations for which the proposed approach as yet has no status and on which there is as yet no scientific consensus.

Step 3: Case studies

To make the methodological proposals as concrete as possible, in the form of (draft) calculation rules, we first developed a calculation tool, which the research team could use to perform calculations for specific products, and then used this tool in a number of case studies. These calculations were made in several rounds, because during the case studies new issues arose in connection with the calculation of the carbon footprints, which in turn could lead to new methodological proposals. The methodological options defined in Step 2 were ranked as follows in the calculation tool:

- ‘should’ = standard calculation rule
- ‘may or can’ = standard options, which are always calculated
- ‘could’ = facultative options at the user’s own discretion.

Step 4: Synthesis

In the last step the results of our own research and the PAS 2050 were combined to produce:

a this report containing a review of the methodology and proposals for best practice for horticultural products;

b a protocol with guidelines, calculation rules and standard values for the calculation of the carbon footprints of horticultural products;

c a calculation tool with which Dutch growers and traders can perform calculations for their product, business or range of products.

The PAS 2050 is a general specification for calculating carbon footprints of products and services. It is not geared specifically to horticultural products. The method for horticultural products developed in this project can in many ways be seen as a further specification of PAS 2050. In a number of areas, alternative proposals were made or further details were given on specific topics that are addressed but not elaborated in PAS 2050. In the synthesis stage, the previously formulated facultative options were worked up into best practices.

[3] Especially IPCC (2007), NIR (2006) and carbon footprint calculation protocols by the Dutch Ministry of Environment (Ministerie van VROM), and various recent Dutch studies into greenhouse gas emissions that are related to agriculture, such as Schils *et al.* (2006).

Structure of the report
In Chapter 3 we introduce several case studies, give the reasons for selecting these cases and present an overview of the results of the case studies. The case studies generated insights into the range of attributed greenhouse gas emissions per kilogram of product and the relative contributions made by processes and activities to the total carbon footprint. The results from these case studies provided information for use in delimiting the horticultural products system. This is examined in detail in Chapter 4, which is the first of six chapters that explore the methodological options. All these chapters are structured in the same way.

In the first section of each chapter, a methodological issue is described from two perspectives: 1) the LCA methodology and the IPCC guidelines for quantifying greenhouse gas emissions, and 2) the relevant PAS 2050 proposal for the issue. The following section reviews the calculation methods for horticultural products. The proposed methods are either presented in the form of a choice between the different options available for calculating the greenhouse gas emissions within an LCA, or, when there is no existing method, a proposed new calculation method. In the third section, the choice is translated into concrete guidelines for the calculation of the carbon footprints of horticultural products. Finally, recommendations are made for further research on new methodological elements and for revising and updating the calculation method.

The total package of calculation standards, forms the basis for the protocol for calculating carbon footprints of horticultural products. This protocol is published separately and mirrors the chapter structure of PAS 2050. Running through the protocol, there are two variants of the methodological options treated in this report:

1 a further specification of PAS 2050;
2 a recommended alternative to PAS 2050.

Table 2.1 shows the relation between the chapters in this report and the calculation options (specification and/or alternative method) in the protocol.

2.1 Intermediate deliverables

A number of intermediate deliverables were produced during the project, which were not published. Two of these are the calculation tool for researchers and the case study reports.

Calculation tool for researchers
The proposals drawn from the methodological development process were formalised in the form of a calculation tool designed for use in the case studies by the participating researchers at the Agricultural Economics Research Institute (LEI-WUR) and Blonk Milieu Advies to determine the effects of different methodological approaches. The tool was designed primarily for a systematic study to determine how big an impact the differences in the method have on the outcome of the calculations for various horticultural products. The calculation tool was also used by the researchers as a point of departure for the development of an application for external use.

Case study reports
A large number of case studies were carried out at various stages during the course of the project. Reports were compiled on some of the case studies, but these were not published because the methods used in the

reports were not the same as the method proposed in this final report. The overall results of the case studies are reported here in Chapter 3.

Table 2.1 Chapter breakdown and relation to the horticulture protocol

Chapter Section	Topic	Proposed calculation option for the protocol
4	System delimitation (PAS 2050-2008 Chapter 6)	Further specification of PAS 2050 with horticulture defaults
5.2	Allocation with CHP (PAS 2050-2008 Chapter 8.3)	Further specification of PAS 2050 and alternative proposal
5.3	Cropping plan allocation (PAS 2050-2008 not defined)	Further specification of PAS 2050
5.3	Combined production within the business	Further specification of PAS 2050
5.5	Recycling and waste processing (PAS2050-2008 Chapter 6.4, 8.2 & 8.5)	Further specification of PAS 2050 and alternative proposal (based on system expansion)
5.6	Use of manure (PAS 2050-2008 not defined)	Further specification of PAS 2050
6	Soil and fertilisation (PAS 2050-2008 Chapter 7.8)	Further specification of PAS 2050
7	Land use and land conversion (PAS2050-2008 Chapter 5.4 and 5.5)	Alternative proposal to PAS 2050
8	Transport (supplementary to PAS 2050-2008 Chapter 5.1 and Chapter 8.4)	Further specification of PAS 2050 Alternative proposal for air transport
9	Use of data (PAS 2050-2008 Chapter 7)	Further specification of PAS 2050 Foreground data: defaults for horticulture CHP emissions and default CO_2 chains for 100 horticultural products Background data: set of defaults for production, recycling and use of materials, fuels and energy carriers Alternative calculation for peat substrate

3. Case studies

3.1 Selection of case studies

The selection of the case studies was based on the purposes of the case studies:

- First, to give insight into the relative contributions to the carbon footprint of a horticultural product made by the different processes and activities in the supply chains. These relative contributions make recommendations on system delimitation and data requirements possible, so data collection efforts can be streamlined.
- Second, the case studies were carried out to obtain insights into the effects of the methodological choices. These choices not only affect the final results of the calculations, but they also have implications for the data requirements of the various options. Practical considerations also play a role in deciding which method to use. For example, the data collection effort for a calculation must be weighed against its contribution to the final result.

Table 3.1 lists the selected case studies and the themes in which methodological issues occur that were investigated in each case study.

Table 3.1 The methodological issues investigated in each case study

Case study	Country	Theme with methodological issue
Vegetables and fruit		
Tomatoes, with and without CHP	Netherlands	*Allocation with CHP, modelling methane slip*
Organic tomatoes	Netherlands	*Organic cultivation system*
French beans in various forms of packaging	France	*Cropping plan, packaging data, allocation between materials*
Bananas	Ecuador	*Sea transport, nitrous oxide, tropical soils*
Strawberries (greenhouse, staging vs. field)		*Peat substrate, variation within a crop*
Pineapples (conventional and organic)	Costa Rica	*Sea transport, nitrous oxide, tropical soils*
Apples	Netherlands	*Cooling and contribution to greenhouse gas score*
Apples	New Zealand	*Sea transport*
Cauliflower, conventional	Netherlands	*Cropping plan, allocation when manure is used*
Cauliflower, organic	Netherlands	*Organic cropping plan*
Edible fungi		
Mushrooms, fresh	Netherlands	*Manure allocation*
Mushrooms, processed, various packaging	Netherlands	*Manure allocation, contribution of processing*
Cut flowers and pot plants		
Roses	Kenya	*Air transport*
Roses	Netherlands	*Allocation with CHP, data on methane slip*
Phaelenopsis (various cultivation methods)		*Effect of different cultivation periods*
Poinsettia		
Ficus (different cultivation methods)		*Effect of different cultivation periods, peat substrate*
Hydrangea		*Effect of different cultivation periods, peat substrate*

3.2 Design and implementation

Because the case studies were designed primarily to facilitate the development of the methods, it was decided to work with illustrative practical situations that provide information about commonly used cultivation practices for a product. For this purpose, it was not necessary to collect the most detailed data. It was sufficient that the data gave a good impression of practical issues and the relative significance of data for the carbon footprint. Moreover, the cultivation conditions often did not represent the average situation for a crop in a specific country. Although the absolute results of the case studies give a good impression of the crop's carbon footprint, they are not average figures and can, therefore, not be used for making comparisons with results from other case studies.

The primary cultivation data used in the case studies were derived from the following sources. For the Netherlands, most of the data used were KWIN data (*quantitative information of agricultural businesses*, published in yearly reports by Wageningen UR), sometimes supplemented with information from growers and crop supervisors. For the cases studies in which the crops are grown outside the Netherlands, we used data published in the literature (tomatoes in Spain) and primary data from growers, plantations and traders (pineapples, bananas). For data on processing, transport and background processes, such as the production of energy and packaging materials, we drew on a large number of sources in the literature, which are discussed in Chapter 10.

Various allocation methods were used in the case studies: economic allocation, system expansion and allocation based on physical characteristics. In the first draft of PAS 2050, economic allocation was proposed as the standard allocation method in cases involving co-production. To demonstrate the effect of choosing this method instead of other allocation methods, we decided to perform all the calculations using the two other allocation methods as well.[4] In addition, using the calculation tool for researchers made it easy to investigate the effect of varying the generic parameters and the use of certain datasets.

All the calculations were based on the weight of the product, including the weight of the packaging and other accompanying materials or products as supplied to the supermarket. For fruit and vegetables, the weight is also a logical unit, but this is not the case for cut flowers and pot plants, which are sold individually, per pot or per bunch.

3.3 Results

The case studies are not reported separately, because they were carried out during the course of the project and the results were used for the development of the methods. Moreover, for some of the case studies no final calculations were made using the method in the form in which it is finally recommended. The results of the case studies obtained from the method as it stood at that stage are shown in Figures 3.1, 3.2 and 3.3. The results shown are those obtained using a single allocation method.[5]

The carbon footprints can vary by a factor of two, depending on the specific crop cultivation techniques and circumstances; this variation is therefore not due to the method, but to the underlying cultivation data. An additional large variation between the results is a product of the differences between the methods and the data used.

The results in Figures 3.1, 3.2 and 3.3 give a good indication of the range within which the carbon footprints of a certain product category lie, and the relative contributions of different emission sources in the supply chain. For fruit and vegetables, the carbon footprints of the products vary by about a factor of twenty, depending on whether the product is grown in a heated greenhouse or in the field and on the use of materials, such as peat substrate. The greenhouse gas emissions from transport by sea only becomes

[4] Using the results obtained in this way it was also possible to respond to the drafts of the British PAS 2050 specification.

[5] We originally used three allocation methods.

significant when very long distances are involved and when the greenhouse gas emissions from the remainder of the supply chain are relatively low. The generally limited contribution made by sea transport to the carbon footprints of fruit and vegetables is a remarkable outcome of the study. It should be noted that none of the fruit & vegetable scenarios investigated involved air transport. The contribution made by emissions from the use of peat substrate to the carbon footprints was also observed to be highly significant. These emissions arise from the oxidation of fossil carbon in potting compost during cultivation and during subsequent use.

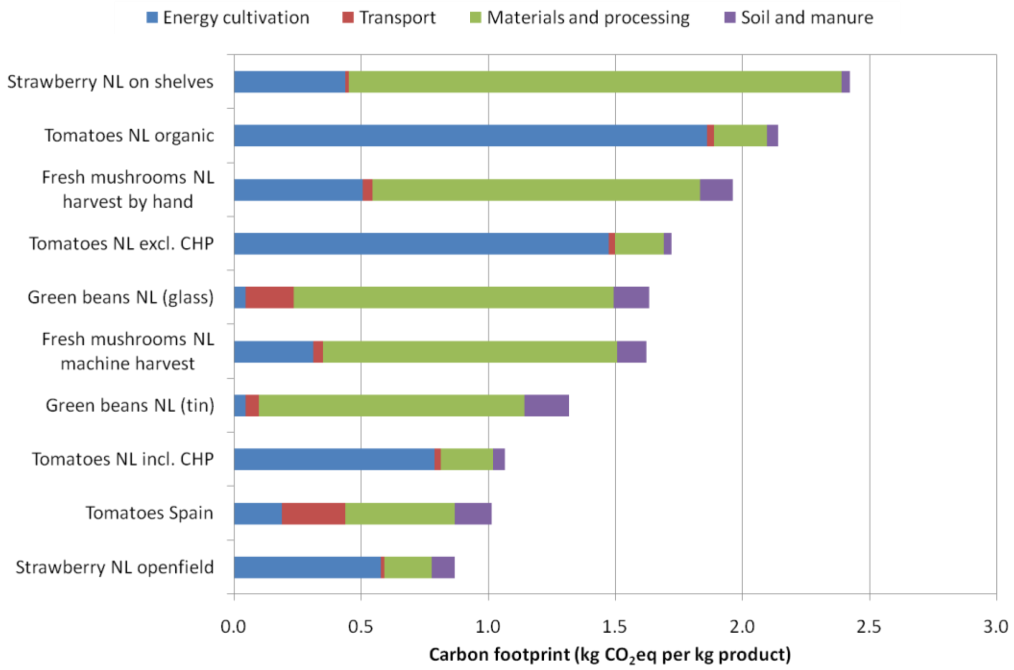

Figure 3.1 Greenhouse gas emissions from fruit and vegetables

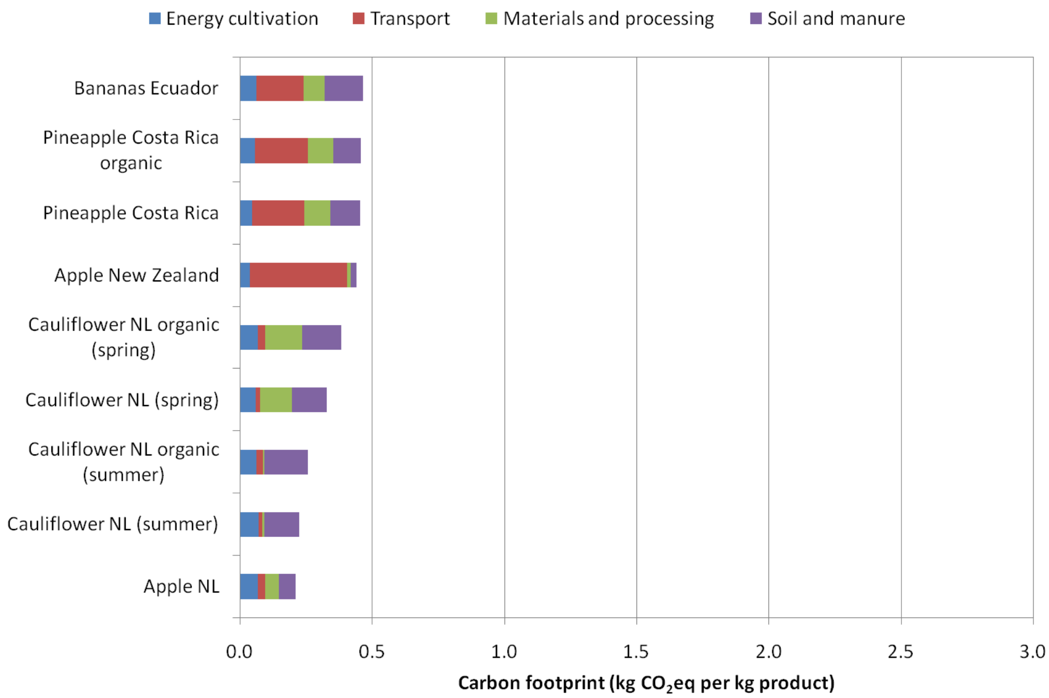

Figure 3.1 Greenhouse gas emissions from fruit and vegetables (continued)

The greatest methodological effects on the results for the fruit and vegetables investigated in this study are from:

- the allocation with combined heat and power (CHP) for tomatoes (see section 5.2);
- the allocation to materials recycling and waste processing in the cases in which products are preserved (see section 5.5);
- system delimitation for the oxidation of peat substrates in the strawberry and mushroom case studies (Chapter 10).

The carbon footprints of pot plants and cut flowers investigated in the case studies vary by a factor of ten. The biggest contribution of the different emission sources to the carbon footprint is from natural gas and electricity used to heat and light the greenhouses, but the contribution from potting compost is also large. Air transport is included in one case study (roses from Kenya). In this case almost all the greenhouse gas emissions are due to the air transport.

The biggest methodological effects on the results are due to the following methodological parameters:

- system delimitation for the oxidation of peat substrate (inclusion or exclusion of the use phase);
- the assumptions for loading, type of aircraft and greenhouse gas emissions from air transport.

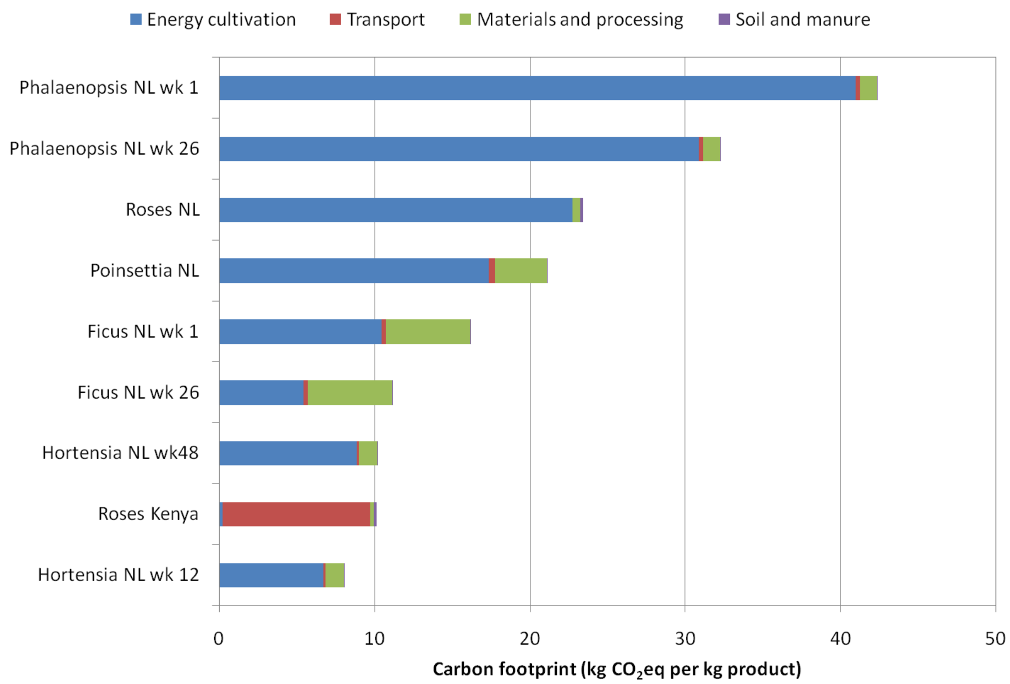

Figure 3.2 Greenhouse gas emissions from cut flowers and pot plants[6]

[6] During the course of the project the procedure for calculating the greenhouse gas emissions from air traffic was revised. As a result of this, the carbon footprint of roses from Kenya are about 40% lower than given in Figure 3.2 (see Chapter 9 for more on this topic).

Figure 3.3 gives a better visual indication of the relative contributions of different emission sources to the carbon footprints of the products in the case studies. For products with relatively large contributions of emissions during the cultivation phase owing to the use of energy and the oxidation of peat substrate, transport is of little or no significance, unless this is by air. Transport by road or sea only becomes a dominant factor for products with somewhat lower carbon footprints (lower than 0.5 kg CO_2eq per kg of product). Towards the bottom end of the spectrum the carbon footprints of products are increasingly dominated by the nitrous oxide (N_2O) emissions arising from nitrogen fertilisers or nitrogen fixation (in case of legumes, such as green beans). The insights gained from the case studies will be discussed in more detail for each methodological issue in the following chapters.

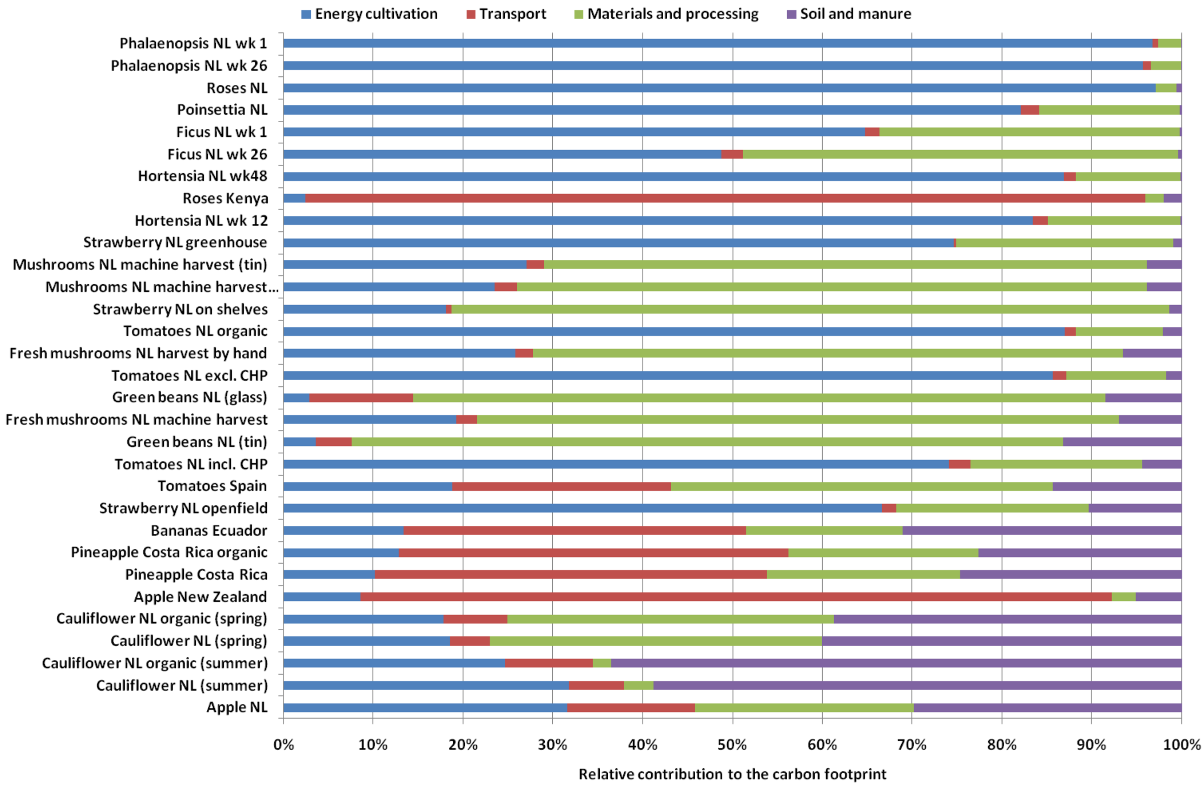

Figure 3.3 Relative contributions by the various components in the supply chain to the total greenhouse effect (the greenhouse effect increases from the bottom to the top of the chart)

4. System delimitation

4.1 Problem description

Before the carbon footprint of a horticultural product can be calculated, a number of questions on whether or not to include certain processes in the calculation have to be answered:

1. Delimiting the supply chain: *how much of the horticultural product's lifecycle should be included?*
2. Significance: *which processes make a significant contribution?*
3. Influence (marginal analysis): *to what extend are processes influenced by a change in the supply chain?*
4. Depth in the supply chain: *is a consistent policy for delimiting the supply chain applied to the production of the goods used?*

1. Delimiting the supply chain

Figure 4.1 shows the processes in the "full" lifecycle of a horticultural product, from cultivation to consumption and waste processing. Cultivation of plant materials and crop growing are processes specific to the horticultural part of the supply chain. The other processes in the supply chain (such as processing and distribution) are often less specific because the horticultural product is then part of a more generic production process. The horticultural product is presented for sale in retail (for example, a supermarket) and sold, after which it is kept, prepared and consumed, after which part or all of the product is sent for waste processing. The lifecycle processes are fed by energy and materials production, which in turn are fed by a deeper layer of energy and materials production.

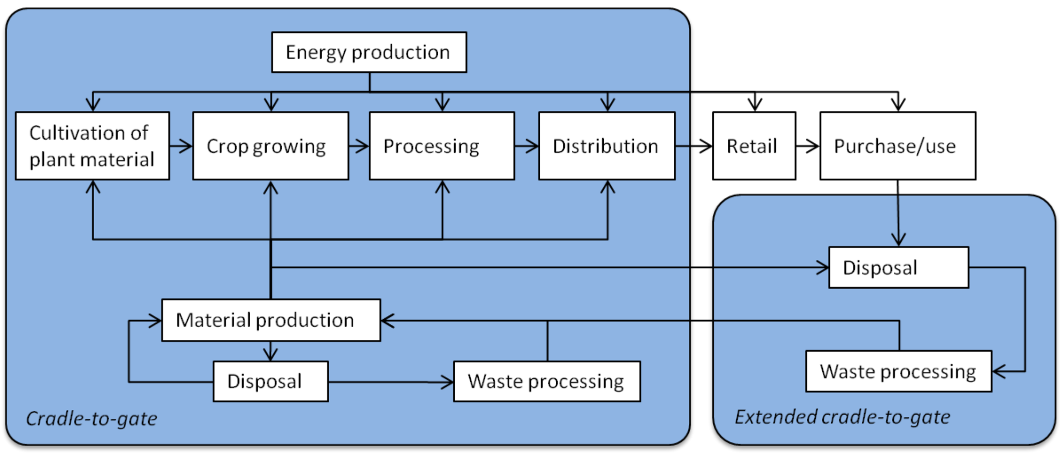

Figure 4.1 Flow diagram of the processes in the horticultural supply chain

There are several logical places in the lifecycle, where the system boundary can be drawn. PAS 2050 defines two analytical situations: 'cradle-to-gate' and 'cradle-to-grave'. A cradle-to-gate analysis includes all the processes until the product is delivered to the receiving organisation. This may be a supermarket, distribution centre or a grower/producer. What happens to the product after that is not included in the calculation and is the responsibility of the purchaser or customer. In the cradle-to-grave system delimitation the whole lifecycle from propagation to use and waste processing is quantified. This system delimitation includes all the activities and emissions during the final consumption phase of the product. An intermediate form, which is not mentioned in PAS 2050, but is often used in LCAs, is a cradle-to-gate approach in which the whole lifecycle of the materials used in the chain as far as the gate is included in the calculation. In Figure 4.1 this 'extended cradle-to-gate' approach is represented by the second shaded area on the right. In the case of horticultural products the question is whether the more limited or the extended version of the cradle-to-gate analysis is the most appropriate.

2. Significance

By significance we mean how much a process contributes to the carbon footprint of a product. PAS 2050 includes a number of guidelines for determining this. Based on the best available knowledge, we should include all emission sources that make a substantial contribution to the carbon footprint to be calculated. When performing the calculations it is not always possible to estimate whether a component in the supply chain will make a substantial contribution, and therefore PAS 2050 recommends first carrying out a *screening LCA*. PAS 2050 also includes the following criteria for deciding whether to include or exclude processes from the calculation:

- A greenhouse gas analysis that does not include the use phase should include:
    - all emission sources that make a material contribution;
    - at least 95% of the anticipated carbon footprint;
    - where a source (for example, the use of gas in greenhouse horticulture) accounts for more than half of the carbon footprint, at least 95% of the remaining anticipated greenhouse gas emissions.
- A greenhouse gas analysis of the use phase should include:
    - all emission sources that make a material contribution;
    - at least 95% of the anticipated carbon footprint.

If less than 100% of the anticipated greenhouse gas emissions have been determined by the calculation, the results should be scaled up to correct for this.

Because we have performed a large number of screening LCAs, we can refine the PAS 2050 guidelines to form a concrete set of recommendations on whether or not to include specific processes in the calculation.

