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Contributions to LCA methodology for agricultural systems.

Site-dependency and soil degradation impact assessment.

Tesi Doctoral

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Certifiquem: que la present memòria, titulada "***Contributions to LCA Methodology for Agricultural Systems. Site-dependency and soil degradation impact assessment***", ha estat realitzada sota la nostra direcció a la Unitat de Química Física del Departament de Química de la Universitat Autònoma de Barcelona pel llicenciat Llorenç Milà i Canals, i constitueix la seva Tesi per optar al grau de Doctor en Ciències Ambientals.

I perquè així consti, signem el present certificat a Bellaterra, 28 de febrer de 2003.

Dr. Xavier Domènech i Antúnez	Dr. Joan Rieradevall i Pons
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Al meu pare, perquè sense ell mai no m'hauria posat a fer la tesi,
i a la meva mare (perquè sense ella ni tan sols seria aquí!)

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Llorenç

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Acronyms and Symbols used throughout the thesis

Acronyms

ADI: Acceptable Daily Intake
a.i.: active ingredient
anova: Analysis Of Variance
BAT: Best Available Technology
Btk: *Bacillus thuringiensis* Berliner subspecies *kurstaki*
BUWAL: *Bundesamt für Umwelt, Wald und Landschaft* (Swiss Federal Agency for the Environment, Forests and Landscape)
CAN: Calcium Ammonium Nitrate
CEC: Cation Exchange Capacity
CML: *Centrum voor Milieukunde*, Leiden (Centre for Environmental Science, Leiden University, The Netherlands)
COD: Chemical Oxygen Demand
CpGV: *Cydia pomonella* Granulosis Virus
EDIP: Environmental Design of Industrial Products
EF: Effect Factor
EI99: Eco-Indicator '99
EMPA: *Eidg. Materialprüfungs- und Forschungsanstalt* (Swiss Federal Laboratories for Materials Testing and Research)
FAO: Food and Agriculture Organisation
fNPP: free Net Primary Production
GAP: Good Agricultural Practice
GLASOD: Global Assessment of Soil Degradation
HDPE: High-Density Polyethylene
IFP: Integrated Fruit Production
ISO: International Standards Organisation
LCA: Life Cycle Assessment (or Analysis)
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
LSF: Life Support Functions
MSDS: Material Safety Data Sheet
NMVOC: Non-Methane Volatile Organic Compounds
NPP: Net Primary Production
OFP: Organic Fruit Production
OM: Organic Matter
PDF: Potentially Disappeared Fraction (of species)
RUSLE: Revised Universal Soil Loss Equation
SETAC: Society for Environmental Toxicology and Chemistry
SMEs: Small and Medium-Sized Enterprises
SOC: Soil Organic Carbon
SOM: Soil Organic Matter
TOC: Total Organic Carbon
TRV: Tree-Row-Volume
UNECE: United Nations Economic Commission for Europe
UNEP: United Nations Environment Programme
u.v.: ultraviolet
WD: Wheel-Drive

Symbols

α_{act}: number of plant species per m^2 (actual number)

α_{ground}: rate constant for the daily loss through evaporation from the ground ($days^{-1}$)

α_{plant}: rate constant for the daily loss through evaporation from the plant ($days^{-1}$)

α_{ref}: number of plant species per m^2 (reference or potential number)

A_a: area occupied by activity “a” (ha)

δ: Fraction of water entering the system that is drained

δx_1: relative error of variable x_1

Δx_1: relative error of variable x_1

ΔQ: change in (land) quality, i.e.: impact on land

f_a: fraction of pesticide reaching the air

$f_{draining}$: fraction of leached pesticide that is drained by draining systems to surface watercourses

f_{drift}: fraction of sprayed pesticide drifting off the orchard

f_g: fraction of pesticide reaching groundwater

f_{ground}: fraction of sprayed pesticide reaching the ground

$f_{ground,a}$: fraction of pesticide volatising from the ground

$f_{leaching}$: fraction of pesticide on the ground that leaches down the soil to groundwater

f_{plant}: fraction of sprayed pesticide ending on the plant’s surface

$f_{plant,a}$: fraction of pesticide volatising from the plant

f_{runoff}: fraction of pesticide on the ground that runs off to surface watercourses

f_s: fraction of pesticide remaining in soil

f_{vol}: fraction of pesticide volatilised (either from plant’s or ground’s surface)

f_w: fraction of pesticide entering surface watercourses

hp: horse power (1hp = 0,7457 kW)

K_d: Soil partition coefficient (concentration ratio between soil solid phase and aqueous phase at equilibrium)

K_{OC}: Soil organic partition coefficient (K_d divided by the fraction of SOC)

K_{OW}: Distribution coefficient for a substance in the two-phase system octan-1-ol/water

λ: Rate for microbial degradation in soil ($days^{-1}$)

L: Leaf Area Index (m^2 leaves / m^2 ground)

L_a: land use for activity “a” (ha·year)

LSF_a: impacts on life support functions due to activity “a” (ΔQ·ha·year)

Γ: Fraction of the field surface occupied by the first six tree rows on either side of the field

SOM_a: level of soil organic matter during activity “a” (%; $Mg \cdot ha^{-1}$; etc.)

SOM_{ref}: reference level of soil organic matter in a specific site (%; $Mg \cdot ha^{-1}$; etc.)

$\tau_{½,soil}$: Half-life in soil

τ_{ground}: (pesticide’s) residence time in the ground

τ_{plant}: (pesticide’s) residence time on the plant

$t_{harvest}$: time between pesticide application and harvest (days)

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CHAPTER I. INTRODUCTION

"There is nothing as practical as a good theory"
Alfred N. Whitehead

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This introductory chapter is aiming at providing the reader with the purpose and content of the thesis. Thus, the concepts of sustainable development and agricultural impacts on the environment are described. Then, I present some of the approaches to the analysis of these impacts and a new tool for the assessment of the environmental impacts of human activities: Life Cycle Analysis (LCA). Finally, the contents and methodology used in each part of the thesis are described in section I.2.

This thesis is the result of a concern on the environmental consequences of agricultural activities and of a deep motivation to help in designing sustainable food[1] production systems so human life may be preserved. For a better understanding of the main issues discussed in the thesis, this first section describes the environmental problems generated by agricultural activities and provides some of the concepts for its environmental analysis.

Sustainable development and agriculture

Agriculture may be defined as the deliberate use of land for the cultivation of edible plants or animals (Spedding 1975), although the production of fibre, timber and increasingly fuel and other materials should be included as agricultural activities as well. The use of land is possibly one of the most typical characteristics of agriculture, and it is often argued whether highly mechanised cultures in hydroponics or intensive chicken production in cages may be even considered agricultural activities at all.

Basically, sustainable development may be defined as the way of fulfilling our needs so that future generations can still fulfil theirs. Ways of fulfilling needs are considered sustainable when they comply with three basic requirements:

- Technically feasible and economically viable
- Socially acceptable
- Environmentally sustainable

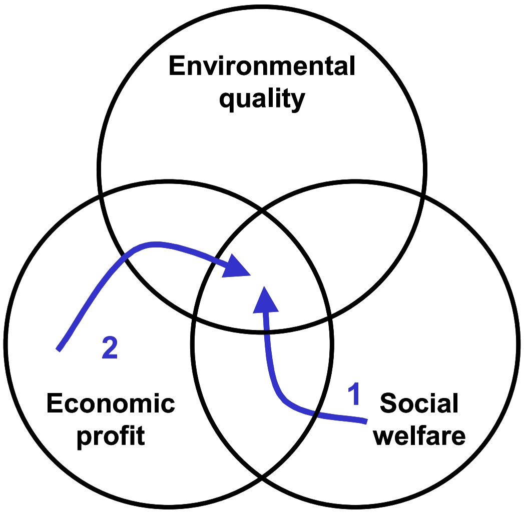

Figure I-1: Sustainable development lies in the intersection of environmental, economical and social aspects.

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[1] and fibre, and timber, and fuel… The thesis is mainly referred to farming systems aiming at food production, but similar considerations may be done for forestry or non-food agriculture.

Line 1 in Figure I-1 represents a typical implicit approach to sustainable development in developing countries, where mainly social and economic aspects are considered in order to maintaining people's access to (material) environmental resources (Martínez Alier 1995). Within the "environmentalism of the wealthy" two main trends can be distinguished: a post-materialist concern about environmental amenities and the environmental movements against the (material) "effluents of the affluence" (Martínez Alier 1995). The latter trend is represented by line 2 in Figure I-1. Other approaches have appeared. The consideration of social aspects into companies and social movements mainly in developed countries has lead to concepts such as fair trade, corporate social responsibility, etc.

Among human activities, agriculture is the one related to possibly the most basic human need: feeding people. Besides, agricultural activities generate several environmental problems, which can be generally grouped into the following categories:

- Impacts related to energy consumption (global warming, acid rain, resource depletion, etc.)
- Surface- and groundwater pollution (nitrates, pesticides, etc.)
- Toxicity impacts primarily related to agri-chemical use
- Decrease in soil quality (soil degradation, pollution, erosion, etc.)
- Water depletion
- Decrease of biodiversity in cultivated land

Social and economic problems of agriculture are usually interconnected with the environmental conditions as well. The distribution of good soils and favourable growing conditions do not match that of the population (UNEP 1999), leading to social, economical and environmental unbalances. In many places throughout the world characterised by low yields and high population densities, millions of small farmers have been forced to increase the pressure on land, thus deepening the problems of soil degradation and poverty. Oppositely, in other areas economic incentives are given to farmers in order to reduce production and thus stabilise market prices. Subventions and quotas are a common tool to increase or reduce production. Another social trend with deep economical and environmental consequences is the rising demand for meat, which may encourage farmers to displace subsistence food crops in many regions of the world, thus using land in a less efficient way (UNEP 1999).

It is therefore crucial to achieve a sustainable way of producing food (and fibre, and timber) in order to allow for present and future human development. This thesis considers the environmental aspects of sustainable agriculture.

First approaches to the environmental analysis of agriculture

If we are to reduce the environmental impact of agricultural production, tools for the measurement of the consequences of changing these systems are needed. In order to guide decision-making in a structured manner, many indicators and methods have been suggested for the assessment of agricultural technologies impacts on the environment.

The first studies focused mainly on the energy issues. They represented simplified energy balances of the agricultural system, which assessed the total energy consumption (including energy in inputs). In this field, David Pimentel has been one of the most active contributors (see Pimentel *et al*. 1973; Pimentel *et al*. 1975; Pimentel & Pimentel 1979), giving energy consumption figures for several agricultural activities such as pesticide formulation, fertiliser production, irrigation, etc. In the last years, studies on energy agricultural consumption have increased in complexity and comprehensiveness including also the impacts related to transportation in a worldwide economy. Thus, the German Wuppertal Institute provided some interesting figures for the consideration of an agricultural system using ingredients coming from far-away places. For instance, Stefanie Böge established in 1993 that the journeys accumulated by strawberry yoghurt (including its ingredients and its cup) totalled 3,500 km plus 4,500 km for the supplier's supply transport.

More recently, the environmental assessment of agriculture turned to more local problems, such as the toxicity caused by diffuse contamination from agri-chemicals leaving crop fields (either through leaching to groundwater, affecting the surrounding environment, etc.). Examples are found in European legislation on water quality: Directive 91/676/CEE on water pollution by nitrate used in agriculture; Directive 2000/60/CE on the communitarian framework on water policy (which explicitly mentions nitrate and biocides as priority substances). Also pesticide residues in food are obviously a main concern, as it can be seen in Directive 2000/42/CE (which modifies the annexes in Directives 86/362/CEE, 86/363/CEE, and 90/642/CEE, on maximum contents of pesticide residues in cereals, animal products, and other vegetable products). Much of this legislation has actually been developed due to consumers' pressure, often through retailers and wholesalers (e.g.: Eurep GAP).

Land protection becomes a key issue to achieve sustainable development. As a matter of fact, terrestrial ecosystems rely on vegetable production, and plants depend on soil as a substrate for life (physical support, nutrient source, etc.). Land is the main basis for food, fibre, timber and fuel productions in the world; in Europe, 90% of these productions come directly from soil (EEA & UNEP, 2000). But land degradation has dramatic effects on crop productivity: 2 billion hectares of land are affected by human-induced soil degradation and 12 million hectares of arable land are lost every year due to erosion and land degradation (EEA & UNEP, 2000).
Consequently, many studies are focused on this problem. Some of them relate soil degradation to the (economical and technical) effort needed to supply services no longer provided by soil. Pimentel *et al*. (1995) demonstrate that in North America between 200 and 1000 years are needed to create 1 inch (2.54 cm) of topsoil, while this is the part of soil eroded in 16 years as an average and calculate that the cost of replacing for lost soil's services account for around US$ 400 billion

annually on a global level[2]. In Spain, ICONA (1991) estimated the costs of erosion to be € 280 million annually, and would require an investment of € 3 billion in a 15-20 years period for measures against erosion. Daily (1997), talks about the high prices that hydroponic cultures must pay in order to substitute for pest control (through pesticides), buffering capacity (through high technology pumps and sensors), etc. due to the lack of soil.

In addition, the magnitude of land's importance is enforced by its decreasing availability[3] due to two combined tendencies:

- population growth,
- loss of agricultural soil (quantitative loss through erosion, and qualitative loss through land degradation, i.e.: loss of soil quality).

According to Pimentel *et al*. (1995), 0.5 ha of arable land/capita is needed to adequately feed people. However, only 0.27 ha/capita of arable land is available nowadays[4] and this amount is decreasing due to the factors stated above. By relating land availability to the likely uses that are going to be demanded in the next years, Weidema (2000) concludes that arable land will be the "ultimate" limiting resource before energy and any other mineral resource. Measurements of the specific yield of a piece of land arise as typical indicator from these concerns, and pursuing an increase in land productivity turns out as a logical goal.

Sustainability indicators

Apparently, the high complexity of the sustainability concept cannot be condensed to a single simple definition (Pannell & Glenn 2000). It requires indicators that can focus on different aspects of the production system and measure progress towards reducing negative impacts (Wearing 1997). With such indicators, the changes in quality caused by different management techniques in the production system can be modelled and decisions can be made on the basis of solid information, rather than intuition.

Several indicators have been suggested to date focusing on the several components affected by sustainability: cultural, ecological, agricultural, and economic.

In the case of the ecological axe and depending on the analyst's values, different aspects of the agricultural system are considered as the more relevant ones. As it has been previously noted, such indicators may be the consumption of agri-chemical inputs (fertilisers and/or pesticides); overall energy consumption (energy for machinery use, ideally including inherent energy in inputs,

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[2] The estimate is done taking both direct (replacing water and nutrients that are lost with soil in agricultural land) and indirect (mainly costs off-site, due to siltation of rivers and dams, effects on human health, etc.) costs into account. Intrinsic values and other types of degradation (such as acidification, salinisation, compaction, etc.) are not included.

[3] Expressed as amount of land (ha) per capita.

[4] This figure is 0.25 ha/capita according to Wackernagel & Rees (1996) and 0.24 ha/capita according to FAOSTAT (1997). The decreasing figures are consistent with the tendency described in the text (note the dates of the publications). UNEP (1999) confirms this tendency, and notes that the global availability of cropland has fallen by some 25% over two decades, from 0.32 ha/capita in 1975 to 0.24 ha/capita in 1995.

transportation[5], etc.); presence/absence of indicator species[6]; amount of soil eroded; specific yield; etc. On a more local level within the farm, other suggested indicators include microbial biomass within the soil; organic matter in soils; protein levels of crops; diversity of production; earthworm density in soil; soil pH; effective crop root depth; and depth to groundwater table (Pannell & Glenn 2000).

Another set of farm level indicators is suggested by Rigby *et al*. (2001), who use five aspects of the horticultural production: seed source, pest/disease control, weed control, maintenance of soil fertility and crop management. They also suggest a method to weigh these aspects, based on the way they relate to different dimensions of sustainability (minimising off-farm and non-renewable inputs, maximising natural biological processes, and promoting local biodiversity).

Wratten *et al*. (1997) describe the Selwyn Stewardship Monitoring Scheme, a multi-sectoral and multi-disciplinary project monitoring long-term changes in biological and physical aspects of farming activities sustainability in New Zealand. They use a wide array of indicators, including a suite of invertebrate species, two bird species, soil organic carbon and aggregate stability, nutrient leaching, energy efficiency (energy “harvested” per energy used), biochemical markers of sub lethal effects and productivity, among others.

Reganold *et al*. (2001) provide an example of the use of sustainability indicators covering environmental and economic issues for the comparison of several apple production systems (organic, conventional, and integrated). Bailey *et al*. (1999) suggest the use of nitrate residues in soil, changes in earthworm biomass, numbers of pre-set invertebrate species, etc.

The evolution in the environmental analysis of agriculture has provided increasing levels of information and accuracy in the prediction of environmental impacts. However, most of these approaches lack consistency. As each set of indicators is usually derived in a particular situation, there are problems of transferability and relevancy in different conditions. As the methods are not generally standardised, the subjective values of the analyst affect the choice of indicators. Therefore, several agricultural systems analysed with different sets of indicators cannot generally be compared, and decision-making about the reduction of environmental impacts is slowed down by the need of case-by-case development of indicators.

A global approach to the assessment of environmental impacts from agriculture

LCA is possibly the most sophisticated tool for the analysis of the environmental impacts of human activities. LCA not only takes a cradle-to-grave view of activities that avoids the transfer of environmental burdens from one life cycle stage to another, but also tries to cover all the relevant impacts that can be affected by human activities, rather than just single indicators. This approach offers a degree of objectivity that enables to compare on the basis of global, rather than only local impacts. With this objectivity, agricultural practices can be analysed, compared and classified according to their environmental relevance.

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[5] See, for example, Jungbluth *et al*. (2000).

[6] For example, high biodiversity of the natural enemies capable of providing effective control of pests is likely to reduce the need for other interventions, while achieving economic sustainability for the grower (Wearing 1997).

LCA was conceived within the industrial concern for “the effluents of the affluent” (Martínez Alier 1995) to assess ways to reduce the environmental impacts of any activity. Therefore, the analysis is not aiming at determining which activities compromise sustainable development, but supports industrial decision-makers in the process of reducing the environmental impacts of their activities (Baumann 1998).

However, LCA usefulness in aiding decision-makers in agriculture needs to be further explored. The application of LCA to agriculture is recent, most of the case studies having been developed in Central and Northern Europe from the 1990s (Weidema 1993). These applications are typically used to describe agricultural systems in order to gain knowledge about the environmental hot spots, or to compare alternative production systems.

The differences between industrial and agricultural systems originate many methodological problems for agricultural LCA. The fact that industrial systems are mostly independent from their surroundings has lead to a site-independent methodology for LCA. However, the life cycle steps in close contact with the environment (such as agriculture, resource extraction or landfilling) are site-dependent by nature.

Therefore, a proper check on the standard LCA hypotheses and procedures should be done for its application in such systems. This PhD thesis is thus aimed at providing a more solid base for the use of LCA in the environmental assessment of agriculture.

I.2. Objectives, structure, and methodology of the thesis

This thesis lies thus at the crossroads of the issues discussed above. On one hand, agriculture is one of the human activities causing a more extensive degradation of the environment, and at the same time is crucial for human development. On the other, LCA is being developed and successfully applied as a new tool in the decision-making process for the reduction of environmental impacts of human activities. Mainly, it has been developed within the industrial sector, and in Northern countries (Europe and North-America). With this scope in mind, several objectives have been set:

1. Provide a better knowledge and understanding of agricultural systems and their environmental hotspots;
2. Determine how LCA can contribute to the knowledge and comparison of such impacts between agricultural systems;
3. Contribute to the methodological development of LCA in order to allow for a more generalised and sound application to the comparison of agricultural systems.

Structure and methodology

The thesis is structured in five parts: introduction, three chapters where some of the issues identified as more crucial are developed, and a final chapter with the general conclusions of the thesis and some future outlook.

In chapter II, LCA is described using the main literature references and LCA is applied using standard methodology to what could be called “an industrial system with agricultural stages”: the leather industry. It is an application of LCA with the aim of helping policy-making, in an eco-label scheme. Apart from conclusions on the usefulness of LCA for policy-making, it is shown that the impacts due to agricultural stages in a broader industrial LCA can have a significant contribution to the overall environmental impact of the system.

In addition, potential for improvement and methodology gaps in the application of LCA to agricultural systems are detected. In particular, it is found that some of the important impacts caused by agriculture are not covered by present methods for Life Cycle Impact Assessment (LCIA). Indeed, most impact categories are aimed at characterising the effects of material and energy consumption; as different farming types are not only characterised by different consumption of energy and materials (as most industrial systems are), new methods should be developed. In order to provide a state of the art in agricultural LCA and to understand how other authors have dealt with these methodology gaps, a thorough literature review is included. As a conclusion, it can be said that other authors have not successfully dealt so far with all these methodology gaps. Thus, LCIA of agriculture should be still further developed in order to distinguish between different types of agriculture.

Chapter III presents a detailed application of current LCA methodology (chiefly represented by the ISO standards series 14.040) to different apple production systems. Therefore, standard LCA methodology is applied in order to determine its appropriateness for agricultural systems. From the conclusions of the literature review (Chapter II), one of the aspects that deserve attention in agricultural LCA is the extent to which site-dependency affects the results, both of the inventory analysis and of the impact assessment. Consequently, an extensive and detailed description is devoted to the analysed systems in order to catch the importance of site-specific information for the LCA results. A deep analysis of the causes of site-dependency is developed based on the apple production study conducted in close cooperation with farmers. This analysis represents an important contribution to the understanding of methodological problems of agricultural LCA. Indeed, one of the main findings is that the environmental differences between agricultural systems are not only due to the technology ("type" of agriculture), but also, and to an important extent, to site characteristics. This fact suggests that agricultural LCA should be strongly site-specific, both in the inventory and in the impact assessment phases. It must be noted that this conclusion contrasts with the general idea that LCA must assess for potential impacts, disregarding local effects; this idea is not applicable when comparisons between agricultural systems are performed.

Chapter IV deals with one of the main aspects that lack methodology development in LCA: the assessment of land use impacts. The steps suggested by the relevant references (mainly ISO and the SETAC[7] working group on life cycle impact assessment) are followed in order to suggest a new method for the impact assessment of soil quality degradation (which affects the life support functions of land). A review of existing land use impacts characterisation methods is first done, together with an explanation of the framework for land use impact assessment in LCA. Following the recommendations of the ISO standards (ISO 14.042:2000), enough scientific basis should be given every time a new indicator is suggested. Therefore, a thorough literature review is offered that provides the reader with facts suggesting soil organic matter as a proper indicator for soil quality. Particularly, a deep review on the role of soil organic matter in the life support functions of land gives evidence of the representation of this indicator.

Then, the new method is discussed in the light of the international standards for LCA. The procedure for the implementation of the method is developed, using the guidance of the LCIA framework for land use impacts. In order to facilitate the data collection, existing models for predicting the evolution of soil organic matter are suggested, and a proper explanation of such models is provided. Finally, an example of application of this method in an agricultural LCA is given.

The conclusions are structured in order to capture the main points discussed throughout the thesis. For each one, a brief overview is given on the approaches and suggestions found in the literature and the current state-of-the-art. Then, the main findings of the thesis are contrasted to what has been said on the subject. Finally, some outlook and future research needs are suggested.

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[7] Society of Environmental Toxicology and Chemistry.

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CHAPTER II. LIFE CYCLE ASSESSMENT OF AGRICULTURAL PRODUCTS.

"Among material resources, the greatest, unquestionably, is the land. Study how a society uses its land, and you can come to pretty reliable conclusions as to what its future will be" (p.102)
"The 'ecological problem', it seems, is not as new as it is frequently made out to be. Yet there are two decisive differences: the earth is now much more densely populated than it was in earlier times and there are, generally speaking, no new lands to move to; and the rate of change has enormously accelerated, particularly during the last quarter of a century" (p.103)
E. F. Schumacher (1973), Small is Beautiful. Economics as if people mattered

Table of contents

This chapter presents Life Cycle Assessment (LCA) in the context of tools aimed at providing information for the environmental improvement of human activities. To do so, LCA is defined and the phases that constitute it are briefly described. For a better understanding of the type of information that can be gained with such a tool, section II.2 presents an application of LCA to an eco-labelling criteria-setting procedure. More precisely, the eco-label for leather products is the object of the application. This application shows how agriculture represents an important share of the environmental impacts of leather, and thus raises the point of the application of LCA to agricultural systems. The historical achievements and main research fields in agricultural LCA are then presented in section II.3. Section II.4 finally points the main research needs for a sound application of LCA to agriculture, providing a link and a justification for the following chapters.

II.1. Life Cycle Assessment

Life Cycle Assessment or Analysis (LCA, from now on) was developed in order to help in reducing the environmental effects of industrial production, as it has been presented in the introduction. This section gives the basic references to LCA and some historical review, which is important for the understanding and actual justification of the needs addressed in the dissertation. The state of the art of LCA development is provided by the review of the ISO series 14 040x. These standards currently provide one of the main sources for guidance in the application of the method, while the methodological development is done in other forums.

II.1.1. Definition

LCA is a management tool that allows for an assessment of the impacts inflicted to the environment throughout a product’s life cycle, from resource extraction to waste management, including all the production, transport and usage stages. The assessment is done in such a way that environmental burden transfers between environmental media or life cycle stages are avoided. Fundamentally, LCA is a material and energy balance applied to the product’s system, combined with an assessment of the environmental impacts related to the inputs and outputs to and from the product system. From this assessment, LCA gives criteria for decision-making on issues such as product development, policy making, strategic planning, etc. (see Figure II-1). SETAC[1] defined LCA in one of the most cited references in this field (Consoli *et al*. 1993):

> *“The Life-Cycle Assessment is an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and material uses and releases to the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling and final disposal.”*

The International Standards Organisation (ISO) has also provided very relevant input to the process of defining LCA. According to ISO, LCA is divided in four main phases, which are closely interconnected (see Figure II-1):

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[1] Society for Environmental Toxicology and Chemistry. This Society is responsible for much of the international discussions on LCA methodology development.

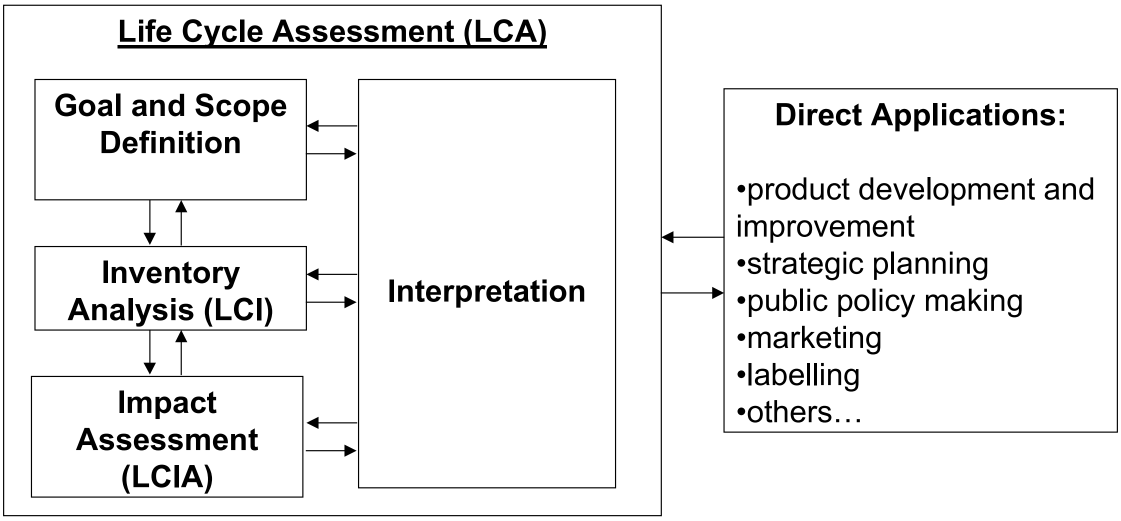

Figure II-1: Framework for Life Cycle Assessment (ISO 1997).

In brief, the goal and scope definition must clearly state the intended objectives of the LCA application, and define the system under study: its function, the system's boundaries, the hypotheses in the study, the data requirements, etc. Then, the life cycle inventory analysis (LCI) must detect those substances crossing the system's boundaries that may be relevant from an environmental point of view. The environmental significance of these substances is assessed in the life cycle impact assessment phase (LCIA). The interpretation is the final phase of the LCA, in which the results of LCI and LCIA are discussed in the light of the goals set in the beginning of the study. LCA is an iterative procedure, and the results of one phase may affect the requirements and definition of other phases.