3. Influence (marginal analysis)

The third question is to what extend processes are influenced by changes in the supply chain. This is a dynamic analysis in contrast to the static carbon footprint analysis. However, some emissions are not included in a carbon footprint, because these emissions would also occur if the product were not produced. For example, domestic and travel emissions of entrepreneurs and employees are usually not included in the calculation.

Certain processes in the supply chain would hardly be affected if the product were no longer produced. An example is the production of straw. Straw is a product of the cultivation of wheat, and although most of the upstream greenhouse gas emissions are allocated to the grain, the rest is allocated to the straw. The carbon footprint of strawberries from a strawberry grower who uses straw therefore includes the upstream greenhouse gas emissions that are allocated to the straw. However, the volume of straw produced does not depend on the demand for straw by the strawberry grower, but is sold on the open market for various uses, regardless of the way strawberries are produced. It can therefore be argued that the greenhouse gas emissions due to a change in the demand for straw can be ignored when analysing the choice between using straw or not by a strawberry grower.

Two types of LCAs are distinguished in the LCA literature: attributional and consequential LCA. In an attributional LCA we calculate the carbon footprint (the sum of greenhouse gas emissions that occur in a supply chain and that can be attributed to a product or service); in a consequential LCA we calculate the change in LCA caused by a shift from one specific chain to an associated chain. PAS 2050 recommends using attributional LCA, in which the greenhouse gas emissions from straw, for example, are calculated using economic allocation. In a consequential LCA the greenhouse gas emissions of wheat cultivation for straw production may be ignored and a substitution scenario is constructed from a market analysis.

4. Depth in the supply chain

The fourth question relates to the depth of the analysis of the materials used and the products in the supply chain. In theory, we have an endless chain of production of energy and materials, which in turn are needed for the production of the energy and materials used in horticulture. Where in the supply chain should the system boundary be drawn, and should this be applied consistently or on a case-by-case basis depending on significance (point 2)? A key consideration here is the use of capital goods. The energy and materials production in capital goods supply chains often make a negligible (not substantial or significant) contribution to the carbon footprint. However, for horticulture and arable farming there are studies that show that they make a substantial contribution and therefore recommend including them in the analysis (Nemecek *et al.* 2003 and 2004). PAS 2050 recommends not including the carbon footprints of capital goods in the calculation.

4.2 Review of solutions

Here, we describe a review of solutions to the questions described in the previous section, in the same order.

1. Delimiting the supply chain

The cradle-to-gate system delimitation as proposed by PAS 2050 is too limited because it does not reveal part of the predictable greenhouse gas emissions arising from materials use. We therefore propose that the cradle-to-gate analysis also includes the use and disposal phases of the materials in the end product. This is in line with the LCA method most widely used in comparative studies of materials and packaging systems. By including these phases we take account of the consequences of the use of materials in a product, even when the environmental impacts occur further down the supply chain. The effects in each country depend on the specific fractions of materials collected for recycling and the waste processing method that is used (landfill or incineration followed by landfill). Using this information, a producer can make decisions on which packaging materials to use or which substrate materials to use. For example, the choice of packaging material for preserved French beans (glass jar or can) has an effect of about 20% on the carbon footprint. Incidentally, this choice does not depend on the chosen allocation method (see Chapter 5). Another example is the choice of substrate material, which can prevent considerable amounts of attributed greenhouse gas emissions from the oxidation of the substrate elsewhere in the chain.

In contrast to the cradle-to-gate approach in PAS 2050, we recommend including the downstream effects of the materials used in the calculation. The grower and processor then obtain a much more complete overview of the greenhouse gas emissions that are attributable to the product and the possibilities for influencing them. The buyers or customers can then consider obtaining their products from growers that cause less greenhouse gas emission per unit of product.

2. Significance

The case studies carried out in this project, several additional studies and other sources have given us a good understanding of which processes make a substantial contribution to carbon footprints of horticultural products and which processes make smaller contributions. On the basis of this we can make recommendations on which processes to include, which can considerably speed up the process of data collection and the calculation of emissions in the supply chain. The breakdown of the carbon footprints (relative contributions of different emission sources) can be used to divide horticultural products into six categories:

1 Heated cultivation without air transport
2 Heated cultivation with air transport
3 Protected and/or unheated cultivation in soil, with air transport
4 Protected and/or unheated cultivation in soil, without air transport
5 Field cultivation without air transport, processed
6 Field cultivation without air transport, unprocessed

Table 4.1 lists, for each horticulture category, the contributions to the total carbon footprint made by the various processes. This table can be used to streamline the data collection.

Table 4.1 Contributions to the carbon footprints made by processes and materials used in a supply chain to the distribution centre

Product category	Estimate (kg CO_2eq/kg)	Contribution to the greenhouse effect of more than 5%	Mostly low contribution (1–5%)	Mostly negligible contribution (<1%)
1. Heated cultivation without air transport	1–50	Energy use in the greenhouse; Peat substrate	Substrate materials (non-peat); N fertiliser; Packaging materials; Transport; Cooling and storage; Propagating material	Pesticides; Phosphate; Potassium
2. Heated cultivation with air transport	3–60	Energy use in the greenhouse; Peat substrate; Air transport	Substrate materials (non-peat); N fertiliser; Packaging materials; Transport; Cooling and storage; Propagating material	Pesticides Phosphate Potassium
3. Protected and/or unheated cultivation in soil, with air transport	3–12	Peat substrate; propagating material; Air traffic	N fertiliser; Packaging materials; Building materials; Crop protection material; Energy use on farm; transport (other); Cooling and storage	Pesticides Phosphate Potassium
4. Protected and/or unheated cultivation in soil, without air transport	0.3–2.5	Peat substrate; Propagating material; N fertiliser; Materials Transport	Packaging materials; Building materials; Crop protection material; Energy use on farm; Transport (other); Cooling and storage; Pesticides; Potassium and phosphate	
5. Field cultivation without air transport, processed	0.5–25	N fertiliser; Transport (large distances); Energy processing; Packaging	Packaging materials; Energy use on farm; Transport (other); Cooling and storage; Capital goods	Pesticides Phosphate Potassium
6. Field cultivation without air transport, unprocessed	0.1–0.8	N fertiliser; Transport (large distances); N fertiliser production; Energy use on farm	Pesticides; Potassium and phosphate; Cooling; Capital goods	

3. Influence (marginal analysis)

In an attributional LCA we calculate the carbon footprint (sum of greenhouse gas emissions that occur in a supply chain and that can be attributed to a product) based on a static situation of the current (or historic) production, in which, if there is co-production, the environmental load is distributed across the chain by means of allocation. In a consequential LCA, changes are investigated by determining which processes are influenced by the difference in the situation after the change compared to a situation in which this change would not take place. The basic method for an attributional LCA is that all processes are included that can reasonably be linked to the supply chain under investigation. Nevertheless, there is usually an implicit delimitation to exclude certain processes, because they are not really influenced by the supply chain under investigation. These include commuter travel, housing for agricultural entrepreneurs, supporting services for the entrepreneur, *et cetera*. This demarcation is often applied as an unwritten rule, which is also followed here.

4. Depth in the supply chain
Theoretically, the calculation should include all the underlying processes in a supply chain, and preferably at the same 'depth'. However, the more distant the process is from the main processes in the chain, the scarcer the information. Scarcity of information leads to great uncertainties in the calculation. A practical solution for defining the boundaries of the supply chain is to only include the underlying processes for which sufficient information is available or by making use of defaults. Theoretically, the same 'depth' should be maintained, unless there are practical reasons for not doing so.

For the time being, we propose following PAS 2050, which means, for example, including the production of energy carriers but not the production and depreciation of machines, means of transport and capital goods. Taking this approach will underestimate the carbon footprint by on average a few percentage points. This is something that can be improved in later updates of the method.

4.3 Recommendations for the protocol and calculation tool

We make the following recommendations for calculating the carbon footprints of horticultural products:

- Include in the calculation those processes which are expected to contribute more than 1% to the carbon footprint, except for the production of capital goods.
- Correct for any storage (processes not included in the calculation).
- Clearly state whether any other processes than those recommended in PAS 2050 have been included.

Table 4.2 contains some results of calculations of greenhouse gas emissions from the use of capital goods (materials use) in greenhouse cultivation, and the use of biocides, phosphate and potassium in arable farming. The use of capital goods in greenhouse horticulture depends heavily on the yield per square metre.

For most arable crops, the greenhouse gas emissions from the use of biocides and phosphate is about 2 kg CO_2eq per tonne of product. For by far the majority of crops, this figure will be less than 1% of the carbon footprint. However, the carbon footprints of cooled strawberries and asparagus are much higher than the averages, which is mainly due to the relatively low yields in tonnes per hectare (compared with comparable crops). In these cases the use of pesticides and phosphate should be included in the calculation. For most arable crops the average greenhouse gas emissions from the production and use of potassium are 3.3 CO_2eq per tonne of product. For some crops this figure exceeds the 1% limit and therefore, it should be included in the calculation.

Table 4.2 Some results of calculations of greenhouse gas emissions from the use of capital goods (materials use) in greenhouse cultivation, and the use of biocides, phosphate and potassium in arable farming

Process	Greenhouse gas emissions (kg CO_2eq/tonne)
Materials use, greenhouse tomatoes (58 kg/m^2)	85
Materials use, greenhouse roses (10 kg/m2)	453
Average pesticide use, arable farming	2
Pesticide use, tomatoes (cooled) (17 tonnes/ha)	14
Pesticide use, asparagus (5.2 tonnes/ha)	20
Average phosphate use, arable farming	1.5
Phosphate use, asparagus (green) (4.2 tonnes/ha)	28
Average potassium use, arable farming	3.3
Potassium use, asparagus and broccoli (7.5 tonnes/ha)	15

4.4 Recommendations for further research and future updates

We have no specific recommendations concerning the part of the method dealing with system delimitation. We do, however, have some recommendations of a more practical nature:

- Refine understanding of the contribution made by processes and the resulting raising factors.
- Monitor international developments in methods for system delimitation and adjust the calculation accordingly.

5. Allocation

5.1 Introduction and theoretical framework

At various places in the production chain the problem arises of how to allocate environmental impacts between different products produced by one process. There are three possible situations that need to be addressed:

- *Co-production* is where a unit process (one part of the total process) produces several products at the same time. Some examples of this are: 1) the use of CHP (combined heat and power) in greenhouse horticulture, in which electricity, natural gas and carbon dioxide are produced at the same time; 2) the processing of horticultural products can involve the production of by-products that are used elsewhere (e.g. bean tips as animal feed); 3) co-production in arable farming, for example the production of grains and straw.
- *Combined production* is where a farm produces several products during a certain period in various unit processes, each of which is dependent on the others. Examples of this are: 1) arable cropping plans in which crops are cultivated according to a certain sequence (sequential cropping) and a rotation (different crops from year to year); 2) treatment and processing operations by a horticultural farm in which the energy streams in the various treatments and processes are interlinked.
- *Waste processing and recycling* is where a waste stream from one production chain provides the raw material input for another.

The ISO (International Organization for Standardization) has drawn up general principles for allocation within LCAs in the international standard ISO 14044. This proposes the following sequence of allocation methods:

1 Dividing the process into smaller processes in which no co-products are produced (avoiding allocation).

2 Expanding the production system by adding several functions and alternative production methods.

3 Allocating the environmental load between the co-products according to physical or other explanatory variables (e.g. mass, energy content or financial revenue/economic allocation).

PAS 2050 follows this standard, except that in the third method only economic allocation is recommended.

For co-production, the allocation sequence in ISO 14044 results in an approach that tries to avoid allocation. Avoiding allocation when there is co-production can be achieved in two ways: 1) by dividing the process up into sub-processes in which no co-production occurs; or 2) expanding the system to include more functions in the calculation. The first approach is often not possible: for example, when the horticultural business operates a system for the combined production of heat and electricity (CHP as used in horticulture). The second method includes electricity production as an extra functionality in addition to tomato cultivation by the grower in question. In the first instance this leads to the production of several products, whereas we focused on tomatoes. This problem can be overcome by not including the avoided electricity production in the analysis. The question that then arises is: how much electricity would have been produced if the grower in question had not supplied electricity to the grid? If this option is not feasible or desirable, the greenhouse gas emissions can still be allocated, for example on the basis of energy content or financial revenue. In section 5.2 we take a more detailed look at the allocation problem for horticultural CHP and formulate our recommendation.

In addition to CHP in horticulture, co-production also occurs when products are divided up into different co-products for different uses or markets, which can take place at various points in the chain.[7] For example in apple production, when some of the apples harvested are unsuitable for marketing as fresh products because they are damaged and are therefore sold to the food processing industry (to make juice or apple syrup). The food processing industry also sorts and removes products for different uses. These products are then sold for use as livestock feed (e.g. carrot and bean tops).

Horticultural processes and the efficiency of these processes are often interlinked to a greater or lesser extent. This is not necessarily due to co-production in one specific process, but rather involves the whole network and the efficiency of different processes. This includes the general processes and activities that always take place regardless of the type of production, such as the light and temperature regulation in production areas. But many processes involve certain baseline emissions and an optimal efficiency, depending on the type of production (a good analogy is a car with the motor idling when stationary and which has a cruising speed at which it runs at maximum fuel efficiency). Such situations pose complicated allocation problems. In horticultural supply chains, these issues arise in two situations: 1) when crops are grown as part of a cropping plan (crop rotations, sequential cropping); and 2) in processes elsewhere in the chain in which a company processes several products during a certain period of time. In section 5.3 we examine the cropping plan allocation and in section 5.4 the combined treatment and processing of products.

After disposal, the product is recycled or sent for final waste processing. PAS 2050 contains a number of general guidelines for this phase, which can also be used for horticultural systems. However, one specific topic is not dealt with in these guidelines: the production and application of fertilisers. This is examined in detail in section 5.5. In section 5.6, the topic of waste processing and recycling is elaborated for the horticultural sector.

Before we go into the choice of specific allocation rules, we first define a general 'allocation philosophy' for the calculation of the carbon footprints of horticultural products. In doing so, we build on the recently published working draft of the ILCD (International Reference Life Cycle Data System). This is a major initiative by the European Union for the further harmonisation of LCAs (ILCD 2008). It will probably become an important standard for the implementation of LCAs. The ILCD states that there is no 'one size fits all' solution for the allocation sequence, but there are a number of criteria for selecting and using allocation rules in specific situations. Product carbon footprints are calculated for specific purposes. For each purpose there is a particular allocation system. The ILCD has therefore drawn up a number of criteria for the selection of allocation rules[8]:

- Choose an allocation method that matches the purpose of the analysis and the modelling principle derived from this: is the aim to model changes or to describe an existing situation?
- Avoid implausible outcomes caused by changes in system variables connected with the allocation (large price fluctuations in economic allocation or choices about avoided production when expanding the system)

[7] In arable farming co-production also occurs during cultivation. For instance, straw from grain crops is sold for different purposes; in the economic allocation method, about 10–20% of the upstream greenhouse gas emissions are allocated to the straw.

[8] In a latter draft of the ILCD these rules are not explicitely mentioned anymore. However we thought them very useful in the context of defining a set of allocation rules which is applicable to a wide range of products with a sector.

- Avoid choices that are hard to justify because of the poor availability of data or the large quantity and complexity of data
- Avoid (subjective) choices without an underlying principle that are difficult or impossible to reproduce
- Ensure that the allocation rules are applicable to recycling without the need for detailed information about the second life of the material
- Be acceptable and understandable for stakeholders (fair across competing products, plausible and possible to communicate and explain)Make only reasonable demands on data provision (costs)

The ILCD then select a number of application areas for allocation rules. One of the application areas is the preparation of an EPD (Environmental Product Declaration). This appears to be very similar to carrying out a greenhouse gas analysis of products. The main thrust of the recommendation of the EPD is:

1. Employ a descriptive method (attributional LCA) in which, if there is co-production, the co-product:
   a. leaves the system, use physical or economic allocation, or
   b. the product is used elsewhere in the system, use system expansion based on substitution of processes.

For horticultural products this EPD proposal is used as the guiding principle for allocation. PAS 2050 deviates from this and proposes first using system expansion or if this is not practically feasible, economic allocation. PAS 2050 does not recommend the use of physical allocation. Our aim is to use a consistent set of allocation rules for horticultural products. In line with the EPD recommendation, the main components are as follows.

5.1.1 Proposal for allocation principles

Allocation principle 1. Categorisation of situations

There are three important situations involving co-production in horticultural supply chains.

1 Co-production in which a product leaves the system

2 Co-production in which a product enters the system as a raw material

3 Final processing in which a ‘feedback loop’ can arise (combination of situation 1 and 2)

When making a choice between a physical or economic allocation it is important to consider whether the co-products are functionally and physically comparable, or whether they have different uses. In the first case, an allocation based on physical characteristics is preferred and in the second case we choose economic allocation. If materials or energy are returned to the system (recycling) other recommendations are made for allocation. Table 5.1 lists preferred allocation systems recommended for the three situations with particular specifications.

Table 5.1 Recommendations for preferred allocation systems in the three situations with particular specifications

Situation	Specification 1	Specification 2	Recommended allocation for protocol horticultural products
1. Co-production in product system	1.1. Division of one or more inputs into several outputs with comparable features and/or functionality:	1.1.1 Without feedbacks to the product system	Allocation based on one or more physical features
		1.1.2 With feedbacks to the product system	Compensate for feedbacks at the primary production input, then allocation based on one or more physical features
	1.2. Division of one or more inputs into several outputs with different features and/or functionality:	1.2.1 Without feedbacks to the product system	Economic allocation based on average prices of freely tradable products
		1.2.2 With feedbacks to the product system	Compensate for feedbacks at the primary production input, then economic allocation based on average prices of freely tradable products
2. Influx of co-products from another product system	2.1 No allocated environmental effect from another product system		Treat as a primary raw material
	2.2. Environmental effect from another product system is allocated	Due to waste processing function	Calculate the environmental effect imported from another product system on the basis of physical features
		Due to economic value	Calculate the environmental effect imported from another product system on the basis of economic allocation
3. Final processing	3.1 With feedbacks to the product system		Compensate for feedbacks at the primary production input and total primary energy use
	3.2 Without feedbacks to the product system		Treat as 1) co-production

Allocation principle 2. The sum of allocated subsystems is equal to the total of non-allocated system
The leading principle for the specific allocation solutions is that the sum of all allocated greenhouse gas emissions in a system must be equal to the sum of the 'non-allocated' greenhouse gas emissions in the system.

Allocation principle 3. Division of combined process systems into unit processes
Subdividing complex production systems into unit processes is only necessary if it is desirable for the purpose of the study, practically feasible and does not introduce any additional subjectivity or sensitivity. If it is not necessary, an input/output allocation based on physical or economic features is sufficient.

Allocation principle 4. ILCD criteria
We recommend consulting the above mentioned ILCD criteria for applying allocation rules. In summary, these criteria are designed to ensure that the allocation choice is a) practical (regarding data collection), b) reproducible, c) comprehensible and d) identifiable.

5.2 Combined heat and power (CHP) in greenhouse horticulture

5.2.1 *Problem description*

A significant proportion of Dutch greenhouse horticulture businesses produce energy as well as crops. A CHP plant produces heat, carbon dioxide and electricity from natural gas. The heat and carbon dioxide and part of the electricity are used in the greenhouse, the remaining energy (often in the form of electricity) is sold. If another product besides the crop is produced, the question that arises is how the greenhouse gas emissions from the CHP unit should be allocated between the co-products.

5.2.2 *Review of solutions*

Dividing the process up into smaller processes in which no co-production occurs is not possible when a horticultural business operates a CHP unit because the production of heat and electricity by a CHP unit are inextricably linked. There are therefore two options for allocating the greenhouse gas emissions of a horticultural business between the crop and other products:

1. System expansion
2. Physical or economic allocation

For the system expansion option we describe the PAS 2050 method and a variant of this method that is more consistent with the allocation principles we have formulated for horticultural products. For the allocation option we describe, compare and assess three methods. In the subsequent sections we make recommendations for the protocol, the calculation tool and further research. We illustrate the various options using two example businesses: a tomato and a rose producer, both of which have a CHP unit and supply electricity to the national grid (Table 5.2). In the example calculations we include only the greenhouse gas emissions arising from the consumption and supply of electricity. The greenhouse gas emissions that are associated with materials use, fertilisation and transport make a relatively limited contribution and so we ignore these here.

Table 5.2 Production and energy inputs of the example rose producer and tomato producer

Parameter	Unit	Rose	Vine tomato
Luminance	lux	8000	0
Income from horticultural product	€/kg	7.4	0.8
Income from electricity production	€/kWh	0.08	0.08
Combined heat & power	MWe/ha	0.55	0.5
Yield of horticultural product	kg/m^2	$12.5 \leq 250$ $stems/m^2$	56.5
Supply of electricity (in peak/off-peak hours)	kWh/m^2	66 (47/19)	178 (127/51)
Gas consumption CHP	m^3/m^2	83.9	49.7
Gas consumption boiler	m^3/m^2	0	15
Electricity purchases	kWh/m^2	92	10

Allocation option 1: System expansion

The principle of system expansion is that the supply of the co-product avoids the production of a comparable product elsewhere. This method is inherent to consequential life cycle analysis. With regard to CHP, PAS 2050 expressly prescribes the method of system expansion to offset the co-production of electricity. PAS 2050 is not clear about which electricity production is avoided by applying a CHP. For the Dutch situation in 2007, we interpreted the protocol as such that the emissions avoided by the supply of electricity by growers with a CHP unit are 463 g CO_2 equivalent per supplied kWh, assuming that the average electricity production in the Netherlands is avoided, rather than electricity supply (which includes import).

Table 5.3 shows, the greenhouse gas emission per produced kWh varied between 2006 and 2007. Electricity production in the Netherlands in 2007 was 'cleaner' than in 2006, which means that the avoided greenhouse gas emissions is lower. In turn this means that when electricity is supplied from CHP the greenhouse gas emissions per unit change in production of a horticultural product was higher in 2007 than in 2006.

Table 5.3 Greenhouse gas emissions (g CO_2/kWh) from the average use of primary sources for steam production (Groot & Vreede 2007; Groot & Vreede 2008)

	Carbon footprint 2006 (g CO_2/kWh)	Carbon footprint 2007 (g CO_2/kWh)
Electricity imports	586	622
Average electricity production in NL	543	463
Supply mix NL (incl. green electricity)	458	426

The greenhouse gas emissions due to change in the production of greenhouse horticulture products where CHP is used therefore depends on the performance of the electricity sector. Moreover, this performance depends on the specific mix of electricity production. The PAS2050 does not give clear guidelines on which electricity production (power generated by nuclear energy, natural gas, fuel oil, coals) is avoided when applying a CHP. Are all sources of electricity generation avoided or is it realistic to assume that only electricity generation with some sources is avoided? The answer to this question is decisive for the outcome because electricity is produced in a variety of ways and the greenhouse gas emissions per kWh are heavily dependent on the type of production (Table 5.4).

Table 5.4 Carbon footprint of electricity produced from different primary energy sources (Seebregts & Volkers 2005; Sevenster et al. 2007; Groot & Van de Vreede 2007 and 2008)

	Emissions (g CO_2/kWh)
Nuclear power	0
Natural gas CHP	300[1]
Natural gas CCGT (most modern and efficient method)	353
Natural gas average	450 - 454
Fuel oil	660
Coal	870

[1] allocated between electricity and heat based on exergy

To come to an appropriate solution in which electricity production is avoided, we consulted a number of experts from the horticultural sector, the energy market, and the horticultural and energy research communities. Two aspects are decisive in the supply of electricity by horticultural businesses:

- The time of delivery: peak or off-peak hours.
- Long-term or short-term contracts.

Electricity production is driven by demand. From Monday to Friday during the day and in the evenings (plateau or peak hours) the demand is higher than at night or in the weekend (off-peak hours). Peak and off-peak electricity is charged at different rates. During off-peak and peak hours there is always a certain *base load* electricity production and an additional variable production. The base load is the amount that is produced constantly. The exact matching of supply and demand is achieved using a number of flexible production units. When electricity production is avoided, a relevant factor is whether the electricity is delivered under a long-term contract (for example, growers sign supply contracts for 2010 as early as 2008) or under short-term agreements, for which prices can vary considerably. It is expected that most of the electricity supplied under a long-term contract will be sold to the consumer.

During peak hours the base load is topped up with power generated primarily by coal-fired and gas-fired plants and with imported electricity. Adjusting power supplies to match demand is managed by regulating output from natural-gas-fired power stations. The consulted experts recommended to assume that the average electricity production is generated using natural gas and that this is replaced by electricity from CHP units at greenhouse horticultural businesses. During off-peak hours the marginal electricity supply is generated by coal-fired power stations. This means that when CHP units at greenhouse horticulture businesses deliver electricity to the grid during off-peak hours, this replaces electricity generated from coal (Table 5.5).

Table 5.5 Avoided greenhouse gas emissions for electricity supplied by horticultural CHP units.

	Avoided emissions (g CO_2/ kWh)	Share	Background
Peak hours	450	71%	Average natural-gas-fired power station in the Netherlands
Off-peak hours	870	29%	Average coal-fired power station in the Netherlands
Weighted average	570	100%	

Table 5.6 shows the result of the calculation via system expansion in which a distinction is made between supply during peak and off-peak hours. A question still remaining is to what extent in practice information will be available about the amounts of electricity supplied during peak and off-peak hours. If that is not known we can work with average shares (for example, 2/7 or 29% in off-peak hours and 5/7 or 71% in peak hours).

Table 5.6 Greenhouse gas emissions due to change in production of a horticultural product for the assumed ratio between electricity supplied in peak (5/7) and off-peak (2/7) hours and greenhouse gas emissions per avoided kWh electricity production

Parameter	Unit	Rose	Vine tomato
Greenhouse gas emissions per horticultural product	kg CO_2eq/kg	15.7	0.72
Greenhouse gas emissions of avoided electricity	kg CO_2eq/kWh	0.570	0.570

An advantage of system expansion for greenhouse horticulture with CHP is its simplicity. For each supplied kWh we calculate the avoided emissions. The avoided emissions is a fixed amount for off-peak and peak hours. Currently there is no adequate way of calculating more specific values.

Allocation option 2: energy content

A CHP unit produces heat, electricity and carbon dioxide (CO_2) from natural gas. Usually, all the heat and in some cases also all the electricity produced by a CHP unit is used for the cultivation of the crop (Figure 5.1).