Detailed descriptions of the methodology can be found elsewhere (Consoli *et al*. 1993; ISO 14.040-43, see Table II-1; Wenzel *et al*. 1997; Fullana & Puig 1997). Consequently, only those aspects directly related to the present dissertation will be thoroughly developed in the following chapters.

II.1.2. LCA history

One may consider that the origin of LCA lies in the energetic crises of the late sixties and early seventies, which forced industries to look for energy efficient solutions for their products. In this way, the concept of product life cycle was born, as it was necessary to reduce energy consumption in all the stages implied by the product's cycle: from raw material extraction up to waste management. The first study considered to be an LCA is a project commissioned by The Coca-Cola Company to the Midwest Research Institute in 1969, with the aim of comparing different possibilities for packaging from the point of view of emissions and material and energy consumption. This study was called REPA: Resource and Environmental Profile Analysis (Fullana & Puig 1997).

More studies such as the one described were performed during the seventies, but in the late seventies and until mid eighties the interest for such analyses decreases, probably due to the improvement in the economy (Fullana & Puig 1997).

From mid eighties, though, the interest for resource consumption and emissions minimisation increases again, and so does the practice of Life Cycle Inventories (LCI). At the same time, different institutions (EMPA[2] and BUWAL[3] in Switzerland; CML[4] in the Netherlands; etc.) developed methods for the aggregation of substances into "impact categories".

In the nineties the generalised use of LCA as a support tool for decision making starts, both in industries and in the public sector. In this sense, the publication of several LCA methodological guides by different institutions (U.S. Environmental Protection Agency; BUWAL; CML; the Nordic Council of Ministers; SETAC[5]; etc.) was crucial. These institutions also provide databases of basic data.

The evolution of LCA is relevant for this dissertation in the fact that the method was created by the industrial sector with the aim of assessing industrial products (e.g.: packaging). This is a crucial fact that will be further developed in the following sections of this chapter.

II.1.3. LCA State of the Art

ISO has already published the main standards of the series 14.04x for LCA (see Table II-1). This fact will probably derive in a much more generalised use of LCA, as one of the problems that industries find in it is the low comparability between studies. Until ISO took the initiative of normalising LCA, SETAC had been the most active institution in the search for methodological consensus. After ISO 14.040, SETAC has continued in LCA development (mainly in Europe, but also in North America and Asia). The development has focused both on methodological problems (life cycle impact assessment, data quality, sector-specific methodologies, etc.) and on practical application aspects (LCA in decision making, life cycle management, etc.). Besides, life cycle thinking is being applied in simpler methods that work with the framework of LCA but simplify the structure and data requirements. The idea is to make it more applicable in situations where a lot of decisions have to be made in a short period of time (such as in product development).

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[2] EMPA = *Eidg. Materialprüfungs- und Forschungsanstalt* (Swiss Federal Laboratories for Materials Testing and Research)

[3] BUWAL = *Bundesamt für Umwelt, Wald und Landschaft* (Swiss Federal Agency for the Environment, Forests and Landscape).

[4] CML = *Centrum voor Milieukunde*, Leiden (Centre for Environmental Science, Leiden University, The Netherlands).

[5] The SETAC 'Code of Practice' (Consoli *et al*. 1993) is one of the most cited references in the field.

Table II-1: ISO series of standards for LCA (14040 series: Environmental management. Life cycle assessment.)

Standard	***Title / Main contents***
ISO 14.040:1997	Standard on Principles and Framework
ISO 14.041:1998	Standard on Goal and scope definition and inventory analysis
ISO 14.042:2000	Standard on Life cycle impact assessment
ISO 14.043:2000	Standard on Life cycle interpretation
CD 14.047	Draft for a Technical Report with examples for ISO 14.042 on life cycle impact assessment
CD 14.048	Draft for a Standard on data format
TR 14.049:2000	Technical Report presenting examples of application of ISO 14.041 to goal and scope definition and inventory analysis

Today, the attention is focused on the Life Cycle Initiative, a joint program led by UNEP and SETAC in order to “develop and disseminate practical tools for evaluating the opportunities, risks and trade-offs, associated with products and services over their whole life cycle”[6]. Mainly, the Life Cycle Initiative is aimed at facilitating access to inventory data and providing impact assessment procedures that are adapted to practitioner’s needs. The idea is to facilitate a global application of the tool, both in rich and poor countries, and in big companies and SMEs.

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[6] Extracted from UNEP’s press release 2002.04.29 in Prague (Czech Republic). For more information about the Life-Cycle Initiative see http://www.uneptie.org/pc/sustain/lca/lca.htm

II.2. Example of Application: LCA of leather

In order to gain a clear view of LCA, the method was applied in the analysis of leather. This material has the advantage that even though it is an industrial product, agricultural stages are also involved in its life cycle. Therefore, the importance of agricultural stages and the adequacy of LCA for their assessment could also be checked. The Catalan Autonomous Government commissioned this study in order to apply its results in the procedure of criteria setting for an eco-label for leather products. The main characteristics of this eco-label are thus presented in the first section. Then, the study scoping is briefly presented, and the main conclusions and outcome of the project are finally discussed.

II.2.1. The Catalan Eco-label for leather

In 1994, the Catalan Government issued the decree for an eco-labelling program (Decree 316/1994; 14.12.1994) with two main objectives:

- To promote the design, production, commercialisation, use and consumption of products that favour waste minimisation and to encourage by-product reuse and recycling, especially for energy and water saving,
- To deliver clear and truthful information about the environmental quality of specific products to consumers and users. The objective is to guide consumers in their choice of purchase.

The symbol for this eco-label (see Figure II-2) is called "*Distintiu de Garantia de Qualitat Ambiental*" (Emblem of Environmental Quality Assurance).

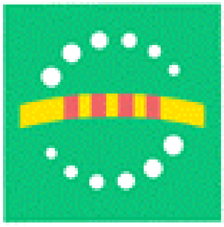

Figure II-2: Emblem for the Catalan Eco-label.

The Decree was modified in 1998 (Decree 296/1998; 17.11.1998) to include services, and today there are environmental criteria approved for nineteen product and service categories, with over eight hundred products and services having the Emblem[7]. The study presented in this report is the first Life Cycle Assessment (LCA) conducted with this objective (Milà i Canals *et al*. 1998a).

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[7] Current use of the Catalan eco-label at the moment of writing this dissertation. Information consulted at the website of the environment department of the Catalan Government, on-line: http://www.gencat.es/mediamb [September 2002].

The economic importance of the leather industry in Catalonia[8] and the increasing environmental awareness of consumers justified the interest of the Catalan Government for an eco-label of leather products.

II.2.2. Goal definition and scoping of the leather LCA study

In order not to lengthen this chapter too much, only the essential information on the leather LCA for the reader to understand the conclusions is given here. For a deeper description of the goal and scoping and detailed information on the life cycle of leather, the reader can refer to the original report (Milà i Canals *et al*. 1998a).

In this case study (Milà i Canals *et al*. 2002; 1998a; 1998b), Life Cycle Assessment (LCA) was used to detect the environmental "hot spots" in the chrome-tanned bovine leather industry[9], with the goal of guiding the criteria setting procedure for the Catalan eco-label of leather. Those stages in the life cycle of leather occurring "from cradle to gate" were studied. The production chain starts with the agricultural products (fertiliser and pesticide production is also included) needed for cattle raising, it is followed by the slaughterhouse, and ends at the tanning industry gate. Main chemicals and waste flows in and out of this chain have also been included in the analysis.

The users of the information provided by this study were the members of the Environmental Quality Council, which is the competent body for criteria setting in Catalonia. The scope of the study was the Catalan leather industry, and as the data collection was performed during 1997 and 1998 the technological state-of-the-art of that moment was used. The main assumptions considered on technological issues for the LCI calculations are summarised in Table II-2. These assumptions reflect the state-of-the-art of the leather industry in Catalonia at the time of the study.

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[8] Spain is the main European leather producer after Italy, and more than 60% of the Spanish leather industries are located in Catalonia.

[9] The original study also contains information on vegetal-tanned leather. Chrome tanning is the method for processing leather mainly used for shoe uppers, garments, furniture, etc., while vegetal tanning is mainly used for shoe soles and hardwearing leather goods (suitcases, belts, boots, etc.).

Table II-2: Main assumptions in the Life Cycle Inventory of leather.

Life cycle stage	*Aspect*	*Assumptions*
Agriculture	Fertiliser use	Mainly organic fertilisers (cattle manure) supplemented with mineral ones (chiefly P). The amount used equals the theoretical amount extracted by crops.
	Fertiliser emissions	Emissions from fertilisers (NH_3, N_2O, NO_x, NO_3^-, heavy metals) are estimated using the recommendations of Audsley *et al.* (1997).
Cattle raising	Type of cattle	Cattle are raised in stables for 10 months, and then slaughtered for meat production. Calves are produced in separate farms, usually dairies (where males are sold for meat) or farms specialised in meat-breeding production.
	Animal waste management	Animal wastes are collected in deep litter and stored in loose heaps for three months. After storage, the manure is spread on crop fields.
Slaughterhouse	Product allocation	7.7% of the emissions produced up to the slaughterhouse (agriculture and cattle raising) are allocated to leather, based on an economic partitioning of burdens (total market value share of raw hide, amongst the slaughterhouse products). Meat is the main product of cattle raising, and it carries over 90.6% of the environmental impacts of agriculture and cattle raising.
	Waste management	The slaughterhouse works with blood recovery in order to prevent blood spills to wastewater.
Storage	Type	Raw hides are preserved with salt (NaCl), and during storage they have to be kept refrigerated for two months per year on average.
Tanning	Common practices	Fleshing is carried out after liming. For the tanning operation, an intermediate scenario between a traditional technology (low temperature, low exhaustion) and a new technology (high temperature, high exhaustion) is considered. Finishing operations are considered to be those typical for shoe uppers.
	Product allocation	In the splitting phase, splits with an economic value are obtained. They represent 33% of hide's weight in the moment of splitting and 5.5% of the economic value.
	Waste management	Burdens of the wastewater system are calculated using the energy consumption needed to reduce COD (biological treatment considered). In the landfill, complete anaerobic degradation without biogas recovery is considered. Heavy metal content of wastes is considered as an emission to soil. Energy consumption in landfill is typical for Catalan landfills: 6.72 MJ t^{-1} of waste treated (Rieradevall *et al.* 1997).
Transportation	Distances	Transport distances for the main input materials (fertilisers, pesticides, salt, chromium salts) are calculated from the typical places of origin in Catalonia.

Impact assessment has been carried out up to characterisation, as no further steps were necessary in order to detect the environmental “hot” spots. The impact categories considered are Global Warming (GW), Human Toxicity (HT), Ecological Toxicity (Aquatic -AET- and Terrestrial –TET-), Photochemical Ozone Formation (POF), Nutrification (N) and Acidification (A). The methods used for characterisation (see Table II-3) were state-of-the-art in LCA studies when the study was performed.

Table II-3: Impact categories considered in the leather LCA.

Impact category	*Unit*	*Comments and References*
global warming	kg CO_2	Only emissions from non-renewable sources have been considered. Carbon fixation by plants in agriculture is not considered as negative emissions. Characterisation factors are taken from IPCC (1994). A 20-year scenario is considered.
photochemical oxidant formation	kg C_2H_4	Photochemical Ozone Formation Potentials (POFP) are obtained from the United Nations Economic Commission for Europe (UNECE 1991).
acid rain	kg SO_2	The acidification capacity of each substance is calculated as the ability to give H^+ ions when reaching water or soil ecosystems. A maximum scenario is considered in which nitrogen substances contribute to acidification, in addition to sulphur. A detailed discussion of the different possible scenarios can be found in Heijungs *et al*. (1992) and Finnveden *et al*. (1992).
nutrification	kg PO_4^{-3}	Nutrification includes all impacts due to an increased level of macro-nutrients, both in terrestrial and aquatic ecosystems. These impacts may be summarised as an increase in oxygen consumption for biomass degradation. The relative capacity of different substances to deplete oxygen (including organic matter) is used as a characterisation factor (Heijungs *et al*. 1992).
human toxicity	equivalent kg of lead emitted to air	Human and Ecological Toxicity have been characterised including a fate and exposure analysis, using the characterisation factors provided by the method Critical Surface Time 95 (CST95) (Jolliet & Crettaz 1997).
ecological toxicity (aquatic systems and terrestrial ecosystems)	equivalent kg of zinc emitted to water (Aquatic); equivalent kg of zinc emitted to soil (Terrestrial).	

In addition, indicators[10] have been used for total energy consumption (in kWh – for electricity - or MJ – for fossil fuels). The difference of these with the impact categories is that indicators do not represent a measure of any environmental impact, but are basically parameters that give information on possible sources of impact.

II.2.3. Interpretation: main results of the leather LCA

The relative contribution of the different stages of the life cycle to the impact categories and indicators are shown in Figure II-3. From this figure, the high energy consumption in the agricultural phase is noticeable (around 55-60% of the whole life cycle of leather). This result is especially remarkable if we bear in mind the fact that only 7.7% of the impacts generated in this phase have been allocated to leather. Besides, the kind of agriculture considered is not regarded as a very energy-intensive one. The tannery is important in most of the impacts considered, as well as agriculture. Also cattle raising presents important contributions in many impact categories. As

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[10] An environmental indicator is a simplified measure of an environmental impact, which does not always imply an environmental assessment, but includes some information on the state or direction of an environmental aspect. For a deeper discussion on indicators, see section IV.1.1. in Chapter IV.

shown in Figure II-3, the slaughterhouse and storage play a minor role in the generation of environmental impacts during the life cycle of leather.

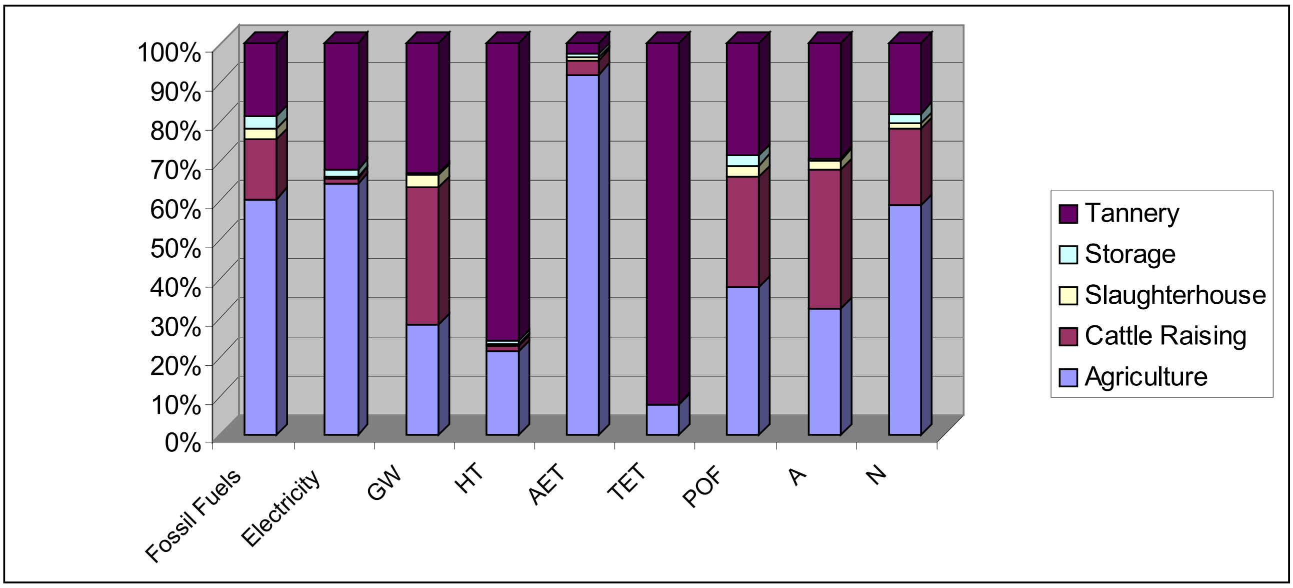

Figure II-3: Relative contribution of each leather life cycle stage to impact categories and indicators.

NOTE: Fossil Fuels: Fossil Fuels Consumption; Electricity: Electricity Consumption; GW: Global Warming; HT: Human Toxicity; AET: Aquatic Ecotoxicity; TET: Terrestrial Ecotoxicity; POF: Photochemical Ozone Formation; A: Acidification; N: Nutrification.

Table II-4: Summary of impacts and possibilities for improvement in the life cycle of leather.

Impact	*Phase*[a]	*Subst.*	*Origin*	*Possibilities for improvement*
Energy Consumption	Agriculture (55-60)		field operations	reduction of energy intensity
			mineral fertilisers production	reduction of mineral fertilisers use
Global Warming	Cattle Raising (36)	CH_4	rumen	stable gas collection
	Tannery (33)	CH_4	landfill biogas	biogas collection, wastes reduction
	Agriculture (28)	N_2O	denitrification	fertilising management (timing, dose, type of fertiliser, etc.)
Human Toxicity	Tannery (76)	Cr	wastes in landfill	wastes reduction, incineration of wastes with Cr recovery
	Agriculture (21)	NO_3^-	leaching from fertilisers	fertilising management (timing, dose, type of fertiliser, etc.)
Aquatic Eco-toxicity	Agriculture (92)	Hg, Cd	mineral fertilisers production	reduction of use of mineral fertilisers
		NO_3^-	leaching from fertilisers	fertilising management (timing, dose, type of fertiliser, etc.)
Terrestrial Eco-toxicity	Tannery (92)	Cr	wastes in landfill	wastes reduction, incineration of wastes with Cr recovery
Photochemical Ozone Formation	Agriculture (40)	NMVOC	energy consumption	reduction of energy intensity
	Cattle Raising (28)	CH_4	rumen	stable gas collection
	Tannery (23)	CH_4	landfill biogas	biogas collection, wastes reduction
Acidification	Cattle Raising (37)	NH_3	volatilisation from animal wastes	animal wastes management with the aim of N emissions reduction
	Agriculture (32)	NH_3	volatilisation from organic fertilisers	fertilising management (timing, dose, type of fertiliser, etc.)
	Tannery (29)	NH_3	anaerobic degradation in landfill	biogas collection, wastes reduction
Nutrification	Agriculture (59)	NH_3	volatilisation from organic fertilisers	fertilising management (timing, dose, type of fertiliser, etc.)
		NO_3^-	leaching from fertilisers	
	Cattle Raising (20)	NH_3	volatilisation from animal wastes	animal wastes management with the aim of N emissions reduction
	Tannery (18)	NH_3	anaerobic degradation in landfill	biogas collection, wastes reduction

[a]: in parentheses, relative contribution of the phase to the impact (%).The cells are shadowed for the agricultural stage to highlight its environmental relevance.

Table II-4 summarises the main substances responsible for the impacts in the life cycle of leather, and whether possibilities for improvement were detected. Only Agriculture, Cattle Raising and the Tannery are included in this table, as they are the only relevant phases from an environmental point of view. The impacts where agriculture presents significant contributions are shadowed in order to stress the environmental relevance of this life cycle stage.

II.2.4. Conclusions for the eco-label criteria-setting

The main conclusions that can be drawn from these results are:

- The main impact-generating stages in the life cycle of leather are agriculture, cattle raising and the tannery.
- The slaughterhouse and the storage are not relevant from an environmental point of view.
- The most relevant emissions are process- or input-related, while energy-related emissions play a significant role only in photochemical ozone formation (POF).

The first conclusion of the study implies that there are three main stages in the life cycle of leather where impacts are predominantly generated: agriculture, cattle raising and the tannery. Hence, the specific criteria for the eco-label of leather could focus on these stages as it is suggested below.
It must be noted that the important contribution of agricultural and livestock production stages to the overall impact are quite surprising, bearing in mind that only a small percentage of the impacts in this life cycle stages was allocated to leather.

Improvement opportunities

Particularly, the following points from the LCA study were highlighted to help in the setting of criteria (Milà i Canals *et al*. 1998b):

1. The criteria should take into account the chromium emissions from the **tannery**, both in tannery solid wastes and in the wastewaters:
    - Related to the solid waste, minimisation of its production by an optimisation of hide use would be a good first approach. Thence, a criterion on the quantity of solid waste per ton of leather could be useful.
    - Also the total amount of chromium sent to landfill is a relevant criterion, though the impacts in the landfill do not originate only from this substance (the ammonia and methane emitted as a result of degradation are also of relevance). Thus, chromium recycling in - or outside - the tannery should be promoted. As a last option, incineration with energy and chromium recovery can be performed.
    - Minimisation of chromium emitted to water is also significant, as the presence of chromium in the sewage sludge makes it unable to be applied as manure. Hence, a possible criterion could be a minimum percentage of recycling of chrome liquors, or even a maximum amount of chrome emitted to water.

2. In **agriculture and cattle raising**, the criteria should focus on energy consumption, both direct (e.g.: in field operations) and indirect (e.g.: in inputs production) and emissions from organic wastes:
    - A recommendation can be made to tend to a less material and energy-intensive agriculture. If possible, criteria should be set to control the maximum amount of mineral fertilisers used in agriculture (e.g. criteria for “organic agriculture”). Nevertheless, not enough data were gathered in order to determine that trade-offs between fertiliser use, energy consumption, and land use do not counteract in organic agriculture.
    - The management of organic fertilisers should be controlled, as ammonia emissions coming from this source are a main impact generator. This last recommendation applies also for cattle raising.

It must be noted, though, that criteria for the agricultural phase probably lie beyond the scope of the eco-label for leather. Instead, a criterion could involve the use of hides from organically grown calves. Nevertheless, criteria for organic agriculture or livestock production do not usually take into account aspects regarding gaseous emissions[11], which were the source of impact detected in this LCA study. On the other hand, organic agriculture considers aspects that cannot be included in LCA studies so far: soil quality, animal welfare, biodiversity conservation, etc. The only recommendation that can be made, then, is to promote the use of a life cycle approach in the establishment of organic agriculture criteria. As noted above and below, LCA itself will have to be further developed in order to do so.

The Catalan eco-label for leather products

As the actual criteria for the eco-label of leather products have already been established (DOGC 3150, 30.05.2000), it is interesting to see to what extent were the results of the LCA study applied to them. Apart from the general criteria that any product must fulfil in order to get the Catalan eco-label, five specific criteria were defined for leather products. Table II-5 summarises the criteria for the Catalan eco-label for leather products, comparing them to the criteria that were suggested by the LCA study (Milà i Canals *et al*. 1998b).

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[11] See the European regulation (CEE) 2092/91, from 24th June 1991, on organic agricultural production.

Table II-5: Comparison of the recommendation for criteria setting in the LCA study and the actual criteria for the Catalan eco-label of leather products.

Issue / Stage	Criteria recommended in the LCA study (Milà i Canals *et al*. 1998b)	Criteria for the eco-label of leather products (DOGC 3150, 30.05.2000)
Solid waste from the tannery	Reduction of the quantity of solid waste per ton of leather	Waste production in the last year must be 10% smaller than the average of the last 3 years
Chromium content in leather	Reduction of the total amount of chromium sent to landfill	Max. 10 ppm: As, Cd, Cu, Pb. Max. 5 ppm: Cr (VI), Hg.
Wastewater emissions	Set a maximum amount of chrome emitted to water	The limits of COD, suspended matter and heavy metals in water must comply with legislation
Hazardous substances	*- Not considered -*	A list of forbidden substances is given
Washable mineral substances	*- Not considered -*	The content cannot be higher than 1% in weight
Energy intensity in agriculture	Reduce mineral fertilisers and energy consumption in agricultural operations	*- Not considered -*
Organic waste and fertilisers management	Management should be made with the aim of reducing N emissions: type of waste collection, timing of application, etc.	*- Not considered -*

The three first criteria keep a close correlation to the conclusions of the LCA study, although no criteria are set on the agricultural phase. Actually, it was expected that no criteria would be set on the agricultural stage, as it would be too difficult to control from an eco-label scheme. Therefore, it can be concluded that LCA provided useful information to aid decision-making in the criteria setting procedure. Particularly, a good “environmental picture” was obtained for the leather production chain, which allowed the relevant “hot spots” to be detected. Of course, the translation of the LCA information to environmental criteria for the eco-labelling scheme also had to include other types of data: economic, technological (particularly feasibility of controlling the criteria), social, commercial, etc. This is what the Council for Environmental Quality did in order to set the criteria published for the Catalan eco-label for leather products.

Nevertheless, final criteria for the leather eco-label are mainly focused on human toxicity (addressing some of the substances detected to be more relevant by the LCA study), with no attention to sources of other environmental impacts such as Global Warming, Acidification, etc.

Environmental relevance of the agricultural stage

One of the interesting points detected in the LCA of leather was that the agricultural phase (including cattle raising) represents a very important share of the total environmental impacts, even though only a small portion of the impacts occurring in this phase is actually allocated to leather. Consequently, the environmental implications of a shift to a more “environmentally friendly” agriculture in Catalonia should be determined, as present knowledge is limited to qualitative information. Nevertheless, this shift would affect many aspects not currently included in the impact assessment phase in LCA. Therefore, for an analysis of these environmental implications to be sound, it is necessary to elaborate new impact categories that bring them into account. Examples of such aspects are soil quality, biodiversity, land use, animal welfare, etc. The needs for methodological development of agricultural LCA are further explored in the following section.

The application of LCA to leather showed that agriculture may be the source of highly relevant environmental problems, even in a non-strictly agricultural sector such as the tanning industry. On the other hand, some methodological gaps were suggested, which demand for a deeper insight into the requirements for a sound environmental analysis of agriculture. This section presents the main particularities for the application of LCA to agriculture.

II.3.1. Agricultural *vs*. industrial systems

LCA is a tool for the analysis of systems from an environmental perspective. The nature and properties of the system under study is thus of major importance for the development of the tool. As mentioned above, LCA has been mainly developed for the assessment of industrial systems, which are essentially different in many aspects from the agricultural systems that need to be assessed in agricultural LCA. Cowell & Clift (1997) suggest that industrial systems can be defined as those based on extraction and processing of non-living materials ("non-renewable" resources) for use in the human economy, while agricultural systems involve cultivation of crops and livestock to obtain "renewable" resources. Actually industrial systems can also process "renewable" materials (e.g.: in the food "industry", leather manufacture, wood constructions, etc.), and so this distinction is mainly valid for the resource acquisition phase only. When the resources are being processed, the same considerations can be chiefly made for living and non-living materials, with the only likely exception of burdens allocation, as real wastes are often produced in processing of non-renewable materials, while mostly valuable by-products are created in the processing of renewable materials. Consequently, the term agricultural system is reserved in this dissertation to refer to the material acquisition phase involving crop cultivation and livestock production, while the further processing of these resources can be mostly considered as an industrial system.

Main differences between industrial and agricultural systems

The differences between industrial and agricultural systems will explain many of the problems that can be found in agricultural LCA, and so they are summarised in Table II-6 and further explained below.

Table II-6: Main characteristics of industrial and agricultural systems.

Characteristic	*Industrial Systems*	*Agricultural Systems*
Dependency from location	Highly independent (except in the boundaries with nature: raw materials extraction and waste disposal)	Highly dependent (some degree of independence can be gained at the expense of energy and infrastructure: greenhouses)
System boundaries	Clearly defined	Unclear, both physically and temporally
Main source of impacts	Energy and materials consumption	Land use, energy and materials consumption, and field emissions
Degree of knowledge	High (simple and pre-designed processes)	Relatively low (complex, natural processes)
Functionality	One or few functions	Multifunctional

Probably the main aspect that needs attention when discussing about differences between industrial and agricultural systems is the degree of dependence from the location. Apart from the factories that work directly with the resources extracted from land, a modern factory can be located almost anywhere. Also, the characteristics of production plants can be chiefly the same in different locations, and so the results from LCA conducted in Asia and in Europe on the same industrial product using similar technology might render almost the same results. Of course, energy production can differ from one place to another (introducing the obvious differences due to e.g. different electricity production mixes), but energy consumption will not significantly change. Conversely, agricultural systems are actually installed in one location or another depending on the main characteristics of this location: climate and land attributes. As an example, Beaufoy (2001) finds huge variations in olive farming within the EU, which are apparent across three broad categories: plantation characteristics and farming practices (technology type and producer's habits); physical and biological conditions of the location; and socio-economic situation of the holding. In order to gain a certain degree of independence from its surrounding environment, an agricultural system must expend energy and infrastructure. In this sense, greenhouses are an extreme case of independence, while hydroponics can actually be considered an industrial rather than agricultural system, due to its degree of independence from the location (and particularly from soil).

Besides, the limits of the production system are clearly established in industrial systems. These limits even have a physical translation in the factory walls. From a temporal point of view, it is also quite clear when an industrial process does begin and when does it end, and so processes and their impacts can easily be allocated to products. This is not the case in agricultural systems, where physical and temporal limits of the system are unclear. Even though the surface boundaries of a crop field can be easily set, it can be argued whether these are the real limits of the system. The reason is that processes taking place out of these boundaries do affect the agricultural system under study, e.g.: activities affecting pollinator insects' activity. Besides, the vertical boundary of the system is not clear either: the soil is a continuous system, but only parts of it are of interest for the agricultural system. From a systems' analysis perspective, an emission only becomes so when it crosses the system boundary, and so it must be clear where does the soil belong to the environment and where to the system. Also the temporal limits of an agricultural system are unclear, because many activities happening before sowing actually affect the system. For instance, fertiliser use does not only benefit the current crop, but also remains of the nutrients will benefit future crops, and so part of the impacts of fertilising should be allocated to those crops.

The relatively high degree of independence of industrial systems with their surroundings is also translated to a low degree of localisation of their impacts. Thence, even though local impacts due to land occupation and effects of direct emissions are important next to factories, most impacts of industrial systems occur at a global scale, and can be greatly dispersed. This is mainly due to the fact that most impacts are linked to material and energy consumption, and that materials and energy may be extracted and processed far away from the production centres. In the case of agricultural systems, materials and energy consumption are an important source of impacts as well, but many impacts actually occur in the agricultural field. Actually the conditions of this field will determine most of the impacts, and *vice versa*: most impacts will actually affect the conditions of the field. Land use related impacts become a key issue for the agricultural systems' environmental performance.

Another relevant aspect when discussing differences between industrial and agricultural systems is the degree of knowledge on the system. Industrial systems are actually designed by humans, and so most details of their functioning are perfectly known. In the case of agricultural systems, on the other hand, humans are only taking profit of natural systems that have been modified to better suit our interests. The knowledge in natural systems is much more limited and they are ruled by biological processes, which increases their complexity and reduces their predictability.

Usually, an environmental assessment method tries to determine which are the environmental consequences of the delivery of a function to humans. I.e.: society needs to develop particular functions (feed people, move from one place to another, protect people from cold, etc.), and environmental assessment tools must determine the environmental impacts derived from accomplishing these functions by different means. The environmental impacts are then expressed as the amount of a relevant impact indicator (e.g.: equivalent kg of CO_2 for global warming) per unit of function, or functional unit (e.g.: covering 1 m^2 of wall during 10 years). In this sense, it must be noted that agricultural systems are multi-functional, and so it is difficult to define which is the functional unit delivered by the system. When a system produces more than one function, the environmental impacts caused by the system must be proportionally allocated to the different functions. Industrial systems generally deliver only one function (usually a product) and when more than one product is produced, clear physical or economical relationships between them exist that make allocation of causalities easy. In the case of agricultural systems, and ecosystems in general, the relationships between functions are not clear.

II.3.2. Methodological problems in agricultural LCA

The following paragraphs present the main methodological problems in agricultural LCA. These problems are predominantly caused by the differences between industrial and agricultural systems summarised in Table II-6.

Definition of a functional unit

As agricultural systems are naturally multi-functional, the definition of a functional unit is not always a straightforward procedure. Sarah Cowell (1998) refers to this multi-functionality when discusses about the definition of the functional unit. Accordingly, agriculture's function can both be related to keeping the land to a definite shape and composition or to the production of products. Furthermore, agricultural products can be characterised by mass, energy, nutrient content, meal portions, etc., which renders the definition of a functional unit a complex and usually case-dependent process. Haas *et al*. (2000) provide an interesting example of the consequences of using different functional units on the LCA results; further discussion and examples on this issue can be found in section III.1.2. of this dissertation.

System boundaries: temporal and physical limits

As it has been pointed above, the system boundaries are ill-defined in agricultural systems. Even though LCA is often referenced to as "cradle to grave analysis", most agricultural (particularly food) LCA often disregard the use phase (i.e.: consumption of the food) (Cowell & Clift 1997; Haas *et al*. 2000). The inclusion of use and waste management phases would imply to analyse the effects of food consumption in sewage treatment, which would occur regardless the system under study. Nevertheless, Cowell & Clift (1997) argue that this exclusion could compromise the identification of opportunities for environmental improvements.

Ancillaries[12] are not generally included in the boundaries of industrial systems unless they make a significant contribution to the LCA results. This is not often the case, as ancillaries are used in a rather efficient way by industrial systems (i.e.: a factory produces a huge amount of products before becoming obsolete; a truck transports a lot of products; etc.). On the other hand, Cowell & Clift (1997) discuss that the consideration of what can be considered as an ancillary in agriculture is less evident. Machinery and farming infrastructure are often used less efficiently than in industrial systems, and so the allocation of its production to the functional unit is usually relevant. Besides, they suggest that soil should be considered as an ancillary, because its quantity and quality, affected by the agricultural practices, have a crucial role in future productivity of the system. Then, a Soil Quality Index should be developed in order to include soil quality degradation in the LCIA.

Apart from the physical limits discussed in the last paragraphs, Cowell (1998) raises the question of the time boundaries, and suggests that activities in the past affecting actual productivity should also be included in the analysis. Examples of such activities are fertiliser use that is useful for more than one crop, hedges construction and maintenance, etc. Therefore, the system under study

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[12] Materials or products that contribute to maintenance of processes but are not intended to enter the product (Fava *et al*. 1990).

should include all these relevant activities, and hence comprise full crop rotations, whole trees life cycles, etc.

Allocation

As discussed previously, agricultural systems produce by-products or “near-to-waste” (Cowell 1998) materials, which usually raise allocation problems in the inventory phase of LCA. Moreover, when whole crop rotations are included in the analysis, partition of environmental burdens amongst them is usually needed. There are methods to avoid allocation problems, but these generally affect other phases of the LCA, such as impact analysis. For instance, Cowell (1998) suggests that the inclusion of soil quality and quantity into the LCIA greatly reduces the allocation problem for crops, although it then requires the development of a convenient impact indicator. This issue is further explored in Chapter IV of this dissertation.

In addition, the carbon cycle raises an allocation problem in agricultural systems. Carbon fixation by plants has been considered as a negative emission[13] of CO_2 by some authors, while others disregard this emission because CO_2 is anyway released in a usually short period when organic materials are degraded. The development of an organic matter indicator for soil quality in the fourth chapter of this dissertation will also give some input to this issue.

Life Cycle Impact Assessment

As for LCIA, the main topic found in the agricultural LCA literature is the need to develop impact categories related to resource consumption, particularly in the case of land use. Three aspects related to agricultural land use need to be taken into account according to Cowell & Clift (1997): actual or potential productivity of land; effects on biodiversity; and aesthetic value of landscapes. Many other authors also highlight the crucial importance of these aspects in agricultural LCIA (Mattsson *et al*. 1998; Haas *et al*. 2000). The issue is thoroughly analysed in the report of the SETAC working group on the LCIA categories dealing with resources (Lindeijer *et al*. 2002), where the economic aspect of competition over land is also highlighted.

The loss of biodiversity has been the land-use-related impact that has obtained more attention. Cowell (1998) suggests a procedure to include biodiversity as an impact category in her PhD thesis, and many other methods have been suggested, ranging from classifying land according to its degree of “naturalness” (the Hemeroby concept, see Brentrup *et al*. 2002 for a review) to data-intensive models with a high degree of complexity. Many other relevant references for biodiversity assessment within LCIA can be found in the literature (e.g.: Lindeijer *et al*. 1998; Müller-Wenk 1998; Köllner 2000).

Also soil quality and generic land quality indicators have been studied in order to assess the impacts on potential productivity of land. Many contributions dealing with this issue can also be found in the literature (Blonk *et al*. 1997; Cowell 1998; Baitz *et al*. 1999; Lindeijer *et al*. 1998; Milà i Canals *et al*. 2000, 2001). The aspects on land productivity are further explored in the fourth chapter of this dissertation.

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[13] A negative emission refers to the fixation of a substance of concern, leading to a decrease in the concentration of that substance and thus a beneficial effect. Carbon fixation by plants (leading to a decreased CO_2 concentration in the atmosphere) is a typical example of what can be considered a negative emission.

Finally, the aesthetic value of landscape lies deep in the subjective values of society. Therefore, its inclusion in environmental LCA has been object of controversy, and a hard issue to model. Nevertheless, some examples of application of this aspect can be found, where this subjectivity is highlighted (Mattsson *et al*. 1998; Haas *et al*. 2000).

Site-dependency

Another issue that has generated some controversy is whether LCA needs to be site-dependent. This question is multi-faceted and different authors regard at different aspects when discussing it. Originally, LCA was conceived as a site-independent environmental assessment, mainly due to data availability and the nature of the assessment. Indeed, in industrial systems mainly the technology type needs to be assessed with LCA, which advocates for a site-independent analysis due to the relatively high degree of independence from the location in industrial systems. Nevertheless, this may not hold true for some applications of LCA, and particularly for some sectors such as agriculture.

Wenzel (1998) discusses on the issue of site-dependency as related to the type of decision to be made based on the LCA results (application). According to him, three key variables determine the need for site-dependency: the nature and extent of the environmental consequences of the decision (including the occurrence of trade-offs between impact categories); the social and economic consequences; and the context of the decision. These variables have effects on the scoping, inventory, and impact assessment phases of the LCA. Wenzel (1998) concludes that the LCA applications needing to be site-dependent are mainly production technology assessment (Best Available Technologies), choice between alternative suppliers, and marketing. Oppositely, he suggests that LCA applied to societal activities planning and legislation, product development, and eco-labelling criteria setting would not need to be site-dependent.

Other authors have pointed out that, regardless of the application of the results, site-dependency is needed for some impact categories (particularly those having effects at regional or even local levels). For instance, Ross & Evans (2002) maintain that excluding temporal and spatial site-dependent information to support decision making at the policy making level reduces the usefulness and credibility of LCA results. Thiel *et al*. (1999) suggest a multi-tool approach in order to address local and regional impacts in LCIA, with a mix of LCI, environmental impact assessment and environmental fate models using fuzzy expert systems. Krewitt *et al*. (2001) derive characterisation factors for SO_2, NO_x, fine particles and NMVOC for impacts on several local and regional impact categories (human health, acidification, eutrophication and man-made environment). They conclude that including site-dependent data in the assessment results in a significant variation in the damage factors. In the SETAC Working Group on LCIA (Udo de Haes *et al*. 2002), the concept of Generic Application Dependency is used to refer to the fact that impact categories should be modelled in a way that allows for site-dependency when the application requires so, but can also be applied in a generic way, without site-dependent information.

In the case of the agricultural sector, the environmental consequences related to agricultural systems depend on both the technology and the site where agricultural production takes place. Audsley *et al*. (1997) point that inventory data may be very dependent upon local conditions, even though they do not further explore this issue. Cowell & Clift (1998) suggest that site-dependent aspects might have a greater influence on the LCA results than activity-dependent aspects. The LCAnet Food project also identified the role of geographical variations in the agricultural LCA results as a research priority, but this could not be satisfactorily addressed during the project (Olsson 1999). This influence may be derived from the inventory results (e.g.: on the substances emitted in different locations, which are affected by site characteristics such as soil and climate), or from the impact assessment results (e.g.: through the effects on local impacts such as land use impacts, toxicity, etc.).

As a conclusion, site dependency may be related to scoping, LCI and LCIA, and it may be considered from the point of view of application, sector, or impact category. In the third part of this thesis the effects of site-dependency on scoping and LCI of an agricultural LCA are discussed, while the need to incorporate a very site-specific impact category is the main focus in Chapter IV.

II.3.3. Main events in the development of agricultural LCA

Given the methodological problems described in the last section, several European projects have been undertaken in order to try to solve them, or at least to set some basic scientific ground to help in the research of alternatives. Cowell (1998) makes a thorough review of the main projects and research groups in Europe from 1993 (when the first Expert Seminar was held, see Weidema 1993) until 1997. Of these, probably the concerted action AIR3-CT94-2028 for the European Commission (Audsley *et al*. 1997) has been the one addressing more methodological problems, and has become a basic reference in the field of agricultural LCA. In that project, eight research groups from Central and Northern Europe (Austria, France, United Kingdom, Switzerland, the Netherlands and Denmark) analysed wheat production under three cropping schemes (conventional, integrated and organic), and tried to solve methodological problems separately. Through several workshops, best practices were suggested for each of the methodological problems.

A similar project, though wider in the participation of research groups and countries, started in 1997 with the aim of addressing application problems for LCA of food products, both related to methodology and data gaps: the LCAnet-Food project (EU-97-3079)[14]. Over 30 Research groups (from academia, industry, and consultancy) coming from fourteen European countries plus representatives of the European Commission participated in the construction of a European network for Life Cycle Assessment within the food chain. Their mission was[15]:

- to evaluate and report the state of the art of present LCA methodology with special emphasis on applications and knowledge gaps within LCA works dealing with the entire food chain
- to develop a Strategic LCA Research Programme focused on the food chain
- to initiate and promote the formation of a pan-European data base for LCA within the food chain

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[14] The full name of the project is *EU-97-3079 - An environmental study - LCA network on foods*. It is a concerted action in the Food and Agricultural Programme (FAIR).

[15] A thorough description of the project can be found in the web page: http://livs.sik.se/sik/affomr/miljo/lcanetf.html

One of the results of the LCAnet Food Concerted Action was an Invitational Expert Seminar on LCA of Food Products. The report of this seminar (Weidema & Meeusen 2000) deals with the problem of selection, exchange and interpretation of agricultural data for use in LCA.

Table II-7: Main events in the development of agricultural LCA.

Year	*Event*
1993	First expert seminar on Agricultural LCA (Weidema 1993)
1995-1997	Concerted Action AIR3-CT94-2028 of the European Commission on Harmonisation of Environmental LCA for Agriculture
1996	International Conference on Application of Life Cycle Assessment in Agriculture, Food and Non-Food Agro-Industry and Forestry (Ceuterick 1996)
1997	Publication of the results of the concerted action (Audsley *et al*. 1997)
1997-1999	LCAnet-Food Project (EU-97-3079)
1998	International Conference on Application of Life Cycle Assessment in Agriculture, Agro-Industry and Forestry, in Brussels, Belgium (Ceuterick 1998)
1998	First doctoral theses on LCA in agriculture (Cowell 1998; Andersson 1998)
2000	Publication of the results of the Invitational Seminar on LCA of Food Products (Weidema & Meeusen *et al*. 2000)
2001	International Conference on LCA in Foods, in Gothenburg, Sweden (SIK 2001)

II.4. Conclusions for Chapter II and research needs detected in agricultural LCA

From the LCA of leather, several conclusions can be drawn in relation to agricultural LCA:

- The agricultural phase has proved to be environmentally relevant even in a non-agricultural study.
- Some of the main options for reduction of the environmental impacts of leather require a more environmentally sound agricultural and livestock production.
- Not all relevant aspects of agriculture could be taken into account because no methodology is currently available for them. The environmental impacts of agriculture must be clearly determined in order to get a clearer picture of the environmental hotspots in the life cycle of leather.
- New aspects in the environmental assessment of agriculture need to be assessed for a sound comparison of alternatives. These aspects have not traditionally been included in "industrial" LCA and so new methods need to be developed: land use (including soil quality and biodiversity), animal welfare…
- The definition of system boundaries plays a key role in the contribution of each life cycle stage to some environmental impacts (toxicity), as it determines whether certain substances can be considered as emissions (particularly heavy metals, but also pesticides).
- Traditionally, eco-labels for agriculture do not include environmental aspects that are found to be highly relevant by LCA: energy consumption and nitrogen emissions from fertilisers (both mineral and organic).

The review of the state of the art in agricultural LCA suggests that this is a recent field of research, with the first references appearing in the early 1990s. Some research issues have already been addressed in the literature, however there is still not enough scientific agreement on some of the most controversial issues. The following areas show important methodology gaps:

- In LCIA, new impact categories need to be adequately developed for the agricultural LCA to be sound, particularly a comprehensive approach for land use impacts, including biodiversity and soil quality.
- The need for including site-dependency in agricultural LCA is still not properly understood. This is translated into the effects of site-dependent conditions for the LCI results, and the possibility of incorporating site-specific information in some impact categories.
- The definition of system boundaries and the functional unit remains unclear in some aspects, namely whether soil should be included as a new impact category in order to avoid allocation problems. In addition, the way in which carbon fixation by plants and emissions of "renewable" carbon should be allocated amongst an agricultural product's life cycle stages is still a matter of discussion.

Land use related impact categories are crucial if different agricultural technologies are to be soundly compared. As these impact categories are intrinsically local in its scope, the question of site-dependency in LCA needs to be properly addressed first. This will help in determining whether site-dependent data are relevant in agricultural LCA, and thus whether the inclusion of site-dependent impact categories would pay the additional effort of collecting them.

This discussion leads the reader to the third chapter of the thesis, where a detailed application of LCA to a purely agricultural system is performed. The object of study is apple production in New Zealand. Integrated and Organic Fruit Production sites were compared from two different regions, with the idea of detecting the hotspots of these agricultural systems. Also the extent to which environmental impacts depend from technology choices or site characteristics was studied. The development of one of the impact categories that have been detected as more necessary for agricultural LCA is addressed in Chapter IV: degradation of soil quality.

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CHAPTER III. THE IMPORTANCE OF SITE-DEPENDENCY IN AGRICULTURAL LCA.

"It's easier to disintegrate an atom than a preconception"
A. Einstein

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Of the methodology gaps in agricultural LCA detected in Chapter II, the extent of site-dependency in the LCI and LCIA require extensive research. In order to study in detail which are the main sources of impact in agriculture, a detailed LCA was undertaken in an agricultural sector with a high added value: apple production in New Zealand. The overall objective was to gain a deep understanding of agricultural systems and the problems that arise in analysing such systems, in order to detect the aspects that still need further research. With this goal in mind, the state-of-the-art in agricultural LCA was applied step-by-step. an in-depth discussion of the systems under study is given in order to determine the dependency of the LCA results on the techniques used in different systems and the site conditions.

Section III.1 of the present chapter presents the Life Cycle Assessment of apple production in New Zealand, with an introduction to the apple sector in that country and the goal and scope definition for this LCA. Section III.2 gives a thorough description of the systems analysed in the inventory phase of LCA, with a special attention to the modelling aspects that have been used in the calculation of field emissions, and the production of some agricultural inputs that had not been described before in the literature. The results of the impact assessment phase are given and commented in section III.3, where also new characterisation factors for toxicity impacts of many agro-chemicals are provided. Section III.4 is the interpretation of the LCI and LCIA results in the light of the objectives set in the beginning of the study. More precisely, the effects of the technology, region, and site characteristics on the results are first checked, and opportunities for improvement are suggested. In addition, the relevance of inputs production (mainly machinery and pesticides) is analysed, and some needs of further research are highlighted. Finally, section III.5 offers a deep insight into the discussion on site-dependency in agricultural LCA, which was initiated in Chapter II.

III.1. Introduction: the New Zealand Apple LCA

The methodological problems related to agricultural LCA that have been highlighted in the previous chapter motivated a further investigation of its application to agricultural systems. In order to better understand practical problems arising from agricultural LCA, a study on apple production was undertaken in HortResearch[1], lead by Graham Burnip and Dr Max Suckling. The antecedents of the study start in 1998, when a Master student from Denmark initiated a new line of research by performing a simplified LCA of apple production (Hermansen 1998). This was followed by the stage of Dr Sarah J. Cowell in HortResearch (in 1999), which further increased the interest of a thorough application of the method, in order to explore the possibilities of LCA for the New Zealand apple industry (and to the agricultural sector in general). Another relevant reference for this study is Stadig (1997), who compares apples grown in Sweden, France and New Zealand using LCA.

The main advantage of this study is the close cooperation between HortResearch and individual apple growers in New Zealand, which enabled an extensive data collection and system's knowledge at the level of individual grower's practices from different sites and regions within New Zealand. This is a key point in reviewing the aspects that determine the environmental impacts of apple production, and gives an added value for the discussion of site-dependency in agricultural LCA.

III.1.1. Apple production in New Zealand

The New Zealand apple industry is largely focused on the export of fruit to Northern Hemisphere markets, mainly to the European Union (Batchelor *et al*. 1997). Today, New Zealand's apple production is moving to more environmentally friendly ways of production, with 100% grower adoption of the so-called Integrated Fruit Production (IFP), and 10% of total production using Organic Fruit Production (OFP). Particularly, European retailers are asking pipfruit producers in New Zealand to grow fruit under the most environmentally favourable conditions, in addition to comply with safety requirements imposed by the governments.

Integrated Fruit Production (IFP)

The proposal of an IFP scheme was a New Zealand apple market initiative, designed to maintain market share in the sense of starting a more environmentally friendly way of apple production. This was initiated at a time when New Zealand's share was under threat from other countries beginning to compete with its, until then, premium apple varieties. The principles of IFP are defined as (Batchelor *et al*. 1997):

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[1] HortResearch Ltd. is a Research Institute in New Zealand devoted to horticultural crops (pest and disease management, post-harvest treatments, development of new varieties, etc.), environment (soil and water protection, bioremediation, pesticide residue testing, etc.), plant genomics, bioactives and bioengineering technologies. Consulted on-line http://www.hortresearch.co.nz [2002.11.08].

> *"The economical production of market-quality fruit, giving priority to sustainable methods that maintain consumer confidence and are the safest possible to the environment and human health".*

Integrated Fruit Production (IFP) represents the rationalisation of conventional (industrialised) production systems. Thus, environmental problems such as nutrient loss and pest resistance to conventional treatments due to their overuse are recognised, and measures are undertaken in order to avoid them. Fertilisers are applied basing the doses on soil's needs, rather than following fixed rates.

In the case of disease control, the New Zealand IFP guidelines for use of fungicides in pipfruit are based on three key restrictions:

- Limits to post-harvest fungicide use in order to minimise fruit residues (Manktelow *et al.* 1997);
- Limits on the amount of applications per season of dithiocarbamate (EDBC) fungicides, in order to avoid disruption of integrated control.
- Limits on the amount of applications per season of demethylation inhibitory (DMI) fungicides, in order to reduce the likelihood of fungicide resistance developing.

In the case of insecticide use, pest and beneficial insects in the crop are monitored, and sprays used only when justified; in response to set thresholds. In addition, preference is given to using only biologically benign insecticides (i.e.: affecting only the target species).

Organic Fruit Production (OFP)

An "organic" production system has also been under development (Burnip & Thomas 1993), which aims to provide consumers with fruit certified to identified standards. The New Zealand Biological Producers and Consumers Council, Inc. (Bio-Gro) are the main certifiers of organic fruit in New Zealand. Organic Production is defined as (Bio-Gro 1994):

> *"The production scheme which seeks to produce food of optimum quality, and to manage productive systems according to a total concept that endeavours to make them sustainable and non-polluting of the environment, while providing an appropriate level of income to the producer(s), families and communities".*

Its philosophy is based on naturally occurring processes, and so encourages internal stability of production systems, rather than relying on external control measures. Hence, Organic Fruit Production (OFP) is less intensive in agrochemical and synthetic fertilisers input to the orchard than IFP. Particularly, it tries to avoid the use of soluble mineral salt fertilisers, while banning the use of most synthetic chemical pesticides. Instead, it promotes the cycling of nutrients to sustain and enhance natural fertility of soil, and relies on biological ways of avoiding pests. Organic fertilisers can be used, and the growers use mulching in the tree line in order to prevent weeds, but also as a source of nutrients. Apart from biological control of pests through the promotion of beneficial insects, other types of biological control are used in OFP, such as pheromone mating disruption or natural pest viral and bacterial diseases. However, this system is currently reliant on broad-spectrum fungicides (copper and sulfur), in the absence of fruit varieties with both resistance to apple blackspot (*Venturia inaequalis*, Cooke, G. Wint) and the quality attributes required of an export market. Neither synthetic herbicides nor fruit thinning and plant growth control agents can be used in OFP.

Further details on the accepted materials and practices under the OFP system can be found in NZ Biological Producers & Consumers Council (Bio-Gro, 1994), and will be described in the following sections.

Although some of these characteristics make OFP a bit more expensive than IFP, it must be taken into account that commercial success is not its only aim. The protection of the environment is also one of the main objectives of OFP, and so it must be regarded as a benefit as well.

Today, all growers of exported fruit in New Zealand follow either IFP or OFP guidelines.

III.1.2. Objectives and scope of the study

The phase of goal definition and scoping of the LCA tries to precisely describe the breadth and depth of the analysis, with the main objectives, the intended audience, the system's function and boundaries, data quality requirements, the main hypothesis, etc. (ISO 1997). Thus, in this section the primary and secondary goals of the New Zealand apple LCA are first described, and the studied system is precisely defined in order to understand the decisions made in the inventory and impact assessment phases of the LCA. The object of study –apples- and the characteristics of the producing regions are given, as well as the functional unit to which the results are referred. Finally, the system boundaries and the procedure for data collection and environmental impact assessment are given.

Goals of the study

The LCA study was performed mainly with the aim of detecting the environmental hotspots of two different systems for apple production, Integrated and Organic, in two New Zealand regions: Central Otago (CO) and Hawke's Bay (HB). The idea behind this aim was to provide data for a rough comparison of Integrated Fruit Production (IFP) and Organic Fruit Production (OFP), and highlight the environmental relevance of agricultural production in different regions. The results of this first goal were presented in an international conference of LCA in Food production (Milà i Canals *et al*. 2001).

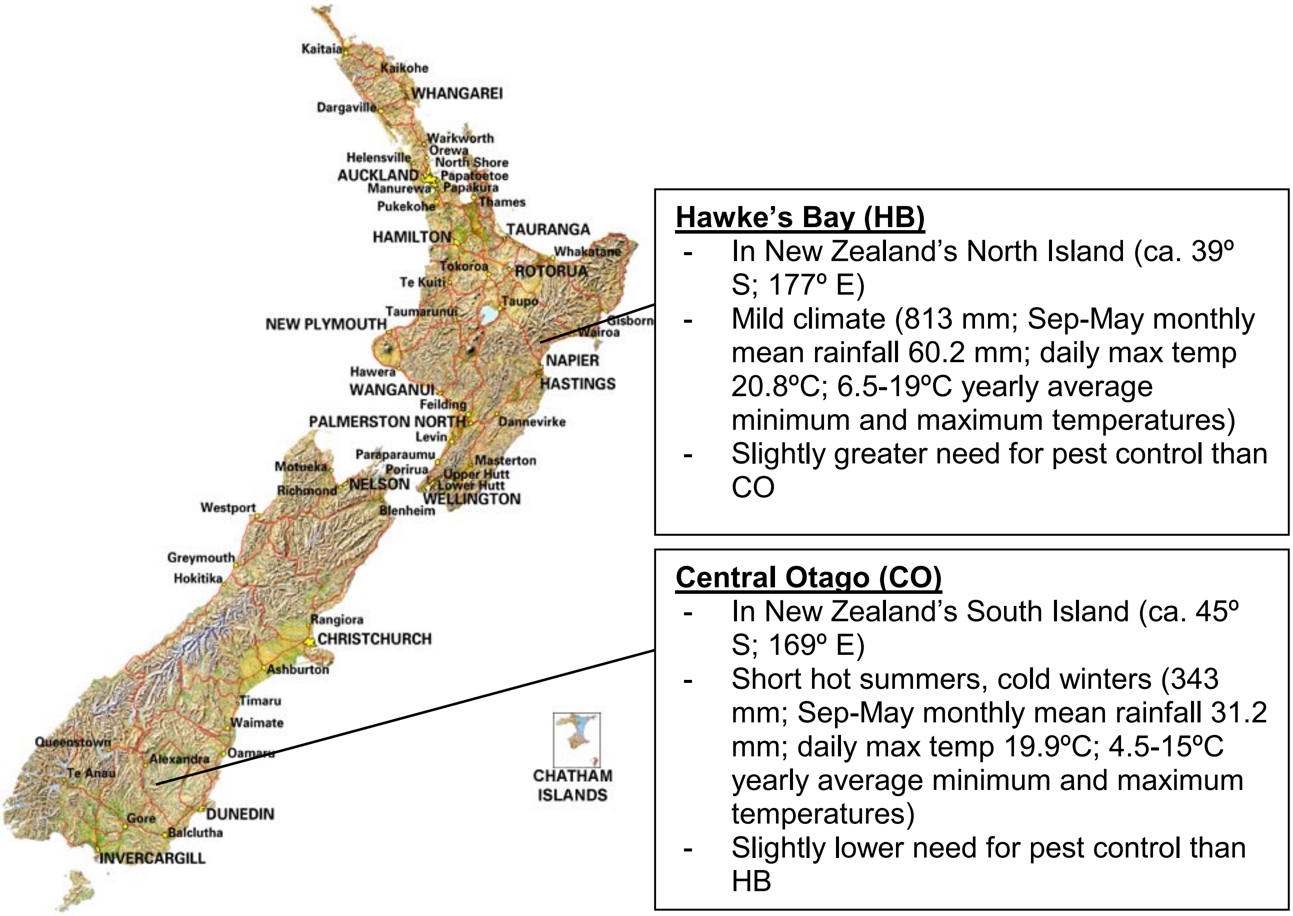
During the course of the study huge differences were detected between the different producers participating in the study, which could not be only attributed to the "technology type" (OFP or IFP) or the region. Consequently, a new goal appeared: the study was aimed at determining whether technology or region choice are the only parameters that determine the environmental impacts of agricultural production, or there are more parameters affecting results, such as the exact location, producer's practices, etc. In other words, this new goal seeks an answer to the question "what is the extent of site-dependency in agricultural LCA?"