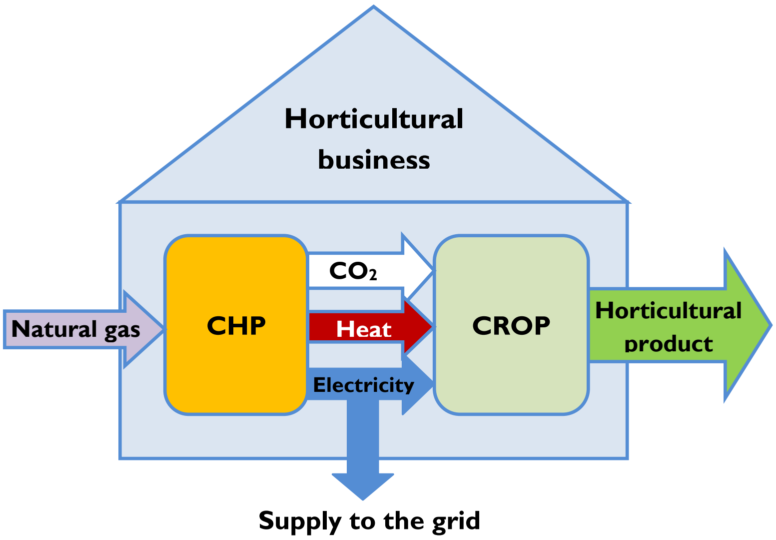

Figure 5.1 Diagrammatic representation of CHP energy production and crop production in a horticultural business

The greenhouse gas emissions from the combustion of natural gas in CHP can be allocated between the products according to the energy content of the heat and electricity produced. The core of this method is that where energy is exported (sold by the business to third parties) the gas input to the CHP unit is reduced by a certain amount according to the efficiency of the CHP unit. The remaining natural gas used is allocated to the crop. This calculation is made in the following steps:

a) Assuming an electrical and thermal efficiency of 40% and 50% respectively (Van der Velden 2008) one cubic metre of natural gas produces 12.7 MJ electricity and 15.8 MJ heat (assuming an LHV of 31.65 MJ for natural gas at 100% efficiency);

b) We assume a 96% effective use of heat in the greenhouse (Smit & Van der Velden 2008), which means that one cubic metre of natural gas delivers 15.8 * 0.96 = 15.2 MJ useful heat;

c) This means that 12.7 / (12.7+15.2) = 45.5% of the natural gas input can be attributed to electricity production;

d) The production of one kWh requires an input of 1/[12.7/3.6] = 0.28 m^3 natural gas to the CHP unit, of which 45.5% can be allocated to the production of electricity, and therefore the input of natural gas to the CHP unit is 0.129 m^3.

Therefore, to divide the input of natural gas to the CHP unit between the supply of electricity to the grid and the generation of energy for use in the cultivation of the crop, 0.129 m^3 gas has to be subtracted from the gas input to CHP for each kWh supplied to the grid. This is shown in Table 5.7 for the two example businesses, with the result expressed in kg CO_2 emissions per kg product.

Table 5.7 Allocation of the environmental load of CHP at the rose and tomato producers based on energy content and the resulting greenhouse gas emissions per kg horticultural product

Parameter	Unit	Rose	Vine tomato
Gas consumption CHP	m^3/m^2	83.9	49.7
Supply of electricity	kWh/m^2	66	178
Deduction from gas input to CHP (electricity supply x 0.129)	m^3/m^2	-8.5	-23
Net gas consumption CHP	m^3/m^2	75.4	26.7
CO_2 emissions from net gas consumption CHP (kg)	kg CO_2eq/m^2	164	58
CO_2 emissions from energy use (gas-fired boiler, electricity purchases)	kg CO_2eq/m^2	51	35
Yield of horticultural product	kg/m^2	12.5	56.5
CO_2 emissions per kg product	kg CO_2eq./kg	17.2	1.63

In this method we use standard values for CHP efficiency based on Van der Velden (2008). Few research results are available on the actual efficiency of CHP in practice. Vermeulen (2008) derived an average efficiency of 42% for CHP units between 1000 and 2000 kWh (the most commonly used capacity class) from an inventory of efficiencies claimed by the manufacturers. Experience shows that these stated efficiencies are often not achieved in practice, and so 40% electrical efficiency would appear to be a good estimate. In addition, an average thermal efficiency of about 50% derived from this inventory is close to the standard value. For the use of heat we assume a standard value of 96% (Smit & Van der Velden 2008). However, in practice the use of heat will vary from producer to producer and between seasons.

Allocation option 3: crop requirements

For the allocation option based on crop requirements we work with the specific inputs needed by the crop. The demands of the crop can be calculated using a model by Wageningen UR Greenhouse Horticulture, which calculates the warmth, light and CO_2 needed by a crop. The model translates these requirements into the volume of natural gas needed by the CHP unit to meet these requirements. This in effect identifies the proportion of the total natural gas consumption that is needed to meet the crop's requirements. This identified volume of natural gas then forms the input for the analysis of the greenhouse gas emissions per unit of horticultural product (Table 5.8)

Table 5.8 The calculation method for allocation based on crop requirements and the results of this calculation

Part		Parameter	Unit	Rose	Vine tomato
Total	A	Gas consumption CHP	m^3/m^2	83.9	49.7
	B	Gas consumption boiler	m^3/m^2	0	15
	C	Electricity purchases	kWh/m^2	92	10
	D	Electricity purchases without CHP	kWh/m^2	343	10
	E	Electricity supply to the grid	kWh/m^2	66	178
Model:	X	Gas consumption to meet crop thermal requirements		13.1	34.6
	Y	Gas consumption for electricity production		63.3	26.7
	Z	Gas consumption to produce CO_2 for use by the crop		7.5	3.4
Calculation:		Gas consumption to meet crop requirements =			
		X + Z + Y*(D-C)/(D-C+E)	m^3/m^2	70.7	23.0
		Electricity purchases to meet crop requirements (=C)		92	10
Result:		Greenhouse gas emissions per kg product	kg CO_2eq./kg	16.4	1.48

An advantage of this method is that the energy input needed to meet the crop's requirements can be identified from the total energy consumption by the horticultural business. This allows the energy input to the horticultural product be determined quite accurately. A limitation is that the model can only be used for a limited number of (standard) situations and is therefore not widely applicable in practice.

Allocation option 4: economic allocation

Economic allocation is a method in which the environmental load of a process (and the preceding supply chain) is allocated between the products according to the ratio of the economic yield of those products. For the two example businesses this allocation, the associated greenhouse gas emissions per horticultural product and the electricity supplied is set out in Table 5.9.

Table 5.9 Proportion of the total economic yield of the rose and tomato producers that is obtained from the horticultural products and the electricity supplied

Parameter	Unit	Rose	Vine tomato
Proportion of economic revenue obtained from horticultural product	-	95%	76%
Proportion of economic revenue obtained from electricity supply	-	5%	24%
Greenhouse gas emissions per kg horticultural product	kg CO_2eq./kg	17.7	1.91
Greenhouse gas emissions from electricity supplied	kg CO_2eq/kWh	0.191	0.191

The outcomes from economic allocation depend on price and market trends. If the prices obtained for electricity supplied increase (and the yield of the horticultural product remains the same), the greenhouse gas emissions of the horticultural product will decline (Figure 5.2). This effect becomes more pronounced as relatively more electricity is supplied. This can be seen clearly in Figure 5.2; the line for tomatoes is much steeper than for roses.

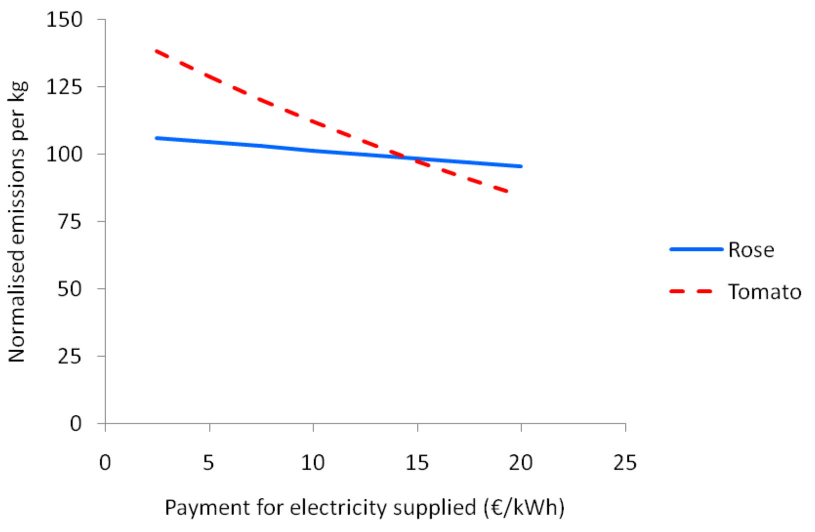

Figure 5.2 The effect of the price paid for electricity supplied on the greenhouse gas emissions per kg horticultural product, normalised according to the energy content (100).

An advantage of economic allocation is that it is widely used in LCA studies. A disadvantage is that the result depends on external factors, such as the prices on the energy market. Moreover, it is not easy to collect data at the business and sector levels on the proportions of the total proceeds that are obtained from the horticultural products and the electricity supplied.

Comparison and appraisal

Different methods for dealing with co-production with CHP are: the consequential analysis expanding the product system (according to PAS 2050 and our recommendations = best practice) and the attributional analysis allocation (based on crop requirements, energy content and economic yield). The results are summarized in Table 5.10. Assuming the same production levels, the greenhouse gas emissions of a rose and a tomato producer without CHP is approximately 19.4 and 1.55 CO_2eq per kg product respectively. For roses we see that regardless of the method used, the example business with CHP causes fewer greenhouse gas emissions. Whereas we calculate more attributed greenhouse gas emissions for tomato growing with CHP using the economic allocation method, the result from the calculation using the system expansion method is clearly lower. The allocation based on energy content and crop requirements gives a higher and lower score respectively.

Table 5.10 Greenhouse gas emissions per kg horticultural product calculated using the different allocation methods

	Rose (kg CO_2eq/kg)	Tomato (kg CO_2eq/kg)
Allocation based on energy content	17.2	1.63
Allocation based on crop requirements	16.4	1.48
Allocation based on economic yield	17.7	1.91
System expansion best practice	15.7	0.72
System expansion PAS 2050[1]	16.2	1.05

[1] avoiding production mix NL 2007 (463 g CO_2eq/kWh)

The general allocation philosophy described in section 5.1, in which the first step is to compensate for feedback to the supply chain, can be applied here. Energy is used and energy is produced, and the latter can be offset. We should be aware, though, that the form of energy differs and therefore additional processes have to be taken into account, namely electricity production in a gas-fired and a coal-fired power station. An additional argument for choosing to expand the product system in this case is the comparison between cultivation systems with and without CHP and the additional electricity production required to obtain the same functionality. Figure 5.3 shows the difference in calculated greenhouse gas emissions between the example business with CHP and a business without CHP when they produce equal amounts of tomatoes and electricity (equal to the amount supplied from CHP), assuming average Dutch central production. Greenhouse gas emissions from production without CHP are 1.55 kg CO_2eq per kg and the difference is 0.8 kg CO_2eq per kg tomatoes (Figure 5.5). If the situation at the level of the individual business leads to a lower greenhouse effect at the system level, it is acceptable that this is also reflected in the greenhouse effect of the tomatoes produced.

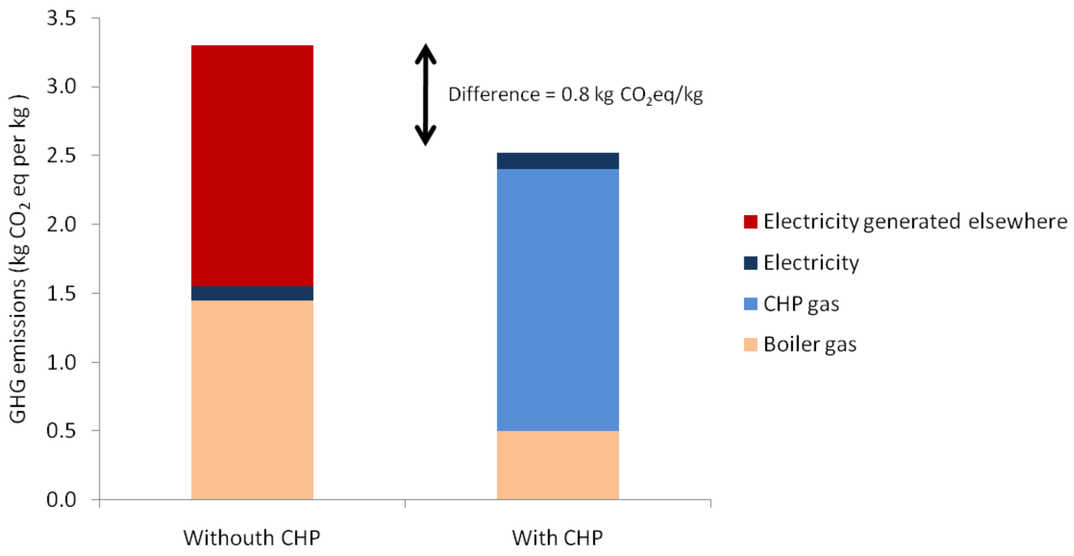

Figure 5.3 The difference in greenhouse gas emissions (in kg CO_2eq per kg tomatoes) between the example tomato producer with CHP and a producer without CHP including electricity generated elsewhere, which is equal to the electricity production at the tomato producer with CHP

Below we describe with the help of a number of figures how the total environmental load of a business with CHP is allocated between different products (supplied electricity and tomatoes) using the different allocation methods.

System expansion

In essence, expanding the product system involves subtracting the avoided greenhouse gas emissions from electricity production from the total emissions of a business with CHP. Depending on the principles used for calculating the avoided emissions from electricity production, this leaves a remaining amount of emissions that are due to change in production of the horticultural product. If we compare this result (0.72 and 1.05 kg CO_2eq per kg tomatoes for best practice and PAS 2050 respectively) with the greenhouse gas emissions for tomato production without CHP and the actual difference (1.55 and 0.8 kg CO_2eq per kg tomatoes respectively) it is clear that using this method more or less the whole difference is allocated to the horticultural product. With the best practice method just a little more is allocated to the horticultural product and with the PAS 2050 method slightly less. In itself this is not a problem, but we have to consider the fact that no (or a small remaining part) of the greenhouse gas emissions saving is allocated to the electricity supplied by horticultural CHP. The electricity supplied by horticultural CHP is then allocated greenhouse gas emissions equal to the avoided emissions. This is done to satisfy Principle 2 of our allocation rules, which requires that the sum of all allocated emissions is equal to the total emissions at the system level. The consequence of this is that when determining the greenhouse gas emissions of the generated and supplied electricity in the Netherlands, the emissions from the electricity produced by CHP units in the horticultural sector should be included in these greenhouse gas emissions. In the best practice method these greenhouse gas emissions are 570 g CO_2/kWh and using the method based on production mix in the Netherlands in 2007in they are 463 g CO_2/kWh.

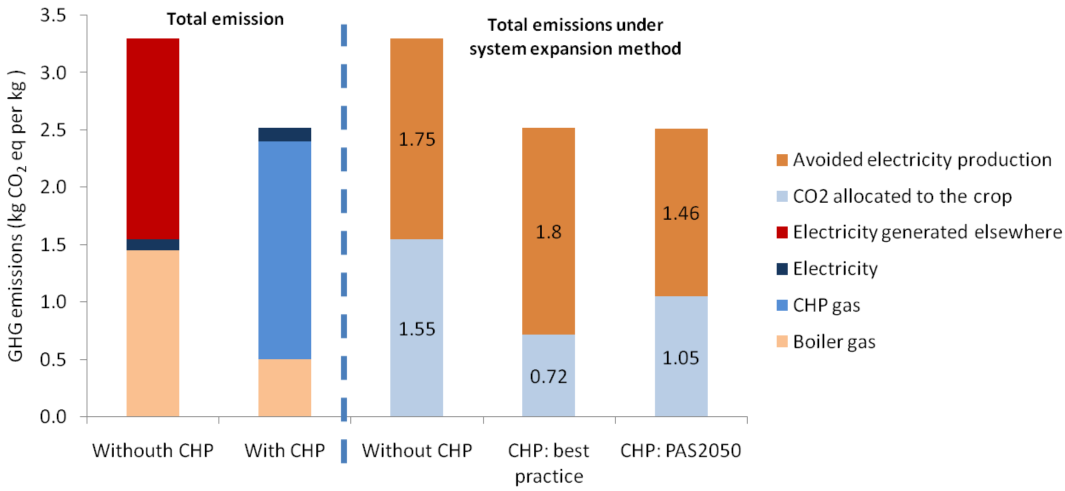

Figure 5.4 Greenhouse gas emissions per kg tomatoes in the two versions of system expansion in which the emissions from avoided electricity are subtracted from the total emissions

Physical and economic allocation

The environmental load of the CHP unit can be allocated on the basis of economic yield, energy content and crop requirements. Figure 5.4 shows the allocations resulting from these three allocation keys. For economic allocation this means the following: In the case of the example tomato producer, the horticultural product represents 76% of the economic yield. This means that 76% of the total environmental load is allocated to tomato production. If we compare the results of these greenhouse gas allocations in Figure 5.5 with a business without CHP, using this method the business with CHP is allocated more greenhouse gas emissions per kg horticultural product. This means that by applying CHP at the system level in this way, the advantage accrues entirely to the supplied electricity. Using this method, the greenhouse gas emissions per kWh supplied electricity is 191 g CO_2 per kWh.

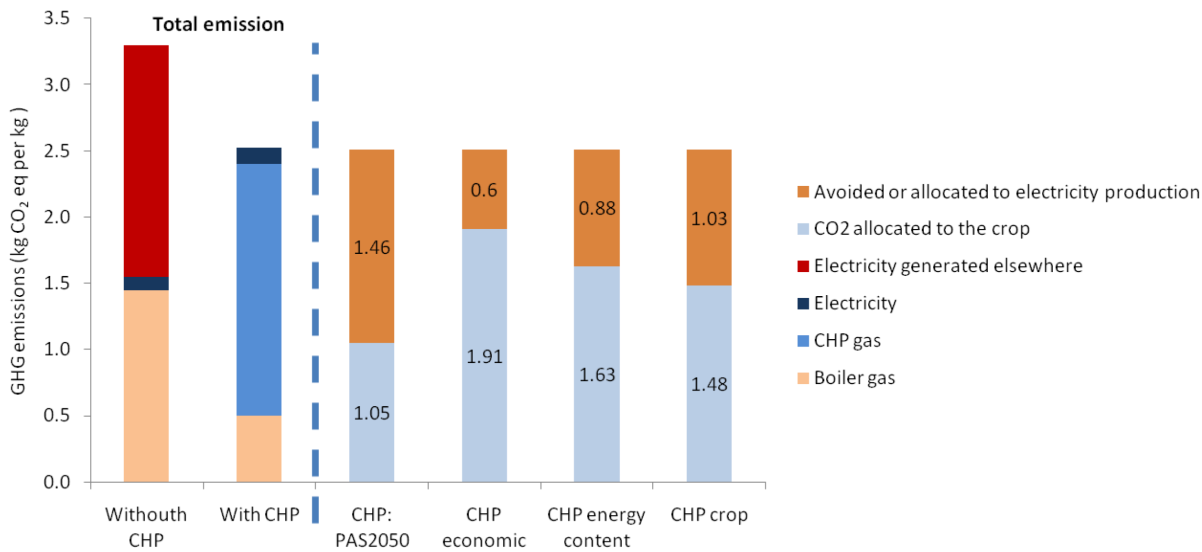

Figure 5.5 Greenhouse gas emissions per kg tomatoes for the different allocation options

In the allocation method based on energy content, the greenhouse gas emissions from electricity production are subtracted from the total greenhouse gas emissions from crop production by the business. The remainder is allocated to the horticultural production and are about the same as these emissions for a horticultural business without CHP. Therefore, using this method the advantage at the system level also accrues to the supplied electricity. In the method of allocation based on crop requirements, part of the energy input is allocated to the crop. The result is virtually equal to the outcome for the business without CHP (the CHP crop bar in Figure 5.5).[9]

Thus, depending on the chosen option the difference in greenhouse gas emissions from the use of CHP at the system level can be allocated between the horticultural product and the supplied electricity in different ways. In the system expansion method the advantage accrues entirely to the horticultural product; in the physical and economic allocation methods it accrues almost entirely to the electricity. Deciding which product should be given the advantage or how this can be allocated between the products is difficult. But given the fact that the introduction of CHP at the system level delivers an environmental advantage, it is logical to attach part of this advantage to the production of the crop. This line of reasoning, therefore, is an argument for the system expansion option. At the same time, allocating the advantage must be done in a consistent manner. If the advantage accrues entirely to the horticultural product, no environmental benefit can be attributed to the supplied electricity. This would mean that the greenhouse gas emissions of the electricity grid would have to be corrected.

Further, it is interesting to see how changes in the use of CHP or electricity production at horticultural businesses affect the environmental score under the different calculation options. Figure 5.6 illustrates how the environmental score per kg tomatoes changes (relative to a kg tomatoes produced on the example business without CHP = 100). Figure 5.6 shows that under the system expansion method (according to Best Practice) the greenhouse gas emissions per kg tomatoes falls significantly as the use of CHP rises to 100%. Beyond that point the greenhouse gas emissions rise again, but the rate of this rise is less than the rate of decline to 100% CHP use. The economic allocation and the allocation based on crop requirements lead to a rise in greenhouse gas emissions per kg tomatoes as the use of CHP increases. Beyond 100% use of CHP (beyond the point at which the heat is no longer effectively used) the greenhouse gas emissions rise at a faster rate. Under the method of allocation based on crop requirements, the greenhouse gas emissions remain almost constant because the calculation remains based on the inputs that are actually required by the crop.

[9] This is logical and means that the crop model apparently predicts the necessary inputs well because the outcome is comparable to a business without CHP. However, this method also allocates the environmental benefit at the sytem level to the supplied electricity.

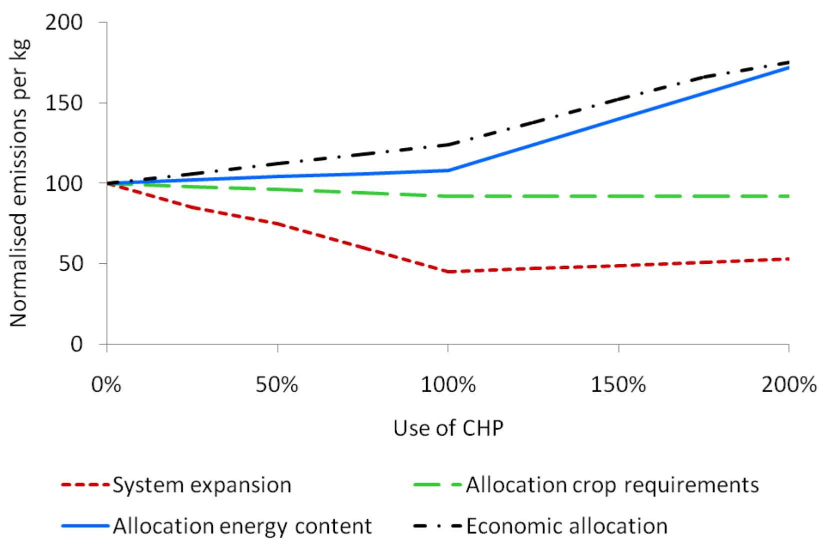

Figure 5.6 Greenhouse gas emissions per kg tomatoes at the example tomato business with increasing use of CHP (100% is the point at which the heat demand for production is fully met by the heat produced by the CHP unit) under four different allocation methods (the system expansion method is Best Practice)

5.2.3 Recommendations for the protocol and calculation tool

With regard to the issue of co-production of electricity by a horticultural CHP unit, we recommend expanding the product system according to the Best Practice method. In this method the avoided electricity is taken to be the marginal electricity production in peak and off-peak hours (with a fixed ratio between the two) and the greenhouse gas emissions associated with the electricity produced by CHP are systematically included in the national calculation of the greenhouse gas emissions from electricity production. In concrete terms, this means that the greenhouse gas emissions of electricity production in the Netherlands will rise because for the time being the environmental benefit of generating electricity via CHP is allocated to the electricity (see, for example, Groot & Van de Vreede 2007 and 2008). In the calculation tool we recommend presenting the results obtained using the best practice method as well as the results calculated according to PAS 2050.

5.2.4 Recommendations for further research

We recommend monitoring the degree to which countries and sectors with CHP choose the same calculation options for comparable situations. In this section we have not pursued two alternative avenues for allocation, because we thought they would not give a sound reflection of the “value” of the different outputs or are not practically feasible. The first is physical allocation based on the energy content of heat (exergy), electricity and carbon dioxide. In this method a relatively large greenhouse effect is allocated to the electricity production because heat is a low value product. Following this method would result in an extremely low allocation fraction to horticultural products The second is economic allocation in which the allocation fraction is not based on the value of the tomatoes but on the value of produced heat and carbon dioxide which otherwise had been purchased based on the production of conventional technology (a sort of shadow price). We think that this latter method might be applicable, but is highly dependent on many assumptions on shadow technology. However, it is possible that in future both of these options will become of interest for further investigation if system expansion with CHP does not eventually become the consensus method.

5.3 Cropping plan allocation

5.3.1 Problem description

Many field vegetables are cultivated according to a cropping plan, in which in the same year several different crops are grown on separate plots according to a rotation in which each crop is followed by the next in consecutive growing seasons. The fertilisation of the crops takes account of the delayed release of nutrients from fertilisers applied to crops previously grown on the same plot. When fertilising the plots, vegetable growers and arable farmers also take account of the availability of nutrients following the harvesting of the first crop, especially when animal manure and organic matter is applied to the plot.

Literature on cropping plan allocation in LCA is limited. However, various authors note that the allocation method used to allocate fertilisers to crops can be decisive for the outcomes (Nemecek et al. 2001; Zeijts 1999). This is because of the large number of emissions that occur during fertilisation and the production of fertilisers (Table 5.11) and the contribution made by fertilisation to the greenhouse gas profile of horticultural products that are grown according to a cropping plan (Figure 5.7).

Table 5.11 Greenhouse gas emissions from various processes associated with fertilisation

Process / emission source associated with fertilisation	Emissions
Background emissions attributable to agriculture	CO_2 from oxidisation of organic matter CO_2 from oxidisation of peat N_2O from background nitrogen deposition
Application and production of artificial nitrogen fertiliser (available during cultivation)	N_2O and CO_2 from production of nitrogen fertiliser N_2O from conversion of applied N (distinction between direct and indirect)
Application of nitrogen in animal manure (available during cultivation)	N_2O from applied nitrogen (distinction between direct and indirect); CO_2 from energy used by agricultural machinery
Production of animal manure	CO_2 and other greenhouse gases resulting from the inclusion of transport and production in the calculation
Nitrogen fixation	N_2O from nitrogen fixation (distinction between direct and indirect)
Nitrogen in crop residues	N_2O from nitrification of nitrogen in crop residues
Total application of P_2O_5 and K_2O	CO_2 from production pathway
Application and production of OS	CO_2 from production pathway and N_2O from applied N in the compost

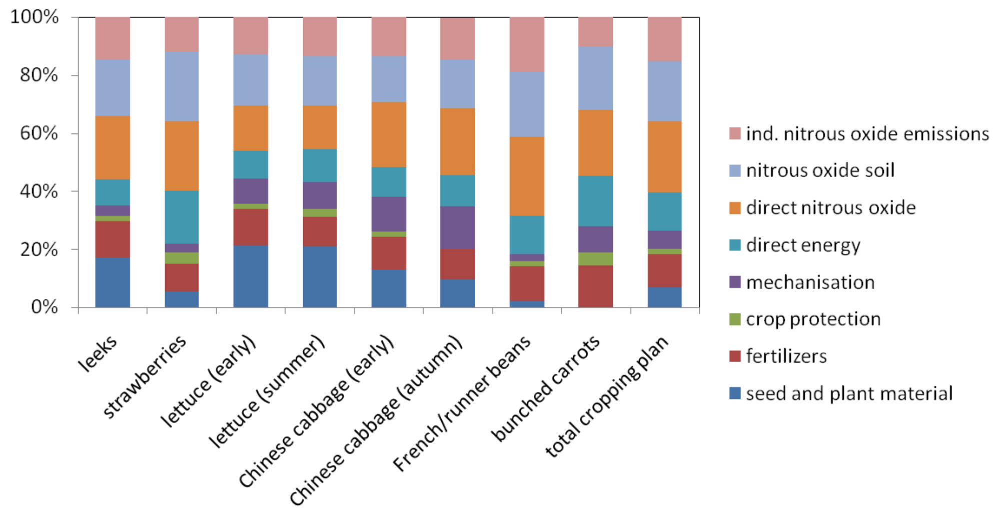

Figure 5.7 The relative contribution of fertilisation to the greenhouse gas profile of horticultural products in a cropping plan

The Dutch agricultural LCA methodology project drew up a systematic method in 1996 (Wegener Sleeswijk *et al.* 1996). In essence, the method can be summarised in the following recommendations:

- The nitrogen content of a fertiliser that becomes available during the year of its application is allocated to the crop.
- The total doses of phosphate and potassium are divided between the crops in a cropping plan in proportion to the amounts recommended in the 'Quantitative Information on Arable farming and Field Vegetables' (KWIN Akkerbouw en Vollegrondsgroenten).
- Each crop can benefit equally from the effective organic matter and the poorly degradable nitrogen fraction in animal manure because it improves the general fertility of the soil. Both nitrogen fractions are divided between the crops in the cropping plan in proportion to their cultivated areas.
- The nitrogen from crop residues is divided between all the crops in the cropping plan in proportion to their cultivated areas.