Some secondary objectives of the study were to suggest improvements in both IFP and OFP and to detect research needs for a more generalised application of LCA to NZ agriculture. The need for such use of LCA is increased by the fact that importers of apples from New Zealand are increasingly interested in the environmental consequences of apple production in different places. For instance, SABA Trading (a Swedish importer) commissioned a LCA for the comparison of apples from different suppliers (in Sweden, France and New Zealand), in order to get relevant and transparent environmental information for their customers (Stadig 1997). Finally, the study was also intended to increase environmental awareness of NZ agricultural sector.

Object of study and sites location

Apple production in New Zealand orchards is the object being studied. As different apple varieties (cultivars) have different needs, a single variety has been elected for the study: Braeburn. The election was based on the sensitivity of this variety to a storage disorder known as bitter pit (explained below).

As mentioned in the objectives, orchards in the North and South Islands of New Zealand were selected for the study. The general location of the areas under study can be seen in Figure III-1.



Hawke's Bay (HB)
- In New Zealand's North Island (ca. 39º S; 177º E)
- Mild climate (813 mm; Sep-May monthly mean rainfall 60.2 mm; daily max temp 20.8ºC; 6.5-19ºC yearly average minimum and maximum temperatures)
- Slightly greater need for pest control than CO

Central Otago (CO)
- In New Zealand's South Island (ca. 45º S; 169º E)
- Short hot summers, cold winters (343 mm; Sep-May monthly mean rainfall 31.2 mm; daily max temp 19.9ºC; 4.5-15ºC yearly average minimum and maximum temperatures)
- Slightly lower need for pest control than HB

Figure III-1: Map of New Zealand and details of the studied areas.

System's function and functional unit

The functional unit is the reference unit to which the system's inputs and outputs are related. It is called "functional" because it should be related to the function of the system in order to be able to make fair comparisons between different product systems performing the same function, or apparently similar products performing different functions. In most cases, the definition of a functional unit is a rather straightforward process, which uses a familiar unit such as one kg of product as a reference. Nevertheless, it must be noted that the definition of a functional unit has profound effects on the results of any LCA, and many aspects should be considered when analysing such results. Hermansen gives an elegant discussion on this issue in her Master's thesis (Hermansen 1998), and further references can be found in section II.3.2 (second chapter of this dissertation).

For this study, the functional unit has been set to **1 ton of apples of export or local market quality**. This seems consistent with the general function of an apple orchard (the object of the study): producing apples. But an important consideration arises here: is "apple production" the main function of an orchard? Or is it "giving profit to the producer"? In this latter case, the market value of the product should be included in the functional unit (e.g.: 1,000 NZ$ of net profit), and aspects such as the production costs, the pack-out[2] and price of apples would come into play. The market value can probably be considered as a good approach to functional unit, but many paradoxes could appear in the results: for instance, if bigger apples are paid better than small apples, then the environmental impacts per kilogram of small apples would be higher, even though the production systems could be exactly the same. Moreover, small apples might have more nutrients per kg, and so they could provide more nutritional function; if this is the case, then the economic value would be even less advisable. Actually, Hermansen (1998) mentions different qualities of apples that could be considered when defining the functional unit:

- energy content [kcal]: this would be relevant if the main system function was "to keep hunger away"
- flavour [sugar content?]: apples as a snack?
- nutritional content [content of vitamins, minerals, antioxidants…]: fruit as a healthy food and source of nutrients
- beauty [?]: if apples are considered as a nice thing to have on a table
- …

Different consumers may thus be asking for different functions when consuming apples, which makes the definition of a real and comprehensive functional unit almost impossible. Therefore, different functions can be fulfilled with apples of different quality. In New Zealand, the highest quality is called "export grade" (grade 1), while apples for local markets (grade 2) are perfectly edible but usually do not meet the export requirements for size, colour, etc. Finally, the process apples (grade 3) are not suitable for markets (chiefly due to aesthetics) and are used in the food industry (mainly juice, but also jams, canned fruit, etc.).

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[2] The pack-out is the percentage of the production that can be sold for direct human consumption in export markets.

The “landscape maintenance function” of agriculture can also be taken into consideration, and then a surface measure (e.g.: 1 ha of orchard) could be used as a functional unit. This option has been disregarded in the present study because it does not reflect the situation in New Zealand’s apple industry, but could be considered as an option when all other functions are accomplished and apples are mainly produced to keep the traditional landscape[3] (see Cowell 1998). Besides, with such a functional unit almost unproductive systems could be rated as more environmentally sound.

Using one ton of apples of grades 1 and 2 (export and local markets) acknowledges that the main function of an apple orchard is to produce apples for (direct) human consumption, while keeping an eye on the producer’s profitability through the inclusion of only the grades that make for most of the orchard’s market value. The practical implications of such allocation procedure are shown in Table III-13 (page 66) where the allocation factors are included for each site in the study, according to their productivity. The LCI is thus calculated for 1 ha (practical unit for data collection) and the results referenced to the functional unit afterwards.

System boundaries

The system’s physical boundaries are set in the whole orchard, including a tree wind shelter that is usually found in New Zealand apple orchards (see Figure III-2). On the vertical axis, soil is considered as part of the system (and thus of technosphere) down to a depth of 1 m. Substances crossing these boundaries will be considered as emissions to the environment. The limit has been established at 1 metre depth because substances reaching this depth will probably leach to groundwater, and thus be a threat to humans.

In the case of ancillaries, only machinery use has been analysed. Soil quality degradation has not been assessed due to lack of methodology, even though this is recommended in Audsley *et al.* (1997), Cowell (1998) and other specialised literature. Farming infrastructure (buildings, irrigation infrastructures, etc.) and its maintenance has neither been included.

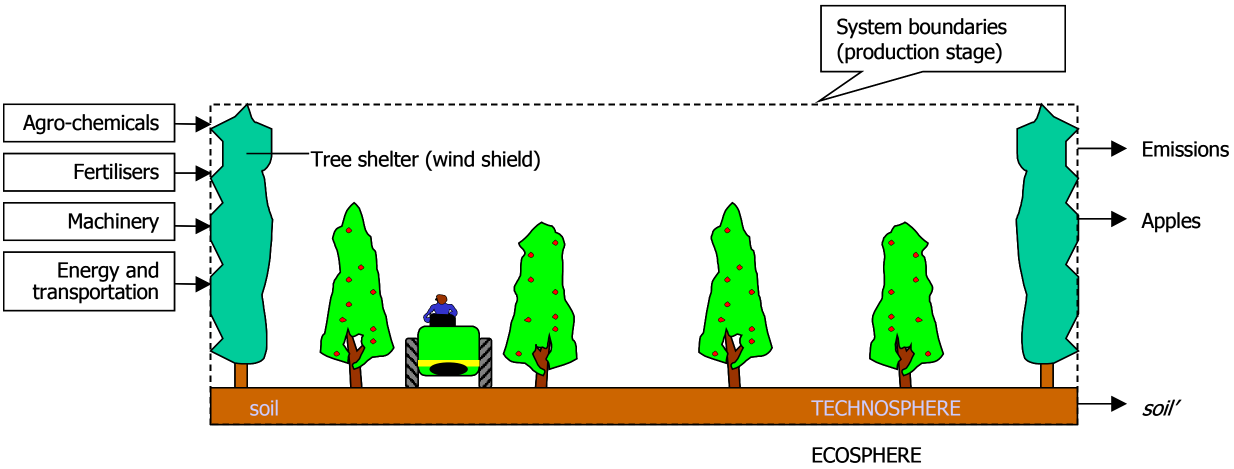

Figure III-2: System boundaries during the production stage.

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[3] Actually, this option is not so remote in a framework such as the European Union, where productivity is not the problem, and incentives are actually being given with the aim of reducing productivity while keeping the landscape.

As for the time boundaries, only one year of the orchard's high yield period has been considered in the study. This decision may have some drawbacks in the assessment of apple orchards, which are often cultivated for more than 20 years. The reason is that many operations are performed during the different periods of the orchard that will affect the whole lifetime of the trees[4]. Cowell (1998) suggest that the inclusion of full crop rotations in LCA boundaries is a more correct approach, as they allow for the analysis of operations affecting different crops in the rotation. In a similar way, the whole lifetime of the trees should be included in order to assess the effects of such operations. Nevertheless, for practical reasons it is very difficult to collect data for the full lifetime of the orchard, and besides the goals of the study could be reached with the analysis of only one year.

Even though soil quality has not been assessed in the apple LCA, the substances emitted to soil remaining in soil after the time boundaries are crossed (at harvest) are also considered as an emission to soil. Thence, in Figure III-2 a "*soil '* " is depicted as leaving the system (after harvest), in order to show that the differences in soil (related to toxic substances) are included in the system's analysis. This is an important point, as these substances would not be considered as emissions if the whole orchard lifetime were analysed. Their inclusion is consistent with the need of leaving the soil in the same conditions as it is found in the beginning of the system (Audsley *et al.* 1997, p. 85).

Finally, from a life cycle perspective, only the phases from cradle to gate are analysed, as the transportation of the finished product, consumption, and final waste disposal are not relevant for the purposes of the study (see Figure III-3, in page 53).

Data collection

Orchard-specific data of high quality was needed for the accomplishment of one of the goals of the study: to assess site-dependency in agricultural LCA. Data for agricultural inputs consumption and agricultural practices were obtained directly from individual producers, who filled a questionnaire for the season 1999-2000. This questionnaire had been previously prepared using the experience of HortResearch staff and field studies with the producers, and is included in APPENDIX III.1. Some further checking had to be done by telephone interviews in most cases from June to August 2000. It must be noted that when working with data from single producers, no generalisation of the results can be done to apple production in New Zealand, as they do not necessarily represent average practices. Besides, results may be affected by other factors apart from the growing techniques and the climate and soil conditions, such as individual cropping practices. These facts are actually one of the goals that had to be accomplished with the apple LCA, and so are not regarded here as actual drawbacks.

On the other hand, expert judgement (staff from HortResearch) was used to get region and technology reference values ("common practice"). Technology reference values were needed for the detection of an environmental picture of the hot spots in apple production, related both to technology types (IFP and OFP) and the regions under study (Hawke's Bay and Central Otago). The problems related to reference data collection are that no account can be taken of the local

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[4] Hermansen (1998) distinguishes an establishing phase (1 year); a first low yield period (3-5 years); the high yield period (10-20 years); the final years with old trees and low production (0-5 years); and the "destruction"

conditions, such as climate and particularly soil quality. Besides, reference data are hard to find, and usually they are not representing any single producer, except in the case of pesticide use, where real producers usually follow recommendations and thus the reference use is close to a "standard".

Many databases have been used for data collection for the "background system". Examples of such data are agricultural inputs production, machinery production, energy provision, etc. Some of the substances used in the systems under study had never been assessed before from an LCA perspective (mainly those used in biological pest control systems); therefore, a deeper analysis of their industrial sectors is provided.

Life Cycle Impact Assessment

The impact categories used in the LCIA phase of the study are briefly defined in Table III-1 (Milà i Canals *et al*. 2001).

Table III-1: Impact categories used in the LCIA of apple production.

Impact category	*Unit*	*Comments and References*
global warming	kg CO_2	Only emissions from non-renewable sources have been considered. Carbon fixation by plants in agriculture has not been considered as negative emissions. Characterisation factors are taken from Albritton *et al*. (1995).
photochemical oxidant formation	kg C_2H_4	Photochemical ozone creation potentials for low NO_x areas. Factors for low NO_x concentrations have been considered to better represent rural areas, where most of the emissions from apple orchards occur. Characterisation factors are taken from Andersson-Sköld *et al*. (1992).
acid rain	kg SO_2	Characterisation factors, corresponding to substance's relative capacity to release hydrogen ions, respective SO_2, are taken from Hauschild & Wenzel (1998).
nutrification	kg NO_3^-	EDIP method is used, considering an aggregated equivalency factor for P or N limited ecosystems. Characterisation factors are taken from Hauschild & Wenzel (1998).
human toxicity (from air, water and soil)	m^3 of compartment (air, water or soil) needed to dilute the emissions to a concentration that has no adverse effects on humans	EDIP method (Hauschild & Wenzel 1998). Direct human toxicity through the ingestion of apples containing pesticide residues has not been considered because the use phase is not included in the study
ecological toxicity (acute and chronic toxicity in aquatic systems and chronic toxicity in terrestrial ecosystems)	m^3 of compartment (water or soil) needed to dilute the emissions to a concentration that has no adverse effects on ecosystems	EDIP method (Hauschild & Wenzel 1998). Acute ecological toxicity in soil is not included, even though Hauschild & Wenzel (1998, p. 240) suggest it may be relevant in agricultural soils, where pesticides are sprayed on soil. The reason is that no effect of substances in soil is considered until soil "crosses" the system's temporal boundaries at harvest, when only chronic effects would be occurring. No eco-toxic effects are considered from emissions to air and groundwater for the reasons explained in Hauschild & Wenzel (1998).

In the case of global warming, fixation of CO_2 in the agricultural production phase has not been considered as a negative emission. Carbon emissions/sequestration from agriculture is part of a

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phase (1 year).

short bio-geo-chemical cycle. Therefore, it is usually suggested to include “negative” and “positive” emissions in order to better represent its balance (Guinée *et al*. 2001, p. 481). Nevertheless, in the fourth part of this dissertation it is argued that only the carbon that ends up fixed in soil organic matter should be considered as a real “negative emission”. As no carbon balance was applied in the apple LCA due to lack of methodology, no negative emissions have been considered.

Fate of contaminants (particularly pesticides and heavy metals) has been thoroughly modelled in order to properly consider toxicity impacts. Toxicity characterisation factors (both for human toxicity and eco-toxicity) have been obtained from the EDIP method (Hauschild & Wenzel 1998). For most of the pesticides used in the system under study, new factors have been obtained, using the method described in Hauschild & Wenzel (1998). These new characterisation factors are shown in Table III-33 in page 98, and the data needed for their calculation is described in APPENDIX III.2.

Also an indicator on the competition aspect of land use has been included as a measure of land use efficiency. This is expressed in *ha · year*. It must be noted, though, that this indicator is not an environmental impact category, but merely addresses an economic endpoint: the human competition over a limited resource (land). According to Lindeijer *et al*. (2002) this competition might even be considered from an environmental point of view, as human uses also “compete” with natural ones. On the other hand, indicators on land use efficiency tend to depict more intensive systems as environmentally preferable over extensive ones, due to the smaller amount of land needed to produce a certain amount of product. Nevertheless, intensive systems usually entail deeper degradation of land (in terms of soil quality or bio-diversity), and therefore the short-term efficiency might hide long-term unsustainability of the system. These aspects could not be considered in the apple LCA due to methodology gaps, but are further explored in the fourth chapter of this dissertation.

Finally, a simple indicator expressing the amount of non-renewable energy consumed in each site is included as a picture of the source of many impacts. This is actually only the compilation of a parameter (energy consumption), where some valuation is put on the source of energy: all non-renewable energy sources are added with an equal weight (1) and renewable energy (from Sun in photosynthesis, electricity from hydro stations or geothermal…) is not considered (i.e.: the weight is 0). Energy consumption determines to a great extent many impact categories, as it will be seen in the results.

Uncertainty and consistency analyses

In order to assure some degree of consistency in the results, a qualitative uncertainty analysis is undertaken. Thus, once the life cycle impact assessment (LCIA) phase has been done, the inventory data that mostly determine the LCA results will be determined. These parameters are checked for their confidence, and if any value having a big influence on the results is found to be not reliable, this is stated so it can be considered in the interpretation.

In addition, some qualitative analysis of the error is included. As there are many inputs to the analysis, this will only be done for the factors chiefly affecting the results. In these values, an estimation of the range within which they may vary is done, and confidence margins are established accordingly. The qualitative estimation of error margins is explained throughout the text.

III.2. LCI: Apple Production Systems' Description

The conduction of an LCA requires a thorough knowledge of the system that is being analysed. A simplified representation of this system is depicted in Figure III-3, where the parts of the system included in the analysis are shown within the system boundaries. Also a distinction of what has been considered within the foreground system and the background system is made. This distinction is useful because a greater knowledge is required for those phases directly in contact within the product life cycle (the foreground system). The foreground system for the apple LCA is described in section III.2.1, where an overall definition of the operations for apple production is given, both for IFP and OFP. Detailed information for particular producers is given in section III.2.2, with specific values for the different environmental aspects.

Sections III.2.3 and III.2.4 deal with specific modelling of relevant emissions from the apple orchard, coming from fertilisers and pesticides, respectively. These emissions are generally labelled as "Field processes" in Figure III-3, and lie within the foreground system as well.

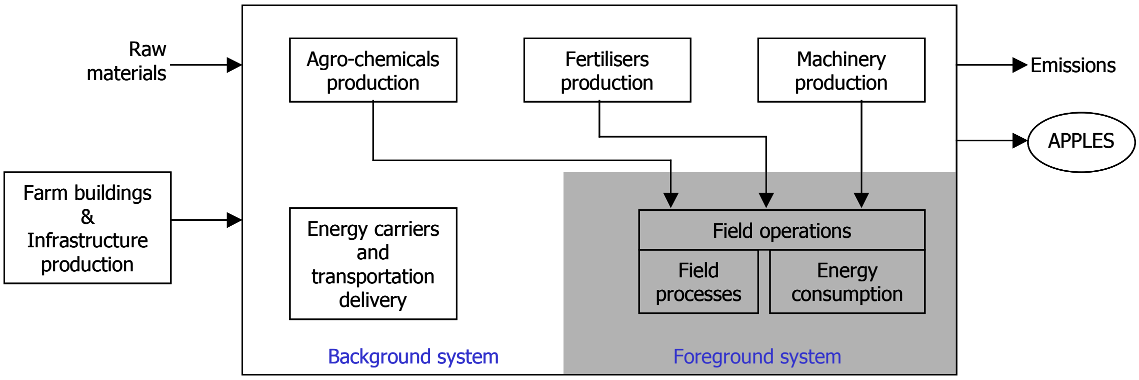

Figure III-3: Schematic diagram of the system under study.

NOTE: "Agro-chemicals production" refers to "Insecticides, Fungicides, Herbicides & Plant Growth Regulators production". "Energy carriers and transportation delivery" should be connected to the rest of sub-systems, but connectors have not been drawn for the sake of visual clarity.

Most other data (in the "background system") was gathered from the literature (general databases and studies on production of inputs for agriculture), and references for these aspects can be found in sections III.2.5 to III.2.8. Substances for the biological pest control used in OFP were an exception for this, as they have not been studied previously, and so no data for their production can be found in the literature. A detailed description of their manufacture, including environmental data for the LCA study, can be found in section III.2.6. Section III.2.5 also includes information specific for the apple LCA, corresponding to the considerations for machinery that is not described in the literature.

The production of farm buildings and infrastructure has been left out of the system, as explained in section III.1.2.

III.2.1. Apple production operations in IFP and OFP

Figure III-4 is a graphical representation of the operations that take place during apple production. It is actually an amplification of the foreground system in Figure III-3, with the direct inputs to the apple orchard and a simple graphical representation of the timing of different operations: the horizontal axis represents a crop calendar, from May to July (when the trees are pruned) to April (harvest ends).

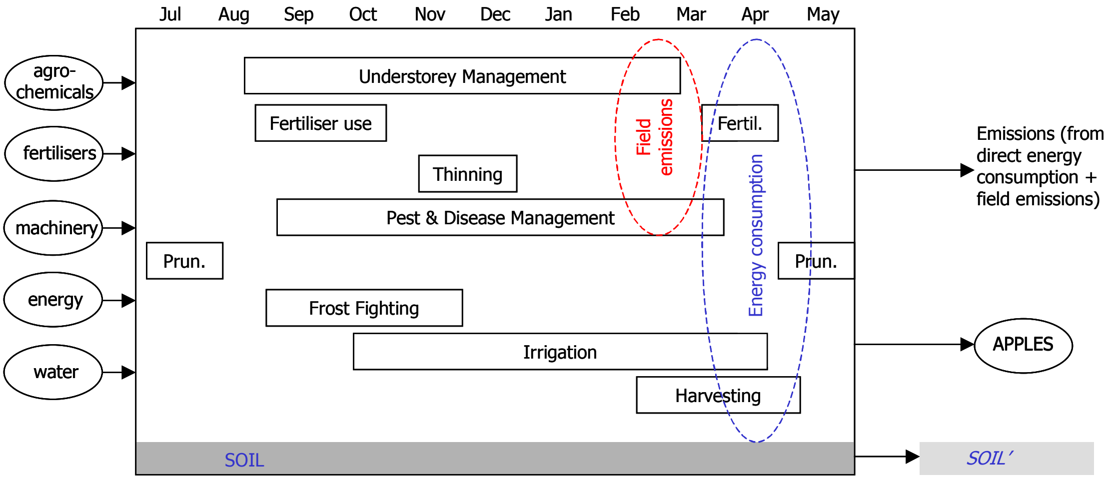

Figure III-4: Field operations in the production stage of the apple life cycle in New Zealand.

Field emissions have been considered mainly for understorey management (herbicide emissions in IFP), fertiliser use, thinning (only in IFP as well), and pest and disease management, and this has been simply represented in Figure III-4 with the label "field emissions" embracing only these operations. Energy consumption, on the other hand, has been studied for all field operations. Note that some operations in Figure III-4 can occur throughout the growing season, while others are more punctual (e.g.: pruning, thinning, harvesting…). This can actually present some variations depending on the region and the technology used (integrated or organic fruit production). For instance, the addition of fertiliser usually starts earlier in OFP because the fertilisers used there (manure, compost) slowly release their nutrients, while early and mid-season fertilising is found in IFP. Indeed, the durations and timing presented in Figure III-4 are only a coarse approximation, as these aspects may vary greatly from Hawke's Bay to Central Otago, and usually also between orchards within the same region. Table III-2 depicts the operations in which differences between regions and technologies exist, and the main reasons for these differences.

Note also in Figure III-4 that a "*Soil ’* " is depicted as leaving the system after harvest; this is to represent the variation in soil quality that should be assessed in the LCIA. As noted in section III.1.2 (System boundaries), though, only the substances emitted by the system that remain in soil after harvest are included in the inventory as emissions, and no changes in soil quality in a broader sense are assessed.

Table III-2: Main differences in field operations as depending from technology and region.

Operation	*Differences in technology type (IFP / OFP)*	*Differences in regions*
Understorey Management	YES (use of herbicides in IFP; mulching more usual in OFP)	NO
Fertilising	YES (type of fertilisers)	NO
Pest and Disease Management	YES (approach to pest management and type of substances)	YES (intensity of pests related to climate)
Pruning	YES (more time-intensive in OFP; fate of prunings)	NO
Thinning	YES (chemical thinning in IFP; type of substances)	NO
Irrigation	YES (slightly higher water consumption in OFP expected)	YES (source of water; irrigation system)
Frost Fighting	NO	YES (greater need in CO than in HB)
Harvesting	NO	NO

In the following sections, the main operations in apple production are described. Along with a general definition of the operation, the main differences in IFP and OFP are described. If differences exist between regions, these are also addressed.

Understorey management

Understorey management refers to the operations performed on the vegetation other than the shelter trees, and different than the apple trees. While this vegetation (mainly grass) protects soil from erosion and enhances orchard's bio-diversity, it also uses soil resources (water and nutrients) that are thus not available to trees. Therefore, this vegetation must be managed in some way.

In IFP, the tree line is kept free of vegetation with the use of herbicides (ca. 1m either side of tree), while the alley is maintained in a grass/legume planting. This grassing helps to create a sward which is persistent, can produce nitrogen through white clover (*Trifolium repens*) N fixation (Goh *et al*. 1995) and can be a nutrient supply to the apple tree through herbage biomass cycling (Marsh *et al*. 1996). Besides, the vegetation cover prevents erosion. Herbicide application on the tree line is usually performed once to three times per season, with specific machinery attached to a tractor. The chemicals most commonly used are Amitrole and Glyphosate. The alley is mowed 4 to 8 times per season, with the mown herbage sometimes applied to the tree line as mulch, but more frequently left in the alleyway.

In OFP, the routine use of herbicides is banned[5]. Thus, instead of creating a herbicide strip in the tree line, weed growth is prevented either by a mulched line of ca. 0.5m under the trees, or using a swing-arm mower. Mulch may be added from outside the system (e.g.: pea straw or bark may be used), or the prunings and herbage may be used instead. The mulching is not only done to prevent weeds, but also as a source of nutrients and organic matter that maintains sustainable fertility levels of soil while closing the nutrient cycle. Mowing of the alley is undertaken 5-11 times per season, and between once and three times per season also the tree lines are mowed with a

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[5] A pine oil based herbicide is now available and is acceptable to Bio-gro in certain circumstances, but cannot be used on a routine basis.

special equipment: a swing-arm mower. A petrol-powered weed-eater is often used for the mechanical removal of weeds.

No significant differences are observed between the different regions under study in relation to understorey management.

Table III-3: Main technological and regional differences in understorey management.

Understorey management		***Technology***	
		IFP	***OFP***
Region	***Hawke's Bay***	Herbicide strip in the tree line. Alleyway with grass, mowed 4 to 8 times per year. Mowed grass usually left in the alley, or applied as mulch to the tree line.	The tree line is mulched. Alleyway with grass, usually legume-based to improve nutrient cycling, mowed 5 to 11 times per year. Grass clippings are often applied to the tree line as mulch (once to thrice per season). Weeds are mechanically removed with a weed-eater.
	Central Otago	No relevant differences with Hawke's Bay.	No relevant differences with Hawke's Bay.

Fertiliser use

The objective of fertilising is to keep a balance between the nutrients exported with the crop and the inputs of nutrients by natural processes. As these substances are generally exported more rapidly than they can be cycled by natural processes, some external input is needed (although for N, apple trees have a low requirement compared with many other tree fruits, with estimates varying from 30-80 kg N ha^{-1} year^{-1}). The overall goal of fertilising is to thus increase the field's productivity.

In IFP, mineral fertilisers are used, and the only difference with conventional agriculture is that a balanced perspective is introduced. Hence, fertiliser application rate is usually calculated from leaf and soil analyses. The most commonly used fertilisers in apple production in New Zealand are Calcium Ammonium Nitrate (CAN) and urea. It is also common to apply urea 5% at leaf fall, in order to aid in the breakdown of leaves and reduce the blackspot inoculation the following spring.

The principle underlying fertiliser use under an OFP scheme is to ensure that adequate levels and mixtures of nutrients are available to plants, achieving a cycling of nutrients that has as few losses as possible. At the same time, soil fertility and life supporting ability has to be enhanced, with a special emphasis on soil organic matter and soil organisms, while pollution of the surrounding environment should be avoided (Bio-Gro 1994). Mainly composts and animal by-products (meat and bone meals, fish by-products, etc.) are used as fertilisers in organic apple orchards. Compost is usually applied with a fertiliser spreader, and some foliar fertilisers (animal and seaweed product preparations) are sprayed with an air-blast sprayer. Also biological activators, such as Bio-Dynamic preparations, are allowed in OFP. Nevertheless, the amount used and the nature of these substances suggests that they will be irrelevant in the overall environmental impacts of apple growing. Thus, the production and use of these biological activators have been excluded from the study.

Differences in fertiliser use do not depend on regions, but on locations, as they are due to the soil's condition. These differences can be huge, as it will be noted when comparing the different systems under study.

Table III-4: Main technological and regional differences in fertiliser use.

Fertiliser use		Technology	
		IFP	**OFP**
Region	**Hawke's Bay**	Mineral fertilisers are used. Doses are calculated based on leaf and soil analyses.	Organic fertilisers such as compost, animal manure and food industry by-products are used.
	Central Otago	No relevant differences with Hawke's Bay.	No relevant differences with Hawke's Bay.

Pest and Disease Management

Insect pest and disease management is the group of operations aiming at reducing the impact of a number of competitors and disorders found in apple production. Usually these problems do not actually affect the edibility of apples, but affect the appearance of the fruit. Pests and diseases also need to be managed due to the phyto-sanitary requirements of importing countries. Both aspects are very important when the product has to be sold to modern markets. The main goal of pest and disease management is thus to keep the highest proportion of crop for the market. The most important insect pests affecting apple trees are codling moth (*Cydia pomonella*, L.), tortricid leafrollers[6], scale insects[7], woolly apple aphid (*Erisoma lanigerum*, Hausmann) and mealybugs (*Pseudococcus longispinus*, Targioni Tozzetti). There are two key apple diseases in New Zealand that are caused by fungi: these are blackspot (*Venturia inaequalis*, Cooke, G. Wint) and powdery mildew (*Podosphaera leucotricha*, Ellis & Everh, E. S. Salmon).

The approach traditionally taken by "industrialised" agriculture has been blasting insects with an insecticide aiming for eradication. Eradication, even for relatively short periods is not sustainable or usually even feasible. This approach having proved its inefficacy without compromising human (and ecosystem's) health, other approaches promoting natural pests' enemies, or affecting pests' life cycles, have been suggested by integrated and organic agriculture.

Successful pest management in IFP relies on careful monitoring of the pest life cycle. Once the population reaches a set threshold, a selective pesticide is applied. Mating disruption (where sex

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[6] There are different species of leafrollers affecting apple crops: lightbrown apple moth (*Epiphyas postivittana*, Walker), greenheaded leafrollers (complex of 2 species: *Planotortrix octo*, Dugdale; *Planotortrix excessana*, Walker), brownheaded leafrollers (complex of 2 species: *Ctenopseustis herana*, Felder & Rogenhofer; *Ctenopseustis obliquana*, Walker).

[7] The two main species of scale insects are: oystershell scale (*Quadraspidiotus ostreaeformis*, Curtis) and San José scale (*Quadraspidiotus perniciosus*, Comstock).

attractant pheromones confuse the adult male moths and prevent them from mating) is also used for some species of leafroller and codling moth, although the use of this technique is not widespread amongst IFP orchards. Also natural enemies of pests are promoted in IFP pest control. In the case of fungal diseases, fungicides are only applied when climatic conditions are likely to be favourable for disease development (e.g.: when leaf wetness duration and temperature exceed thresholds). Additionally, side effects of fungicides are studied in order to promote the use of those substances that do not have negative effects on natural enemies of pests.

Thus, pesticides are only applied in IFP when their use is justified, according to pre-defined thresholds of actual crop risk. Records are kept of all pesticide use and are routinely audited to ensure compliance.

Finally, bitter pit is a serious storage disorder of apples, and its incidence is related to fruit calcium levels. Susceptibility to bitter pit varies between cultivars, with Braeburn and Cox Orange the most susceptible. Typically, 12 to 15 applications of calcium-based products[8] are used per season on susceptible cultivars.

Pesticides and calcium are applied to tree foliage and fruits in IFP with air-blast sprayers, which use a PTO[9] powered pump and fan units. Usual size of tanks is 2000 litres. Total number of applications varies greatly from orchard to orchard, because different products (insecticides, fungicides and calcium) may be applied together, and at different concentrations. Also, the number of applications is affected by grower-, region- and variety-dependent factors: in the North of New Zealand, incidence of insect pests is greater due to higher temperatures, while in regions with a heavy rainfall a higher fungicide use is expected. Suckling *et al*. (1999) assess a relative importance of the main apple pests within some districts in New Zealand, where some basis for the different insecticide use in them can be found (see Table III-5 for the importance in Hawke's Bay and Central Otago).

Table III-5: Importance of apple pests within each of the districts of New Zealand assessed in the study. Importance increasing from 0 (absent) to 5 (major pest) (Suckling *et al*. 1999).

Pest	*Hawke's Bay*	*Otago*
Leafrollers	5	5
Codling moth	4	5
Woolly apple aphid	4	2
European red mite	2	1
Two-spotted spider mite	1	2
Apple leafcurling midge	3	2
Froggatt's apple leafhopper	2	1
Mealybugs	4	0
Scale insects	2	3

Today, there is a tendency towards applying pesticides at more concentrate rates (around 500 litres·ha^{-1}), because of higher spray retention observed at these concentrations (Manktelow 1998). Concentrate spraying, thus, has an effect on pesticide fate (due to higher proportion of pesticide

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[8] Generally, calcium chloride.

[9] Power take off, a device that transmits the power of the tractor's engine to the machines attached to the tractor.

reaching and remaining on the target), and on fuel consumption (because lower volumes of spraying mean less time per application, typically 25% less time[10] than with dilute spraying at 2000 litres·ha^{-1}). Thus, it is expected that concentrate spraying will have a relevant effect on LCA results.

The pesticide products in use by growers change from year to year. New products are developed and enter the market, leading to changes in the relative pricing structure of products. Additionally, pesticide use is affected by changes to pesticide residue level tolerances set by export markets. Consequently, it is almost impossible to define a "reference" pesticide use, particularly for fungicides, and particularly between seasons. This is highlighted in Table III-13 (page 66), where important differences in pesticides and calcium products consumption are observed between particular orchards and region- and technology- "reference values". As explained in section III.2.2, below, reference values are the ones considered to be more representative of a particular technology type (IFP or OFP) for a given region. They are obtained mainly from expert judgement, and can thus be considered as the state of the art, but do not represent average practices.

Natural enemies of pests and diseases are to be encouraged in OFP, and providing them with shelter and not using broad-spectrum pesticides does this. Some mineral pesticides are allowed though restricted. Amongst the most widely used of these substances are sulphur preparations (e.g.: Kumulus, Thiovit), lime sulphur, copper hydroxide (e.g.: Kocide, Blue Shield), and mineral oils[11] (e.g.: D C Tron, Sunspray Oil, Mobil Superior 663). The use of these substances is subject to control under OFP schemes (Bio-Gro, 1994). Also biological controls such as insect diseases (e.g.: *Granulosis virus*, *Bacillus thuringiensis*) and mating disruption (pheromones) may be used in OFP.

As explained above, differences in regions occur because colder sites have generally less problems with insects, while in wetter conditions fungi find it easier to develop. Codling moth completes only one generation per year in Central Otago, but has two summer generations in Hawke's Bay, where its control is slightly harder and pheromone ties are used, frequently in conjunction with applications of *Cydia pomonella granulosis virus* (CpGV, e.g.: Madex). Also leafrollers are a more serious problem in Hawke's Bay. This pest is usually fought with the application of *Bacillus thuringiensis*. These differences are expressed in Table III-13 (page 66), where the rates of application of pesticides considered in this study are shown.

As for fungal diseases, they are also slightly harder to tackle in Hawke's Bay due to its higher summer rainfall. Nevertheless, this fact is not clearly translated into higher rates of application of fungicides, as it is shown in Table III-13.

For reasons that are still not well understood, bitter pit is not a serious problem in OFP. The producers interviewed for the study, who do not generally use calcium applications in their orchards, have confirmed this.

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[10] According to Rue Collin, orchardist. Personal communication by interview, July 2000.

[11] Mineral oils are applied as a general insecticide, as they create a thin film on eggs and larvae that suffocates them.

Table III-6: Main technological and regional differences in pest and disease management.

Pest & Disease management		*Technology*	
		IFP	***OFP***
Region	***Hawke's Bay***	Synthetic pesticides are used when insect populations reach pre-defined thresholds or when conditions are favourable for fungal development. Integrated pest management includes other ways of controlling pests, such as promotion of natural pest's enemies and mating disruption. Calcium products are used against bitter pit.	Encouraging of natural pest enemies. Use of bio-pesticides: *Bacillus thuringiensis*, Granulosis virus, pheromone mating disruption. Copper- and sulphur-based mineral pesticides are allowed, though restricted. No need to use calcium products for bitter pit.
	Central Otago	Insect pests and fungal diseases are less hard to tackle in Central Otago due to a drier and colder climate.	Insect pests and fungal diseases are less hard to tackle in Central Otago due to a drier and colder climate.

Pruning

In fruit production, pruning is done with the aim of assuring light and space for the young wood that carries the current and future crops. In this way, all the fruit can develop satisfactorily, and thus the proportion of crop that can reach the market (the "pack-out") is higher. Standard orchard layout in NZ is based on single row plantings spaced at 2-3 metres with rows 4-5 metres apart, depending on rootstock and variety used. The most common apple tree canopy training in New Zealand is the "ideal slender pyramid" (Manktelow 1997).

Both in IFP and OFP, pruning is usually done by hand using hand-operated pruners, loppers and saws and using manual ladders for elevation. Commonly used machine-operated equipment includes compressed air operated pruners and motorised hydraulic ladders (hydra-ladders).
Prunings are usually kept in the orchard by mulching with a mulching mower, although some orchards remove them and burn them. While the mulching helps cycling the nutrients and organic matter within the orchard soil, removing and burning prunings is usually faster to do, and therefore some producers prefer to do so.

In OFP, pruning is performed in the same way as in IFP. Nevertheless, the amount of hours destined to this operation in OFP is usually higher than in IFP orchards. This is due to the fact that in OFP it is very important that fruit size and colour meets exportation requirements in order to increase the pack-out. In a way, this operation can be considered as a pre-thinning (see below). Prunings are always mulched into the tree row, in order to provide some protection for the soil, avoid weed germination, and enhance nutrient cycling.

Table III-7: Main technological and regional differences in pruning.

Pruning		Technology	
		IFP	**OFP**
Region	**Hawke's Bay**	Trees are pruned to an ideal slender pyramid with hand-operated pruners with the aid of ladders and hydraulic ladders. The prunings are either mulched or taken off the orchard and burnt.	Pruning is performed as in IFP, although more time is usually devoted to it in OFP systems because it is considered as a pre-thinning. The prunings are always mulched and usually applied to the tree line as a source of organic matter and nutrients.
	Central Otago	No relevant differences with Hawke's Bay.	No relevant differences with Hawke's Bay.

Thinning

Fruit thinning is one of the key issues for apple growers. The primary objective of fruit thinning is to reduce the number of fruit per tree, which increases fruit size and colour, and hinders biennial bearing (i.e. alternate years of high and low fruiting). Furthermore, thinning results in fruit that is more evenly distributed within the tree canopy. This facilitates spray and light penetration, reduces potential insect feeding sites, and aids fruit drying after rain or irrigation, reducing fungal pathogen establishment. It is therefore a critical step to the production of high quality fruit, and a big part of the "art" of apple growing that growers have to learn.

In IFP, fruit thinning is achieved using chemical thinning agents during flowering, and by hand thinning from early to mid season. Carbaryl, which is also an insecticide (e.g. Carbaryl; Sevin 80WP) and 1-naphthlyacetic acid (e.g. Fruitfed ANA) are applied by air-blast sprayer. Ethryl (phosphonic acid) and Cylex (synthetic cytokinin) are also used as fruit thinning agents in IFP, but were not encountered in this study. The application of thinning products is always done at dilute concentrations. The effects from chemical fruit thinning agents are highly variable between cultivars, and very dependent on climatic variables at the time of application. For many growers, getting chemical thinning right within a particular cultivar determines the amount of profit that they will make, because if chemical thinning doesn't work well, they have to spend more on labour.

Orchard workers using ladders or hydra-ladders undertake hand thinning to refine chemical thinning. No significant differences between regions are to be expected for this particular operation.

Conventional thinning products are forbidden in OFP. Most thinning is currently undertaken by hand, usually with the help of hydra-ladders. This increases the cost of organic apple production in comparison to IFP, as hand thinning rises the costs of thinning from NZ$1.90 to NZ$6 per tree (Mannering 2000). Today, a lot of research is going into finding sprayable compounds that can be used to thin fruit and which are acceptable to organic certification agencies (e.g.: Bio-gro). Such compounds currently centre on blossom burners like salt (NaCl) and lime sulphur. The move to this approach has recently begun, with some Hawke's Bay organic growers using them for the first time during the 2001-2002 season.

Table III-8: Main technological and regional differences in thinning.

Thinning		Technology	
		IFP	**OFP**
Region	**Hawke's Bay**	Chemical thinning agents are applied using air-blast sprayers. Some hand thinning has to be done, with the help of hydra-ladders.	Only hand thinning is performed, which increases the cost per hectare in OFP due to the high energy consumption of hydra-ladders and labour. New products are being applied with air-blast sprayers (e.g.: salt) that will reduce costs.
	Central Otago	No relevant differences with Hawke's Bay.	No relevant differences with Hawke's Bay.

Irrigation

There are three main types of irrigation systems in apple orchards: overhead, dripper and micro-sprinkler irrigation systems. Under tree dripper and micro-sprinkler systems are most common in Hawke's Bay, whilst overhead systems are more commonly used in Central Otago due to the need for frost fighting in that area (overhead sprinklers can be used for both irrigation and for frost fighting). Water may be pumped onto the orchard using either diesel or electric pumps. The source of irrigation water varies between different areas. In Otago, surface water is used, while groundwater is the main source in Hawke's Bay.

Total use of water varies enormously between orchards, but no consistent differences have been found between regions. Total energy consumption for irrigation is related to the quantity and quality of water applied, the distance of the water source from the orchard, the depth of groundwater, and the type of irrigation system.

The irrigation system in OFP is similar to that in IFP, although water requirement might be a bit higher in OFP due to denser understorey vegetation competing with the apple trees. Electricity consumption for pumping water has been considered the same, as there is no reason to expect different technologies in OFP.

Table III-9: Main technological and regional differences in irrigation.

Irrigation		Technology	
		IFP	**OFP**
Region	**Hawke's Bay**	Groundwater is generally used to irrigate. The most common irrigation system in Hawke's Bay is micro-sprinklers.	The system is as in IFP, but a slightly higher water consumption is expected due to the higher needs of a denser understorey herbage.
	Central Otago	In Central Otago, water comes from surface courses, and overhead sprinklers are most common due to the need of frost-fighting (see below).	In Central Otago, water comes from surface courses, and overhead sprinklers are most common due to the need of frost-fighting (see below).

Frost Fighting

Frost Fighting are operations aimed at avoiding damage to the crop when temperatures fall below 0ºC. Usually the idea behind these operations is precisely preventing temperatures dropping below 0ºC. Sunburn to the fruit can occur during the hottest days of summer. Activities to reduce sunburn damage are undertaken in order to prevent high temperatures causing similar effects as low temperatures.

The need for frost fighting is a major difference for the regions under study. While this is a common practice in Central Otago most years, it is seldom necessary in Hawke's Bay. Actually, in this latter region often sunburn control, rather than frost fighting, is needed. The systems used for frost fighting are many; most of them are based on watering the trees, but other approaches such as the use of wind machines are not uncommon.

A special consideration for technology use has to be done at this point, as huge differences in energy consumption have been found between Hawke's Bay and Central Otago whilst the differences in water consumption (both for irrigation and frost fighting) were small. In the sites under study, higher electricity consumption was observed in Central Otago. This fact contrasts with the water source, as Central Otago orchards are usually watered with surface water, which should mean lower energy consumption than pumping groundwater (which is the common practice in Hawke's Bay). The need for frost fighting might be the key point here, as the more frequent occurrence of frosts in Central Otago might be forcing producers to have more powerful pumping machinery in order to be able to quickly water the whole orchard with overhead sprinklers to avoid frost damage. This is in contrast to a watering system designed for irrigation, where typically only 1/3-1/2 of an orchard can be irrigated simultaneously. Such a system requires less powerful pumping machinery, and tends to be more energy efficient. On the other hand, possibly the type of sprinklers used in Central Otago (overhead sprinklers) might require more energy (water must be pumped over the tree canopy).

Frost fighting is exactly the same for both IFP and OFP, and no differences in water consumption are considered here (the water use in frost fighting is proportional to the number of times this is applied, and not to vegetation coverage).

Table III-10: Main technological and regional differences in frost fighting.

Frost fighting		***Technology***	
		IFP	***OFP***
Region	***Hawke's Bay***	Frost fighting is only occasionally necessary in Hawke's Bay, and when it is the irrigation system is usually connected. Other systems include the use of wind machines.	As in IFP.
	Central Otago	This operation is commonly needed in Central Otago (between 10 and 15 times per season). The irrigation system is normally used, and sometimes complemented with auxiliary pumps to irrigate the whole orchard at once.	As in IFP.

Harvesting

Harvesting of apples in IFP is done by hand with the use of hydra-ladders. Once harvested, bins of apples are transported from the orchard to a central storage point using a tractor with a forklift attached.

Yields may vary largely depending on producers, region, and cultivar, but it was not possible to determine a region-dependency in productivity.

Harvesting operations in OFP are similar to those in IFP (by hand with the use of hydra-ladders). The duration of this operation depends mainly on yield and orchard characteristics (e.g.: size of trees). While a lower use of hydra-ladders might thus be expected in OFP, hydra ladder use appeared more dependant on producer preference than any other factor.

As in IFP, yields may vary largely depending on different factors; no significant differences between Hawke's Bay and Central Otago were observed, though. Even though productivity in OFP is lower than in IFP, the pack-out in OFP has been found to be slightly higher than in IFP, as well as the market values of OFP products.

Table III-11: Main technological and regional differences in harvesting.

Harvesting		***Technology***	
		IFP	***OFP***
Region	***Hawke's Bay***	Harvesting is done by hand, with the help of hydra-ladders. The time devoted to this operation depends mainly on yield and on orchard characteristics (size, age, distribution of trees…). No significant differences between systems and/or regions are expected.	
	Central Otago		

III.2.2. Description of the sites under study

Now that the basic operations for apple production have been described, details on how the different sites perform these operations are given below. Along with the particular apple producers, regional and technology reference data will be presented. Reference data are obtained from expert advice and do not represent average values or actual technical recommendations. They should be regarded as best estimates of what could be considered as "normal", but with no statistical value. In the case of pesticide use values, though, they are of high significance due to the periodical reporting of pesticide spraying to exporting bodies, which is used as the source of information. The sites have been coded to describe the technology type (IFP or OFP) and region (HB or CO), along with a number (for particular orchardists) or "Avg" for reference values data (see Table III-12).

Table III-12: Codes for the sites under study.

Code	*Technology*	*Region*	*Producer*
IFP_HB_1	Integrated	Hawke's Bay	Mrs. Diana Gillum
IFP_HB_2	Integrated	Hawke's Bay	Mr. Rue Collin
IFP_CO_1	Integrated	Central Otago	Mr. Michael Benny & Son
IFP_HB_Avg	Integrated	Hawke's Bay	Region + Technology Reference
IFP_CO_Avg	Integrated	Central Otago	Region + Technology Reference
OFP_HB_1	Organic	Hawke's Bay	Mrs. Heather Gregory
OFP_CO_1	Organic	Central Otago	Mr. Dan Harland
OFP_HB_Avg	Organic	Hawke's Bay	Region + Technology Reference
OFP_CO_Avg	Organic	Central Otago	Region + Technology Reference

Table III-13 presents a summary of the main direct inputs and outputs for all the sites.

Table III-13: Direct inputs to and outputs from the systems under study.

		System								
		IFP					OFP			
Concept	Units (/ha·year)	HB_1	HB_2	CO_1	HB_Avg	CO_Avg	HB_1	CO_1	HB_Avg	CO_Avg
Understorey Management										
Glyphosate (Roundup, Touchdown, etc.)	kg a.i.*	3.12	0.95	1.35	0.94	0.94	-	-	-	-
Amitrole	kg a.i.	-	0.56	-	0.52	0.52	-	-	-	-
Irrigation + Frost Fighting										
Water	litres	1.2E+6	5.0E+6	8.6E+6	5.5E+6	5.5E+6	10.1E+6	11.5E+6	6.5E+6	6.5E+6
Thinning										
Carbaryl	kg a.i.	1.45	2.82	1.6	1.6	1.6	-	-	-	-
NAA	kg a.i.	-	0.01	0.01	0.01	0.01	-	-	-	-
Fertilising										
CAN	kg N	40.5	50	108	54	54	-	-	-	-
Urea	kg N	1.4	-	-	46	46	-	-	-	-
Solubor/Bortrac	kg B	0.2	-	20.5	-	-	-	-	-	-
Calcium Oxide	kg CaO	8.4	-	-	-	-	-	-	-	-
Manganese Sulphate	kg $MnSO_4$	4	-	-	-	-	-	-	-	-
Calcium Nitrate	kg N	2.1	-	-	-	-	-	-	-	-
Magnesium	kg Mg	1.4	-	-	-	-	-	-	-	-
Compost	kg	-	-	-	-	-	5,000	500[a]	5,000	5,000
Pest & Disease Management										
Chlorpyrifos (Lorsban)	kg a.i.	2.16	1.87	-	2.3	2.4	-	-	-	-
Tebufenozide (Mimic)	kg a.i.	0.54	0.27	0.24	0.68	0.57	-	-	-	-
Mineral oils	litres	60	41.6	50	20	40	40	40	40	40
Lufenuron (Match)	kg a.i.	0.10	0.12	0.10	-	-	-	-	-	-
Triflumuron (Alsystin)	kg a.i.	0.25	-	-	-	-	-	-	-	-
Diazinon (Basudin 50WP)	kg a.i.	-	2.56	-	0.75	-	-	-	-	-
Azinphos Methyl (Gusathion M35)	kg a.i.	-	0.67	-	-	-	-	-	-	-
Buprofezin (Applaud)	kg a.i.	-	-	0.25	-	-	-	-	-	-
Bacillus thuringiensis (Dipel)	litres	-	-	-	-	-	12	4	8	4
Granulosos virus (Madex)	litres	-	-	-	-	-	16	8	16	-
Pheromone ties	Ties	-	-	-	-	-	-	1000	1000	1000
Dithianon (Delan)	kg a.i.	0.65	0.60	-	0.65	0.5	-	-	-	-
Cyprodinil (Chorus)	kg a.i.	0.90	0.09	0.60	0.9	0.6	-	-	-	-
Dodine (Dodine)	kg a.i.	2.56	1.17	3.20	2.56	0.64	-	-	-	-
Ziram (Mizar Granuflo)	kg a.i.	-	8.20	13.68	2	4.5	-	-	-	-
Bupirimate (Nimrod)	kg a.i.	0.50	-	-	0.5	0.5	-	-	-	-
Triadimefon (Bayleton)	kg a.i.	0.08	-	0.13	0.19	0.15	-	-	-	-
Captan (Captan 80WP)	kg a.i.	4.80	-	-	3.20	-	-	-	-	-
Mancozeb (Manzate 200)	kg a.i.	2.00	-	-	2.03	-	-	-	-	-
Flusilazole (Nustar 20DF)	kg a.i.	0.06	-	-	0.06	-	-	-	-	-
Difenoconazole (Score 10WG)	kg a.i.	0.05	-	-	0.05	-	-	-	-	-
Copper Oxychloride 50%WP	kg Cu	-	2.54	-	-	-	-	-	-	-
Nitrothal isopropil (Pallitop)	kg a.i.	-	0.45	1.00	-	0.70	-	-	-	-
Metiram (Polyram)	kg a.i.	-	5.54	10.50	-	2.10	-	-	-	-
Kresoxim methyl (Stroby)	kg a.i.	-	0.09	0.50	-	-	-	-	-	-
Myclobutanil (Systane 40W)	kg a.i.	-	0.24	0.10	-	-	-	-	-	-

Table III-13: Direct inputs to and outputs from the systems under study. (continued)

		System								
		IFP					***OFP***			
Concept	***Units (/ha·year)***	***HB_1***	***HB_2***	***CO_1***	***HB_Avg***	***CO_Avg***	***HB_1***	***CO_1***	***HB_Avg***	***CO_Avg***
Pest & Disease Management (contd.)										
Copper hydroxide (Kocide/Blue Shield)	kg Cu	1.95	-	-	-	-	2.76	0.13	2.80	0.13
Sulphur (Kumulus)	kg a.i.	-	-	-	-	-	4.80	6.40	4.80	6.40
Calcium polysulphides (Lime Sulphur)	kg a.i.	-	-	-	-	-	18.00	12.00	18.00	12.00
Calcium chloride (Caltrac, Stoppit, etc.)	kg a.i.	51.90	18.79	21.12	48	48	-	3.46	-	-
Machinery + Fuel										
Diesel	Litres	235	419	259	289	260	316	365	270	238
Petrol	Litres	179	59	164	195	195	1,118	260	401	401
Electricity	MJ	410	2,606	25,404	5,500	5,500	6,570	8,107	6,500	6,500
Tractor	Hours	64.5	54.7	42.4	71.3	66.5	88.8	68.5[b]	68.7	63.4
Hydra-ladder	Hours	78	25.2	71.4	75	75	400	112.2	145	145
Mower	Hours	5	2.3	4	5	5	4	13.7	8	8
Swing-arm mower	Hours	-	-	-	-	-	3	9.1	6	6
Mulch-mower	Hours	2.5	-	1.4	2	2	0.6	2	2	2
Weed-eater	Hours	-	-	-	-	-	0.1	2.1	1.5	1.5
Herbicide sprayer	Hours	2	1.6	3	2	2	-	-	-	-
Air-blast sprayer	Hours	11	13.3	19.2	19.9	15.1	11.7	10.5	10.7	5.4
Fertiliser spreader	Hours	4	0.8	1.5	2.4	2.4	-	1.1	-	-
Manure/Compost spreader	Hours	-	-	-	-	-	2	-	2	2
Wind Machine	Hours	-	4	-	-	-	-	-	-	-
Forklift	Hours	-	36.67	-	-	-	-	-	-	-
Products										
Export & local apples (grades 1 and 2)	Ton	64	71	68	49	49	59	44	48	48
Process apples	Ton	21	8	53	21	21	2	6	12	12
Total product	NZ$	53,740	39,268	35,890	40,460	40,460	118,461	78,671	98,160	98,160
Allocation factors										
For 1 ton of grades 1 & 2 apples	ha·year / 1 ton grade 1&2 apples	0.0156	0.0140	0.0147	0.0204	0.0204	0.0169	0.0229	0.0208	0.0208

*: a.i. stands for active ingredient (the active ingredient refers to the pesticide present in a formulation as described by the common name, and is the part of a pesticide formulation from which the biological effect is obtained).

[a]: meat & bone meal.

[b]: 60hp tractor.

Apart from the substances that are consumed in each orchard, the main difference between producers is the mechanisation of operations. Table III-14 gives details on the use of self-propelled machines, which further explain the figures for machinery and fuel consumption presented in Table III-13 (above). The machines used for irrigation and frost fighting are not included in Table III-14 due to the huge variability in machinery types and use between orchards.

Table III-14: Use of powered machinery in field operations (excluding irrigation and frost fighting). Data expressed in hours·ha^{-1}·year^{-1}

	System								
	IFP					***OFP***			
Machine, Operation	***HB_1***	***HB_2***	***CO_1***	***HB_Avg***	***CO_Avg***	***HB_1***	***CO_1***	***HB_Avg***	***CO_Avg***
Tractor									
Mowing	5	2.27	4	5	5	4	13.71	8	8
Swing-arm mowing	-	-	-	-	-	3	9.14	6	6
Spraying pesticides or Ca, dilute	4.42[a]	6.90	17.18[a]	16.75	12.06	6.5[a]	10.5	10.72	5.36
Spraying pesticides, concentrate	5.65[a]	3.41	-	-	-	5.16	-	-	-
Spraying thinners	1	2.96	2	3	3	-	-	-	-
Spraying herbicides	2	1.60[b]	3	2	2	-	-	-	-
Spreading fertilisers	4	0.75	1.45	2.4	2.4	[c]	1.14	-	-
Spreading mulch/compost	-	-	-	-	-	2	-	2	2
Collecting prunings	-	0.11	-	-	-	-	-	-	-
Mulching prunings	2.5	-	1.4	2	2	0.63	2	2	2
Harvesting	40	36.67	13.3	40	40	67.5	32	40	40
TOTAL	**64.47**	**54.66**	**42.33**	**71.15**	**66.46**	**88.79**	**68.49**	**68.72**	**63.36**
Hydra-ladder									
Pruning	12	5	5.83	10	10	90	36	30	30
Thinning	16	3.33	14.71	15	15	85	43.2	60	60
Applying pheromone ties	-	-	-	-	-	-	5	5	5
Harvesting	50	16.83	50.83	50	50	225	28	50	50
TOTAL	**78**	**25.16**	**71.37**	**75**	**75**	**400**	**112.2**	**145**	**145**
Weed-eater									
Mechanical weed removing	-	-	-	-	-	0.125	2.14	1.5	1.5
Forklift									
Harvesting	-	36.67	-	-	-	-	-	-	-

[a]: including the time for sprayed fertilisers.
[b]: Rue Collin actually uses a motorbike for spraying herbicides.
[c]: bio-dynamic preparations are sprayed.