This method forms the basis for the allocation of greenhouse gas emissions associated with the application of fertilisers. An important philosophy underlying this proposal is that a portion of the fertilisers applied in a cropping plan is intended for specific crops and another portion is applied with the aim of maintaining general soil fertility, which benefits all the crops. This proposal does not provide answers to several questions:

- In a cropping plan, the application of animal manure adds a large quantity of minerals to a relatively small part of the total area covered by the cropping plan. The amount of nitrate leaching that leads to nitrous oxide emissions does not follow a linear relationship to the amount applied (Drecht *et al.* 1998) so that leaching from animal manure applied to the land may be higher than would be expected on the basis of the average application in the cropping plan. Is it possible to derive a crop-specific allocation method that allocates nitrate leaching and the resulting nitrous oxide emissions between the crops?
- Is there a difference in the leaching of nutrients from organic animal manure, conventional animal manure and artificial fertilisers?
- How should nitrogen fixation be dealt with, and how should this be allocated between the various crops?
- How should sequential cropping and catch crops be dealt with?

5.3.2 Review of solutions

To explore the above-mentioned problem definitions for cropping plan allocation an expert meeting was organised, at which fertiliser experts from the Agricultural Economics Research Institute (LEI-WUR), Applied Plant Research (PPO) and the Louis Bolk Institute were invited to brainstorm about a crop-specific approach. An important observation by the expert group was that the relation between leaching and fertilisation practice at the cropping plan level is already complex, without even considering how to allocate between crops. Opinions were divided about the utilisation of nitrogen from applied animal manure (conventional and organic) compared with artificial fertilisers. Most experts share the feeling that more nitrogen is lost from conventional manure applications, but that this is certainly not the case for the use of animal manure in organic farming systems. An important parameter for nitrogen leaching is the mineral nitrogen content of the soil following the harvesting of the crop, which in turn depends on the amount of nitrogen in the crop residues and the time of harvesting. The leaching also depends on what happens after the harvest. The initial conclusion from the expert meeting and the LCA literature was that for the time being there is no point in further refining the method with respect to nitrate leaching resulting from the concentration of animal manure on a single plot or field. A second outcome concerned a methodological idea explored in one of the case studies for French beans, but it was decided for the time being not to recommend this as a method for calculating emissions from fertilisation in a cropping plan.[10]

Considering the outcome of the expert meeting, we noted that a further refinement of allocation in cropping plan fertilisation that goes beyond that proposed by Van Wegener Sleeswijk (1996) is not advisable. We therefore adapt this approach for inclusion in the protocol. Figure 5.8 is a diagrammatic representation of the emissions from fertilisation and the background emissions from conversion into carbon and nitrogen using two types of allocation: 1) allocation in proportion to surface areas; and 2) allocation in proportion to the characteristics of the crop and the economic yield of the crop. Some of the fertilisation data are not allocated.

If we add nitrogen fixation to the proposal by Wegener Sleeswijk we can elaborate this to obtain a preferred calculation method (Table 5.12). An underlying assumption is that the cropping plan remains on average more or less the same over the years, otherwise the allocation between crops will not be correct. The question of whether an economic allocation should be carried out at the cropping plan level has not been considered in this calculation method. PAS 2050 states a preference for economic allocation. We propose a physical allocation approach based on the mineral needs of the crop.

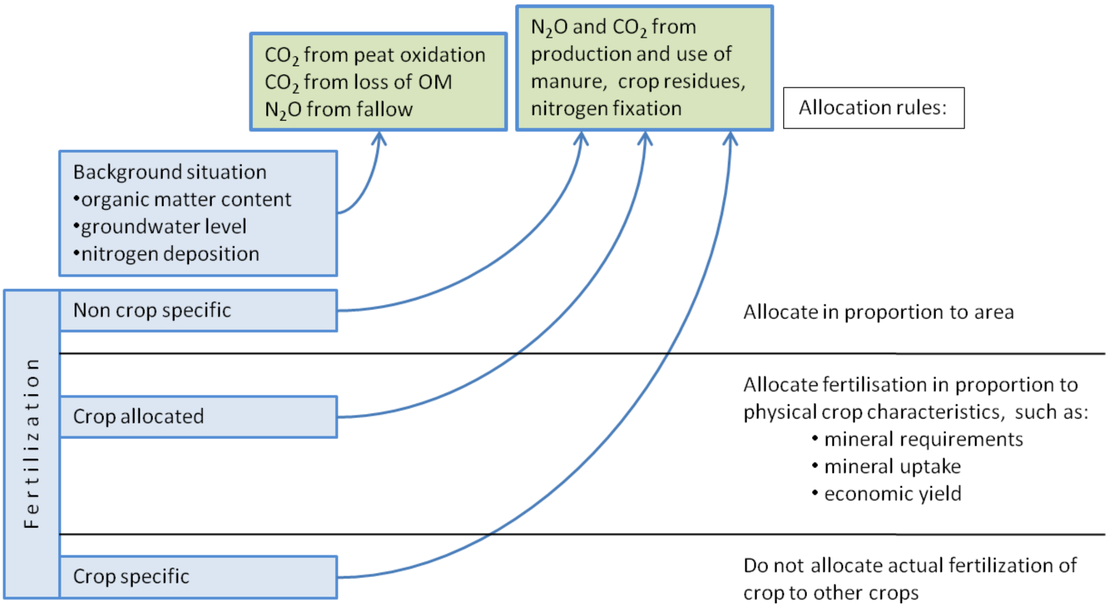

Figure 5.8 Diagrammatic representation of the emissions from fertilisation and the background emissions from conversion into carbon and nitrogen using two types of allocation.

[10] The core of this idea is to determine the marginal effect of a specific crop on the nitrogen emissions of an average cropping plan. This was later rejected because it is more appropriate to a consequential rather than an attributional LCA method and because it requires large amounts of data.

Table 5.12 A conceptual model for cropping plan allocation

Process / emission source	Allocate in proportion to areas of crops	Allocate in proportion to crop yield and harvest characteristics	No allocation
Background emissions attributable to agriculture	Preferred option		
Application and production of artificial nitrogen fertiliser (available during cultivation)		Option when only total fertilisation data are available	Option when data on fertilisation per crop are available
Nitrogen from animal manure application (available during cultivation)		Option when only total fertilisation data are available	Option when data on fertilisation per crop are available
Nitrogen from animal manure application (available after cultivation)	Preferred option		
Production of animal manure	Preferred option		
Nitrogen fixation		Option when only total nitrogen fixation in cropping plan area is known	Option when nitrogen fixation by the crop is known
Nitrogen in crop residues	Preferred option		
Total application of P_2O_5 and K_2O		Preferred option	
Application and production of OS	Preferred option		

5.3.3 Recommendations for the protocol and calculation tool

For the protocol and calculation tool it is important to match the calculation method to the available data to ensure that the calculations are feasible in practice. The allocation principles can then be translated into a number of allocation rules. Table 5.13 lists the allocation key for the following data availability:

1. Fertiliser doses for the total cropping plan and crop areas
2. Fertiliser doses for the total cropping plan and crop areas, and the crop mineral requirements for standard yields
3. Fertiliser doses for the total cropping plan and crop areas, and crop mineral requirements for actual yields

The concrete calculation rules arising from this review have been included in the proposed protocol for horticultural products.

Table 5.13 Cropping plan allocations for different data availabilities

	1) Fertiliser doses for total cropping plan and crop areas	2) Fertiliser doses for total cropping plan and crop areas and standard crop mineral requirements	3) Fertiliser doses for specific crops, individual crop mineral requirements for standard and actual yields
Allocate to area	Production of animal manure	Production of animal manure	Production of animal manure
	N-r fraction of animal manure	N-r fraction of animal manure	N-r fraction of animal manure
	N in crop residues	N in crop residues	N in crop residues
	OS fraction non-animal-manure	Os fraction non-animal-manure	Os fraction non-animal-manure
	N in artificial fertiliser		
	N rapid fraction		
	N fixation		
	P_2O_5		
	K_2O		
Allocate to crop based on mineral requirements		N in artificial fertiliser	
		N rapid fraction	
		N fixation	
		P_2O_5	P_2O_5
		K_2O	K_2O
No allocation			N in artificial fertiliser
			N rapid fraction
			N fixation

5.3.4 Recommendations for further research

In our research we found few proposals for cropping plan allocation. However, it is likely that in a number of sectors, such as processed arable products and animal feeds, this problem is already on the agenda as part of the method for calculating the greenhouse effect of products. We recommend that any future update of the procedure includes an inventory of the available proposals for cropping plan allocation and an assessment of whether any new calculation rules can be derived from these proposals.

5.4 Allocation for more complex product systems

Allocation for more complex product systems vary from business-level emissions to product emissions in the vegetable trade, treatment and processing, storage and distribution centre.

5.4.1 Problem description

The processes within horticultural businesses, how these are organised, their efficiency and the greenhouse gases produced during these processes are often connected. Figure 5.9 is a diagrammatic representation of these relations for a situation in which the outputs of one or more general processes within a business are used as inputs to product-specific processes. Examples of general processes are: heat production or combined production of heat and power within a business, and the heating or cooling of the main production area.

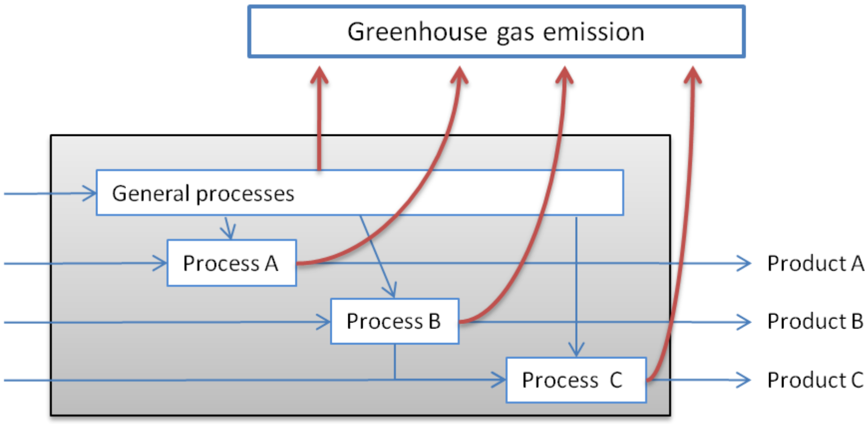

Figure 5.9 Connections between processes and the calculated greenhouse effect of products

There are also product-specific processes. Process A in Figure 5.9, which produces product A, is fed partly by general processes and partly by specific processes. It is also possible that an output from one process forms an input to another process. For instance, process C is fed by a specific input, a general input and an input from production process B. The question is how to deal with this situation.

5.4.2 Review of solutions

Vegetable processing systems (for example preservation or frying) often receive inputs of a large number of crops, which then go through more or less the same process in the processing plant and are then used in the preparation of a large number of products. In these cases the calculation of greenhouse gas emissions can be made at three different aggregation levels:

1. Input–output analysis based on a physical or economic parameter for the whole system
2. Hybrid analysis
    a. with global process analysis: in which the 'fixed' greenhouse gas emissions from the baseline emissions of the operation of the plant are allocated between the products on the basis of an input–output analysis, and only a specific analysis is performed for products when clearly different processes are used or where process parameters lead to significant deviations from the results of the input–output analysis.
    b. with a detailed process analysis: in which, as far as possible, the product-specific situation forms the basis of the analysis, to which the 'fixed' greenhouse gas emissions are added
3. Process analysis
    a. in which the specific emission are calculated on the basis of business-specific efficiencies and processes
    b. in which only the marginal emissions from the specific product are determined.

A solution for general situations depends on the specific situation of the business in question. It is in any case advisable to start with an input–output analysis of the whole business and then to refine this to the product level to permit a global or even detailed hybrid analysis. To illustrate, the greenhouse gas emissions related to the process of canning kidney beans can be calculated in the following way. First, the annual accounts of the canning factory can be consulted for information at the business level on energy inputs, raw materials and outputs in the form of products, co-products and wastes (products with a negative value that are sent for final processing). Then product-specific parameters that apply only to the product, such as the packaging used and the co-products and waste streams from the production process, are collected. Finally, a determination is made of the extent to which the product has process-specific parameters that deviate from the average process data. These may be, for example, an additional stage in the process or differences in cooking time and the heat required to heat up the product, which in turn depends on the dry matter content. If the deviation from the process-specific parameters is large and has a noticeable effect on the greenhouse gas emissions in the production chain, for example more than a one percent difference, it is recommended that the analysis is refined using the process-specific parameters. Another criterion for deciding whether or not to refine the analysis is whether the difference is big in comparison with the baseline emissions of the plant. The allocated baseline emissions per unit of product also fluctuate from year to year as a result of differences in production volume, depending on the economy and size of the harvest.

In practice, most analyses are either global or detailed hybrid analyses. A major advantage of these analyses is that the baseline emissions are not underestimated and the interrelations between energy flows are revealed. Such underestimates can occur in process analyses, which are usually based on several process parameters. Moreover, in some cases process analyses can lead to overestimations, for example when a business is more efficient than would naturally be evident from a process analysis because certain materials and energy streams within the business are linked. A well-known example is the overestimation of the energy used to dry by-products, which is often done entirely or partially with residual heat.

A special form of process analysis is the marginal analysis that can be carried out as part of a consequential LCA. What happens when a product is no longer produced in the factory, but in another one, or vice versa? This analysis is not developed further here because it is not part of the basic principle.

5.4.3 Recommendations for the protocol and calculation tool

We recommend the use of an iterative process that starts with an input–output analysis, which is then refined by carrying out a hybrid analysis.

5.4.4 Recommendations for further research

There are no specific recommendations concerning further research or expected trends that need to be taken into account.

5.5 Recycling and waste processing

5.5.1 Problem description

The use of materials can make a substantial contribution to the carbon footprint of a horticultural product (see Chapter 3). The carbon footprints of used materials are determined by a number of factors, the most important of which are the production process, the amounts of primary and secondary materials used in the process and the way in which wastes are processed. The type and efficiency of the production process are treated in the section on background data in Chapter 9. In this section we look more specifically at how recycling and waste processing should be allocated. In Chapter 4 we determined that a full analysis should be made for all the materials that are used in the pathway from production to retail, including the recycling and waste processing following disposal of the product.[11] In section 5.1 we defined a number of allocation principles for final processing. These are worked up in more detail here. The most important principle is that we compensate for feedbacks to the chain via recycling of materials and energy. We therefore calculate a net demand for materials and energy from the primary demand by compensating for feedbacks.

Materials recycling

The method used to compensate for feedbacks into the chain is proposed by various materials producers in different countries (WRAP UK, World Steel Association) and also forms the basis for the calculation of the carbon footprint of packaging in the Netherlands (Bergsma 2004; Sevenster *et al.* 2007). The materials producers in particular emphasise the importance of this approach, because the use of primary and secondary materials in the production of a product and the recycling of materials after disposal vary widely depending on the use of the product. For example, minimal amounts of secondary materials are used in the manufacture of the steel used to make cans, whereas after disposal most of this steel is recovered for use in other products with other product requirements. The question is whether analyses of the production of packaging steel should be based on the actual use of materials or the loss of materials associated with the specific use of the product, which has to be made up by the introduction of new primary materials into the materials cycle. We illustrate the importance of this using an example calculation. In the first instance, a steel container is produced mainly from primary raw materials in a blast furnace. A small amount of scrap metal (four percent) is added for the purpose of conditioning in the furnace, but the steel is produced mainly from iron ore, limestone and coke. Based on this actual situation, the carbon footprint of packaging steel is about 2.7 kg CO_2eq per kg packaging steel. However, if the calculation is based on the primary production needed to compensate for the loss of steel from the chain, the carbon footprint turns out to be much lower, at about 1.1 kg CO_2eq per kg steel. This difference arises from the big difference between the greenhouse gas emissions from the primary and secondary production pathways.

Table 5.14 Greenhouse gas emissions from the use of steel, accounting for primary and secondary raw materials inputs and allocated to material production and product [based on WRAP and Ecoinvent]

		Production emissions (kg CO_2eq/kg)	Carbon footprint (kg CO_2eq/kg)
Actual input of primary raw materials	96%	2.8	2.7
Actual input of scrap metal	4%	0.3	0.0
Total			2.7
Loss of steel from the chain compensated for by primary production	30%	2.8	0.8
Production from collected scrap metal	70%	0.3	0.2
Total			1.1

PAS 2050 states that when materials recycling is involved the calculation of emissions should be based on the actual use of primary and secondary materials. It does not use the method of compensating for the use of primary materials due to materials recycling in the chain. In principle this approach requires relatively few data because the fate of the material after recycling does not have to be considered. The disadvantage is that recycling efforts in the chain are not revealed, or only to a very limited extent.[12] Moreover, we question whether this recommendation in PAS 2050 is consistent with the recommendation to use the compensation method in cases where electricity is produced by CHP.

[11] Except the materials in capital goods and the materials that make a very small contribution to the carbon footprint

[12] What is revealed is the avoided waste processing, but the effect of this is negligible for non-combustible materials such as steel, glass and aluminium.

The following questions are relevant with respect to materials recycling.

1. What method should be used to include compensation for materials losses in the calculation?
2. Is the compensation method feasible in practice, and what data have to be used for this?

Waste processing

Waste processing raises a similar compensation issue as for materials recycling. Waste processing involves the conversion of materials into energy. Plastics, wood, paper, cardboard and other organic products have a calorific value that can be recovered in waste processing techniques such as incineration, anaerobic digestion and composting. When calculating the greenhouse gas emissions of these materials it makes a big difference whether or not the energy recovered during processing is used to compensate for energy used in the chain. PAS 2050 in not clear about what should be done in these cases. Using energy recovered during waste processing to compensate for energy used in the chain would be consistent with the allocation of energy compensation for CHP.

The following questions are relevant with regard to the inclusion of waste processing in the protocol for the calculation of greenhouse gas emissions arising from the production of horticultural products.

1. How should compensation for energy conversion in the processing of waste materials be included in the calculation?
2. Is the compensation method feasible in practice, and what data have to be used for this?

5.5.2 Review of solutions

Materials recycling

Various proposals have been made for averaging the use of a secondary material in a country based on actual proportional inputs to production and the recycling rate, corrected for losses from recycling (wear and tear, mixing/dilution, dispersion) (Blonk 1992; Kortman 1996; Bergsma *et al.* 2004; Birat 2006; CE 2007). The most practical method amounts to the following: when there is a recycling process in which the material is fed back for reprocessing to make the same sort of products, the percentage of the total inputs made up by secondary materials is taken to be an average of the actual inputs and recycling following disposal of the product.

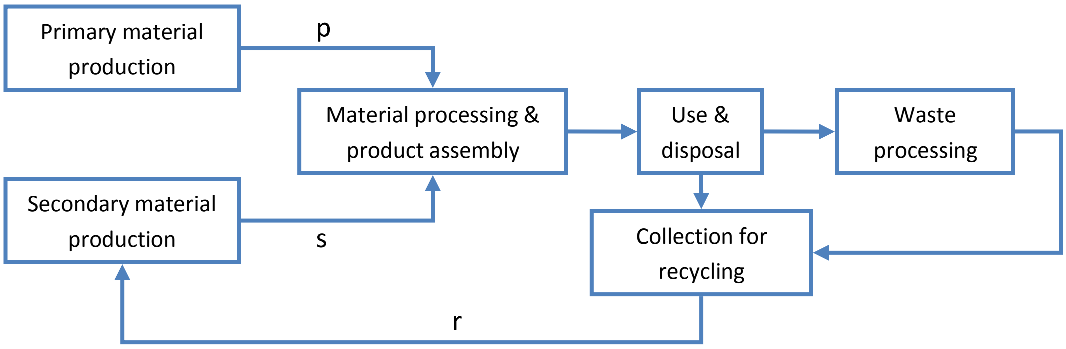

Figure 5.10 Diagrammatic representation of a materials cycle

The carbon footprint of a product is then calculated as follows:

$$C_P = (1-(r+s)/2) * C_{PMP} + (r+s)/2 * C_{SMP} + C_{PV}$$

C_P	is the greenhouse gas emissions from the manufacture of the product in kg CO_2eq/kg
r	is the recycling percentage following use and disposal of the product
s	is the actual input of secondary material to the production of the material for the product
p	is the actual input of primary material to the production of the material for the product (p+s=1)
C_{PMP}	is the greenhouse gas emissions arising from primary material production in kg CO_2eq/kg
C_{SMP}	is the greenhouse gas emissions arising from secondary material production in kg CO_2eq/kg
C_{PV}	is the greenhouse gas emissions arising from material processing and manufacture of the product in kg CO_2eq/kg

Below we discuss the following complicating factors:

1 Wastage
2 Recycling of process waste
3 Loss of quality through recycling
4 Integrated versus separate primary and secondary production
5 Time

Factor 1: Wastage
Materials are lost from the production process at various points. This includes waste, which goes for final processing, but also material that is lost during use through wear and tear, oxidation or other chemical conversions. The proposed calculation of greenhouse gas emissions uses only the fraction [*r*] of this material that becomes available for recycling. No precise data on this loss of material from the system.

Factor 2: Recycling of process waste
Some relatively clean material is lost during materials processing and product assembly operations and this is collected for materials recycling. For a more precise calculation a distinction should be made between a recycling percentage for materials processing and product assembly (*rp*) and a recycling percentage following use and disposal (*ra*). This makes the calculation more complex because many more data are required on the inputs to and outputs from materials processing and product manufacture. Birat *et al.* (2006) propose a method for doing this for steel recycling. We do not go into this here because our concern is the horticulture protocol and it would make this considerably more complex. However, it is something that can be looked at in future in future.

Factor 3: Loss of quality
Not all materials retain the same functional characteristics after use and recycling. Metals and glass can in theory be endlessly recycled, but this is not the case for materials with a fibrous or polymer structure. These materials are subject to wear and tear, which limits the number of cycles the materials can go through and means that in time a permanent input of primary materials is necessary to make good this loss of quality. The recycling of paper and cardboard leads to a reduction in the length of the fibres in these materials, which limits the number of possible cycles to about six. That means that a continual input of primary material is needed to compensate for the loss of quality. In practice, glass and metal also lose some of their quality through mixing with other materials or alloys and colour mixing. More differentiated collection and recycling

can considerably reduce the required inputs of primary materials. There is also a category of materials that cannot be fed back into the same process. Although concrete and many granular materials are recycled, they are not reused for the same applications because the materials are chemically converted in a way that does not permit reprocessing them into the original materials. The resulting materials are therefore used as substitutes for other materials in low grade applications. This can also be the case for materials that are in principle recyclable, but because of mixing with other materials can only be used in manufacturing processes as substitutes for other cheaper materials, for example plastic bollards and posts, which are in fact replacements for timber products.

Factor 4: Integrated versus separate primary and secondary production

There are various points in the chain where primary and secondary products come together. For glass and a few metals the secondary material is fed into the same process in which primary raw materials are used to manufacture the product. For plastics, paper and cardboard, and aluminium, the production process involving secondary materials is completely separate from the primary process. For steel, both are possible: some of the scrap metal is fed into the blast furnace and some into the electric steel process.

Factor 5: Time

For materials used in products with a long life, the calculation is much more complex because of the stock aspects and the differences in manufacturing technology and the collection infrastructure following production and disposal. Birat *et al.* (2006) have drawn up a partial solution for dealing with the complexity of steel recycling. We do not elaborate this because long-lasting products, such as capital goods, are not included in this study.

For the time being, we use the averaging method for closed loop recycling. Figure 5.11 compares the averaging method and the PAS 2050 method (bottom bar) for aluminium. As recycling percentages rise the carbon footprint of one kilogram of aluminium decline significantly.

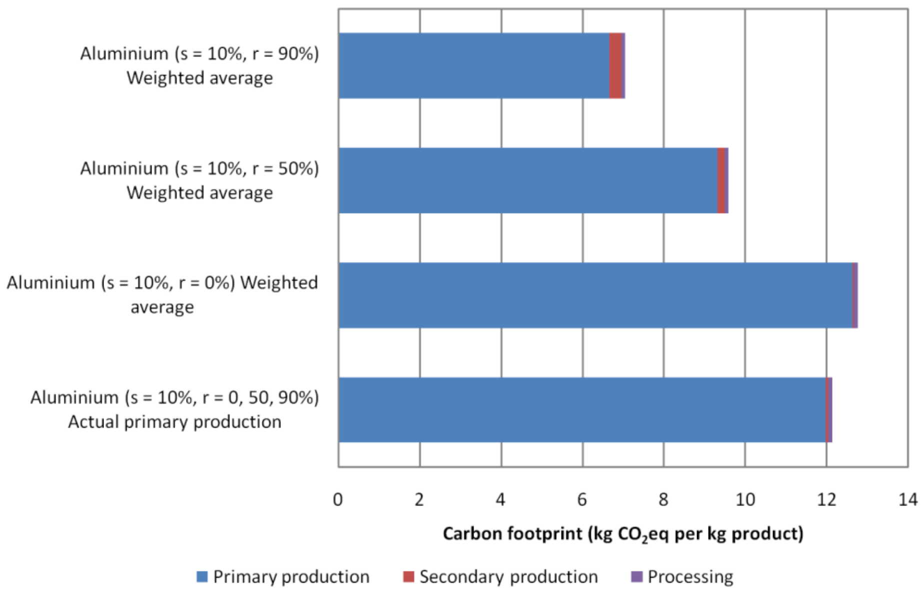

Figure 5.11 Greenhouse gas emissions of an aluminium product for different calculation methods and recycling percentages

Waste processing

Products that go for waste processing have various characteristics that are relevant for the calculation of the carbon footprint:

- Organic carbon content
- Fossil carbon content
- Nitrogen content
- Moisture content
- Calorific value

In the Netherlands and many other countries, waste is treated to recover energy and materials and compress the remaining material before it is land-filled. The specific form of treatment and processing for each waste stream is set down in the legislation. In the Netherlands a significant form of treatment for materials like residual paper/cardboard and plastics is incineration with energy recovery. Organic materials with a high moisture content are sent for composting or anaerobic digestion. In these waste treatment processes the materials are chemically converted and their calorific value is partly recovered to produce energy carriers (electricity, heat, methane), products (mineral concentrate, compost, *et cetera*) and residual material, which is then land-filled.