IFP_HB_1 (Diana Gillum)

The Gillum Springfield Trust is located in Napier, in the Hawke's Bay area of New Zealand's North Island. It is a medium sized orchard of 16.4ha where several apple varieties are grown (Braeburn, Royal Gala, Brookfield, Aurora and Pacific Rose). During the period of the study, the productivity for Braeburn apples was around 85 tons/ha, and the pack-out 73%. The price for IFP export apples from this orchard is the highest found in the study: NZ$ 0.82·kg^{-1}, which explains for the high retail value. Process apples are sold at NZ$ 0.06·kg^{-1}, which is the average for process IFP apples.

The use of a small tractor and the relatively low machinery-intensity explain the low fuel consumption. In addition, Diana uses concentrate-spraying volumes most of the times, which contributes to fuel saving. As for hydra-ladder use, Diana's figures are very close to what can be considered an IFP reference.

Soluble fertilisers (CAN, Urea, calcium nitrate and some trace elements) are used to keep the nutrient balance, and the prunings are added to soil in order to provide some extra nutrients and soil organic matter.

Diana uses a very efficient irrigation system, with under tree sprinklers that are activated every ten nights from November to March. An electric pump feeds water to the sprinklers, and the low water use explains the incredibly low electricity consumption for Diana's orchard. The efficiency in water use for irrigation, added to the low need for frost fighting in The Gillum Springfield Trust, are the reasons why water consumption is only one fourth of the reference in this orchard (see Table III-13). Indeed, the irrigation system is used once every two years on average for frost fighting purposes; this method is occasionally complemented by urea spraying on leaves.

Diana uses a great variety of pesticides, including substances that are generally only used in OFP. This fact, added to the high doses she is using (usually above the reference), suggests a strong incidence of pests and diseases in the past. Spraying is done both at concentrate and dilute volumes, which added to the combination of several products in each spraying event, contributes to a short time devoted to spraying.

IFP_HB_2 (Rue Collin)

The Rakaunui Fruit Company is located in Hastings, in the south of Hawke's Bay. Eleven apple cultivars were grown in this 30ha orchard, with productivity for Braeburn apples of ca. 79 ton/ha (pack-out: 73%). Apple quality is high, with a price for export apples of NZ$ $0.61\cdot kg^{-1}$ and for process apples of NZ$ $0.08\cdot kg^{-1}$. Rue also sells 17% of his production in the local market, at NZ$ $0.25\cdot kg^{-1}$.

The machinery is used only when necessary, and Rue tends to save machinery hours in each operation; consequently, his machinery use figures (both for tractor and hydra-ladder use) are around the smallest of all the studied sites. Particularly, the time devoted to pesticide spraying and harvesting (which generally determine machinery use in IFP) is quite short, thanks to improved time efficiency in these operations. The practice of concentrate spraying is particularly important in the case of pesticide spraying. On the other hand, though, the use of two extra and high fuel consuming machines for harvesting (forklift) and frost fighting (wind machine) avoids the translation of this time efficiency into fuel savings, and particularly diesel consumption is quite above the reference in this orchard.

A very low fertiliser use is observed in this orchard. Besides, prunings were being collected and burnt outside the orchard in the seasons observed in this study, which suggests a possible increased need for fertilisers in the future. As a nutrient balance perspective was not considered in the study, this event could not be included.

An electric pump is used for pumping groundwater to the irrigation system once every ten nights from November to March, whilst a fuel-powered wind machine is used for frost fighting. Actually frost fighting is not always necessary in Hawke's Bay, but Rue needs to perform these operations three times per year as an average.

In the case of pesticides, a great variety of them is used in the orchard. Several of them are usually applied at a time, and so the time devoted to pesticide spraying is reduced.

IFP_CO_1 (Michael Benny & Son)

The Bennies' property, Leaning Rock orchard, is a mixed pipfruit and summerfruit property close to Alexandra (Central Otago, in New Zealand's South Island). Leaning Rock has about 10 ha planted out in several apple varieties, including Braeburn and Pacific Rose^{TM}, Fuji, Pink Lady, Pacific Beauty^{TM}, Sonja, Pacific Queen^{TM}, Cameo and Pink Kiss. Total apple productivity is very high (around 120 ton/ha), but the quality was not so good in the study year, with a pack-out of only 56% and a price of NZ\$ 0.50·kg^{-1} for export apples and NZ\$ 0.03·kg^{-1} for process apples. Note that this fact gives a productivity of export and local apples in the range of the other orchards, and so the effects on the functional unit are not relevant. This is the only orchard were it could be argued that process apples are not only a "by-product", but they are possibly a part of the orchard production strategy.

Tractor use is very low, which allows for relatively low fuel consumption. The use of hydra-ladders is close to the reference for IFP; the slightly lower value is explained by the time devoted to pruning, which is a bit shorter due to the younger (and thus smaller) trees existing in Leaning Rock.

The owners describe Leaning Rock as being located in a gravel pit, as the soil is very poor. This is confirmed by the soil analyses facilitated by the Bennies for this study, where a very low CEC[12] value is said to be "overriding all soil properties". The poor soil quality has immediate consequences for fertiliser use -which is very high and frequent due to low soil fertility and specially low CEC- and irrigation -water use is also quite high probably due to the low water holding capacity of soil-. Not only CAN is used in this orchard, but also some trace elements have to be added (particularly boron, which is applied as a spray, thus increasing spraying time of the tractor).

Overhead sprinklers are fed using a 110 hp electric pump. With this system, though, they are only able to irrigate one third of their orchard at any one time. The whole orchard is irrigated every 3 days from October to mid April, at 13.2 mm/irrigation event. Frost fighting is needed between 6 and 15 nights per season (a total of 40 hrs/season has been considered in this study). As the whole orchard needs to be watered when frosts occur, they use truck motors (Diesel, 5785cc) for the remaining two thirds of the orchard. These motors are responsible for over one third of the total diesel consumption of the orchard.

Pesticide use in Leaning Rock is slightly higher than the reference considered for IFP in Central Otago (see Table III-13), even though some critical pesticides such as Chlorpyrifos (organophosphate) are not used. Most substances are sprayed at medium volume (generally at 1000 litres/ha).

IFP_HB_Avg

Hawke's Bay is one of the world's key apple growing regions producing premium export fruit. An average production of 70 tonnes of apples per hectare has been considered in both Hawke's Bay and Central Otago. The average pack-out (apples for export) is 70%, while the 30% are local market and process apples. The prices for export IFP apples are NZ\$ 0.80·kg^{-1} according to the exportation body (ENZA), while process apples are sold at ca. NZ\$ 0.06·kg^{-1}.

In the case of field mechanisation, no significant differences are found between regions. The only operation that requires different amount of tractor-hours is pesticide spraying, due to the different

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[12] Cation Exchange Capacity.

pesticide needs in both regions (as explained above). Hawke's Bay requires slightly more pesticides than Central Otago, and thus tractor use (and diesel consumption) is also slightly higher. The "reference orchardist" does not practice concentrate spraying. The tractor engine rating heavily influences fuel consumption (see Table III-26, in page 89), and it is difficult to determine a reference for this figure. In the present study, it was considered that the average tractor is 47hp, which is quite small but the most common in apple orchards.

CAN and urea are the most common fertilisers being used in Hawke's Bay (and in Central Otago). This nutrient input is complemented with the application of prunings as mulch, which acts as a soil carbon source.

The same value for water consumption of $5 \cdot 10^6$ litres$\cdot$ha^{-1} has been used both in Central Otago and Hawke's Bay[13], as no significant differences in irrigation are expected between regions despite the differences in rainfall. In Central Otago, though, irrigation is generally carried out more often at lower water volumes, due to the dry climate, and the return period there is 6 days, compared to 10 days in Hawke's Bay. Also the technology used is slightly different: in Hawke's Bay under-tree sprinklers are most common, while overhead sprinklers are used in Central Otago due to the need for frost-fighting. In the present study, electric pumps have been considered the reference technology for water pumping. A wide range of power consumption has been found in the different orchards, which covers a ten-fold variation with values from 400 to 4000 MJ/million litres of water pumped. Data for the particular apple producers suggest that the figures for Hawke's Bay might remain in the lower part of this range, possibly due to a more energy-efficient type of sprinklers (dripper and micro-sprinklers). Nevertheless, not enough data were gathered to confirm this issue, and so a final energy consumption of 1000 MJ/10^6 litres of water has been considered both in Hawke's Bay and in Central Otago.

It has been considered that the most common method for frost fighting is the use of the irrigation system during the pre-dawn period (delivery of ca. 25 mm of water each time). This operation has to be undertaken, as an average, twice per season in Hawke's Bay and ten times per season in Central Otago.

The use of pesticides has been obtained from ENZA[14] and the expert judgement of HortResearch staff[15]. All producers must maintain records of pest and disease management practices including the pesticides that have been used, and present these to the exporter (ENZA) at the end of the season. This is done as an audit requirement of the IFP standards. HortResearch maintains a database of pesticide use (by pesticide, quantity, orchard, location, and season) on behalf of the industry, and consequently the data quality for this issue is very high.

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[13] This is equivalent to a rainfall of 500 mm, or 500 l$\cdot$m^{-2}.

[14] In the moment of the study, ENZA used to be the total pip fruit industry, both the production and exporting sides, and owned ENZA IFP. Since the pip fruit market deregulation in NZ, ENZA has now changed to ENZA FRUIT and concerns itself solely with exporting fruit. Pipfruit NZ now administers the production side, including the IFP program, which is trademarked as NZ Pipfruit-IFP. (Graham Burnip, HortResearch. Personal communication on 5th September 2002).

[15] Dr. Jim Walker, scientist Integrated Pest Management (IPM). Personal communications on September 2000.

IFP_CO_Avg

Central Otago is also one of the main fruit producing regions in New Zealand. The reference system for Central Otago IFP has used the same references as the Hawke's Bay system. Therefore, the only differences are those described in the Hawke's Bay system description (pesticide use, irrigation infrastructure and timing, and frost fighting). Pesticide use is slightly lower in Central Otago, particularly for fungicides, even though the differences are not very big, and actually the doses for some substances are slightly higher in Central Otago than in Hawke's Bay, as it can be noted in Table III-13.

OFP_HB_1 (Heather Gregory)

The Mahora Stud Farm Orchard is located in Hastings, in the south of Hawke's Bay. Its owner, Heather Gregory, grows several apple varieties in 8ha (2.7 ha of Braeburn). Even though the productivity is not as high as IFP orchards (ca. 61 ton/ha were harvested in 1999-2000), the pack-out is incredibly high (96%). This, together with the high quality of the fruit grown (and thus high market price: NZ$ 2.00·kg^{-1} for export apples and NZ$ 0.18·kg^{-1} for process apples), creates a big economic value of the product.

She puts extra care on the apple trees training, particularly pruning and thinning. This is translated into an extraordinarily big hydra-ladder use (almost three times as much as what can be considered a reference value for OFP; see Table III-14). The high petrol consumption is thus probably the major drawback for the environmental sustainability of her orchard. On the other hand, tractor use is not very intensive; one of the reasons for this is the time saving resulting from concentrate spraying.

Fertilising is done with compost and enhanced through biodynamic preparations. Organic matter is also added to soil in the form of the prunings, which are mulched onto the tree line.

An electric pump is used for pumping the water for irrigation. Heather irrigates quite often (every night from December to February using micro-sprinklers), and her water consumption is the second highest of the studied systems (see Table III-13). The same system is used when frost fighting is needed, but this is seldom the case (on average, 4 hours/season can be considered).

External inputs for pest and disease management are surprisingly low in the Mahora Stud Farm Orchard, where insect pests especially seem not too big a problem. Apart from the mineral oils, which are used as a broad-spectrum insecticide, Heather used no other products for insect pest control during the study period.

OFP_CO_1 (Dan Harland)

The case of Dan Harland's orchard is very special indeed. It is quite small, with 6ha of apples (Fuji, Royal Gala, Cox orange, Pacific Queen and Pacific Beauty) and 1ha of nectarines. In the case of apples, the trees are very old and have a particularly low productivity (ca. 50 ton ha^{-1}). Even though the pack-out is not bad (87%), the fruit quality was low the season of the study due to hail damage, which explains a lower retail value (NZ$ 1.94·kg^{-1} for export apples, and NZ$ 0.06·kg^{-1} for process apples). The soil is a heavy silt loam.

Great care is put on the alley between the trees, which explains the high values for mowing, swing-arm mowing, etc (see Table III-14). On the other hand, the tractor time devoted to harvesting is very low, which results in a total tractor use around the reference for OFP orchards. Nevertheless, the tractor is very old and powerful (60 hp), and this consequently bears a high diesel consumption value. As for the hydra-ladder, even though he uses it more than an IFP orchard because of the more labour-intensive operations in OFP, hydra-ladder use is much lower in Dan's orchard than in any other OFP orchard.

Instead of normal compost, meat and bone meal (NPK 9:5:0.1, ca. 50% proteins by volume) is used as a source of nutrients. Prunings are also mulched into the tree line as a source of organic matter and additional nutrients.

Central Otago's dry and cold climate explains the high water use for irrigation and frost fighting. Overhead sprinklers are used once per week for an eight hours cycle for irrigation. The same system is used for frost fighting, which is quite frequent in Dan Harland's orchard; as an average, 15 nights per season do need frost fighting during 4 hours (range 2-12 hours), but up to 35 nights were necessary one particularly cold year. It must be noted, though, that this water consumption is extremely high, even for Central Otago (see Table III-13). The irrigation pump is quite efficient, and thus the electricity consumption is not as high as it might be expected.

Regarding pest and disease management, the only surprising thing in Dan Harland's orchard is the use of calcium, which was not used by other OFP growers in this study (and is not usual in OFP according to the experts consulted). Also, the *Cydia pomonella* granulovirus (CpGV) is used in order to reinforce mating disruption in the control of codling moth (*Cydia pomonella*), which is not commonly a hard problem in Central Otago.

OFP_HB_Avg

An average production of 60 tonnes of apples per hectare has been considered in both Hawke's Bay and Central Otago. The average pack-out is 80%, while 20% are process apples. The prices for export OFP apples are NZ$ $2.00 \cdot kg^{-1}$, while process apples are sold at ca. NZ$ $0.18 \cdot kg^{-1}$.

As many operations in OFP are done by hand, the use of hydra-ladders (used to facilitate these operations) is usually higher than in IFP. Again, the regional differences in machinery use are not due to hydra-ladders but to tractor use, and are associated to the differences in pest management. The accuracy of the fuel consumption estimates has to be regarded suspiciously, because a small tractor (47 hp) has been considered, which determines to a big extent this consumption.

Compost is used as a fertiliser, for both nutrient inputs and source of soil organic matter. Other substances have been observed which contribute to soil fertility, but they were not included as an average practice. The prunings are always mulched as a complementary source of organic matter.

Irrigation in OFP is similar to IFP, and the same considerations for technology type can be applied. In OFP, though, water consumption for irrigation has been considered 20% higher (up to $6 \cdot 10^6$ $litres \cdot ha^{-1}$), due to the denser vegetation coverage.

As in IFP, it has been considered that the most common method for frost fighting is the use of the irrigation system during the night (delivery of ca. 25 mm of water each time), twice per season in Hawke's Bay and ten times per season in Central Otago.

Reference pesticide use could easily be obtained from Bio-Gro recommendations and expert judgement from HortResearch[16], as there are not many alternatives in OFP. Nevertheless, differences in the particular substances used are usually significant between orchards. The use of

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[16] Dr. Jim Walker, scientist IPM. Personal communications on September 2000.

sex-attractant pheromones for codling moth management has been considered as the reference practice, even though it was not so widespread in the moment of the study. As it has been said, calcium applications have not been considered in the OFP scenarios due to the general absence of bitter pit in OFP apples.

OFP_CO_Avg

Again, the reference system for Central Otago OFP has used the same references as the Hawke's Bay system. Therefore, the only differences are those described in the Hawke's Bay system description (pesticide use and frost fighting). Pesticide use is slightly lower in Central Otago, as it can be noted in Table III-13.

III.2.3. Field emissions from fertilisers

Many emissions are related to the input of fertilisers to the agricultural soil. These are mainly related to the Nitrogen cycle and the heavy metal content in fertilisers. A whole mineral balance has not been undertaken, and the alternative approaches recommended by Audsley *et al*. (1997) have been used whenever possible.

Ammonia emissions

Ammonia emissions are highly dependent on the moment and site of application, as well as on the type of fertiliser, but for simplicity it has been considered that 15% of the nitrogen applied as urea and 2% of N applied as CAN is lost as NH_3 through volatilisation (Asman, 1992). Calcium nitrate has been considered equivalent to CAN as for ammonia emissions.

In OFP, compost is used as a source of nutrients; in this case, no ammonia emissions have been considered. The reason underlying this assumption is that organic matter in compost is not so labile (ammonia has already been lost in the composting process).

Nitrate emissions

Nitrate leaching is a direct result of an imbalance between net nitrogen-uptake by the crop and the total nitrogen that is returned to it in the form of fertilisers or manure. Several approaches, including different parameters that affect nitrate leaching, are suggested in Audsley *et al*. (1997). They finally recommend a method derived under Danish conditions, which considers the reference leaching and the ratio between actual fertiliser use and the recommended level for that particular crop and field. Nevertheless, no "recommended level" of fertiliser application has been found for apple production, and reference-leaching values may differ greatly. Indeed, a recent study on nitrate leaching in a New Zealand pasture (Green *et al*. 2001) predicts that 38 kg N $ha^{-1}\cdot year^{-1}$ will leach as an average in an irrigated pasture receiving 563 kg N $ha^{-1}\cdot year^{-1}$ (100 kg in the form of mineral fertilisers, and the rest from animal manure and urine). In the same study, a leaching rate of 77 kg N $ha^{-1}\cdot year^{-1}$ is predicted for a dry-land farm receiving 462 kg N $ha^{-1}\cdot year^{-1}$ from the animal returns. Other investigators have found figures that range around the value of 38 kg N $ha^{-1}\cdot year^{-1}$. Haynes & Goh (1980) report a leaching loss of 33.1 kg N $ha^{-1}\cdot year^{-1}$ in an apple orchard in New Zealand receiving 71.6 kg N $ha^{-1}\cdot year^{-1}$ of fertilisers (plus over 500 kg N $ha^{-1}\cdot year^{-1}$ of returns from the trees and mainly the grass under the trees). The reference leaching value for wheat according to Audsley *et al*. (1997) is 35 kg N $ha^{-1}\cdot year^{-1}$. Johnsson & Hoffmann (1998) report standard leaching rates varying from 18 to 53 kg N $ha^{-1}\cdot year^{-1}$ for several types of crops, soils and fertilising regimes in Sweden.

In the case of the apple LCA, no nutrient balance was performed in order to see whether there was excess of nitrogen going into the system. Instead, the same nitrate-leaching rate calculated by Haynes & Goh (1980) was used (33.1 kg N $ha^{-1}\cdot year^{-1}$). The reason for using this value and not a more recent value such as the one given by Green *et al*. (2001) is that it better represents the conditions found in the apple orchard. This value will be used for all the sites under study, even though OFP orchards do not add as much N in the from of fertiliser as IFP orchards[17]. The obvious drawback of such a generalisation is that no difference between systems will be detectable despite differences in fertiliser use and understorey management, which seem to be some of the key factors determining nitrate leaching. Besides, an uncertainty factor of around ±60% should be considered for the nitrate leaching value.

Nitrous oxide emissions

The loss of nitrogen as N_2O from the nitrogen fertilisers is taken from Table III-15, which reflects the ability of wet soil at different times of the year to oxidise nitrous oxide. The figures have been adapted from Armstrong-Brown *et al*. (1994), taking into account the seasonal differences in the Southern Hemisphere.

Table III-15: Loss of N as N-N_2O (% of N applied in granular fertiliser).

Nitrogen fertiliser	***Application time (soil temperature)***	
	November/April (10-20ºC)	***May/October (0-10ºC)***
Nitrate	1.1	1.7
Ammonium	0.5	0.4
Urea	3.0	0.8
Miscellaneous [a]	0.8	1.05

[a]: Assumed to be half nitrate, half ammonium.
SOURCE: Adapted from Armstrong-Brown *et al*. (1994).

The emission factor for CAN has been taken from the last type of fertiliser, "Miscellaneous". No N_2O emissions from compost have been considered.

Nitrogen oxides emissions

According to Audsley *et al*. (1997), N-NO_x emissions can be considered as 10% of N-N_2O.

Methane emissions

Applying ammonium fertilisers reduces the sink capacity for methane in soil. Audsley *et al*. (1997) suggest that an application of 150 kg N per ha in ammonium form reduces this sink capacity in 1 kg CH_4 per ha. In the case of CAN, half of the nitrogen content has been considered ammonium, while in urea all the nitrogen is in ammonia form.

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[17] The data from Haynes & Goh (1980) suggest that most N input to soil comes from grass clippings, and not from fertilising. Therefore, total N input in OFP might even be bigger than in IFP, although this has not been

Heavy metals emissions

Heavy metals entering agriculture from fertilisers are partly taken up by the crop, and thus become part of the technosphere. The heavy metals present in fertilisers that remain in soil after harvest have to be considered as an emission from agriculture to soil, and from soil to surface water. Audsley *et al*. (1997) suggest that the entire fraction not leaving the system with the crop may be considered as an emission to soil. Nevertheless, a small fraction reaching surface water by runoff (0.01%) has been considered in this study, in order to be consistent with the procedure for the calculation of pesticide fractions (see III.2.4, below). This fraction should be subtracted from the fraction remaining in soil in Table III-16, where the heavy metals contents and fractions remaining in soil considered for the fertilisers used in the study are shown.

The figures presented in Table III-16 are estimated from grain crops in Switzerland, the Netherlands and France. Therefore they should be regarded with suspicion, as the crop type and soil conditions (pH, soil organic matter…) will affect the fraction of heavy metal taken up by plants, the fraction sorbed to soil particles and organic matter, etc. An uncertainty factor of ±50% has been considered in the interpretation.

Table III-16: Heavy metal contents of mineral fertilisers (mg per kg fertiliser), and partition between crop and soil.

Heavy metal	***Ammonium Nitrate (27,5-33,5% N)*** [a]	***Urea (46% N)***	***Fraction leaving with the crop***	***Fraction remaining in soil*** [b]
As	0.43	0.4	54%	46%
Cd	0.05	0.05	54%	46%
Co	5	2	54%	46%
Cu	7	6	61%	39%
Hg	0.023	5	54%	46%
Mo	0.25	0.25	54%	46%
Pb	1.9	1.1	24%	76%
Se	0.25	0.25	54%	46%
Zn	50	44	73%	27%

SOURCE: Audsley *et al*. (1997).

[a]: CAN and calcium nitrate have been considered as ammonium nitrate for the purposes of heavy metals content.

[b]: Considered in this study.

Despite the heavy metal content in compost may be high for some types of compost, it is recommended not to charge any heavy metal emissions due to its use to agriculture (Audsley *et al.* 1997). As compost is usually the product of a waste treatment (at least when heavy metals are found in it), these emissions should be allocated to the waste treatment process. Seaweed and meat and bone meal have been considered as compost for this issue.

Copper substances used as pesticides represent a similar case for the emissions of this metal. Thus, all copper added to the system is considered to either leave with the crop or become an emission to soil and surface water. The concentrations of copper in the pesticides used in the sites under study can be found in Table III-17:

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checked in the present study. Marsh *et al*. (1996) also give data supporting the fact that most nitrogen input

Table III-17: Copper content of copper-based pesticides (%).

	Kocide, 40% $Cu(OH)_2$	*Blue Shield, 50% $Cu(OH)_2$*	*Copper oxychloride, 50% $Cu_2Cl(OH)_3$*
Cu	26%	32.5%	30%

III.2.4. Field emissions of pesticides

In general LCA, the environmental fate of most substances is not usually analysed with a great detail. This is due to the fact that not enough information is available on these substances; besides, a more thorough analysis could not be relevant in the sense that the conditions of emission and/or immission are unknown. In the case of pesticides in agricultural LCA, though, it is recognised that they need a special attention; Hauschild (2000) discusses some of the reasons for this need:

- Pesticides, as opposite to most other chemicals that reach the environment, are spread on purpose in parts of the biosphere to control certain life forms.
- Their effect on target organisms is strong and rather specific.
- And finally, and perhaps the most relevant, pesticide use is one of the main differences between conventional (or integrated) and organic agriculture. Hence, for a comparative LCA including these two forms of agriculture, such as the present study, it is crucial that the impacts of pesticides are represented well.

Audsley *et al*. (1997, p. 53) suggest a simplified distribution of the pesticide applied. This distribution is based mainly on Swiss and Dutch conditions, and only uses chemical-dependent parameters (K_d and the half-life due to microbial degradation: $\tau_{½,soil}$) for the calculation of pesticide leaching from soil to ground- and surface water. The final compartments considered for the pesticide fractions are air (assuming that 2% of the pesticide applied will remain in air after 10 minutes); soil (most of the pesticide); water (1.6% as average Dutch conditions, plus fraction of pesticide coming from soil); and in-food residues (8% as an average). They do not consider the metabolites from degradation of pesticides, but insist on the fact that degradation rates have to be taken into account.

The approach suggested by Audsley *et al*. (1997) is good enough when a screening of the potential risks of pesticide use is to be performed, but it barely allows for any site-dependency, or even chemical dependency. Besides, no distinction between different practices (e.g.: spraying pesticides at different concentrations, or using different substances) can be done. Consequently, a more complex model has been used for the estimation of the pesticide fractions that reach each environmental compartment.

Pesticide consumption data has been obtained directly from the farmers, as explained in section III.2.2. The final pesticide emissions have been calculated from the total amount of pesticide being used and the partition analysis suggested by Hauschild (2000), which is further explained and

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in an apple orchard comes from the understorey's grass turnover.

slightly modified in Hauschild & Birkved (2002). Many aspects of this fate analysis, though, have been adapted to New Zealand's conditions, as is explained in the text below.

It must be noted that, as pesticides are applied on purpose to the field, they are not considered an emission until they cross the border between technosphere and ecosphere by leaving the field (see Figure III-2 in page 48, and Figure III-5, below). The amount of pesticide leaving the field (i.e.: the emissions) is what has to be calculated with the fate analysis. This is particularly relevant in the sense that most of the impact derived from these pesticides occurs in the field's soil (e.g., affecting soil biota) and on the surface organisms, not outside the field. Hence, it must be noted that the final environmental impacts taken into account in the impact assessment are those occurring outside the field, although they might not be the most evident.

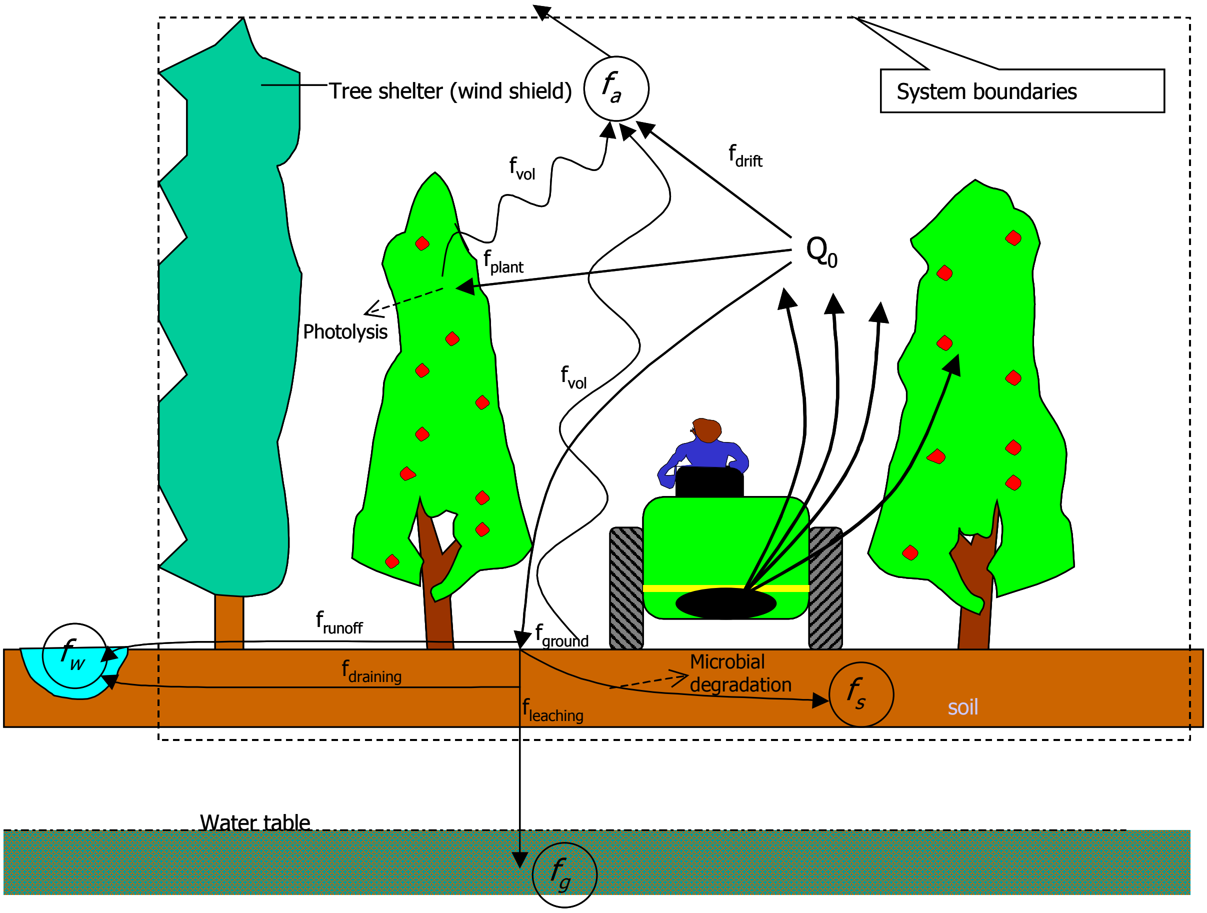

Figure III-5: Dispersion routes following pesticide application (adapted from Hauschild 2000).

Final compartment fractions: f_a: fraction reaching the air; f_w: fraction entering surface watercourses; f_g: fraction reaching groundwater; f_s: fraction remaining in soil.
Intermediate compartment fractions: f_{drift}: fraction of sprayed pesticide drifting off the orchard; f_{plant}: fraction of sprayed pesticide ending on the plant's surface; f_{ground}: fraction of sprayed pesticide reaching the ground; f_{vol}: fraction volatilised (either from plant's or ground's surface); f_{runoff}: fraction of pesticide on the ground that runs off to surface watercourses; $f_{draining}$: fraction of leached pesticide that is drained by draining systems to surface watercourses; $f_{leaching}$: fraction of pesticide on the ground that leaches down the soil to groundwater.

As shown in Figure III-5, when the pesticide is sprayed on the crop, the total amount sprayed (Q_0) is divided into the fractions that deposit on the plants (f_{plant}), on the ground (f_{ground}), or drift off the field and reach the surrounding environment (f_{drift}). Fractions of what has reached the plants' surface or the soil can volatilise (f_{vol}), and portions of it can be degraded (mainly through photolysis) before that occurs. Also, the fraction on soil may be washed by surface run-off into surface waters (f_{runoff}) or may leach to the groundwater (f_g) or to surface waters if the soil is drained ($f_{drained}$). Part of the contaminant in the soil will be degraded by microbial activity, and part may remain in it after the soil crosses the system's boundaries (f_s). Eventually, four fractions can be distinguished that cross the system's boundaries with nature and are thus considered as emissions:

- the fraction that drifts off the system plus the fraction volatilised, which remains in the air (f_a);
- the fraction entering surface water courses from runoff plus drainage (f_w);
- the fraction reaching groundwater through leaching (f_g);
- and the fraction that remains in soil after harvest, when the soil does not belong to technosphere anymore (f_s).

It must be noted that the tree shelter commonly present in apple orchards will act as a barrier, preventing part of the drift from reaching the surrounding environment, as it will be explained below. The fractions that cross the system's boundaries are circled in Figure III-5. The following sections describe the mechanisms affecting these fractions, and the considerations used in the present study.

Wind drift

A fraction of the substance being sprayed is taken off the field by wind, thus reaching surrounding ecosystems. This amount depends on a number of parameters, mainly related to the shape and size of the crop (herbaceous, shrubs, trees…), season (dormant plant or full foliage) and the spraying system (Manktelow 1998). For herbicides, this amount is neglected as the substance is directed to soil.

As a general approach, Hauschild (2000) suggests a model developed by the European and Mediterranean Plant Protection Organisation (EPPO) for risk screening of pesticides (see the solid lines in Figure III-6). From an LCA point of view, the relevant amount of pesticide being taken off the field is that found just at the edge of the field (or at a distance of 1m in Figure III-6), because that is the point where ecosphere begins. Apple trees should be considered as a "tall field crop" (pink line –second one from the top- in Figure III-6), and thus the fraction of pesticide leaving the field with the wind drift according to this figure would be as high as 50%.

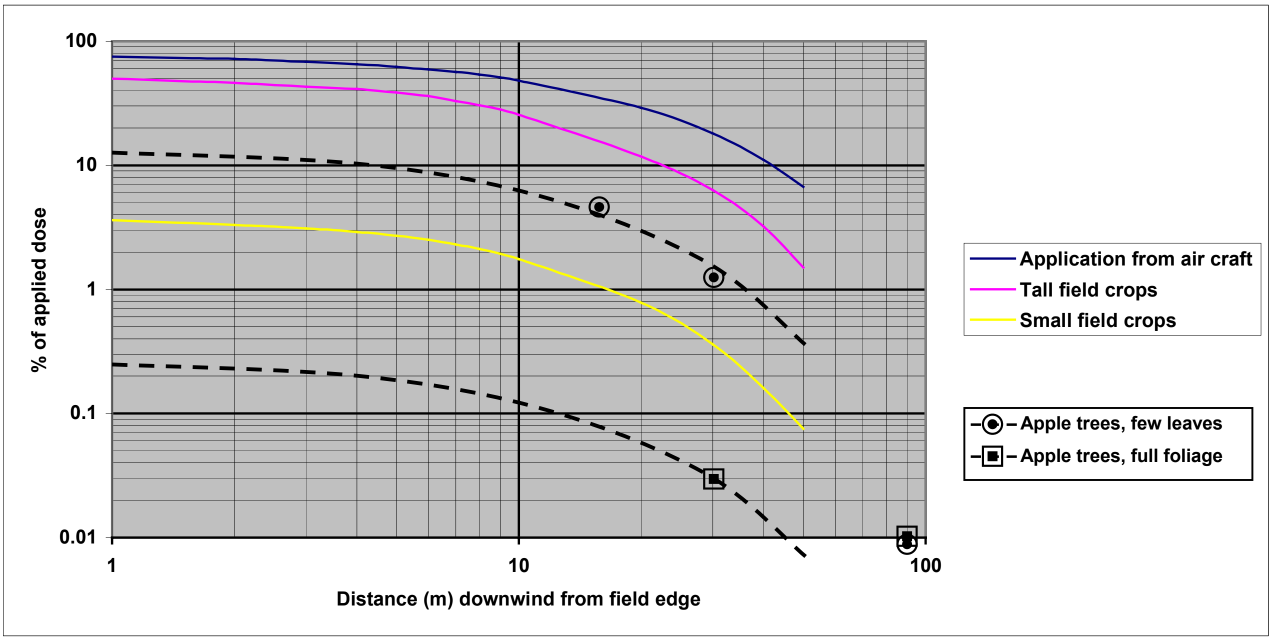

Figure III-6: Deposition curves showing the fraction of pesticide deposited after wind drift as a function of the distance from the edge of the field.

SOURCE: EPPO 1996 (solid lines) and own representation from the values taken from Praat *et al*. 2000 (dashed lines). An uncertainty factor of ±20% should accompany any value taken from either curve (EPPO 1996).

Nevertheless, at least two studies have been developed for the assessment of wind drift of pesticides under New Zealand conditions (Praat *et al*. 2000; Manktelow 1998) that give lower values for the fraction of pesticide that drifts away from the field. Actually, the model suggested by Hauschild (2000) is said to be rather conservative in the same reference ("realistic worst case situation"), and so the wind drift measures from Praat *et al*. (2000) will be used instead. According to their data (see Table III-18), the fraction of pesticide blown off the field is highly dependent on the time of application, as early season applications are sprayed on fewer leaves, and thus the area for interception of the pesticide is much lower.

Table III-18: Effect of crop growth and distance on spray drift.

	Distance from edge of sprayed block (spraying 1st 6 rows)		
Growth stage	**15m**	**30m**	**90m**
Few leaves (September)	4.9%	1.13%	0.007%
Full foliage (December)	N/A	0.03%	0.01%

Source: Praat *et al*. 2000.

Figure III-6 shows that deposition curves follow a similar pattern for different applications. Thus, it can be argued that a similar curve including the values from Praat *et al*. (2000) might well represent a deposition curve for apple trees in New Zealand. Doing this graphically, we have found that during early season spraying, up to 12% of the applied pesticide may be blown off the field, while a wind drift of only 0.24% is expected during full foliage (see the dashed lines in Figure III-6). The correlation of the data with the extrapolated curve is good when there are few leaves on the tree (and values at 15 and 30m both stay within ±20% of the curve, which is the error suggested by EPPO). In the case when there is full foliage, the estimated values are much smaller, and actually only the value at 30m can be used (the curve does not reach the 90m distance). In this case, a bigger error should be expected, but the actual value will probably remain low and almost irrelevant from an environmental point of view.

Also the distance at which the sprayer is operating from the edge of the field is crucial, and only the spraying of the first six tree rows seemed to have an effect on wind drift (Praat *et al*. 2000). As a consequence, the shape of the orchard will play an important role in the amount of pesticide blown off the field. This should be taken into account by multiplying the fraction estimated for wind drift by the fraction of the field surface occupied by the first six rows on either side of the field (Γ). As an example, in a rectangular block consisting of 12 rows of trees this value would be 1, while in one of 20 rows only ca. 63% of the sprayed pesticide would be sprayed in the first 6 rows and thus prone to wind drift. Therefore, values taken from the dashed lines in Figure III-6 should be corrected by the fraction of field in close proximity to edges.

The average shape of apple orchards can be considered as a square 4 ha in size, usually comprising four 1ha blocks (see Figure III-7). As the common distance between apple tree rows is 5 m, this gives 4 blocks of 20 rows, or a square orchard of 40 rows. Only 12 of these 40 rows are subject to off-orchard drift, and thereby the orchard's fraction occupied by the first six rows is 30% (Γ= 0.3). This value has been considered the same in all the sites in the study.

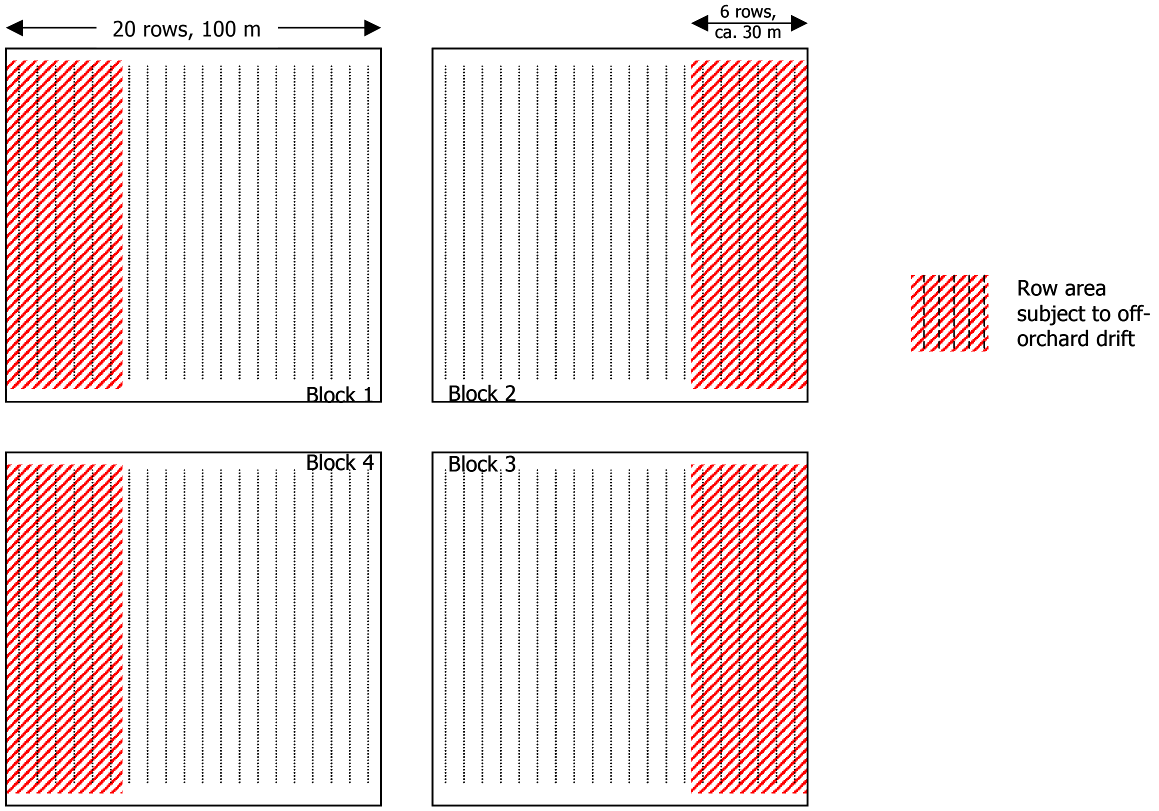

Figure III-7: Typical orchard layout, showing the row area subject to off-orchard drift.

Most apple orchards in New Zealand have boundary shelters, mainly for protection against wind. These hedge barriers will act as physical limits to the orchard, not allowing the sprayed pesticide to be taken off the field. Indeed, Praat *et al*. (2000) report reductions of spray drift of 50-90% when shelter is present. If a hedge barrier is present, the hedge will capture most of the estimated amount of pesticide taken by wind drift; as the hedge is part of the technosphere, this amount of pesticide is not an emission. Instead, the pesticide “captured” by the hedge barriers will be treated as pesticide that reaches the plants’ surface (see below), and can thus volatilise or be degraded through photolysis. A value of 80% of spray wind drift intercepted by the shelter has been considered in this study for all the systems, as all of them have similar tree shelters. The fraction in the drift that is not captured by the tree shelter is a direct emission to air.

Partition between apple trees and field soil

The amount of substance remaining in the field after subtracting the wind drift is divided into the fraction actually ending on the plants (spray deposition or retention) and the fraction on the field soil. Many parameters affect spray retention.

The higher the foliage density at the moment of spraying the bigger the amount of pesticide reaching its target on the plant will be. Hauschild (2000) suggests a simple correlation between the fraction on the ground (f_{ground}) and the leaf area index L (m^2 leaves · m^{-2} ground) in order to include the effect of leaf density on spray deposition. The leaf area index varies during the year, with lower values at the beginning of the season, when the trees do not have their leaves. Also tree density affects this value, as this is strongly related with the existence of spacings between rows and the continuity of canopies (Manktelow 1998).

In addition, parameters such as the spray volume applied play an important role in spray retention, with higher retention rates at lower volumes (concentrate spraying). Manktelow (1998) reports spray retention being 56% higher following 5X concentrate spraying than following applications of ca. 3000 $l \cdot ha^{-1}$ (usual spraying volume in New Zealand is ca. 2000 $l \cdot ha^{-1}$).

There are no models currently available that include all these parameters in the calculation of the spray retention (i.e.: f_{plant}). Instead, empirical estimates of spray retention (see Table III-19) during different times of the year and for different spraying strategies have been used in the assessment of pesticide fate. These values derive from studies on New Zealand apple trees with an ideal slender pyramid training system (Manktelow 1998, p. 60).

Table III-19: Spray retention (f_{plant}, in %) as a function of spray concentration and time of the year (Manktelow 1998).

	Dilute spraying (1500-3000 $l \cdot ha^{-1}$)	*Medium spraying (1000-1500 $l \cdot ha^{-1}$)*	*Concentrate spraying (<1000 $l \cdot ha^{-1}$)*
Dormant trees-Developing foliage (-Mid November)[a]	30%	37%	45%
Full foliage (Mid November-harvest)	60%	72%	85%

[a]: Even though during the development of the leaves the spray retention increases proportionally with leave surface, a discrete situation has been assumed for the sake of simplicity. Thence, trees with developing foliage have been considered as not having leaves at all (dormant stage).

Volatilisation

Once on the soil or on the plant, the pesticide may volatilise. The following expressions from Hauschild (2000) have been used in the assessment of volatilisation of pesticides from ground ($f_{ground,a}$) or plant ($f_{plant,a}$) surface:

Equation 1:

$$f_{ground,a} = 1 - e^{-\alpha_{ground} \cdot \tau_{ground}}$$

Equation 2:

$$f_{plant,a} = 1 - e^{-\alpha_{plant} \cdot \tau_{plant}}$$

These equations assume that volatilisation follows a first order kinetics, where α_i is the rate constant, representing the daily loss through evaporation from ground (i=ground) or plant (i=plant), and τ_i is the residence time. α values depend on the vapour pressure of the pesticide and the surface where they are evaporating from (see Table III-20 and Table III-21). The residence time on the ground (τ_{ground}) is determined by microbial degradation rate, and residence time on the plant (τ_{plant}) is determined by the rate of photolysis or photochemical oxidation. The data needed to determine the fractions volatilised are included in Table III-46 in APPENDIX III.2 for all the pesticides considered in this study.

Table III-20: Evaporation rates for pesticides on soil as determined by the volatility of the substance (EPPO, 1996).

Volatility	*Vapour Pressure, Pa*	*Daily loss α_{ground} through evaporation (fraction of f_{ground}), d^{-1}*
High	$> 10^{-1}$	0.50
Low	$10^{-3} – 10^{-1}$	0.10
Not Volatile	$< 10^{-3}$	0.01

Table III-21: Evaporation rates for pesticides on crop surfaces as determined by the volatility of the substance (EPPO, 1996).

Volatility	*Vapour Pressure, Pa*	*Daily loss α_{plant} through evaporation (fraction of f_{plant}), d^{-1}*
High	$> 10^{-3}$	0.50
Low	$10^{-5} – 10^{-3}$	0.25
Not Volatile	$< 10^{-5}$	0.10

Run-off

The pesticide that has been deposited on the ground may be washed by rainwater to surface waters in case of rain. The fraction actually being washed by run-off (f_{runoff}) depends on a number of circumstances, related to the chemical (water solubility, degradability, volatility and sorptive properties) and to the environment (time prior to rainfall, slope of the field…). As no model for the estimation of a run-off fraction is suggested in Hauschild (2000), an estimate based on empirical data is needed. Hauschild cites a value for this fraction at f_{runoff} = 0.0001; this is based on Danish conditions, where most fields are flat and horizontal, and runoff is dominated by the transport of dissolved substance. This value is assumed acceptable for New Zealand orchard conditions as well, although and uncertainty factor of ±15% is considered.

Leaching

Hauschild (2000) suggests differentiating between the fraction of pesticide that leaches by percolation and the fraction that follows a preferential flow through the macropores of the soil. In the case of percolation, he suggests the PESTLA model, which estimates the fraction of a substance that will leach below 1 m depth in the soil through percolation under typical Dutch conditions (soil type and precipitation). As for preferential flow, he gives some representative data, depending on the soil's texture.

In the case of New Zealand, a mechanistic model developed to calculate pesticide's leaching risk for New Zealand's conditions (PESTRISK) is available (HortResearch, 2000), and it has thus been used for the fraction of pesticide being leached ($f_{leaching}$). In this model, both the characteristics of the soil (mainly organic carbon and water retention) and of the chemical (K_{OC} and residence time in soil, basically affected by microbial degradation) are considered when calculating the probability that a certain amount of pesticide will be leached. The model also takes into account weather data for 30 years in order to estimate the average amount of pesticide that leaches. The hydraulic balance also considers the input of water from irrigation, which differs greatly from site to site as it has been described in section III.2.2. Not only the total amount of water is relevant in this case, but also the frequency of irrigation. The site characteristics introduced in PESTRISK in order to calculate $f_{leaching}$ can be found in Table III-22.

Table III-22: Soil type and irrigation pattern considered for pesticide leaching calculations.

Site	***Soil type***	***Irrigation***			
		Water volume (mm)	***Sprinkler type***	***Season***	***Return period [a] (days)***
IFP_HB_1	Hastings silt loam	120	mini-sprinklers	Nov. - March	10
IFP_HB_2	Hastings silt loam	500	mini-sprinklers	Nov. - March	10
IFP_CO_1	Omahu gravel	860	overhead sprink.	October - April	3
IFP_HB_Avg	Hastings silt loam	550	mini-sprinklers	Nov. - March	10
IFP_CO_Avg	Matapiro silt loam	550	overhead sprink.	October - April	6

[a]: The return period refers to the periodicity of the irrigation events.

The fraction of pesticide being leached depends highly on the moment of application. To consider this, leaching has been estimated from applications in different months. The fractions considered leaching for each month and pesticide are expressed in Table III-47 in APPENDIX III.3 (page 168). These fractions of contaminant reaching the groundwater may be considered as the average yearly fractions in a period of 30 years.

Taking into account that the soil may be drained, part of the fraction of pesticide being leached may eventually end in surface waters. Hence, if δ is the fraction of drainage (fraction of water entering the ground that is drained), one can express the fractions being drained ($f_{drained}$) and reaching the groundwater (f_g) as:

$f_{drained} = \delta \cdot f_{leaching}$

$f_g = (1 - \delta) \cdot f_{leaching}$

Draining systems were not observed in the systems under study, and thus the value assumed for δ in the apple orchards is 0.

Degradation

Hauschild & Birkved (2002) suggest that the pesticide remaining in soil after all these processes should not be considered as an emission, because soil is part of the technosphere. Nevertheless, as it is explained in section III.1.2 (system boundaries), soil is considered to leave the system at harvest, and therefore the fraction of contaminant that remains in soil by harvest should be considered as an emission. Of course, given the organic nature of most pesticides, degradation rates should be considered in this case (as is strongly recommended in Audsley *et al.* 1997). According to Hauschild (2000), the pesticide residence time in soil is mainly determined by the microbial degradation rate. Assuming a first-order kinetics, the fraction of pesticide degraded in soil ($f_{degraded}$) has been calculated as follows (Equation 3):

Equation 3:

$$f_{\deg radation} = \left(f_{ground} - f_{ground,a} - f_{runoff} - f_{leaching}\right) \cdot \left(1 - e^{-\lambda \cdot t_{harvest}}\right)$$

where λ is the rate for microbial degradation in soil (chemical dependent, days^{-1}) and $t_{harvest}$ is the time allowed for degradation before soil leaves the system after harvest (days). λ can be determined from the pesticide half-life for microbial degradation ($\tau_{½}$), a parameter usually found in the literature. The relation between λ and $\tau_{½}$ is:

$$\lambda = \frac{\ln 2}{\tau_{1/2}}$$

Values for $\tau_{½}$ for all the pesticides considered in the study can be found in Table III-46, in the APPENDIX III.2. These values come from experimental studies, and an uncertainty factor of ± 20% should considered for them. The values considered for $t_{harvest}$ depend on the moment of application of pesticides, and have been calculated considering that soil leaves the system on the 30th of May. E.g.: if a pesticide is sprayed in mid November (i.e.: 6.5 months before end of system) $t_{harvest}$ is set at 6.5x30 = 195 days.

Calculation of pesticide fractions

Some general assumptions have been made in order to calculate the fraction of pesticide entering the different compartments:

- Only the active ingredient applied to the field is considered. No effect of adjuvants or metabolites from the active ingredient is considered.
- The final receiving media in the environment are groundwater, surface water, air, and soil.

- In the case of copper substances, a different model has been considered, and it has been explained in section III.2.3 under the heading "Heavy metals emissions". No copper emissions to air have been considered, as this substance will not generally remain in air.

Taking into account all the above mentioned processes and assumptions, the fractions of pesticide reaching the environment are calculated as follows:

1. The wind drift fraction (f_{drift}) is calculated taking into account the effects of the time of application (see Table III-18) and the presence or absence of shelter. In case a shelter is present, the fraction retained by it is added to the fraction on the plants.
2. The fraction on the trees (f_{plant}) is calculated taking into account the time effects due to foliage development and the concentration effects due to spraying volume (see Table III-19). The fraction intercepted by the shelter (80% of f_{drift}) is added to f_{plant}.
3. The fraction of pesticide reaching the ground is calculated from the previous two fractions ($f_{ground} = 1 - f_{drift} - f_{plant}$). In the case of herbicides, 100% of the sprayed substance is considered to reach the ground ($f_{ground} = 1$).
4. The runoff fraction ($f_{runoff}= 0.0001$) is extracted from the fraction reaching the ground.
5. PESTRISK model (HortResearch, 2000) is used to estimate the fraction leached ($f_{leaching}$). Site-dependent conditions have been included with soil and weather patterns (see Table III-22).
6. Volatilisation from ground and from plants is calculated using the formulas in Equation 1 and Equation 2 ($f_{vol} = f_{ground,a} + f_{plant,a}$).
7. The fraction reaching the air compartment (f_a) comes from the wind drift that is not intercepted by the shelter plus the fractions volatilised from the plants and the ground surface ($f_a = 0.2 \cdot f_{drift} + f_{vol}$).
8. The fraction finally emitted to groundwater is equal to the fraction leached ($f_{leaching}$), as no draining systems have been considered.
9. The fraction finally emitted to surface water (f_w) is equal to the fraction washed by runoff (f_{runoff}).
10. The fraction reaching the ground (f_{ground}) that does not leave the system both through runoff, leaching or volatilisation, and which has not been degraded before harvest (Equation 3), remains in soil and is considered as an emission to this compartment (f_s).

The fractions of pesticide reaching each compartment are included for all sites in the study in Table III-47 in APPENDIX III.3 (page 168).

III.2.5. Machinery production and use

It is recognised that machinery production may have a significant impact on the overall results of an agricultural LCA study (Audsley *et al*. 1997). Thus, as a rule it is necessary to include not only the impacts derived from the use of the machinery (mainly related to fuel consumption), but also the impacts arising from the production of the machines themselves.

Machinery production

The impacts of production of machines are estimated from the materials used plus the energy consumed in the production and repairs. Then, this figure is allocated amongst all the service hours of the machine, and the functional unit is charged with the amount of machine-hours associated to its life cycle. Data have been obtained mainly from Audsley *et al*. (1997), and whenever a machine was not included in that report machinery producers have been consulted. The machinery classification suggested by Audsley *et al*. (1997) (see Table III-23) has been used in this study.

Table III-23: Machinery classification according to Audsley *et al*. (1997).

Category		***Description***		***Examples***
A	A1	Self-propelled machines	Small tractors	Tractor 2WD, 55hp
	A2		Large tractors	Tractor 4WD, 67hp
	A3		Other vehicles	Combine harvester
B		Tillage machines		Plough, rotary cultivator, harrow
C		Other machines		Manure spreader, slurry pump, drilling machine, round baler

The characteristics in the production and maintenance of these categories have also been obtained from the recommendations in Audsley *et al*. (1997), and are expressed in Table III-24.

Table III-24: Main characteristics for the different types of machines (from Audsley *et al*. 1997).

Category	% Steel	% Rubber	Energy Consumption for Manufacture (MJ/kg)[a]	Energy Consumption for Repairs (% of Energy in manufacture and materials)[b]
A1	95	5	14.6	45
A2	95	5	14.6	26
A3	95	5	12.9	23
B	100	0	8.6	30
C	100	0	7.4	26

[a]: Energy in manufacture is consumed in the form of electricity.

[b]: The distribution of energy sources for repairing is estimated to be approximately 62% electricity, 26.5% fuel-oil, 3% diesel, and 8.5% natural gas.

The materials composition of the machinery has been simplified to steel and rubber (the latter only for self-propelled machines). The impacts due to the production of these materials have been further simplified to their energy consumption. This is considered to be 33 MJ kg^{-1} in the case of steel (24% electricity, 53% fuel-oil, 6% diesel, 17% natural gas), and 23.4 MJ kg^{-1} in the case of rubber (100% fuel-oil) (Audsley *et al*. 1997). This is actually a simplification of a wide range of values offered by Audsley *et al*. (1997), from 32.6 to 62.5 MJ kg^{-1} in the case of steel production. The figures for energy consumption in the manufacturing process also vary widely, and the reference cited by Audsley *et al*. (1997) is from 1980. Finally, the average energy expenditure on maintenance and repairs may also vary considerably depending on the source.

Further details of the machines considered in the present study have been included in Table III-25. It must be noted that service life of machines may vary considerably depending on the maintenance and the use intensity. For instance, many New Zealand orchard mowers are ancient, having been repaired so many times that it is hard to say it is the same machine as the original, and this is probably the case in the less sophisticated machines (rotary and basic flail mowers). Use intensity also affects the total use in the lifetime, which may differ greatly between users. Therefore, the values given for the total use in lifetime in Table III-25 should be considered with care, and an error factor of ±40% is estimated for them.