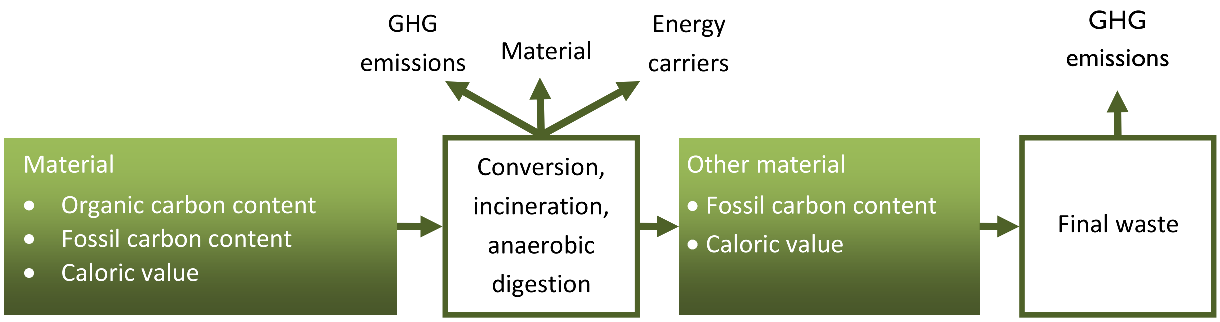

Figure 5.12 Waste processing route of materials

In addition to the useful products, greenhouse gases are also released. Only the carbon dioxide arising from the fossil carbon fraction is included in the calculation. Methane and nitrous oxide emissions are included in their entirety.

Materials therefore contain a considerable potential for greenhouse gas emissions or avoidance of greenhouse gas emissions. This is illustrated by examining the processing of materials in a waste-to-energy incinerator with an electrical efficiency of 20%. When polyethylene (including fillers) is incinerated, on average 2.8 kg CO_2eq per kg are released. At an electrical efficiency of 20% and an avoided greenhouse gas emission due to electricity production of 0.57 kg CO_2eq per kWh, 1.2 kg CO_2eq are avoided. The net effect is then 1.6 kg CO_2eq per kg polyethylene incinerated in a waste-to-energy incinerator. In the same way, the net efficiency for cardboard and VGF (vegetable, garden and fruit waste) can be calculated to be -0.52 kg and –0.11 kg CO_2eq per kg respectively.

The picture is completely different when the same materials are land-filled. In this case the carbon footprint of plastics are 0 kg CO_2eq per kg, because plastics are inert and release no emissions to the air. Cardboard is subject to anaerobic decomposition in the landfill, which releases 0.62 kg CO_2eq per kg material (CE 2007). In each country a certain fraction of a waste material stream is incinerated and a certain fraction is land-filled. A comparison of a number of different landfill and incineration scenarios reveals that the differences in the calculated carbon footprint per material are high. Moreover, it makes a big difference whether the generated electricity is compensated for or not.

Table 5.15 Calculation of the greenhouse effect of materials waste processing (based on Ecoinvent and data from the SEA for the Dutch National Waste Management Plan)

	Lower heating value / LHV (MJ/kg)	Fossil carbon content (kg CO_2/kg)	Electricity use (kWh/kg)	Avoided emissions (kg CO_2/kg)	Net emissions from waste-to-energy incinerator (kg CO_2/kg)
Polyethylene	38	2.8	2.11	1.20	1.60
Cardboard	18	0.05	1.00	0.57	-0.52
VGF	3.5	0	0.19	0.11	-0.11

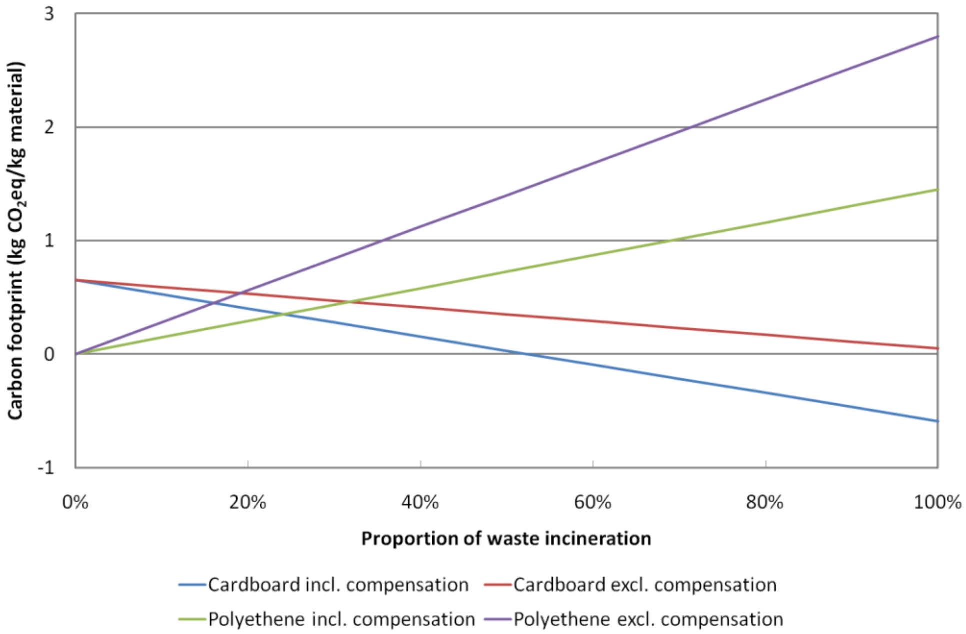

Figure 5.13 Changes in greenhouse gas emissions from waste materials by percentage incineration

Figure 5.13 also shows that manufacturers can choose materials according to the waste processing scenario in a country. If a relatively large proportion of the waste is incinerated, this will deliver a relative advantage to paper packaging.[13]

An important advantage of the PAS 2050 methodology is the lower data requirement for calculating carbon footprints of used materials. This applies to both materials recycling and waste processing. A disadvantage of the PAS 2050 methodology is that it is not consistent with the allocation principles formulated in section 5.1. Moreover, the simplification of the PAS 2050 methodology results in incomplete recording of the greenhouse gas emissions for materials, recycling and waste processing, which means that not all the potential options for improvement are revealed. We therefore propose including compensation for materials recycling and waste processing in the calculation: for materials recycling by averaging the inputs of secondary materials and

[13] Comparisons of the greenhouse gas emissions from the production of packaging depend on the total life cycle of the products concerned. Important factors besides the waste processing scenario are the amount of recycling and differences in weight.

recycling following disposal; and for waste processing by compensation (system expansion) in which the benefits from energy recovery are included in the calculation.

5.5.3 Recommendations for Best Practice in the protocol

In the protocol we recommend calculating the compensation for recycling via averaging and for waste processing via system expansion when energy recovery is involved. This approach requires the collection of specific data on the inputs of primary and secondary materials in material production, on recycling following disposal and on the methods used for processing the wastes materials that are no longer recycled. More data are therefore required to carry out analyses of the greenhouse effect. Data needs can be limited by using a database of standard values for materials, recycling and reuse, and waste processing. These data can be used for an iterative calculation of the greenhouse effect to determine the relative importance of the greenhouse effect of materials use.

5.5.4 Recommendations for further research

PAS 2050 does not provide a clear answer to the issue of recycling and waste processing. It would therefore be advisable to keep track of developments relevant to this topic and to consider whether the calculation methods should be amended in the light of any new insights.

5.6 Including animal manure in the calculations

5.6.1 Problem description

Organic fertilisers are used in the horticultural sector as a source of minerals and organic matter. Different types of organic fertilisers are used, the most common being animal manure, compost and champost (mushroom compost). As the Netherlands has a very high density of livestock farms, there is a surplus of animal manure. Intensive livestock farms with little or no land have to pay arable farmers or growers to take their animal manure and also pay for the transport costs. Mushroom growers also have to pay for the removal of their champost, especially since the animal manure and fertiliser legislation treats the application of champost in the same way as animal manure. These costs vary throughout the year for each type of compost or animal manure and from region to region, but livestock farmers and mushroom growers almost continually have to dispose of their animal manure or champost. In terms of life cycle analysis, this means that these residual products can be considered to be wastes because they have a negative economic value. In agricultural terms, however, these organic fertilisers have value for growers and arable farmers: they add organic matter, nitrogen, phosphate and potassium to the soil. Nevertheless, the payments made to arable farmers and growers for using animal manure and the less than constant quality of the manure lead to a less optimal use of these fertilisers compared to the use of artificial fertilisers in conventional agriculture.

In organic farming the use of animal manure is much more of a necessity than in conventional agriculture. As no artificial fertilisers are used, inputs of organic nutrients are needed to maintain soil fertility. This is also reflected in the prices of organic fertilisers. It is expected that when the standards for the permitted inputs of organic animal manure to organic farms are tightened, prices will rise and that arable farmers will in any case have to pay for some of this animal manure (Prins 2008).

The two different situations for organic and conventional farming are illustrated in Figure 5.14.

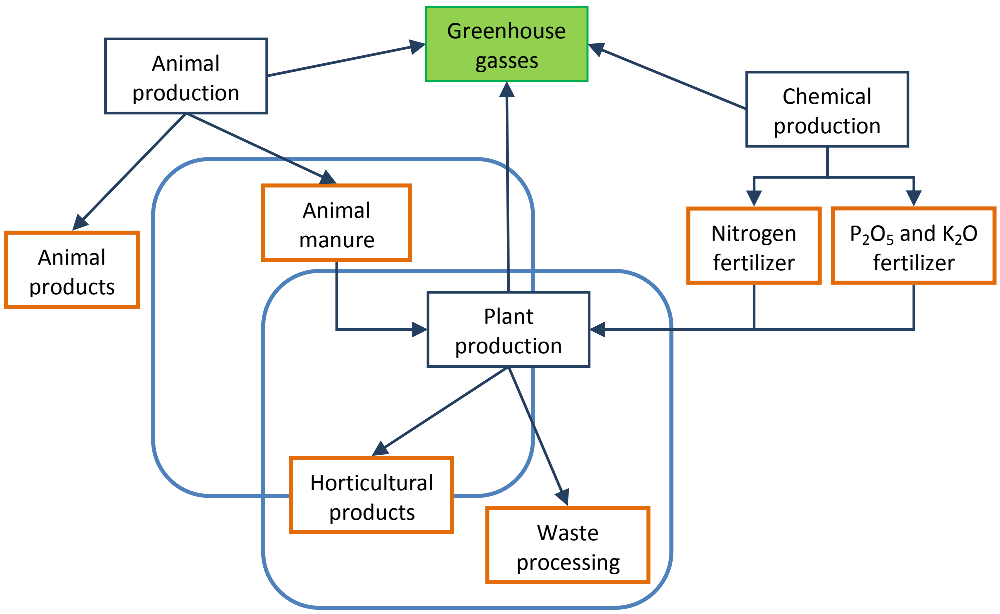

Figure 5.14 Use of animal manure: 'combined use of raw material and waste processing'

5.6.2 Review of solutions

Calculating the greenhouse gas emissions of a horticultural product involves first determining what part of the animal manure production chain and of the use of animal manure should be allocated to the horticultural production chain. The situation is different for Dutch conventional and organic farming.

Animal manure and other fertilisers from conventional agriculture

For conventional farming in the Netherlands, in which animal manure has a negative value and the use of animal manure in horticulture is in effect partly a waste management service for the Dutch livestock sector, we propose the following method based on the allocation principles formulated earlier:

Allocate the emissions from the transport and application of animal manure between livestock production and horticulture, based on the efficiency of application of the animal manure. As a reference for this, we use the efficiency of nitrogen application in relation to the legally determined efficiency of the use of artificial nitrogen fertiliser (Table 5.16 in the Dutch Fertiliser Policy brochure 2008–2009 [Brochure mestbeleid 2008–2009]). We chose to use nitrogen efficiency because this is by far the most important factor in determining the greenhouse effect arising from the use of fertilisers.[14]

[14] A second determining factor is the application of organic matter. At the moment, however, it is difficult to accurately link the effect on the increase or decrease in organic matter content to the application of manure (see also Chapter 7).

Table 5.16 Availability coefficient of different sorts of organic fertiliser

Type of fertiliser	Availability coefficient
Thin fraction (following manure treatment) and slurry	80%
Liquid animal manure on clay and peat	60%
Solid animal manure from pigs, poultry and mink	55%
Solid animal manure from other animals	40%
Champost	25%
Other organic fertilisers	50%

We qualify this proposal with the following points:

1. This method applies only to the situation in which the animal manure has a negative value for the producer. In various other European countries animal manure has a positive value and in these cases part of the environmental load of animal production should be allocated to horticultural production. This method is elaborated for organic production below.
2. Two other methods are also used in LCAs. The 'cut-off method', in which 100% of the emissions arising from the transport and application of animal manure are included in the calculation, and system expansion, in which the application of animal manure replaces the use of artificial fertiliser. The first method leads to higher greenhouse gas emissions for horticulture and therefore to lower greenhouse gas emissions for animal production. The second method leads to comparable greenhouse gas emissions when based on a nitrogen availability coefficient of 60% (Blonk 2008).
3. Nitrogen availability coefficients are also used in the fertiliser legislation for champost, compost and other organic fertilisers, such as various by-products from the food industry. For this we use the following approach. Champost with a nitrogen availability coefficient of 25% is treated in the same way as animal manure because the situation is comparable. Given the biological conversion process involved in mushroom cultivation, mushroom farms can be considered to be comparable in this respect to animal production and face the same problem regarding disposal of their compost. A significant proportion of the compost and other products used as fertiliser is sourced outside the agricultural sector. Some of these organic fertilisers are products with a positive economic value, such as feather meal and blood meal. The production pathways of these products (rendering of animal wastes) are included in the calculation.

Organic

Organic animal manure presents a different situation, namely that the agricultural production system requires the use of this manure. Moreover, the inputs of organic animal manure in organic farming will rise in the coming years, which means that eventually the arable farmers and horticultural growers using this animal manure will have to pay for it.

1. Economic allocation

When organic animal manure has a positive economic value, the economic allocation method can be used to calculate the proportion of the organic animal manure that should be allocated to horticultural and arable production. Research by the Louis Bolk Institute indicates that, in time, a return of five euros per tonne for liquid manure from cattle will be within the range of possible outcomes. Based on this and a balance calculation for the average organic livestock farm (Prins 2005; KWIN 2007; Blonk 2007), we calculate that for each tonne of manure about 20 kg CO_2eq should be allocated to the horticultural grower. For a typical use of 30 tonnes per hectare for many crops, this amounts to about 1800 kg CO_2 per ha. The greenhouse gas emissions per kg nitrogen therefore falls within the same range as for artificial fertilisers.

Table 5.17 Calculation of greenhouse gas emissions arising from the production of organic cattle liquid manure on a dairy farm, with a price for organic manure of €5 per tonne

	kg/ha	kg dry matter/ha	kg N/ha	GJ/ha	€/ha
Manure	3217	353	15.1	5.3	16
Animal production leaving the farm	8101	859	48.8	64.8	2835
Total (ex feed)	11319	1212	63.9	70.1	2852

Greenhouse gas emissions	
kg CO_2/ha	11340
kg CO_2/kg manure/ha	64.0
kg CO_2/tonne manure	19.9
kg CO_2/tonne N	3616

5.6.3 Recommendations for the protocol and calculation tool

The division between animal and plant production systems with regard to the application of animal manure presents a problem in conventional farming because of the lower efficiency of minerals applications due to the manure surplus. An allocation method designed to reveal the effect of changes at the system level should take the waste management function of arable farming or horticulture should into account. For the protocol and the calculation tool it is important to make a distinction between situations in which the manure has no value and those in which it does have value.

In addition, the use of animal manure is a issue because of the necessary interconnections between the plant and animal production systems. This is more of a problem in organic farming because of its greater dependency on animal manure. For organic farming, economic allocation could be a method for allocating part of the animal manure production to the plant production system. This works only when the organic manure really does have a positive and relatively constant value.

5.6.4 Recommendations for further research

Follow-up research could focus on three topics:

- How should the waste management function of the processing of animal manure from conventional farming and horticulture be included in the calculation?
- With regard to organic manure, how should the inter-linkages between plant and animal production be broken down so that some of the greenhouse gas emissions from animal production can be allocated to plant production, and vice versa?
- How should methane and nitrous oxide emissions from the interim storage of animal manure be allocated between animal and plant production?

6. Greenhouse gas emissions from soil and fertilisation

6.1 Problem description

In 2006 total greenhouse gas emissions in the Netherlands were about 207 billion (10^9) kg carbon dioxide equivalents (MNC 2008). Of this, about eight per cent was nitrous oxide (N_2O), approximately half of which were agricultural emissions from soils and livestock farming. Nitrous oxide also makes up about eight per cent of global anthropogenic greenhouse gas emissions (Figure 6.1).

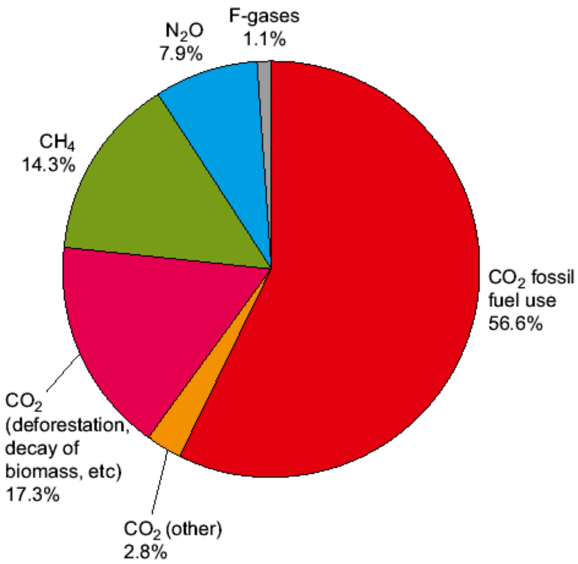

Figure 6.1 Breakdown of the global anthropogenic greenhouse gas emissions (IPCC 2006)

Nitrous oxide is formed in the soil by a combination of microbial processes (such as mineralisation, nitrification and denitrification), which are heavily influenced by fertilisation (amount, type of fertiliser, time of application) and soil conditions. Nitrous oxide emissions from fertilisation and from crop residues can be divided into direct and indirect emissions (Figure 6.2). When fertilisers are applied to the soil, some of the nitrogen in the fertiliser is emitted directly as nitrous oxide (direct emission), part of the applied nitrogen is emitted in the form of ammonia and some leaches to the groundwater or surface waters as nitrate. A proportion of the nitrogen in nitrates that leaches to surface waters is converted to nitrous oxide. Some of the emitted ammonia and nitrogen oxides other than nitrous oxide (NO_x) is deposited on soils and water (deposition). In turn, a fraction of this nitrogen input is also converted to nitrous oxide. When fertilisation is less efficient, more of the nitrogen in the fertiliser escapes to the air in the form of ammonia and indirect emissions will increase.

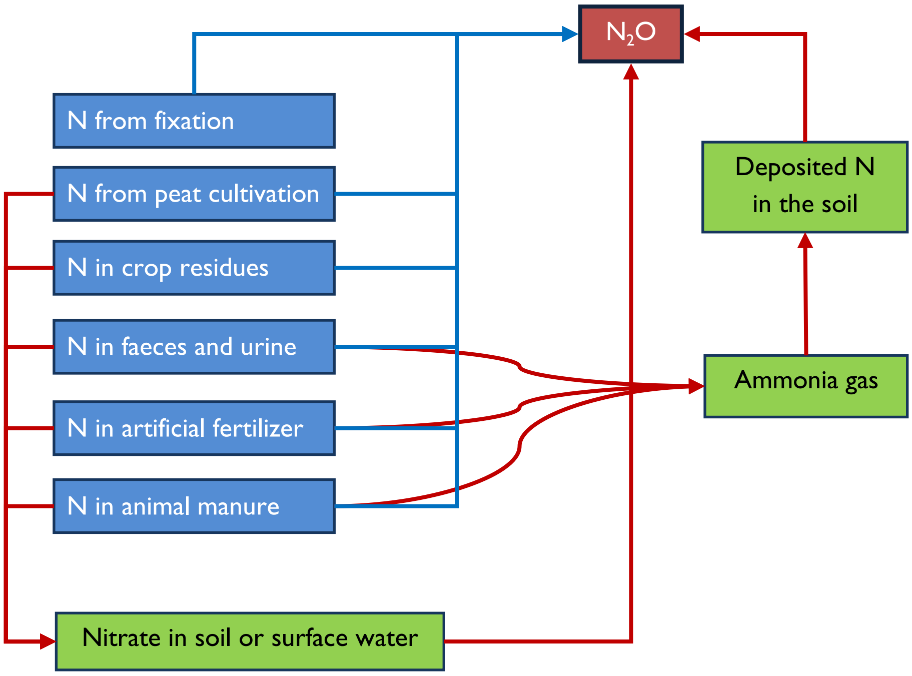

Figure 6.2 Schematic overview of direct (blue arrows) and indirect (red arrows) nitrogen flows that lead to nitrous oxide emissions from cultivation systems

By far the biggest source of nitrous oxide emissions from agriculture are direct emissions (about 60%). Indirect emissions make the second biggest contribution (about 35%). Nitrous oxide emissions from livestock farming make up just a small fraction of agricultural emissions (about 7%) and arise during manure storage and processing (Brandes 2006). Nitrous oxide emissions from the soil are a dominant factor in field grown horticultural products.

In addition to emissions of nitrous oxide that is formed in the soil as a result of fertilisation, nitrous oxide is also formed by soil processes independent of fertilisation. Peat soils used for agricultural production are drained, which leads to oxidisation of soil organic matter. This oxidisation results in emissions of carbon dioxide and nitrous oxide, and ground subsidence of 2–25 mm per year. Peat soils cover about 210,000 ha of the Netherlands (Alterra 2008). The greenhouse gas emissions from the oxidation of peat soils in the Netherlands are estimated to be about 4.6 million tonnes CO_2eq per year.

IPCC guidelines specify methods for calculating the direct and indirect greenhouse gas emissions from soils (IPPC 2006). These guidelines are used for the annual National Inventory Reports (NIRs) that countries have to prepare in accordance with the Kyoto Protocol. The 1996 IPCC guidelines are the standard reference work for compiling NIRs under the Kyoto Protocol until 2012. However, since 1996 new scientific knowledge relevant to the calculation of nitrous oxide emissions has been published by the IPCC itself, as well as by other scientists and technical experts. The IPCC guidelines also allow national calculations to be made using more detailed or more specific data under the Tier 2 and Tier 3 methods, which means that the nitrous oxide calculations may vary between countries. More detailed calculations of nitrous oxide emissions can be expected, particularly in those countries where nitrous oxide from the soil makes a material contribution, where specific research is carried out on this topic, and where these emissions must be monitored under the provisions of the Kyoto Protocol. More detailed, higher resolution or disaggregated data on emissions from the cultivation of crops in tropical countries will often not be available, although emissions in these countries will likely be different from cultivation in more temperate zones.

PAS 2050 provides no more specific guidelines or methods for the calculation of nitrous oxide emissions. However, it does state that the IPCC method, and more specifically the most recent IPCC guidelines, should be followed, preferably using methods at the most detailed possible Tier level. The development of the calculation protocol for horticulture revolves around the following key questions:

- What is the most accurate method for calculating nitrous oxide emissions in the Netherlands?
- Do equal fertiliser inputs in temperate and tropical regions lead to different nitrous oxide emissions?
- Should the same model for nitrous oxide emissions be used in each country?

6.2 Review of solutions

6.2.1 *The Dutch method*

Within the IPCC methodology, countries have the option of working with standard models and emission factors (Tier 1) or a more specific calculation method (Tier 2). The latter is only possible if the more specific method is sufficiently substantiated by scientific data. The Dutch national inventories are prepared using a part specific (Tier 2) and part standard (Tier 1) approach. This approach is described in protocols that are available from the website www.broeikasgasemissies.nl. Under the Kyoto Protocol it was agreed that the national reports for the years covered by the Kyoto Protocol (1990–2012) would be prepared in accordance with the IPCC guidelines of 1996, but with the proviso that during this period new knowledge concerning greenhouse gas emissions would become available. For example, in 2006 the IPCC published new guidelines and in 2007 the Global Warming Potential (GWP) factors for methane and nitrous oxide were revised (IPCC 2007). These new developments should in principle be taken into account in the current reporting. However, it is not clear which amendments can and will be incorporated into the reporting process. This means that there is a choice between compiling the method in line with the annual emission inventory drawn up under the Kyoto Protocol, which is based on partly outdated knowledge, or compiling the method in accordance with the most recent scientific insights (including those described in the IPCC guidelines of 2006), but which are not yet consistent with the Dutch emissions reporting. PAS 2050 opts in principle for the first option: in line with the NIRs, assuming they are compliant with the most recent IPCC guidelines..

6.2.2 *Tropical climates*

Biochemical processes in the soil proceed at a faster rate in tropical climates than in temperate climates. For this reason we investigated whether it would be possible to use more specific nitrous oxide factors for different climate zones. Further analysis of the research underlying the IPCC guidelines shows that the nitrous oxide emissions can vary considerably independently of the climatic conditions. This suggests, for example, that the fraction of nitrogen that volatilises from fertilisers increases as more nitrogen is applied, and that soils with a higher carbon and nitrogen content have higher direct nitrous oxide emissions (IFA-FAO 2001). Local soil conditions, such as soil moisture content, also have a strong influence on nitrous oxide emissions (Mosier 1997; Crill 2000; Weitz 2001). In warm climates soils appear to emit greater quantities of nitrous oxide from fertilisers than in temperate climates, but there is insufficient data available to produce a more detailed breakdown of these emissions for different climate zones (IFA-FAO 2001). IPCC has not incorporated these scientific insights into specific guidelines per climate zone or soil type. Agricultural use of peat soils is the only category for which the IPCC has defined different emission factors in its guidelines.

6.3 Recommendations for the protocol

The PAS 2050 method for calculating nitrous oxide emissions is to use the most specific calculation (highest Tier method) that is employed in the country of production. In effect, this means that the prime guidance in PAS 2050 is based on the IPCC guidelines of 1996, where appropriate supplemented with more specific or higher-order methods included in the National Inventory Reports of the country concerned. A disadvantage of this approach is that no use can be made of the most recent scientific insights. For example, in the IPCC guidelines of 2006 (IPCC 2006) the emission factor for indirect nitrous oxide emissions from nitrate leaching, which was 0.025 kg N_2O-N per kg leached nitrate-nitrogen in the 1996 guidelines, has been adjusted down to 0.0075. Furthermore, the 2006 guidelines no longer include nitrogen oxidisation as a source of nitrous oxide emissions.

In our Best Practice approach we choose to make use of the most recent scientific insights. While this method follows the national methodology for emissions reporting, three elements have been revised where the IPCC 2006 guidelines contain amendments to the 1996 guidelines.

In cases where it is not known how the country of production calculates emissions for its national reports, or if the country does not even report these emissions, the standard (Tier 1) method in the IPCC 1996 guidelines can be used when following the PAS 2050 recommendations, and the general method in the IPCC 2006 guidelines can be used when following the Best Practice method.

6.3.1 The general method in the IPCC guidelines

The IPCC's general method for calculating the greenhouse gas emissions from agriculture is described in the 1996 and 2006 guidelines (IPCC 1996, 2006). The direct nitrous oxide emissions are determined by the nitrogen input via artificial fertiliser, organic fertiliser, urine and excrement, crop residues, nitrogen mineralisation and biological nitrogen fixation. The nitrous oxide emission fraction from these nitrogen sources given in the IPCC guidelines of 1996 and 2006 are listed in Table 6.1. Table 6.2 lists the factors for indirect nitrous oxide emissions. The most conspicuous changes are: 1) direct nitrous oxide emissions from biological nitrogen fixation are no longer included in the calculation; 2) direct nitrous oxide emissions from urine and excrement were not included in the 1996 guidelines but are included in the 2006 guidelines with a factor twice as high as organic fertiliser; 3) volatilisation from organic manure was not included in 1996; 4) the nitrous oxide emission factor for leached nitrogen was reduced from 0.0250 kg N_2O-N/kg NO_3^--N in 1996 to 0.0075 in 2006.

Table 6.1 Direct emissions in the IPCC guidelines

Emission factor	Unit	IPCC 1996	IPCC 2006
Artificial fertiliser, organic fertiliser and crop residues	kg N_2O-N/kg N	0.0125	0.0100
Biological nitrogen fixation	kg N_2O-N/kg N	0.0125	-
Urine and excrement	kg N_2O-N/kg N	-	0.0200
Use of peat soils (temperate climate)	kg N_2O-N/ha	5	8
Use of peat soils (tropical climate)	kg N_2O-N/ha	10	16

Table 6.2 Ammonia and NO_x emissions and nitrate leaching from applications of artificial fertiliser and organic fertiliser, and the fraction that is emitted as nitrous oxide (IPCC 2006)

Parameter	Unit	IPCC 1996	IPCC 2006
Volatilisation from artificial fertiliser	kg NH_3-N/kg N	0.10	0.10
Volatilisation from organic fertiliser	kg NH_3-N/kg N	-	0.20
Volatilisation from faeces and urine	kg NH_3-N/kg N	0.20	0.20
Nitrate leaching	kg NO_3^--N/kg N	0.30	0.30
Emission factor for volatilisation	kg N_2O-N/kg NH_3-N	0.0100	0.0100
Emission factor for leaching	kg N_2O-N/kg NO_3^--N	0.0250	0.0075

6.3.2 Dutch emissions inventory

The Dutch method is described in the National Inventory Report (NIR) (VROM 2008) and uses a combination of standard values (Tier 1) and country-specific emission factors (Tier 2) (Table 6.3 and 6.4). The country-specific detailing in the Dutch method consists of a distinction between application methods for manure, artificial fertilisers and type of soil (mineral: sand, clay; organic: peat). According to the NIR, when calculating direct nitrous oxide emissions ammonia volatilisation should first be subtracted from inputs of nitrogen via organic and artificial fertilisers. The nitrous oxide emissions from the remaining nitrogen inputs are determined using the emission factors in Table 6.3.

Table 6.3 Emission factors in the Netherlands NIR for direct nitrous oxide emissions from agricultural land (source: VROM 2008)

Input source	Direct emission factor (kg N_2O–N per kg N input)	
	Mineral soils	Organic soils
Application of artificial fertiliser		
- ammonia-containing (no nitrate)	0.005	0.01
- other artificial fertilisers	0.01	0.02
Application of manure		
- surface application	0.01	0.02
- low-emission application	0.02	0.02
Livestock grazing		
- faeces	0.01	0.01
- urine	0.02	0.02
Nitrogen fixation	0.01	
Remaining crop residues	0.01	
Agricultural use of Histosols	0.02	

Table 6.4 The fraction of (gross) N applications to organic and artificial fertilisers emitted as ammonia

	Ammonia volatilisation fraction (kg NH3-N/kg N)
Surface application of manure	0.1035
Low-emission application of manure	0.1035
Ammonium sulphate	0.08
CAN (calcium ammonium nitrate)	0.02
Urea	0.15
Other fertilisers	0.034

The indirect nitrous oxide emissions are derived from the volume of ammonia emissions and nitrate leaching arising from the input of nitrogen to the soil. The NIR employs a standard value for nitrate leaching of 0.30 kg NO_3^--N/kg N of the gross nitrogen input (without subtracting the ammonia emissions). This leaching fraction applies to all nitrogen input items. The NIR nitrous oxide emission factor from the deposition of ammonia is 0.010 kg N_2O-N/kg NH_3-N and the emission factor from nitrate leaching is 0.025 kg N_2O-N/kg NO_3^--N (in accordance with IPCC 1996, but not with the 2006 guidelines, Table 6.2). The other nitrogen oxides (NO_x) volatilisation is also derived from the ammonia emissions (15% of the ammonia emissions). This emission has the same nitrous oxide emission factor as ammonia (0.010 kg/kg). The NIR gives standard values for the nitrogen input via crop residues and nitrogen fixation (Appendix 1 in VROM 2008[2]).

6.4 Recommendations for the calculation tool

For the demonstration tool we simplified the calculations by assuming that all cultivation takes place in the Netherlands and that therefore the Dutch method applies. The Dutch method is described in the National Inventory Report (NIR) and uses a combination of standard values (Tier 2) and country-specific emission factors (Tier 2). These include the fraction of nitrogen lost through volatilisation during the application of various fertilisers (Tables 6.3 and 6.4). In the Netherlands there is an even more detailed calculation method available in which the water table has an important influence on the leaching of nitrate. For the time being we ignore this method because it is not included in the NIR.

6.5 Recommendations for further research

The method for calculating nitrous oxide emissions is continually being improved, for example by the IPCC and for the Dutch NIR. We recommend monitoring these developments and assessing whether the protocol for horticultural products should be amended accordingly.

7. Land use and land conversion

7.1 Problem description

Land use and land conversion influence greenhouse gas emissions in various ways.

1 When land is brought into agricultural production the carbon in the above-ground biomass is removed and/or burned. This causes a one-time emission of greenhouse gases.

2 Because the agricultural system often captures much less carbon than the natural system it replaces, a potential amount of carbon storage is eliminated. In addition, the carbon store in the soil (dead organic matter, DOM) is no longer replenished after land conversion, while decomposition continues (Figure 7.1). In natural ecosystems some of the DOM in the soil can become fossilised, depending on local soil conditions. In peat soils, for example, carbon is slowly fixed into organic matter. Decomposing bacteria cannot survive in the anaerobic conditions in the peat and the DOM accumulates. When natural areas are reclaimed for agricultural use, the input of fixed carbon to the stock of DOM is severely reduced (just a small portion remains behind in the form of crop residues). This eliminates most of the sink function of natural ecosystems (Schlesinger 1990). Land use therefore removes a potential long term carbon sequestration in soil organic matter.

3 Besides stopping the process of fossilisation, agricultural reclamation leads to the breakdown of DOM in the soil. Soil drainage, ploughing and fertilisation increase the rate of organic matter decomposition in the soil, which further reduces the soil carbon stock. The rate of decomposition depends on the soil management regime, the crops and the inputs to the soil. For example, when crops are grown that are harvested in their entirety, leaving no crop residues on the soil, the decline in soil carbon is more rapid than when other crops are grown (Lasco et al. 2006). Eventually, this decline in the soil carbon stock will stabilise and a new soil organic carbon balance will be established consistent with the prevailing biotic and abiotic factors.

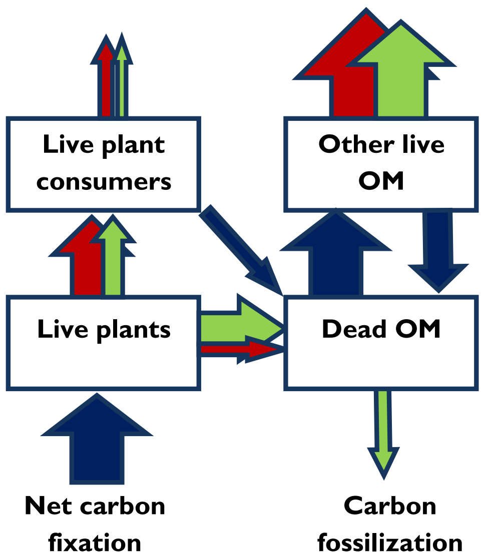

Figure 7.1 Carbon cycle in a natural ecosystem (blue and green arrows) in which fossilisation occurs, and in an agricultural system (blue and red arrows) in which there is no fossilisation.

As Figure 6.1 (in Chapter 6) shows, emissions from land use and land conversion make up more than 17% of the total global anthropogenic greenhouse gas emissions. However, they make up a much higher proportion of agricultural emissions because agriculture is only responsible for a small part of global greenhouse gas emissions and land conversion can be attributed for a large part to agricultural products. It is therefore important to quantify the greenhouse gas emissions related to land use and land conversion as accurately as possible.

PAS 2050 gives a method for attributing the greenhouse gas emissions from land conversion to crop products. As this method is derived from the UK biofuel protocol, it raises a number of questions which are discussed below. PAS 2050 contains no proposals for calculating the greenhouse gas emissions resulting from the blocking of the sink function of soils. However, it does state that specifications for calculating emissions and sequestration arising from changes in soil carbon is desirable in the longer term, particularly in relation to differences in agricultural land management practices. For the greenhouse gas emissions arising from the oxidation of peat land use and land conversion, the IPCC guidelines can be used.

For land conversion, PAS 2050 specifies that the one-time loss of carbon due to the conversion of natural vegetation cover to agricultural land should be amortized over a twenty-year period, which means that five percent of the total greenhouse gas emissions should be included in the emissions for the relevant products in each year during the twenty-year period after land conversion. For example, in the case of soybean cultivation on agricultural land in Brazil that began six years ago following the clearance of natural rain forest, the emissions arising from land conversion should be included in the calculations for the next 14 years, which works out as an emission of 37 CO_2 equivalents per hectare per year for 14 years. The attributed emission is 15 times higher than all greenhouse gas emissions from a hectare of land under soybean cultivation. The reason for choosing the time period of twenty years and not ten, thirty, fifty or one hundred is not explained in PAS 2050. For many other time-limited greenhouse gas emissions a period of one hundred years is used. Quite apart from the more or less arbitrary period over which these emissions should be amortized and the linear reduction, there are a number of objections that can be made to this method:

1 The first objection is theoretical in nature. The method is geared solely to those situations in which a *direct* conversion from natural vegetation to agricultural land has taken place for the cultivation of a specific crop on the land where that crop is grown. If in the meantime another crop has been grown on the land or the land has been used for livestock farming, according to the strictest interpretation, the direct relation between cultivation and the land conversion has been broken. However, soybean is often first cultivated on land which has previously been cleared for livestock farming (Bindraban & Grecco 2008). In this case, should the land conversion be allocated to the soybean cultivation? Another question is how to deal with a crop rotation. If, for example, a cereal crop is grown in the first year, followed by two years of soya beans and then cereals again, should all the emissions from land conversion be allocated to the first cereal crop? The rotation may also include a fallow period, or there may be a fallow period directly after clearance, before the first crop is grown. In any case, it would appear logical to assume that the emissions arising from the conversion should be divided between the crops in the rotation.

   The next step in this line of reasoning is that it is logical to divide the conversions between the types of agricultural use (which often follow a fixed sequence) following the land conversion. The reasons for reclaiming land for agriculture are often complex because economic, political and agricultural factors all play a role. The clearance and reclamation of land may also involve the exploitation of organic products, such as the felling and use of timber as a fuel or material. Various products may be produced during a hypothetical period of twenty years from the time the land was brought into cultivation, such as timber, meat and crops, and all these products have a certain relation to the land conversion. The simplest first-order approach would be to divide the land-conversion emissions between all outputs over a period of twenty years, based on the delivered utility using the economic allocation method. Once this allocation has been done, the greenhouse gas emissions from land conversion can be amortized over a period of 20 years.

2 If 'direct conversion' of a certain area of land is interpreted in a broader sense, as argued in point 1, the distinction between 'direct' and 'indirect' conversion is less stringent. Indirect conversion pertains to conversion that is initiated elsewhere by a change in the demand for all and/or the types of crops. For example, the cultivation of oilseed rape in the EU for use in the manufacture of biofuels displaced other arable crops, which then had to be grown elsewhere. Moreover, the growth of the biodiesel market for oilseed rape has stimulated the production of biodiesel from other oil seed crops, leading to the cultivation of oil palm and soybeans for this purpose, which in turn is pushing up the demand for land to grow these crops. If we abandon the distinction between direct and indirect conversion, we start from a different premise. We then have to consider the land conversion throughout the world or within a country (where policies have a large influence on agriculture and deforestation), the forces driving this conversion, and how the conversion of land at a specific location can be allocated across the demand for the various crops. No method is yet available for doing this. In this study, therefore, we take the first steps towards developing such a method (see section 7.2).

3 Another theoretical objection is that the results of using the 'write-off' method for calculating the greenhouse effect of land conversion can become out of step with the total for all crops in the world. If no more land conversion were to occur in the world, under the PAS 2050 method the emissions arising from land conversion would be included in the emissions calculations for the next 20 years.

4 A practical objection to this relates to the verification of the data collected by the producer. PAS 2050 proposes basing this on a disclosure obligation on the producer who is allocated the highest amount of greenhouse gas emissions from land conversion, unless the producer demonstrates that no or only very little land conversion was involved in their case. This amount is allocated to this producer's product when no information can be provided about the origin of the cultivated raw materials and the land conversion that took place in connection with those raw materials. If only the country of origin is known, the producer is allocated the highest possible amount of greenhouse gas emissions for that country. This approach raises questions about the practical interpretation and verification of the analysis of land conversion, especially when there are many intermediate stages (for example in soybean cultivation) and the interpretation of the concept of direct land conversion is broadened.

Given the above-mentioned objections, which at least call for the further development of the methods in PAS 2050, we propose approaching this issue in a different way. Each year a certain amount of land conversion takes place across the world and this has to be allocated to the expanding areas of agricultural crops.

With regard to the further development of our protocol, we pose the following questions:

1 To what extent is it possible to define an alternative method for land conversion that allocates all conversion from natural to agricultural land in the world based on a statistical analysis?

2 Is it possible to define a method for the loss of the sink function caused by the use of land?

3 Is it possible to define a method for the changes in soil organic matter caused by the agricultural use of land?

7.2 Review of solutions (further analysis)

7.2.1 Land conversion

The basic principle underlying the allocation of land conversion to crops is that additional land is required to meet the growing worldwide demand for agricultural products and that this land can be allocated across the total production volume of agricultural crops. Steinfeld *et al.* (2006) developed this idea in their report 'World's Livestock Long Shadow', in which they determine what part of the greenhouse gas emissions arising from land conversion and land degradation should be allocated to livestock farming. Some aspects of the premises and quantifications are debatable, but the basic idea offers a starting point for allocating land conversion via derived land conversion to derived greenhouse gas emissions. In this study this idea is developed in outline for a number of continents and crop categories. The method consists of the following steps:

1 First, we identify the annual change in agricultural area per crop per country by performing a trend analysis based on FAO statistics (see Table 7.1).

2 For countries where the agricultural area expands, we assume that a fixed fraction of the increase in the areas of the crops whose production is expanding is obtained from land conversion and the remainder from a decrease in the area of other crops (the fraction is equal to 1 - [sum of the areas of crops that decline in area]/[sum of the area of crops that increase in area]).

3 We combine the annual changes in the areas of crops grown in a country on land reclaimed from nature with an estimated amount of above-ground biomass per hectare of converted land (weighted average of areas per type of forest from the FAO data and above-ground biomass per type of forest from IPCC data) and a fixed amount of greenhouse gas emissions per above-ground biomass (1.8 tonnes CO_2eq per tonne; estimated from calculations using IPCC data) (see Table 7.2).

Table 7.1 Trends in relative changes in the areas of various crops based on data from FAOSTAT between 1982 and 2007

Crop	Africa	North America	South America	Eastern Asia	Southern Asia	Southeast Asia	West Asia
Soybeans	2.1%	1.2%	2.7%	0.8%	3.8%	-2.0%	-20.0%
Wheat	0.7%	-1.8%	-0.1%	-1.6%	0.6%	-1.6%	0.8%
Apples	3.6%	0.0%	1.1%	2.5%	1.6%	0.0%	2.1%
Bananas	1.2%	2.0%	1.4%	3.3%	1.4%	1.6%	2.4%
Beans, green	3.1%	0.9%	0.0%	4.1%	0.6%	4.9%	1.3%
Grapes	0.0%	1.1%	0.0%	2.9%	1.8%	2.8%	0.0%
Oranges	1.5%	1.8%	0.9%	1.7%	2.4%	1.7%	1.2%
Pineapples	1.5%	0.0%	2.8%	3.5%	1.9%	0.3%	3.6%
Potatoes	2.4%	0.3%	0.0%	2.6%	1.9%	2.2%	2.8%
Tomatoes	2.4%	0.0%	0.2%	3.3%	2.9%	0.1%	2.3%
Total	0.3%	-0.2%	0.4%	0.4%	0.0%	0.6%	1.9%

Crop	Oceania	Europe Central Asia	Rest of the world	World	Brazil	Argentina	USA
Soybeans	-11.8%	-1.2%	-27.7%	1.9%	2.4%	3.2%	1.1%
Wheat	1.2%	-0.5%	-4.8%	-0.3%	11%	8.8%	-0.5%
Apples	1.2%	0.0%	0.0%	0.6%	1.8%	0.0%	0%
Bananas	1.9%	0.0%	0.0%	1.4%	0.8%	0%	2.0%
Beans, green	0.4%	0.0%	0.0%	2.3%	0.0%	1%	0.6%
Grapes	3.0%	0.0%	0.0%	-0.9%	0.7%	0.0%	1.2%
Oranges	0.0%	0.1%	0.0%	1.6%	0.9%	0.4%	1.8%
Pineapples	0.0%	0.0%	0.0%	1.4%	2.2%	0%	0.0%
Potatoes	0.4%	0.0%	0.0%	0.4%	0.0%	0.0%	0.0%
Tomatoes	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total	-0.3%	-0.1%	0.4%	0.2%	0.7%	0.1%	-0.2%

Table 7.2 Results of calculations of greenhouse gas emissions arising from land conversion to various crops (in kg CO_2eq/ha)

Crop	Africa	North America	South America	Eastern Asia	Southern Asia	Southeast Asia	West Asia
Soybeans	3427	0	6915	1223	194	0	0
Wheat	1165	0	0	0	29	0	1639
Apples	5804	0	2757	3761	80	0	4445
Bananas	1910	0	3427	5016	70	2254	4923
Beans, green	4919	0	0	6104	33	6746	2760
Grapes	0	0	0	4392	90	3806	0
Oranges	2390	0	2308	2611	121	2361	2445
Pineapples	2386	0	7112	5239	96	428	7596
Potatoes	3902	0	66	3886	98	2989	5923
Tomatoes	3851	0	531	5027	146	138	4754
Total	402	0	907	657	1	841	4013

Crop	Oceania	Europe Central Asia	Rest of the world	World	Brazil	Argentina	USA
Soybeans	0	0	0	2830	6731	832	0
Wheat	0	0	0	0	29888	2311	0
Apples	0	0	0	861	5113	0	0
Bananas	0	0	0	2109	2208	0	0
Beans, green	0	0	0	3424	0	257	0
Grapes	0	0	0	0	2089	0	0
Oranges	0	0	0	2355	2442	97	0
Pineapples	0	0	0	2053	6257	0	0
Potatoes	0	0	0	511	0	0	0
Tomatoes	0	0	0	861	0	0	0
Total	0	0	0	325	1883	14	0

The method is feasible when using the values in these tables. The results as presented in Table 7.2, however, are tentative. The values in the table are greenhouse gas emissions from land conversion linked to the cultivation of crops in a number of world regions. We propose using these figures when producers do not have access to detailed data. A higher level of detail would be, for example, the country where the crop was grown and the specific requirements made of the cultivation method and the reclamation of land for the cultivation of that crop. A more country-specific approach can have a considerable effect on the results (Table 7.2, columns for Brazil, Argentina and South America).

Other country-specific calculations are possible, because the necessary data is available via the internet (faostat.fao.org). Exceptions to this method are the following situations:

- The conversion of land is part of the greenhouse gas emissions analysis, which means that if land was converted to agricultural use in the year preceding cultivation in or the year of cultivation, all the greenhouse gas emissions arising from the land conversion have to be allocated to the relevant crop.
- The relation between some crops and the relevant land conversions given in Table 7.1 is different from the average. This may be the case when specific crop criteria are used or the situation in a country is significantly different.

The method for calculating the greenhouse gas emissions arising from land conversion is consistent and gives firm figures. However, in most cases we do not get a definitive answer to the question of whether the emissions arising from land conversion, or how much of these emissions, should be allocated to the cultivation of a single crop. The calculation, therefore, serves mainly to give an indication of the significance of the effect. For the time being we propose reporting the greenhouse gas emissions from land conversion separately.

7.2.2 Loss of the sink function

Loss of the sink function is the carbon dioxide that would have been sequestered if the used land was never converted into agricultural land. This hypothetical situation is called a reference situation. The quantification of the loss of the sink function depends on the choice for what is considered as the reference situation: is it the most recent ecosystem before land conversion, the situation if human settlement (including the construction of dikes, canals, dams, *et cetera*) would not have occurred, or the ecosystem that would occur many years after abandoning the land? Because there are reasonable arguments for each choice, we recommend that the avoided sequestration due to land use is reported separately. We opt for the latter choice. Nabuurs and Schelhaas (2002) estimated that 300 year-old natural forests in Europe sequester about 0.4 tonnes of CO_2 per ha per year. However, there is a great variation between forest types and it also depends largely on the age of the forest (carbon sequestration is much faster in younger forests and the rate constantly decreases). We propose the use of the average value.

7.2.3 Organic matter differences

Various studies have calculated that the organic matter content in Dutch agricultural soils is declining and that therefore these soils emit greenhouse gases (Bos *et al.* 2007; Reijnders unpublished; Vleeshouwers & Verhagen 2001). Vleeshouwers and Verhagen (2001) have developed a model to calculate equilibrium stocks for various types of land use in the Netherlands.

The equilibrium stocks of soil organic matter vary considerably depending on the type of land use, the soil type and soil moisture content, with the degree of disturbance to the soil (ploughing) having a decisive effect on the final value. Permanent grassland therefore scores very well, cereal crops take an intermediate position, tuberous crops have lower scores and horticultural crops have the lowest scores.

In practice, though, the differences in carbon content between grassland and arable land are not as big. Field measurements give the values shown in Table 7.3.

Table 7.3 Carbon stocks in grassland, arable land and forest (source: Smit & Kuikman 2005)

	ha x 1000	C stock (Mtonne C)	tonne C/ha
Grassland	1426	148	96
Arable land	920	85	108
Forest (incl. other nature)	445	31	144
Total	2791	264	106

The stock in arable land in particular deviates significantly fromexpectations . This can partly be explained by the original (natural) carbon stock that was present in the soil before the land was taken into cultivation. Another reason for this difference is the sustained large input of organic matter to the soil via organic fertilisers, and in the past in the form of turves and sods. These two aspects were not included in the calculations by Vleeshouwers and Verhagen according to Smit & Kuiman (2005).

A long-term study (35 years) of the effects of land use (Nevens *et al.* 2003) also indicated a large difference in organic matter content between permanent grassland, permanent arable land and crop rotation. It revealed that the permanent conversion of grassland to arable land led to emissions of 250 tonnes CO_2 per hectare over a 30 year period. For horticultural products, the issue is the size of the annual change in the soil carbon stock. The figures for these losses from various studies are not identical, but most indicate a loss of carbon from agricultural soils (Reinders unpublished, Vleeshouwers & Verhagen 2001). The following questions are relevant with regard to the method of calculating greenhouse gas emissions arising from the production of horticultural products:

- Is it possible to calculate the loss of organic matter for specific crops?
- Is there a difference between organic and conventional arable farming and horticulture?
- What are the differences in soil carbon decomposition between countries?

Bos *et al.* (2007) compared large sets of data on organic and conventional arable and horticultural farms and came to the following conclusions:

1. No trend can be detected in the difference between the measured soil carbon stocks in organic and conventional farms. Sometimes the organic farms score better and sometimes the conventional farms score better.
2. No visible trend can be detected in the soil organic matter content on organic farms; over the years it increases as often as it decreases.

3 A model calculation of the trends in soil organic matter content on conventional and organic farms shows that the soil carbon content on organic farms decreases by 300 kg per hectare per year and on conventional farms by 470 kg per hectare per year.

The results obtained by Bos *et al.* (2007) for organic farming are at variance with results from foreign studies by Rodale (Pimentel 2005), which were checked by CE (Slingerland & van der Wielen 2005). A crucial point that should be noted concerning this foreign research is that it used optimised organic systems in which a linear increase in carbon storage was assumed. In contrast, Bos *et al.* (2007) employed a more realistic equilibrium model and studied comparable Dutch organic and conventional farms. For the time being it is assumed that the results obtained by Bos *et al.* (2007) are representative for the Netherlands and Western Europe. However, given the level of debate about these results, further specification per crop is not yet possible. Moreover, the problem of allocation within crop rotations also needs to be resolved.

7.3 Recommendations for the horticultural protocol

Based on the considerations discussed above we propose the following approach:

7.3.1 Land conversion

When specific information is not available, use the tables of greenhouse gas emissions from land conversion per continent per crop, or – if these are available – the tables per country per crop (Table 7.2). There are now two contrasting situations:

1 Expansion of the agricultural area is an explicit component of the life cycle of the product.

2 Crop cultivation criteria are used, which lead to a lower land conversion area at the macro scale for that crop.

7.3.2 Loss of the sink function

For all land uses, use a standard emission factor of 400 kg CO_2eq per ha.

7.3.3 Organic matter loss due to agriculture

Use the following values for Western Europe or the Netherlands.

Table 7.4 Greenhouse gas emissions due to the loss of organic matter

	Carbon loss C-ha*year
Cropping plan, conventional, Netherlands, clay	450
Cropping plan, conventional, Netherlands, sand	450
Cropping plan, organic, Netherlands, clay	300
Cropping plan, organic, Netherlands, sand	300
Grassland	0

7.3.4 Reporting

As none of the three methods has yet been fully developed, report the results separately.

7.4 Recommendations for further research

The methods proposed here for calculating the greenhouse gas emissions related to land use and land conversion should be considered as a first step towards quantifying the size of the effect in relation to the cultivation of crops. We have also indicated that, given the current state of knowledge, it is important to report the results obtained from using this method separately. Two lines of methodological research still need to be pursued on this topic:

1 How big are the effects of the loss of sink functionality, changes in organic matter content and land conversion? Research will be carried out on this topic at various places in the world. A review of this research and further analysis of the various methods available in the different countries is desirable, after which the calculation per hectare can be updated.

2 In addition, more fundamental research into LCA methodology is desirable with regard to the question of how and to what extent these effects should be allocated to products.

8. Greenhouse gas emissions from the use of peat

8.1 Problem description

Various cultivation substrates are used in horticulture, especially in covered and heated horticultural production. Substrates (such as potting compost) are also used in field cultivation to replace the loss of organic matter or soil removed in root balls (of trees, for example). Peat is an important horticultural substrate: ninety per cent of all growing mediums are based on peat substrate. Each year Dutch potting compost producers import about 4.2 million cubic metres of peat, mainly from the Baltic countries (M. Bertens, personal communication: Estonia, Latvia and Lithuania), the Scandinavian countries (Denmark, Norway, Sweden and Finland), Russia and Ireland (Verhagen *et al.* 2008). We estimate the annual consumption of potting compost in Europe to be 20 to 30 million cubic metres. The other raw materials used to prepare growing mediums are compost and other organic materials not derived from peat.

Peat is a fossil material formed because sphagnum moss fixes carbon dioxide in organic matter. Fossilisation is a very slow process. Under anaerobic conditions the carbon can remain locked up for thousands of years. The extraction and use of peat in potting compost releases this carbon to the atmosphere in the form of carbon dioxide and other greenhouse gases. Energy is needed to extract and transport the peat, which in turn involves the release of greenhouse gases. The extraction of peat is often accompanied by drainage, which makes the conditions in the soil aerobic and causes nitrous oxide to be emitted. When peat is used, for example in potting compost, the fossil organic matter in the peat is oxidised, releasing carbon dioxide and nitrous oxide into the atmosphere.

8.2 Review of solutions

IPCC (2006) describes a method for calculating the emissions arising from the extraction of peat from peat soils for use in the horticultural sector. This method make a distinction between various phases in the supply chain, from extraction to the use phase. Our aim is to quantify emission factors for the amount of peat that is used in the horticultural sector. In doing so we follow the IPCC guidelines as closely as possible. The production cycle of peat extraction consist of three phases:

1 ***Preparation*** The peat areas are prepared for the extraction process. In this phase, drainage ditches are dug to drain the area. When the water table begins to fall the biomass on the surface of the peat (including trees, bushes and living sphagnum moss) is removed. Some areas where peat is extracted have already been drained for other uses. The greenhouse gases released in this phase consist mainly of carbon dioxide from the removal of organic matter and the decomposition of peat as a result of the drainage. The standard value for the duration of the drainage phase is five years. The emissions released during the preparation phase are spread over 35 years, the average time that peat soils can be extracted.

2 ***Extraction*** The peat is excavated in pieces and dried in the sun. This may be done in various ways: vacuum harvesting and non-vacuum block cutting. When it has dried out the peat is transported. The main source of greenhouse gases in this phase is the on-site decomposition of the organic matter in the peat, which releases carbon dioxide and nitrous oxide.

3 ***Other uses*** Peat soils no longer being exploited for the extraction of peat are often used for other purposes and therefore remain drained, which leads to greenhouse gas emissions.

The emission factors for the preparation and extraction phases are specified for nutrient-rich, nutrient-poor and tropical peat soils. The calculation of the greenhouse gas emissions from the use of peat is based on average nutrient content and a temperate climate (the Baltic countries and Ireland). Cleary (2005) estimated the average annual yields from a peat deposit to be 100 tonnes per hectare and the use of fuels during extraction to be 676 kg diesel per hectare and 0.4 cubic metres of gas per hectare.

Table 8.1 Emissions during the preparation and extraction of peat (converted from 5 to 35 years)

	Nutrient-rich peat soil (ha)	EF1	Nutrient-poor peat soil (ha)	EF2	Carbon/nitrogen in emissions (tonnes/ha/y)	Conversion factor (kg/kg)	CO_2 emission (kg CO_2/tonne)
On-site CO_2	0.5	1.1	0.5	0.2	0.00065	44/12	23.83
On-site N_2O	0.5	1.8	0.5	0	0.0042	44/28	42.15
CO_2 preparation	0.5	1.1	0.5	0.2	0.00065	5/35*	3.40

The emissions in Table 8.1 and 8.2 apply to air-dried peat with a moisture content of 35 to 55 per cent and an average relative density of 0.38 kg per kg (Blain 2006). The carbon fraction of air-dried peat is on average 0.43 kg per kg (Blain 2006). Based on Aarts (1999), we assume that 0.60 kg per kg of the carbon fraction will eventually oxidise to form carbon dioxide. The off-site emissions are therefore 0.94 kg carbon per kg peat. We assume that 0.60 kg per kg of the nitrogen in the peat mineralises, of which two per cent is in the form of nitrous oxide. Converted to carbon dioxide equivalents, this is 0.12 kg carbon dioxide per kg peat.

Table 8.2 Emissions arising from the oxidation of peat when it is processed, for example into posting compost

	C or N fraction (kg/kg)	Mineralisation fraction (kg/kg)	Greenhouse gas emissions from peat (kg CO_2eq/tonne)
Decomposition of carbon (off site)	0.425	0.60	935
Decomposition of nitrogen (off site)	0.022	0.60	124

The distance covered when peat is transported by road from the Baltic countries is about 1600 km. For this we have calculated an emission of 21.5 carbon dioxide equivalents per tonne of peat.

Peat is extracted from three types of fields: primary peat-lands; regularly cultivated peat-lands; and forested peat-lands. The highest quality peat comes from primary peat-lands. Peat also comes in different types. The top one and a half metres of a peat deposit consists of white peat, which is drier and has a lighter structure than the lower layer, black peat. There are a number of substitutes for peat, including coir (coconut fibre) and compost. Cultivation methods need to be adapted when working with new potting compost mixtures.

8.3 Recommendations for the horticultural protocol

We recommend using the results of our calculations for the total greenhouse gas emissions from the use of peat per tonne or per cubic metre (Table 8.3).

Table 8.3 Greenhouse gas emissions from the use of peat per component per tonne and per cubic metre (based on 0.165 kg per m³)

	Emissions from peat (kg CO_2eq/tonne)	Emissions from peat (kg CO_2eq/m^2)	Fraction
Preparation phase	3.4	0.001	0%
Peat extraction (on site)	66.0	0.010	5%
Fuel consumption for peat extraction	58.1	0.009	5%
Decomposition of carbon (off site)	935.0	0.146	77%
Decomposition of nitrogen (off site)	123.6	0.019	10%
Transport	21.5	0.003	2%
Total	1207.6	0.188	100%

8.4 Recommendations for further research

The most significant greenhouse gas emission associated with the use of peat is the decomposition of carbon (Table 8.3). The size of this emission is determined by the carbon content of the peat and the degree to which it decomposes. In this study we assume an average carbon content of 0.43 kg per kg (Blain 2006). Blok (2008) assumes a carbon content of 0.58 kg per kg peat; however, he also assumes that peat consists entirely of plant material. He assumes a lower limit for peat for burning of about 0.44 kg per kg, higher than the content estimated by Blain (2006). For uncertainty analyses, we recommend to apply the higher value given by Blok (2008).

In this study we use an expert estimate by Aarts (1999) of 0.6 kg per kg decomposition. Blok (2006) estimates the decomposition of carbon in peat to be 0.85 kg per kg. This value is for a period of 100 years and for peat that is mostly used in horticulture as a substrate, in which a relatively large proportion of organic matter is decomposed. Another use is the application and mixing of peat in field soils, when a relatively smaller proportion of the organic matter will be broken down. According to Blok (2008), in this case 0.6 kg per kg is representative, but for use in horticulture a higher decomposition fraction is more representative. This would mean that using the value 0.6 kg per kg would lead to a significant underestimate of the greenhouse gas emissions from the use of peat. It is therefore essential that further research be undertaken that includes an uncertainty analysis.

9. Transport modelling

9.1 Problem description

Horticultural products are transported as fresh products in one or more steps in the supply chain. Transporting fresh produce can lead to greater time pressures and losses in comparison with non-perishable produce. The time constraints on the transport of fresh produce influences the desired mode of transport (for long distances air transport is faster than sea transport) and the load factor (extra losses versus lower load factor). The case-specific greenhouse gas emissions from a horticultural product are therefore not only dependent on the distance in kilometres, but also on the mode of transport and the loading and transport efficiency.

In literature many emission factors can be found for transportation by various modes of transport. These data are not always reliable and often only an average figure is given for each mode of transport, despite the fact that these are based on various assumptions about loading, extra kilometres and vehicle efficiency. These data are also often aggregated, and it is not clear whether or not they take into account the production of fuels and the production of vehicles and infrastructure.

PAS 2050 contains no concrete pointers for the modelling of greenhouse gas emissions from transport, with one exception. For air transport, PAS 2050 states that the emissions of greenhouse gases from aircraft at high altitudes does not have to be corrected for the emission of various other gases, such as ozone, water vapour and NO_x, that lead to cloud formation, which reinforces the greenhouse effect (radiative factor = 1). For horticulture, it is questionable whether using a set of standard values will be a satisfactory solution. We assume that it will be necessary to make a more precise calculation of greenhouse gas emissions for each transport situation.

9.2 Review of solutions

In this project we used a combination of field data and data from the literature to build a model that can calculate the greenhouse gas emissions per functional unit for various transport situations. This includes parameters for the loading capacity (or type) of the transport mode, the load factor and additional kilometres, which can be adjusted. Table 9.1 shows that these settings can influence the greenhouse gas emissions per tonne per kilometre.

Table 9.1 Greenhouse gas emissions per tonne per kilometre for three modes of transport; Ecoinvent data compared with results from the calculation tool (no additional kilometres is indicated by extra km factor 100%)

Ecoinvent/tool	Transport mode (type/loading capacity	Extra km factor	Intermediate stops	Loading factor	RF	Greenhouse gas emissions CO_2eq/tonne/km
Ecoinvent	Aircraft					1.056-1.963
Calculation tool	Aircraft (B747: 100-300)*	100%	0	76%	1.9	1.0415
Calculation tool	Aircraft (B747: 100-300)*	150%	0	76%	1.9	1.6575
Calculation tool	Aircraft (B747: 100-300)*	150%	1	76%	1.9	1.7126
Calculation tool	Aircraft (B747: 100-300)*	150%	1	70%	1.9	1.8594
Ecoinvent	Lorry (>16 tonnes)					0.1253
Calculation tool	Lorry (24 tonnes)	150%	0	75%	1	0.0919
Calculation tool	Lorry (24 tonnes)	200%	0	50%	1	0.1767
Ecoinvent	Lorry (3.5–16 tonnes)					0.3317
Calculation tool	Lorry (9.25 tonnes)	150%	0	75%	1	0.1757
Calculation tool	Lorry (9.25 tonnes)	200%	0	50%	1	0.3332
Ecoinvent						0.0090
Calculation tool	Container ship (2750 TEU)	150%	0	80%	1	0.0025
Calculation tool	Container ship (5000 TEU)	150%	1	80%	1	0.0015

* Assuming a flight distance of 5500 km in connection with the allocation of the extra stops across the total distance

The model consists of the following elements: aircraft, road and sea transport.

Aircraft transport

Kerosene consumption is modelled for six types of aircraft (Sorensen & Kilde 2001). Equation 9.1 is used to calculate the greenhouse gas emissions in carbon dioxide equivalents arising from the use of kerosene during the flight.

$$GHG_{Air} = ((a*(A_{Air} * f_{Extra})^2 + b*(A_{Air} * f_{Extra})) *GHG_{Kerosine}*RF) + t*LTO*GHG_{Kerosine} \quad (9.1)$$

In which

- GHG_{Air} is the greenhouse gas emissions from the use of kerosene during the flight [kg CO_2eq/kg]
- *a* and *b* are regression factors for calculating the use of kerosene for the distance travelled; the unit for *a* is [kg/km^2] and the unit for *b* is [kg/km]
- A_{Air} is the distance travelled per aircraft [km]
- f_{Extra} is one plus the ratio of the extra distance divided by the distance travelled per aircraft [km/km]
- *t* is the number of intermediate stops
- LTO is the Landing and Take-Off kerosene consumption [kg]
- $GHG_{kerosene}$ is the greenhouse gas emissions per kilogram of kerosene used [3.55 CO_2eq/kg]
- RF is the Radiative Forcing Index [1.0 kg CO_2eq/kg CO_2eq]

The values for LTO, *a* and *b* for the different aircraft types are given in Table 9.2.

Table 9.2 Parameter values for air transport

Aircraft type	LTO (kg)	Kerosene consumption for flight a (kg/km^2)	Kerosene consumption for flight b (kg/kg)	Max. loading capacity[a] (kg)	Max. flight distance (km)
B747 100-300	3414	0.00026	10.3057	100000	9075
B747 400	3403	0.00021	7.736	112400	9200
DC 10-30	2381	0.00022	9.3337	70000	7505
B777	2563	-0.00011	7.52	54884	14316
MD 82	1003	0	3.879	20000	4000
F 100	160	0	2.959	10200	3000

a. Sources: Boeing 2003, Freight Watchers, Airliners

Road transport

Diesel consumption by lorries is modelled on the basis of loading capacity (NMT 2002; Kristensen 2006; Bakker Wiltink 2008; Greenery 2008). Equation 9.2 is the formula used to calculate the greenhouse gas emissions in carbon dioxide equivalents per kilometre travelled.

$$GHG_{Road} = [(a_{Road}*\text{loading capacity [ton]}+b_{Road} * c_{Road} * A_{Road} * f_{extraRoad}]* \rho_{diesel} *GHG_{diesel} \quad (9.2)$$

In which

- GHG_{Road} is the greenhouse gas emissions arising from road transport [kg CO_2-eq./trip]
- a_{Road} is the regression factor for loading capacity (0.0065 kg/tonne)
- b_{Road} is the regression factor for the load factor (0.22247 kg)
- c_{Road} is the corrected load factor [tonne/tonne], which can be calculated using the following formula (TNO personal communication): c = 0.25*load factor [%]+0.75
- A_{Road} is the distance travelled by road [km]
- f_{Road} is one plus the ratio of the extra distance divided by the distance travelled by road [km/km]
- ρ_{diesel} is the fuel density of diesel (0.84 kg per litre)
- GHG_{diesel} is the greenhouse gas emissions per kilogram of diesel used [3.6 CO_2eq./kg]

For cooled transport it is assumed that the fuel consumption is 5% higher.

Sea transport

The model for the fuel oil consumption of container ships is based on the loading capacity of the ships (Maersk Line 2007). The formula used to calculate emissions in carbon dioxide equivalents is:

$$GHG_{Sea} = (0{,}001 * \text{laadvermogen [ton]} + 50.26 * c_{Sea} * A_{Sea} * f_{extraSea} + (d_{Sea}*(t_{Sea}+ 1))*GHG_{stookolie} \quad (9.3)$$

In which

- GHG_{Sea} is the greenhouse gas emissions from sea transport [kg CO_2-eq./trip]
- 0.001 is the fuel oil consumption per tonne of load capacity per km sea transport
- 0.56 is the fuel oil consumption at a load factor of 100% per km sea transport
- A_{Sea} is the distance travelled by sea
- $f_{extraSea}$ is one plus the ratio of the extra distance divided by the distance travelled by sea [km/km]
- c_{Sea} = 0.14*load factor[%]+0.86
- d_{Sea} is the fuel oil consumption in the port, for example for 'hotelling' [4080 kg]
- t_{Sea} is the number of extra stops in ports

- $GHG_{stookolie}$ is the greenhouse gas emissions per kilogram of fuel oil used [3.58 CO_2eq./kg]

The load factor cannot be lower than 0.38, to account for the ballast water needed to maintain stability. Fuel consumption in port is 4080 kg fuel oil, independent of the size of the ship (converted from EPA 2000 and Trozzi & Vaccaro 1998).

The fuel consumption of container ships is calculated on the basis of the loading capacity in TEU, a measure of volume. To calculate consumption per tonne, the load (tonnes) per container and the load factor of the containers (percentage that is loaded) are entered. These form the basis for the calculation of the emissions per tonne of transported product.

Table 9.3 Standard settings for modelling transport emissions in the calculation tool

Variables	Aircraft	Lorry	Container ship
Loading capacity / type	Boeing 747 100-300	14 tonne[a,c]	2750 TEU[c]
Loading capacity [tonne]	100	14	2750*14=38500[d]
Loading factor	76%[e]	100%	80%
Extra kilometres factor	200%	175%	150%
Load factor correction (c)	-	0.25*load factor + 0.75 = 1	0.14*load factor 0.86 = 0.972
Fuel consumption port/airport	3414 kg kerosene	-	4080 kg fuel oil
Fuel density	-	0.84 kg/l[f]	
RF	1.0	-	-

a.TLN; Bakkerij Wiltink 2006; b. Maersk Line 2007c d. CBS 2005; d. Schiphol 2006; e. IPCC 1996 Vol. 2, section 1; f. Sausen *et al.* 2005;

9.3 Recommendations for the protocol and calculation tool

As stated in Chapter 3, the proportion of the carbon footprint of horticultural products that is due to transport is heavily dependent on the mode of transport used. Transport by air has a much higher greenhouse effect per tonne per kilometre than transport by container ship.

For the time being we decided to develop emission models for the three modes of transport encountered in the horticulture cases (aircraft, lorry and container ship) and incorporate these into the calculation tool. Standard greenhouse gas emissions per kilometre were determined, based on average types of vehicle, load factor and extra kilometres. Using the current calculation tool, therefore, it is possible to determine the items responsible for the highest share of greenhouse gas emissions by using the standard settings. If this shows, for example, that air traffic accounts for a major share of the total emissions, it will be possible to use case-specific settings instead of the standard settings. The load factor, intermediate stops and extra distance travelled in kilometres may then affect the total score.

When transport has a marginal influence on the total carbon footprint, the standard settings for the means of transport will be sufficient. When case-specific information on the means of transport (e.g. the size of the vehicle, load factor and extra kilometres) is available, these values can easily be adjusted.

The greenhouse gas emissions from transport per functional unit can be calculated by entering the number of kilometres for the transport from one stage in the supply chain to the next. The calculation tool does not contain built-in greenhouse gas emission values for the means of transport themselves (the materials, construction and maintenance of the vehicle) because it was too difficult to allocate these to the different horticultural products. These items will probably make only a very limited contribution to the total score because these means of transport are intensively used over long periods of time.

9.4 Recommendations for further research

To keep the calculation tool up to date it will be necessary to follow developments in the transport sector, because developments are moving apace. For example, container ships are getting bigger (Man B&W Diesel A/S), reducing emissions per functional unit. Studies are also underway on the feasibility of introducing larger lorries in Europe, which will also lead to lower greenhouse gas emissions per functional unit. Furthermore, there are developments that make it possible to replace air transport of horticultural products with sea transport, which can significantly reduce greenhouse gas emissions.

At the moment the greenhouse gas emissions from aircraft transport are being subjected to intensive scientific study. There is as yet no consensus on whether or not to correct for the radiative forcing (RF) effect of aircraft exhaust gases emitted at high altitudes. For example, it is known that aircrafts directly emit greenhouse gasses (carbon dioxide and methane), but they also have an indirect effect, such as the formation of condensation trails (contrails) and enhanced cirrus cloudiness (Minnis *et al.* 1999; Stuber & Foster 2006). Little is known about these indirect effects on global warming, and opinions differ on this point. The radiative forcing effect, or Radiative Forcing Index (RFI), for aircraft emissions was calculated by IPCC in 1999 to be 2.7, but recently this factor has more often been set at 1 (BSI 2008; Defra 2008). The IPCC guidelines (IPCC 2006) ignore the radiative factor entirely in the chapter describing the method for calculating the greenhouse gas emissions from air transport.

A study by Defra (2008) cites a proposed text explaining the issues related to radiative forcing (see Box 9.1).

Because the RFI has a large effect on the carbon footprint of air transport, it will be necessary to follow developments in this area and possibly to adjust the RFI for air transport in the calculation tool.

Box 9.1: Proposed text explaining the issues surrounding radiative forcing

Aviation has effects on climate beyond that resulting from its CO_2 emissions, including effects on tropospheric ozone and methane from its NO_x emissions, water vapour, particle emissions and formation of contrails/enhanced cirrus cloudiness. This is usually calculated with the climate metric 'radiative forcing'. Aviation was shown by the IPCC (1999) to have a total radiative forcing of 2.7 times that of its CO_2 radiative forcing for a 1992 fleet (the so-called Radiative Forcing Index, or RFI), excluding any effect from enhanced cirrus cloudiness which was too uncertain to be given a 'best estimate'. More recently, the radiative forcing for the year 2000 fleet was evaluated by Sausen *et al*. (2005) which implies an RFI of 1.9, based upon better scientific understanding, which mostly reduced the contrail radiative forcing. Similarly to IPCC (1999), Sausen et al. (2005) excluded the effects of enhanced cirrus cloudiness but others (e.g. Stordal *et al*., 2005) have improved calculations over IPCC (1999), which indicates that this effect may be 10 and 80 mW/m^2 (cf 0 to 40 mW/m^2 of IPCC) but are still unable to give a 'best estimate' of radiative forcing.

Whilst it is incorrect to multiply CO_2 emissions by the RFI, it is clear from the foregoing that aviation's effects are more than that of CO_2. Currently, there is not a suitable climate metric to express the relationship between emissions and radiative effects from aviation in the same way that the global warming potential does but this is an active area of research. Nonetheless, it is clear that aviation imposes other effects on climate which are greater than that implied from simply considering its CO_2 emissions alone.

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10. Data

10.1 Problem description

The reliability and consistency of a calculated carbon footprint of a product depends to a large degree on the nature of the data sources. The results depend on the specificity of the data for the processes being considered and the relative contribution of a process to the total greenhouse gas emissions.

A typical horticultural product goes through the following processes:

- cultivation of the propagation material;
- cultivation of the crop;
- processing (of the crop to consumer product);
- storage and distribution (between and within various stages in the supply chain);
- transport between all stages in the chain to the retail outlet.

For the most part, these processes are specific to the product, and data specific to these processes must be used in the calculation. This method is also recommended in PAS 2050.[15] The closer these processes are to the final product in the supply chain, the less specific they are to the final product. For example, because supermarkets sell many more products than the horticultural product under investigation, a certain proportion of the general processes within the supermarket should allocated to the horticultural product (see also section 5.4).

The processes that are specific to the horticultural supply chain are called foreground processes. We must determine where these process steps are localised and collect as much specific data on them as possible. An example of a foreground process is waste processing.

There are also background processes. These processes are not influenced by the specific horticultural chain, but deliver inputs to the horticultural chain. They include the production of energy carriers, packaging materials and waste processing. Data on background processes can be specified at local, national and global levels. An example of background processes is the production of artificial fertiliser or metals that are traded on the world market. Often more general average data will be used for calculations of background processes. When there is no specific relation between the horticultural chain and these materials, these will be the preferred data to use because it is impossible to predict where specific products are produced. In these cases, a global or European average is preferable to a value for a specific production process at a certain location. Figure 10.1 illustrates the types of processes that are used in a horticultural chain and the required representativeness of the data.

[15] PAS 2050 follows general standards, such as those in the LCA ISO 14044: 2006 with respect to representativeness (period, location, technology), measurement precision and uncertainty, completeness and consistency. It then gives several specifications for the use of primary and secondary data and the degree of representativeness and precision.

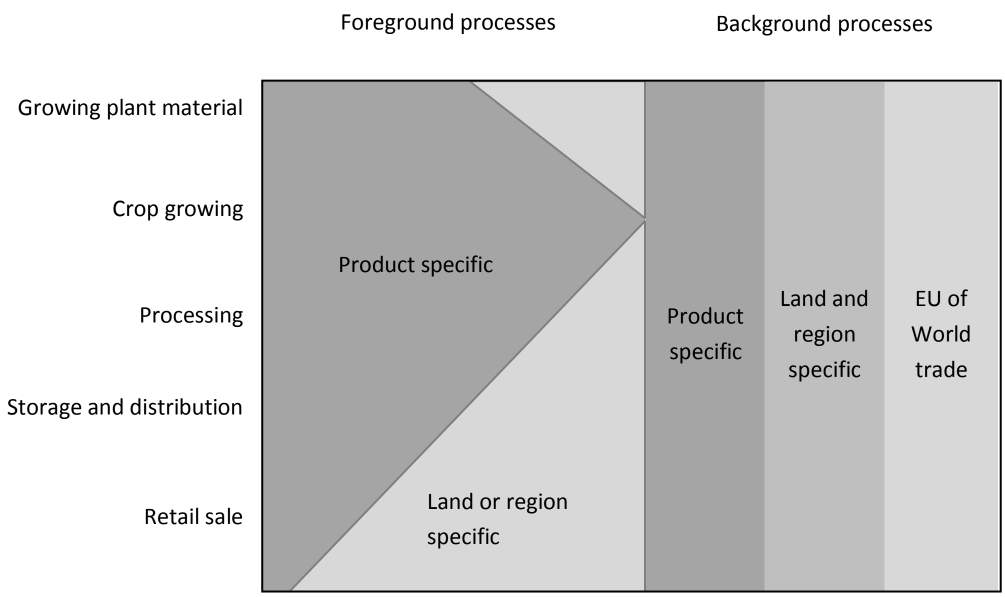

Figure 10.1 Foreground and background processes in a horticultural chain and the degree of specificity of process information

PAS 2050 contains several specific guidelines for the selection and use of data. In this chapter we elaborate on these guidelines. We also review several important foreground data for horticultural products and examine a number of sources of background data.

10.2 Further analysis and proposal for data

10.2.1 Reflection on several relevant PAS 2050 guidelines

PAS 2050 contains several guidelines for the selection and use of data. Here we examine how far these guidelines can be used for horticultural products and identify where they need to be elaborated in more detail.

1. Primary activity data

The organisation implementing the PAS 2050 analysis is required to use primary activity data for the processes and activities it owns, operates or controls. This also applies to downstream processes that take place after the product is delivered to the customer. However, when an organisation compiling a carbon footprint according to PAS 2050 makes a contribution of less than 10% to the upstream emissions of the product delivered to the next stage in the supply chain, the requirement to use primary activity data applies to the first upstream stage that contributes more than 10%. The primary activity data relate mainly to energy consumption and materials use and not to emissions of nitrous oxide and methane.

In concrete terms, this principle means that a company trading in horticultural products has to generate primary activity data on the cultivation or transport with its supplier. This is a logical requirement for the cultivation stage, but it can present greater difficulties for the transport stage. Transport is often contracted out to a transport company, for example an airline. A strict interpretation of this guideline would mean that measurements should be made of the fuel consumption for the required (average or representative) air transport. This can probably be done for large consignments, but for smaller customers these data will probably not be easy to obtain. For consignments of horticultural products, it is desirable to have default values for transport and cultivation.

2. Secondary data

For all other processes the best possible secondary data may be used, based on the LCA ISO 14044: 2006 standard with respect to representativeness (period, location, technology), measurement precision and uncertainty, completeness and consistency. PAS 2050 makes an additional requirement that secondary data obtained from a PAS 2050 analysis is preferred to other secondary data. If these data are not available, the next best preferred data are from peer-reviewed publications, together with data from other competent and independent sources (such as government organisations). PAS 2050 states that ILCD will be considered as a source of secondary data if these are found to be suitable.[16] Based on this specification, we have drawn up specific foreground data for the cultivation of horticultural products in the Netherlands for use as secondary data by trading parties. We have also made a selection of background data, based on the requirements for specific allocation and system delimitation that will apply in the protocol for calculating the greenhouse gas emissions arising from the production of horticultural products. As yet there are no external data sources that fully meet these requirements and so we have compiled our own temporary dataset (see background data).

3. Changes in the life cycle of a product

PAS 2050 contains a number of criteria for regularly updating data. Although these criteria are logical, they are possibly too stringent in relation to the practical aspects of production at horticultural processing firms. We do not go into this further here; whether they are workable or not will have to determined from experience with using them in practice.

4. Variability in emissions arising from the product life cycle

PAS 2050 states that when the greenhouse gas emissions associated with the life cycle of a product vary over time, data shall be collected over a period of time sufficient to establish the average emissions. Where a product is continually cultivated, this period should be at least one year. However, given the possible fluctuations in yield, the average could be calculated from data collected over several years, but on condition that no disruptive situations or changes have taken place during this period. Such disruptive situations may be pest outbreaks, which may reduce yields to below expected levels, or changes in the machinery used, such as the installation and fine tuning of a CHP facility. A case can also be made for correcting for climatic factors. In the Netherlands we already have such a system for correcting for gas consumption in greenhouse horticulture based on degree-days. We propose making these corrections for heated cultivation.

For field crops grown in a rotation we propose using a multiyear average over at least two years, for which inputs and outputs are averaged over this period and allocated to the crops (Chapter 5). In the case of sequential cropping that is not an integral part of a cropping plan or rotation, consideration can be given to taking the cultivation period to be the period over which the greenhouse gas emissions are determined, on the condition that in practice the cultivation period of the crops can be clearly distinguished from the previous and subsequent crops.[17]

5. Data sampling

When there are several production lines or suppliers, data may be collected from a representative sample, with due regard to the LCA ISO 14044: 2006 guidelines concerning representativeness (period, location,

[16] These data are compiled for the European LCA harmonisation project EPLCA.

[17] This implies, among other things, a recommendation to use only annual averages for year-round crops like tomatoes. Revealing the fluctuations in greenhouse effect for each cultivation period is not useful when the grower continues cultivation all year round.

technology), measurement precision and uncertainty, completeness and consistency. In other words, collecting just part of the production data is permitted when a sufficiently convincing case can be made for this. For horticultural products, this is relevant for trading partners and processing industries, such as vegetable processing companies and canning factories. The variation is found primarily in the delivered product. To obtain a reliable analysis it is first necessary to establish categories of homogeneous raw materials and the contributions made by the raw materials that are traded and processed. Of course, how this is worked out in practice depends on the product under consideration. The number of suppliers that have to provide data can rise rapidly. A package of mixed cut vegetables easily contains five different vegetables, which may be sourced from different places from year to year. This means that a sample of four suppliers for each vegetable will probably be needed in order to obtain a reliable result. Data will therefore have to be collected from twenty companies. Depending on the share of the expected greenhouse gas emissions that can be derived in part from the weight fraction and in part from standard greenhouse gas emission calculations for cultivation, it may be possible to reduce the amount of data to be collected.

6. Emissions data for fuel consumption and energy carriers (electricity and heat)
Here, PAS 2050 specifies several aspects that have already been established under the topic of system delimitation, namely, the fact that the production of energy carriers has to be included, from the extraction of the fuels to the delivery of the energy carrier (excluding capital goods). This also applies to renewable or 'green' energy carriers, which means that for biomass the whole production chain has to be included in the calculations. These recommendations are also followed here.

For Dutch electricity consumption, use should also be made of the electricity mix corrected for CHP supply to the grid and for biomass derived from waste processing. The net emission benefits of both processes have already been included in the calculation of greenhouse gas emissions arising from the production of horticultural products (see sections 5.2 and 5.6). In 2007 the greenhouse gas emissions arising from the direct combustion of fuels for the production of a Dutch electricity mix was 0.58 kg CO_2eq per kWh instead of 0.46 kg CO_2eq per kWh (Table 10.1). Table 10.1 does not include the values for the production of natural gas and coal.

Table 10.1 Breakdown of greenhouse gas emissions from electricity production

	Carbon footprint source (g CO_2eq/kWh)	Production shares 2007	Carbon footprint total (g CO_2eq/kWh)	Corrected production shares 2007	Carbon footprint total corrected (g CO_2eq/kWh)
Nuclear power	0	6%	0	11%	0
Natural gas CHP	300	43%	129		0
Natural gas average	450	24%	108	42%	189
Fuel oil	660	0%	0	0%	0
Coal	870	24%	208	42%	366
Other	483	3%	14	5%	25
Total		100%	460	100%	581

To ensure consistent application of the allocation rules, this correction should also be made for foreign electricity production. In most European countries the effect will be smaller because in these countries CHP makes a much smaller contribution to electricity supplies.

10.2.2 Standard secondary data on foreground processes for horticultural supply chains

In this section we examine several important foreground processes and sources of foreground data. These are:

1 KWIN data;
2 Methane slip in horticultural CHP.

1. KWIN data for first-order calculations of greenhouse gas emissions from Dutch cultivation
In the Netherlands, Applied Plant Research (WUR-PPO) maintains several handbooks of technical indices for horticulture. These KWIN handbooks (KWIN stands for 'quantitative information') contain a large number of indices representative of average cultivation situations in the Netherlands and are therefore useful data for a first iteration in the calculation of greenhouse gas emissions. Various KWIN publications are available for:

- arable farming and field vegetables;
- greenhouse horticulture;
- fruit;
- arboriculture.

Using the KWIN data combined with greenhouse gas emissions data on methane slip, peat and the background processes, in many cases it will be possible to make a reliable first-order calculation of greenhouse gas emissions. The KWIN data on greenhouse horticulture, field vegetables and arable farming (KWIN 2007) have been incorporated into the calculation tool which the Dutch horticultural sector can use to calculate its greenhouse gas emissions. Specific data can be added to this tool to produce more accurate results.

2. Methane slip in CHP
When natural gas is burned in a CHP, part of the methane in the gas escapes the combustion process and is emitted with the exhaust gases. From measurements (De Laat *et al.* 2001) and later adjustments (Van Dijk 2004), an average figure for methane slip of 1.8% (percentage of fuel input) can be derived for the CHP units used in greenhouse horticulture. This average was used in the earlier phases of this project (Kool *et al.* 2007). Recent measurements (Dueck *et al.* 2008; Olthuis & Engelen 2007) indicate that in practice the amount methane slip fluctuates around this average. The methane slip in the five CHP units investigated in the WUR research (Dueck *et al.* 2008) varied between 0.7% and 4.5%, confirming that methane slip is positively correlated with CHP output. In other words, the higher the output, the higher the methane slip (Figure 10.2).

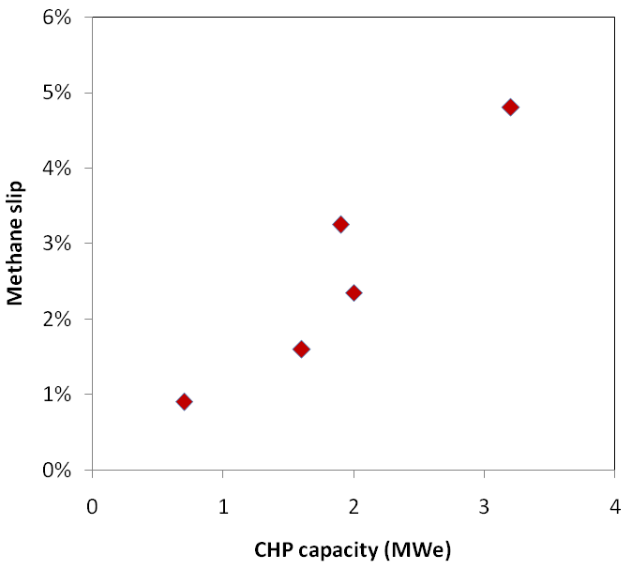

Figure 10.2 Measured methane slip (as a percentage of fuel input) at five CHPs with different capacities (Dueck et al. 2008)

KEMA (Olthuis & Engelen 2007) investigated the methane slip in 10 units with capacities ranging from about 1500 to 5000 kWh and found a similar range of 1.5–4.3%. The results show a distribution of values and confirm the linear relation between CHP output and methane slip, apart from one unit with a large capacity of 5 MWe which had a relatively low methane slip. The average methane slips derived from the WUR and KEMA studies are both 2.5% (as a percentage of fuel input). This average includes the relatively high and low scores from a few companies. The great majority of CHP units in operation have capacities between 1000 and 2000 kWh. The average methane slip of the units that fall within this range, in both the WUR and KEMA studies (rounded off), is 2.3% (or 1230 mg C per m^3).

CHP units have to meet the requirements set out in the Dutch Emission Limits (Combustion Plants) Decree B (BEES-B). On 9 December 2008, the minister of housing, spatial planning and the environment announced in a letter to the House of Representatives that the standards in this decree would be tightened up. This revision of the Emission Limits (Combustion Plants) B Decree (BEES-B) also included a standard for hydrocarbon emissions (including methane) and is expected to come into force before the summer of 2009. The standard for methane in the draft decree is 1500 mg C per m^3 for gas-fired CHP units (VROM 2008; Bussemaker 2008). The level of this limit is equivalent to a methane emission of 528 g CH_4 per GJ fuel input, or a methane slip percentage of 2.8%. This limit is therefore higher than the average figure from the studies by WUR (Dueck *et al.* 2008) and KEMA (Olthuis & Engelen 2007).

In all probability, during the course of 2009, industry will have to meet the emission standard of 1500 mg C per m^3. Given the general picture that most CHP units in use fall within the range of 1–2 MWe and therefore are already within that limit, in this study we use the value for the average methane slip in CHPs within this range, which is 1230 mg C per m^3_o (or a methane slip of 2.3% as a percentage of the fuel input). This value is equivalent to a methane emission of 13.7 g CH_4 per m^3 natural gas burned in the CHP. Converted to greenhouse gas equivalents (the GWP of methane is 25, IPPC 2007), this gives a greenhouse gas emission of 343 g CO_2eq per m^3 gas consumption by the CHP unit. This emission from methane slip is therefore in addition to the emissions from the production and consumption of natural gas. However, the carbon dioxide emitted from the combustion of natural gas in the CHP unit should be adjusted to account for the unburned methane (2.3% methane slip), because this 2.3% from the methane is not burned and would therefore otherwise be counted twice. The combustion of 1 m^3 natural gas, with a methane slip of 2.3%, therefore emits 1.73 kg CO_2eq (instead of 1.77 at 0% methane slip). Given the above, the combustion of 1 m^3 natural gas in the CHP unit therefore produces a greenhouse gas emission of 1.73+0.100+0.34 = 2.17 kg CO_2eq per m^3 gas input.

10.2.3 Data for background processes

Except for products grown in heated greenhouses, the calculated greenhouse gas emissions from a horticultural product are determined largely by processes other than the energy consumed by the horticultural enterprise (see also Figure 3.4 in Chapter 3).

The contribution to the total greenhouse gas emissions from a horticultural product made by the production of fuels, electricity and materials can rise to more than 60% for processed products, but remains at about 10% for cultivation under glass in the Netherlands. The following production processes make an evident contribution to the greenhouse effect:

- production of fuels burned at the horticultural enterprise (oil products, natural gas);
- production of purchased electricity and heat;
- production of artificial fertiliser;
- production of various materials for substrates, staging, cover and greenhouse materials, and packaging, etc.

The choice and reliability of background data and their consistency with the objectives and system delimitation of the LCA are therefore very important. Five types of data sources can be distinguished:

1 primary data sources from industries, trade associations and sectoral research;
2 LCA databases;
3 LCA research;
4 national and international statistics;
5 databases linked to greenhouse effect monitoring and energy benchmarks.

Below we review these data sources and make some recommendations for their use.

1. Primary sectoral data sources

There are various primary data sources for basic materials, packaging materials and artificial fertilisers. Many European and national sectoral organisations collect LCA data and make this available to third parties. Well-known data sources are the databases held by the European industry associations for Plastic, Steel, and Paper and Cardboard manufacturers. The results of thorough studies by various materials sectors are also available, such as environmental impact studies financed by the sector, including studies on the carbon footprint of the supply chains. An example is the study by Davis and Haglund (1999) for the fertiliser industry. These studies also form the core of more centrally managed (commercial) LCA databases, such as the Ecoinvent database (see www.http://www.ecoinvent.ch/ and the next section, LCA databases). Although many of these data are no longer entirely up to date, they are still good enough for a first-order analysis or an analysis in which materials use does not make a substantial contribution to the greenhouse effect score of the horticultural product. On the other hand, in practice it is very difficult to obtain better quality data in the short term. A big advantage of much sector data is that they are collected on a large geographical scale (for example, representative for Western Europe or the Western World), which is also representative for the study because many materials are sourced from the commodity markets and so specific data on a single company are therefore often not available, even if these are more up to date and more accurate.

2. LCA databases

A number of international databases, some commercial and some public, are available for use in LCAs. Well-known and suitable databases are the Danish LCA food data, the 'European' ELCD data and the Swiss Ecoinvent database. All these databases contain mainly European data and are particularly useful because they contain systematically calculated cumulative carbon footprints for the production of different energy carriers. The basic data used to make these calculations are derived mainly from materials producers and international databases maintained for energy monitoring purposes.

The data on materials and artificial fertilisers obtainable from these databases are often derived from the previously mentioned primary data sources, but processed and made as consistent as possible with the system delimitation and allocation rules used in the LCA databases. A disadvantage is that a large proportion of the data in the LCA databases are between 5 and 10 years old. The data on energy processes are more recent.

Another disadvantage of the databases is that that they have been compiled using a system delimitation and allocation rules that differ from those appropriate for use for the greenhouse effect analyses for horticultural products (for example PAS 2050 and the Best Practice delimitation). A favourable development regarding the Ecoinvent database is that it will soon be available in customisable forms for various types of system delimitation and allocation. At the moment it is often not possible to vary the amount of recycling when using the data from LCA databases.

3. LCA research

The same comments apply to LCA studies as for LCA databases. The suitability of data from these studies depends on the appropriateness of the choices regarding system delimitation and allocation and the representativeness of the research. A strategy often followed by LCA researchers when using these studies is not to use the results, but the collected data and adapt these for use in their own LCA model.

4. National and international statistics

Worldwide data on the fuel mix and efficiency of electricity generation (including heat) are collected by the International Energy Agency (www.iea.org). These data are used by the OECD for calculating the greenhouse gas emissions per kWh per country, based on the greenhouse gas emissions arising from the combustion of the different fuels and the energetic efficiency of the power plants (see e.g. International Energy Agency Data Services, 2006, CO_2 Emissions from Fuel Combustion (2007 Edition)). Ecoinvent, ELCD and GENIS provide specific data for the production of electricity in Europe, excluding heat and including the greenhouse gas emissions arising from the production of fuels. For electricity, therefore, complete and recent data are available for each country.

5. Databases linked to greenhouse effect monitoring and energy benchmarks

Another source of data on industrial energy use are the various energy benchmarks. In the Netherlands many companies have signed the energy-efficiency benchmarking covenant under the government's multiyear agreements on energy. This implies that these companies aspire to belong to the most energy-efficient companies in the world and to record their progress. Data on energy consumption are therefore available for many energy-intensive sectors across the world. Although these data are not yet publicly available, their existence shows that more recent data than those included in the LCA databases are available from a central source. The benchmark results from the covenant that have been published show that considerable improvements have been made in energy efficiency and the distribution of energy consumption between companies.

Some data sources for background processes

Below we briefly discuss the available data per materials category and the differences between the data sources. It should be noted that this is not a global inventory of data sources, because this was given a lower priority owing to the less specific nature of these data for horticulture.

Production of fuels

The main fuels used for heating in horticultural supply chains are:

- fuel oil for sea transport, in electricity power stations, in horticultural holdings and processing companies;
- diesel for road transport;
- kerosene for air transport;
- natural gas in greenhouse horticulture, at processing companies and electricity companies;
- coal and brown coal for the production of electricity.

Table 10.2 Differences between Ecoinvent and ELCD data for energy consumption for the production of fuels

	Combustion g CO_2/m^3 or kg	Combustion g CO_2eq/MJ	Production cf Ecoinvent g CO_2/MJ		Production cf ELCD g CO_2/MJ	
Natural gas	1.81	57	10	18%	15.6	27%
Diesel	3.24	76	12	16%	10.4	14%
Heavy fuel oil	3.27	80	11	14%	9.6	12%
Kerosene	3.20	74	12	16%	9.1	12%

Table 10.2 shows that there can still be considerable differences in energy consumption for the production of fuels between the different data sources. Besides differences in system delimitation, there are also important differences in spatial representativeness. The differences in the greenhouse effect during the production stages are great. According to the Ecoinvent database, the additional attributed greenhouse gas emissions above the (full) combustion of Dutch natural gas is 5.3%; for Austrian natural gas this is 38.4% (Table 10.3). In other words, the combustion of natural gas in the Netherlands is much cleaner compared with diesel than in other European countries, such as Austria.

Table 10.3 Additional greenhouse gas emissions above the combustion of natural gas (high pressure) according to Ecoinvent

	Additional emissions owing to upstream production for natural gas
EU average	19.9%
Germany	21.1%
France	21.4%
Netherlands	5.3%
Austria	38.4%
Ireland	7.7%
England	3.5%

German research by the Wuppertal Institute (cited in CE 2006) largely confirms this picture of the additional greenhouse effect from the production of fuels. This research used the GEMIS database: http://www.oeko.de/service/gemis/en/ (Table 10.4).

Table 10.4 Results of the Wuppertal Institute study using the GEMIS database (as cited in CE 2006)

	Full combustion ($g\ CO_2eq/MJ$)	Production to combustion ($g\ CO_2eq/MJ$)
Natural gas	56	10-25
Oil	77	10
Coal	92	15
Lignite	110	27,5

Recent research into the greenhouse gas emissions from the production of natural gas by CE for the International Gas Union also shows that there are large differences in the upstream emissions to storage (Table 10.5).

Table 10.5 Data on upstream emissions from recent research by the International Gas Union

	$g\ CO_2/m3$ natural gas		
	EU average	NWE/E	Russia/Asia
Natural gas production	162	35	120
Natural gas transport	216	11	310
Natural gas combustion	1772	1772	1772
Additional CO_2 emissions above combustion	21.3%	2.6%	24.3%

Proposed standard upstream greenhouse gas emissions for the Netherlands

Given the results from the various databases and LCA studies on upstream emissions, we propose the following factors for the Dutch situation (Table 10.6 and 10.7).

Table 10.6 Emission factors for the combustion and production of fuels

Source	Full combustion ($g\ CO_2eq/MJ$) (Vreuls 2006)	Production to combustion ($g\ CO_2eq/MJ$)
Natural gas	56.8	3
Natural gas production	77	10
Coal	92	15

Table 10.7 Emission factors for the combustion and production of fuels

Source	Unit	excl. pre-combustion (kg CO_2eq. per unit)	Pre-combustion (kg CO_2eq. per unit)	incl. pre-combustion (kg CO_2eq. per unit)
Crude oil	kg	3.13	0.43	3.56
Petrol	kg	3.17	0.44	3.61
Kerosene	kg	3.11	0.44	3.55
Petroleum oil	kg	3.10	0.43	3.53
Diesel	kg	3.17	0.43	3.60
Heavy fuel oil	kg	3.17	0.41	3.58
Lubricating oil	kg	3.03	0.41	3.45
Anthracite	kg	2.61	0.40	3.01
Coke	kg	2.70	0.43	3.13
Coal	kg	2.32	0.37	2.69
Brown coal	kg	2.02	0.30	2.32
Natural gas	m^3	1.78	0.09	1.87

Production of electricity and/or heat

An important and fairly complete source of data on the production of electricity and heat is the annual OECD report 'CO_2 Emissions from Fuel Combustion'. This contains data per country for the release of CO_2eq in kg from energy production (kWh and heat sold) in electricity power stations, reflecting the greenhouse gas emissions arising from the combustion of fuels. The OECD data are based on the data from the IEA, which publishes an annual report on the composition of national electricity generation capacities and their efficiencies. Ecoinvent uses the same data, but separates out heat production and 'adds in' the production of fuels and capital goods (power stations and electricity supply grid).

Table 10.8 Comparison of greenhouse gas emissions from electricity production from OECD (2007) and Ecoinvent (2007).

Country code	Country	Ecoinvent (kg CO_2eq/kWh)	OECD (kg CO_2eq/kWh)	Ratio Ecoinvent/OECD	Difference Ecoinvent - OECD (kg CO_2eq/kWh)
AT	Austria	0.387	0.221	175%	0.17
BE	Belgium	0.330	0.281	117%	0.05
CH	Switzerland, Helvetia	0.111	0.024	464%	0.09
ES	Spain	0.499	0.383	130%	0.12
FR	France	0.089	0.087	103%	0.00
GR	Greece	0.973	0.781	125%	0.19
IT	Italy	0.565	0.455	124%	0.11
LU	Luxemburg	0.558	0.333	168%	0.22
NL	Netherlands	0.669	0.440	152%	0.23
PT	Portugal	0.594	0.452	131%	0.14
DE	Germany	0.639	0.453	141%	0.19
DK	Denmark	0.557	0.308	181%	0.25
FI	Finland, Suomi	0.296	0.261	114%	0.04
UK	United Kingdom	0.582	0.467	125%	0.12
IE	Ireland	0.762	0.573	133%	0.19
SE	Sweden	0.086	0.051	168%	0.03
NO	Norway	0.033	0.007	478%	0.03
CZ	Czech Republic	0.794	0.503	158%	0.29
HU	Hungary	0.618	0.401	154%	0.22
PL	Poland	1.101	0.665	166%	0.44
SK	Slovakia	0.452	0.247	183%	0.20
SI	Slovenia	0.425	0.336	126%	0.09
HR	Croatia	0.465	0.298	156%	0.17
BA	Bosnia-Hercegovina	0.660	0.589	112%	0.07
BG	Bulgaria	0.592	0.471	126%	0.12
RO	Romania	0.652	0.418	156%	0.23
Average					0.15

The difference between the Ecoinvent data and the OECD data is very large in relative terms and varies considerably per country. In absolute terms, this variation is smaller and is on average 0.15 kg CO_2eq/kWh.

Comparing the values for electricity in Table 10.8 with the production mix for 2006 in the Netherlands, including sustainable energy and decentralised CHP (De Groot 2008), we obtain the following overall figures for the Netherlands:

Production mix, incl. CHP, excl. pre-combustion	0.46 kg CO_2eq/kWh
Production mix, incl. CHP, incl. pre-combustion and methane slip	0.51kg CO2eq/kWh
Production mix, excl. CHP, excl. pre-combustion	0.58 kg CO_2eq/kWh
Production mix, excl. CHP, incl. pre-combustion	0.65 kg CO_2eq/kWh

The Ecoinvent figure of 0.67 CO_2eq/kWh is slightly higher than these. A full investigation of the differences that probably result from the choice of system delimitation and basic data was outside the scope of this study.

Production of artificial fertilisers

Davis and Haglund (1999) and Kongshaug (1998) give the original industrial data that are most widely used in studies and which also form the basis of the LCA databases, such as Ecoinvent. Several sources of these data are compared in Table 10.9. The 'Review of Greenhouse Gas Emission Factors for Fertiliser Production' by the IEA bio-energy task force (Wood & Cowie 2004) also identifies these as the most complete sources, and as such they can be used in a first calculation tool.

Table 10.9 Carbon footprints of artificial fertilisers (kg CO_2eq/kg)

Nitrogen fertiliser	Davis & Hagelund 1999	Kongshaug 1998	Williams et al. 2006	Ecoinvent 2007
N (KAS WE average)	7.48	6.89	7.4	8.8
N (urea)	4.00	1.33	3.5	3.4
N (urea, ammonium nitrate)	5.67	4.10		5.9
N (ammonium nitrate)	7.03	6.80	7.2	8.6
P fertilisers				
Triple super phosphate	1.04	0.35	1.2	2.7
Single super phosphate	1.05	0.10	0.6	2.1
NP fertilisers				
Mono ammonium phosphate	0.70	0.31		
Di ammonium phosphate	0.87	0.46		
NPK fertilisers				
Phosphoric acid 15:15:15	1.12	0.97		
Nitro-phosphate 15:15:15	1.18	0.83		

Production of materials

Important materials used in horticultural supply chains are plastics, metals, glass, concrete, wood, and paper and cardboard.

Table 10.10 Important materials used in horticultural supply chains, including product applications

Material category	Materials	Product applications
Plastics	Thermoplastics: LDPE, HDPE, PP, PVC, PETP, PA Synthetic rubbers, SBR	Packaging, agricultural plastic films, plant pots, nappy films, substrates, greenhouses, guttering, piping, etc.
Metals	Steel, Aluminium, Zinc, Copper	Packaging, (electric) wiring, guttering, staging material, greenhouse material
Ceramic and stony materials	Glass, bricks, concrete, rock wool	Packaging, substrates, sheds
Natural materials	Wood, paper, cardboard, peat, potting compost, coconut fibre, etc.	Packaging, construction materials, substrates
Organic chemicals		Pesticides, cleaning agents

Various production routes are available to manufacture these products. Significant variables for the greenhouse effect are:

- the production process;
- the efficiency of the process;

- the proportions of primary and secondary materials used;
- the energy production processes employed or allocated to the product.

As a rule, the higher the use of secondary materials, the lower the greenhouse effect.

The various data sources lead to considerable differences in the carbon footprints of products, processes and materials, but it is not immediately clear what causes these differences. In the further development of the protocol it will be necessary to standardise the use of data sources. The choice of data source has a considerable effect on the carbon footprints of several types of horticultural products for which the use of materials makes a large contribution to the carbon footprint. Careful consideration needs to be given to this aspect when developing the protocol and calculation tool.

In principle, two strategies are conceivable for selecting and managing background data.

1 use existing databases;
2 develop and manage a custom database.

These two strategies are reviewed briefly here.

1. Use existing databases
Making use of existing databases has several big advantages. For example:

- the databases are managed (validated and updated) by a third party, which in turn guarantees
- internal consistency of the data used.

Disadvantages:
- little influence over the quality and improvement of the data;
- knowledge of the structure of the data is often limited;
- data are sometimes/often outdated;
- limited flexibility, for example for calculating the use of secondary materials.

2 Develop and manage a custom database in conjunction with company and sector databases
This approach requires a one-time investment of time and money, but has several advantages over the first option:

- the structure and quality of the data are known;
- the flexible use of secondary and primary materials can be incorporated into the database;
- implementation of the desired allocation rules is possible.

For the time being we have decided to develop a limited standard dataset that offers the possibility of varying the degree of recycling and the waste processing scenario.

10.3 Recommendations for the protocol

For the time being a limited dataset has been incorporated into the tool to allow researchers to make estimates for the most important materials. This is because it is difficult even for researchers in the field of carbon footprints of agricultural products to fill in the necessary information on materials, because this requires highly specific expertise.

10.4 Recommendations for further research

- Datasets can be developed for several products, depending on the target group and the use of the calculation tool.
- Determine the optimum balance between customised databases, flexibility and using mainstream databases.

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Appendix 1. Expert meeting participants

Fertilisation of field crops (14 December 2007, Gouda)

- Peter Dekker, Applied Plant Research (PPO-WUR) – Arable Farming, Multifunctional Agriculture and Field Production of Vegetables
- Harry Luesink, Agricultural Economics Research Institute (LEI-WUR) – Animal Systems Division
- Udo Prins, Louis Bolk Institute
- Peter Vermeulen, Agricultural Economics Research Institute (LEI-WUR) – Greenhouse Horticulture
- Anton Kool, Hans Blonk and Boki Luske, Blonk Milieu Advies (Blonk Environmental Consultants)

CHP and horticultural energy supply (18 September 2008, Zoetermeer)

- Nico van der Velden, Agricultural Economics Research Institute (LEI-WUR), researcher in energy and climate in greenhouse horticulture
- Wouter Wetzels, Energy Research Centre of the Netherlands (ECN), researcher
- Bart Ummels, Delft University of Technology (TU Delft), doctoral candidate in the integration of wind energy into the energy market
- Stijn Schlatman, Cogen Projects, director
- Ferdi van Elswijk, Prominent, energy and environment manager
- Peter Vermeulen, Applied Plant Research (PPO-WUR) – Greenhouse Horticulture, researcher in energy and climate
- Rob van der Valk, Dutch Federation of Agriculture and Horticultural Organisations (LTO Noord Glaskracht), energy policy officer