Table III-25: Main characteristics of the machines considered in the present study.

Machine	*Cat.*	*Weight (kg)*	*Service life (years)*	*Total use in lifetime (hours)*	*Reference*
Tractor 2WD, 55hp [a]	A1	2300	12	7200	Audsley *et al*. 1997
Tractor 2WD, 67hp [b]	A2	3400	12	6000	Audsley *et al*. 1997
Fertiliser Pendulum Spreader	C	125	10	800	Adapted from Hermansen, 1998 [c]
Manure / Compost spreader	C	1400	10	3000	Audsley *et al*. 1997
Air-blast sprayer (2000 l)	C	640	10	3000	Adapted from Hermansen, 1998 [c]
Herbicide sprayer	C	640	10	400	Adapted from Hermansen, 1998 [c]
Mower	C	450	8	400	Adapted from Hermansen, 1998 [c]
Mulch-mower [d]	C	500	8	640	Audsley *et al*. 1997
Weed-eater	C	50	8	300	Own estimate [e]
Hydra-ladder, 12hp	A1	700	10	10000	Own estimate [e]
Motorbike for herbicide spraying	A1	400	10	8000	Own estimate [e]
Forklift	A1	2000	12	5000	Own estimate [e]
Wagon	C	2500	10	1500	Audsley *et al*. 1997
Wind machine	C	400	10	200	Own estimate [e]

[a]: Considered as the 47hp tractor used in most sites of the study.
[b]: Considered as the 60hp tractor used by Dan Harland (OFP_CO_1).
[c]: Mainly the total use in lifetime has been reduced from the figure cited by Hermansen (1998), as her figures were possibly overestimated.
[d]: Assumed to be equivalent to the "straw chopper" cited in Audsley *et al*. (1997), p. 39.
[e]: Obtained from interviews with orchardists and machinery manufacturers.

Energy consumption in field operations

A tractor's consumption depends on the type of operation it is performing and the power use related to it. Thus, "normal-duty" operations such as mowing and harvesting will require less fuel consumption, while spraying pesticides, swing-arm mowing or mulching will require about twice this consumption. Tractor's consumption will also depend upon make and power, as well as many other factors such as slope of the field, weight of the machinery, driver's practices, etc. but these factors have not been included in the present study for the sake of simplicity. Table III-26 includes some fuel consumption values for usual orchard operations performed with different tractors. The values have been gathered from several fruit producers, which makes them representative enough, but due to the reasons explained above an uncertainty factor of ±10% should be considered when interpreting the results.

Table III-26: Fuel consumption (litres diesel per hour) for different orchard operations using different rate tractors.

	Diesel consumption (litres/hour)	
Tractor rate	***47hp***	***60hp***
Operation		
Tractor, Mowing	4.0	5.0
Tractor, Swing-arm mowing	6.0	9.0
Tractor, Air-blast Spraying	6.0	9.0
Tractor, Spraying herbicides	4.0	5.0
Tractor, Spreading fertilisers	4.0	5.0
Tractor, Spreading mulching/ compost	3.0	4.5
Tractor, Collecting prunings	3.0	4.5
Tractor, Mulching prunings	6.0	9.0
Tractor, Harvesting	3.0	4.5

SOURCE: Own estimate from interviews with New Zealand orchardists.

It is often the case that tractor power rate does not match with the requirements of orchard operations. This can be because fuel efficiency is not always a criterion in the selection of machinery. In addition, some farmers have other crops apart from the apple orchard, which may need higher power machines for some operations (e.g.: if they have arable crops and use the same tractor in them, high power rate will be required for ploughing).

Hydraulic ladders, commonly known as hydra-ladders or cherry pickers, are being increasingly used to perform many orchard operations. They are particularly useful to perform manual operations – such as pruning, manual thinning or harvesting - on the top of tall trees. Reducing the labour time allocated to these operations when using manual ladders compensates the fuel cost in hydra-ladders.

Petrol consumption of hydra-ladders is usually independent from the operation, and it has been estimated at 2.3 litres petrol per hour[18]. Nevertheless, if compressed air operated pruners are used plugged to the hydra-ladder its consumption is almost doubled (considered as 4.5 litres petrol per hour[18]).

Weed-eaters are used in OFP to reduce the height of weeds in the tree line. They are usually powered by 2-stroke engines, which use a mix of petrol and mineral oil. The average consumption is 1 litre petrol and 33,3 ml of mineral oil per hour. Mineral oil consumption due to weed-eaters is negligible compared to the consumption as pesticide, and so it has not been included in the analysis.

III.2.6. Pesticides production

The data for pesticide production is generally the hardest to get. Commonly, the access to production data (even simple energy requirements) is not allowed by industries, because of confidentiality. It is thence quite usual that approximations of energy requirements are used, even if these approximations come from stoichiometric calculations rather than real industrial figures.

"Conventional" pesticides

Most of the data for the energy consumption related to pesticide production has been obtained from Green (1987). When the relevant active ingredient was not in Green (1987), the extrapolation procedure suggested by Audsley *et al*. (1997) has been followed. Thence, the following approximations have been used for the agrochemicals of the studied systems:

Table III-27: Extrapolations for pesticide production data.

Active ingredient	*Chemical family*	*Consider as…*	*Source of data*
Herbicides			
Amitrole	Aminotriazole	Chlorsulfuron (urea triazine)	Green 1987
Glyphosate	Organo-phosphate	Glyphosate	Green 1987
Fungicides			
Bupirimate	Pyrimidine	Average fungicide	Green 1987
Calcium polysulphides	Inorganic sulphur	Sulphur	Mudahar & Hignett 1987
Captan	Cyclic imide	Captan	Green 1987
Copper hydroxide	Inorganic copper	Copper hydroxide	Mudahar & Hignett 1987
Copper oxychloride	Inorganic copper	Copper hydroxide	Mudahar & Hignett 1987
Cyprodinil	Anylinopyrimidine	Average fungicide	Green 1987
Difenoconazole	Triazole	Average fungicide	Green 1987
Dithianon	Quinone	Average fungicide	Green 1987
Dodine	Substituted acetate	Metolachlor (acetamide)	Green 1987
Flusilazole	Triazole	Average fungicide	Green 1987
Kresoxim methyl	Strobilurin	Average fungicide	Green 1987
Mancozeb	Dithiocarbamate	Average of Ferbam and Maneb	Green 1987
Metiram	Dithiocarbamate	Average of Ferbam and Maneb	Green 1987
Myclobutanil	Triazole	Average fungicide	Green 1987
Nitrothal Isopropil	Nitrogen compound	Average fungicide	Green 1987
Sulphur	Inorganic sulphur	Sulphur	Mudahar & Hignett 1987
Triadimefon	Triazole	Average fungicide	Green 1987
Ziram	Dithiocarbamate	Average of Ferbam and Maneb	Green 1987
Insecticides			
Azinphosmethyl	Organo-phosphate	Average of Malathion and Phorate	Green 1987
Buprofezin	Thiadiazine	Average insecticide	Green 1987
Chlorpyrifos	Organo-phosphate	Average of Malathion and Phorate	Green 1987
Diazinon	Organo-phosphate	Average of Malathion and Phorate	Green 1987
Lufenuron	Benzoylurea	Average insecticide	Green 1987
Mineral oil	Mineral oil	Mineral oil	PIRA
Tebufenozide	Diacylhydrazine (Ecdysteroid agonist)	Average insecticide	Green 1987
Triflumuron	Benzoylurea (Ecdysteroid agonist)	Average insecticide	Green 1987
Thinning agents (Plant growth regulators)			
Carbaryl	Carbamate	Carbaryl	Green 1987
1-Naphtylacetic acid	Synthetic auxin	1-Naphtylacetic acid	Cowell 1998
Calcium products			
Calcium Chloride	Inorganic salt	Potassium chloride	Mudahar & Hignett 1987
Caltrac (calcium+urea)	Calcium and urea	Dolomite and urea	Davis & Haglund 1999 [a]

[a]: Energy requirements for the production of dolomite and urea have been considered.

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[18] From interviews with orchardists and retailers.

The environmental impacts related to the different active ingredients have been calculated from the energy consumption for the actual production of the chemical ingredients, as well as for the formulation (powder, granule or concentrate) and packaging. The final energy consumption for pesticides production obtained using such procedure is actually quite uncertain, and this should be taken into consideration when interpreting the results. Green (1987) suggests an uncertainty factor of ±10%, which might be a bit higher in more modern products, when the exact production processes are not known because of confidentiality issues. For this study, an uncertainty factor of ±15% has been considered following a precautionary principle, and bearing in mind that most active ingredients used in the apple LCA are chemically more complex than the substances in Green's paper.

Bio-pesticides

Some of the products used for pest management in OFP deserve special attention, as their production was not previously described in LCA studies. This is the case of mating disruption sex pheromone ties, *Bacillus thuringiensis*, and granulosis virus.

The pheromone ties are small plastic tubes containing a solution of sex-attractant pheromones. The plastic is porous polyethylene that slowly releases the pheromones into the air. An aluminium wire embedded in the plastic enables the tubes to be easily tied to tree branches. The environmental impacts related to the production of the tie can thus be approached from the production of each of its components:

- Pheromone solution: 0.1650 g tie^{-1}
- Aluminium wire: 0.3395 g tie^{-1}
- HDPE tube: 1.1665 g tie^{-1}

Data for the production of HDPE and aluminium have been obtained from the BUWAL 250 database (BUWAL 1996). In the case of the pheromone solution itself, the basic procedure described by Green (1987) to estimate the energy consumption of its production has been followed. Energy consumption for the production of the pheromone has been calculated considering the production of ethylene. Actually, and according to Shin-Etsu (the main pheromone producer in the world) pheromones are produced from acetylene[19]. As no data have been found for acetylene production, it has been assumed that its origin is the same as ethylene (crude oil cracking). From the IVAM database (Lindeijer & van Ewijk 1998) the production of ethylene ("Ethylene average APME/ETH") requires 27.01 MJ kg^{-1} of oil (here considered as naphta) and 21.94 MJ kg^{-1} natural gas as feedstock energy, plus 0.45 MJ kg^{-1} electricity + 13.41 MJ kg^{-1} fuel oil as process energy. Besides, the average process energy for insecticides (from Green 1987) is used as an estimate for the transformation of ethylene to pheromones (as process data are confidential); the formulation (as emulsifiable oil) and packaging energy is also included (Green 1987):

- fuel oil: 25.1 MJ kg^{-1} pheromone

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[19] Shin-Etsu Chemical Co., Ltd. Consulted on-line http://www.shinetsu.co.jp [2002.03.19].

- electricity: 83.5 MJ kg^{-1} pheromone
- steam: 41.3 MJ kg^{-1} pheromone

The final energy consumption considered for sex attractant pheromones production is presented in Table III-28. The energy consumed in the ties production should be added to these figures.

Table III-28: Energy consumption for the production of 1 kg of sex attractant pheromone solution (MJ/kg).

Inherent Energy		***Process Energy***		
Naphta	***Natural Gas***	***Fuel oil***	***Electricity***	***Steam***
27.0 MJ	21.9 MJ	38.5 MJ	84.0 MJ	41.3 MJ

Several subspecies of *Bacillus thuringiensis* are common in soil, mills and other insect-rich environments (Copping 1998). During sporulation, this bacterium produces crystal inclusion bodies that are insecticidal upon ingestion to mainly Lepidoptera larvae. In apple orchards, *Bacillus thuringiensis* Berliner subsp. *kurstaki* (commonly known as Btk) is mainly used to fight leafrollers. Controlled fermentation in deep aerobic batch reactors is needed for industrial production of Btk. The operations (González *et al*. 2002) for the preparation of the reactor include sterilisation, which is generally done by raising temperature to ca. 121ºC and may represent a significant part of the energy consumption. During fermentation, the main state variables that affect energy consumption in these reactors are temperature (which must be kept around 30ºC) and oxygen (which must be continuously added to the reactor in order to avoid problems for the culture. Finally, post-treatment operations include separation of the spores and crystals, as well as the formulation (which mixes the active ingredient with emulsifiers, UV protectors, etc.). The endotoxins and living spores are harvested as water dispersible liquid concentrates (Copping 1998). According to Nemecek & Heil (2001), the total process energy consumption for the production of 1 kg of *Bacillus thuringiensis* is 77.2 MJ, in the form of electricity.

As the Btk, the *Cydia pomonella* Granulosis Virus (CpGV) occurs widely in nature, affecting only the codling moth larvae (Tomlin 1995). *In vivo* production is the most widely used technique for industrial production of baculovirus intended for use as bio-insecticides. Therefore, mass insect (codling moth) growing under controlled conditions is needed. The environmental conditions for a proper relationship insect-host (Claus & Sciocco de Cap 2001) are temperature (which must be kept at 20-26ºC), humidity (50-70%), and feeding (which is one of the main parameters affecting total production costs). Insects are grown and infected in special containers that allow an important number of insect larvae to be contaminated at a time (Claus & Sciocco de Cap 2001). The infected moths are then harvested and centrifuged in order to extract the granular occlusion bodies (Tomlin 1995). Formulation of liquid concentrates requires the addition of emulsifying agents and u.v. protectors, as the virus is unstable to u.v. light. No specific data could be found for the production of CpGV. Even though *in vivo* production data may probably vary widely from a fermentation process, the energy consumption from *Bacillus thuringiensis* has been considered as a first estimate of CpGV's production.

III.2.7. Fertiliser production

Energy consumption for the production of Calcium Ammonium Nitrate (CAN) and urea have been obtained from Davis & Haglund (1999). Average data for the production of these fertilisers in Western Europe have been used. The fertilisers consumed in New Zealand are produced mainly in New Zealand, with the exception of CAN that is imported from Germany; therefore, the data used are representative enough.

In the case of compost, seaweed, and meat and bone meal, which are used in OFP, no environmental burdens have been considered for their production, as they mainly come from waste management processes from other systems.

Transportation of the fertilisers from the point of production to New Zealand has been also included (see section III.2.8).

III.2.8. Energy carriers and transportation delivery

This section explains the data sources and considerations for the production of facilities used throughout all the life cycle stages, and for which no specific research has been performed. These include energy production and transportation.

Electricity production

Hydro stations generate most of New Zealand's electricity, the rest of electricity being produced in thermal plants (Ministry for the Environment, 1997). The following mix for electricity production in 1996 can be derived from the report The State of New Zealand's Environment 1997 (Ministry for the Environment 1997, p. 3.21):

Table III-29: Electricity mix in New Zealand and in Europe.

Source	*New Zealand* [a]	*Europe* [b]
Hydroelectricity	79%	16.4%
Gas	12%	7.4%
Geothermal	6%	-
Coal and co-generation	3%	17.4%
Lignite	-	7.8%
Uranium	-	40.3%
Oil	-	10.7%

[a]: Ministry for the Environment (1997). Data from 1996.
[b]: BUWAL (1996).

The electricity produced from "coal and co-generation" has been treated as produced in a coal-powered plant, even though co-generated electricity is usually not charged any environmental burdens in LCA. The environmental effects caused by electricity generation have been calculated from the above mix and the data for electricity production using different technologies from the BUWAL 250 database.

The production of some of the inputs used in the apple LCA requires electricity consumption, as it has been explained in the former sections. In the cases where inputs are produced outside New Zealand, the European electricity mix (electricity UCPTE, see Table III-29) from BUWAL 250 (BUWAL 1996) has been used.

Fuel production and combustion

Emission data for fuel production and combustion have been obtained from the BUWAL 250 database (BUWAL 1996). This includes diesel for tractors, petrol (unleaded), fuel oil, natural gas, steam, and coal. These fuel types are directly consumed by machines, transportation or in production processes. Also energy vectors considered as inherent (or indirect) energy in the production of some substances (mainly pesticides and fertilisers) have been obtained from BUWAL 1996: naphtha, natural gas and coke.

Fuel consumption figures are often found in litres or kilograms, while emissions data are given in kg contaminant per MJ in most databases. The conversion factors used in this study are shown in Table III-30.

Table III-30: Main energy conversion factors used in the study.

Energy vector	*Conversion factor*	*Reference*
Naphtha	46.0 MJ kg^{-1}	Audsley *et al*. 1997 p. 29 (Total inherent energy)
Natural gas	50.3 MJ kg^{-1}	Audsley *et al*. 1997 p. 29 (Total inherent energy)
Steam	46.8 MJ kg^{-1}	Audsley *et al*. 1997 p. 29 (Total inherent energy; considered as fuel oil)
Coke	42.1 MJ kg^{-1}	Audsley *et al*. 1997 p. 29 (Total inherent energy; considered as hard coal)
Diesel	38.4 MJ litre^{-1}	BUWAL 1996 (45,4MJ kg^{-1}, Diesel density: 0,845 kg litre^{-1})
Petrol (unleaded)	38.7 MJ litre^{-1}	BUWAL 1996 (45,8MJ kg^{-1}, Petrol density considered as Diesel: 0,845 kg litre^{-1})

The figures for diesel combustion emissions given in BUWAL 250 database correspond to averages calculated for road traffic under standard conditions, and some comments need to be done here because they have also been used for tractor emissions in field operations. According to Hansson & Mattsson (1999) emissions from tractors show very large variations between different driving operations (due to the different power required from the engine for these operations). They give values for tractor emissions that are down to 50% lower for CO and hydrocarbons than the values calculated for engines in road conditions. Emissions of NO_x and SO_x also tend to be slightly overestimated when using generic databases. In the case of CO_2 emissions, there seems to be no big error when using road traffic data for tractor's emissions. Nonetheless, the figures suggested by Hansson & Mattsson (1999) could not be used in the apple LCA because they are derived for a powerful tractor (70kW) performing operations in an arable crop (ploughing, harrowing…), which require much more power than usual orchard operations. According to Weidema & Mortensen (1995), though, NMVOC, NO_x and SO_x emissions are slightly higher in tractors than in road traffic. In the case of CO emissions, Weidema & Mortensen (1995) conclude the same as Hansson &

Mattsson (1999). Anyway, the uncertainty underlying tractor emissions should be taken into account when the results are interpreted. For CO and hydrocarbon emissions (NMVOC, benzene…) a ±25% error factor is considered, while this error factor is ±10% for NO_x and SO_x.

The same considerations can probably be done for petrol emissions arising from hydra-ladder use, as standard emissions for road traffic have been used (BUWAL 1996). No specific data are available for this type of fuel and machinery, and therefore the standard emission values have been used as well.

Transportation

Transportation of inputs to the place of consumption (the orchard) needs to be included in order to be able to detect its relevancy in the LCA results. For the sake of simplicity, transportation modes were simplified to the three types appearing in Table III-31, where the energy consumption for each type of transportation is shown.

Table III-31: Energy consumption for the transportation modes considered in the study.

Transportation type	*Considerations*	*Data source*	*Energy consumption*
Train	Diesel locomotives (20%) & Electric train (80%)	BUWAL 1996	(0.042 kWh electricity UCPTE[a] + 149.8 kJ Diesel) · tkm^{-1}
Truck	Large truck 40 ton, Average load 50%	BUWAL 1996	1.17 MJ diesel · tkm^{-1}
Ship	Sea Ship, Average load 60%	BUWAL 1996	93.1 kJ fuel-oil · tkm^{-1}

[a]: European electricity mix.

The distances considered for the different inputs are shown in Table III-32. The estimation procedure suggested by Hermansen (1998) was followed in order to get the transportation distances. This procedure can be summarised as follows:

- Transportation by train: bee line + 35%
- Transportation by truck: bee line + 70%
- Transportation by ship: bee line + 20%

Table III-32: Places of origin and transportation distances considered for the inputs to the apple orchard.

Product	Country of origin	Distance transported by (km)		
		Truck	Rail	Ship
Herbicides				
Amitrole 400	Australia	40	0	1700
Roundup G2	Australia	40	0	1700
Fungicides				
Kocide DF (40% Copper hydroxide, Granule)	Germany	200	1500	25200
Dodine 400 (40% Dodine, Liquid)	Germany	200	1500	25200
Stroby WG (50% Kresoxim methyl, Granule)	Germany	200	1500	25200
Polyram DF (70% Metiram, Granule)	Germany	200	1500	25200
Systhane 40W (40% Myclobutanil, Powder)	Italy	400	0	23000
Kumulus (80% Sulphur, Powder)	Australia	40	0	1700
Mizar Granuflo (76% Ziram, Granule)	Germany	200	1500	25200
Bayleton 5DF (5% Triadimefon, Granule)	Germany	200	1500	25200
Chorus (50% Cyprodinil, Granule)	Australia	40	0	1700
Delan WG (70% Dithianon, Granule)	Australia	40	0	1700
Nimrod 25WP (25% Bupirimate,)	Germany	200	1500	25200
Lime Sulphur	New Zealand	20	0	1100
Copper oxychloride	Germany	200	1500	25200
Pallitop	Germany	200	1500	25200
Captan 80WP (80% Captan, Powder)	Germany	200	1500	25200
Manzate 200 (75% Mancozeb, Granule)	Germany	200	1500	25200
Nustar 20DF (20% Flusilazole, Granule)	Germany	200	1500	25200
Score 10WG (10% Difenoconazole, Granule)	Germany	200	1500	25200
Insecticides				
Gusathion M-35 (35% Azinphosmethyl, Powder)	New Zealand	20	0	1100
Applaud 25W (25% Buprofezin, Powder)	Australia	40	0	1700
Match (5% Lufenuron, Liquid)	Australia	40	0	1700
DC Tron (97% Mineral oil, Liquid)	Australia	40	0	1700
Lorsban 50EC (50% Chlorpyrifos, Liquid)	New Zealand	20	0	1100
Mimic 70W (70% Tebufenozide, Powder)	Australia	40	0	1700
Pheromone ties Isomate C Plus	Japan	40	0	5500
Dipel (*Bacillus thuringiensis kurstaki*)	Japan	40	0	5500
Madex (*Cydia pomonella* Granulosis virus)	Japan	40	0	5500
Basudin (50% Diazinon, Powder)	New Zealand	20	0	1100
Alsystin (25% Triflumuron, Powder)	Australia	40	0	1700
Fruit Thinning Agents				
Fruitfed ANA 10% (10% Naphtylacetic acid, Liquid)	New Zealand	20	0	1100
Sevin WP (80% Carbaryl, Powder)	New Zealand	20	0	1100
Calcium products				
Calcium chloride (36% Ca as $CaCl_2$)	China	40	0	3500
Fertilisers				
Calcium Ammonium Nitrate, CAN	Germany	200	1500	25200
Urea, Compost, Meat & Bone meal	New Zealand	20	0	1100
Solubor/Bortrac (15% B + 6.5% N, liquid)	China	40	0	3500
Manganese Sulphate (100% MnSO4, crystaline)	China	40	0	3500
Calcium Nitrate (100% CaNO3, crystaline)	Germany	200	1500	25200
Magnesium Super 80 (45% Mg, liquid)	Germany	200	1500	25200

III.3. LCIA: Main Results of the New Zealand Apple LCA

The results of the life cycle inventory (LCI, section III.2) are long lists of substances entering and leaving the system under analysis and related to some of the operations being performed in this system. The overall objective of the LCIA, as explained in Chapter II (see section II.1.2.), is to render these lists into meaningful figures that enable the interpretation of the results in the light of the goals of the study. This section presents the main results of the characterisation step of the LCIA, and provides the basis for the discussion of the questions set up by the goals of the study.

III.3.1. Special considerations in toxicity categories

New characterisation factors have been derived for the pesticides used in the study, following the EDIP methodology. The procedure followed to calculate these characterisation factors is explained in Hauschild & Wenzel (1998), and therefore only the calculated values are given in Table III-33.

Table III-33: New toxicity characterisation factors for the agro-chemicals used in the apple LCA.

	Human Toxicity				***Ecological Toxicity***		
Emissions to:	*Air*	*Water*	*Groundwater*	*Soil*	*Water*	*Water*	*Soil*
active ingredient	EF (hta) m^3 air · kg^{-1}	EF (htw) m^3 water · kg^{-1}	EF (htg) m^3 water · kg^{-1}	EF (hts) m^3 soil · kg^{-1}	EF (etwc) m^3 water · kg^{-1}	EF (etwa) m^3 water · kg^{-1}	EF (etsc) m^3 soil · kg^{-1}
Insecticides							
Azinphos methyl	4.46E+8	5.28E+7	4.46E+8	2.21E+6	4.23E+5	2.03E+7	2.22E+4
Buprofezin	2.86E+8	7.40E+8	2.86E+7	4.15E+5	2.36E+3	7.14E+1	1.11E+3
Chlorpyrifos	2.86E+7	1.86E+8	2.86E+6	7.36E+4	1.23E+6	3.33E+4	6.20E+3
Diazinon	1.43E+8	3.70E+7	1.43E+7	4.51E+5	2.56E+3	1.11E+5	8.01E+1
Lufenuron	1.43E+9	2.45E+10	1.43E+8	9.04E+6	1.42E+2	3.45E+0	1.71E+0
Tebufenozide	1.50E+8	3.47E+8	1.50E+7	2.11E+5	3.25E+3	1.00E+2	2.63E+2
Triflumuron	3.97E+8	4.19E+9	3.97E+7	1.58E+6	3.91E+5	1.00E+4	4.70E+3
Fungicides							
Bupirimate	2.86E+7	1.86E+6	2.86E+6	1.97E+5	2.12E+2	1.25E+1	1.17E+1
Captan	2.86E+6	2.26E+5	2.86E+5	1.77E+4	5.25E+4	2.94E+3	1.24E+4
Cyprodinil	9.52E+7	1.24E+8	9.53E+6	1.34E+5	9.09E+4	3.03E+3	3.06E+3
Difenoconazole	2.86E+7	5.88E+7	2.86E+6	3.93E+4	4.16E+3	1.30E+2	1.03E+2
Dithianon	2.86E+8	2.57E+7	2.86E+7	1.65E+6	1.42E+4	7.69E+2	1.00E+3
Dodine	2.86E+7	4.89E+2	2.86E+6	1.17E+5	1.89E+3	1.89E+2	9.42E+0
Flusilazole	2.86E+8	2.06E+8	2.86E+7	5.02E+5	2.29E+3	8.33E+1	7.56E+1
Kresoxim methyl	9.85E+6	3.21E+6	9.86E+5	2.71E+4	7.23E+2	3.01E+1	8.03E+1
Mancozeb	9.52E+6	2.64E+5	9.53E+5	3.02E+5	2.50E+2	2.50E+1	6.21E+0
Metiram	9.52E+6	2.47E+3	9.53E+5	2.58E+5	9.09E+2	9.09E+1	4.50E-1
Myclobutanil	1.14E+7	1.29E+6	1.14E+6	5.82E+4	6.69E+1	3.45E+0	6.52E+0
Nitrothal isopropil	5.71E+7	8.16E+5	5.72E+6	8.76E+5	1.86E+3	1.79E+2	1.02E+2
Triadimefon	2.86E+7	4.89E+6	2.86E+6	1.15E+5	1.93E+2	9.09E+0	3.08E+1
Ziram	1.43E+7	2.26E+4	1.43E+6	5.12E+5	1.72E+1	2.00E+1	2.08E+0
Herbicides							
Amitrole	5.71E+8	1.65E+4	5.72E+7	3.73E+6	1.00E+2	1.00E+1	4.70E+1
Glyphosate	9.52E+5	1.24E-2	9.53E+4	9.61E+0	1.16E+1	1.16E+0	2.80E-1
Fruit Thinning Agents							
Carbaryl	2.86E+7	1.44E+5	2.86E+6	7.28E+5	4.54E+2	7.69E+1	7.53E+1
NAA	2.86E+7	1.48E+6	2.86E+6	2.22E+5	5.71E+0	3.60E-1	1.34E+0

NOTE: EF: Effect Factor (hta = human toxicity through air; htw = human toxicity through water; htg = human toxicity through groundwater; hts = human toxicity through soil; etwc = ecological toxicity through water, chronic effects; etwa = ecological toxicity through water, acute effects; etsc = ecological toxicity through soil, chronic effects).

Some pesticides have not been included in Table III-33 because they have very low toxicity values. Most of them are naturally occurring substances (or biological agents): sulphur compounds (sulphur and calcium polysulphides), *Bacillus thuringiensis*, *Cydia pomonella* granulosis virus, and sex-attractant pheromones. Also mineral oils have been excluded from the analysis, as no toxicological problems have been reported to humans and ecosystems in usual practice (Tomlin 1995). In the case of copper substances, copper is the active ingredient that causes toxicity, and its characterisation factors can be found in Hauschild & Wenzel (1998, see Table 7.1 for human toxicity characterisation factors and Table 6.1 for ecotoxicity).

III.3.2. Environmental impacts of apple production in New Zealand

From the LCI, kg of inputs and outputs entering and leaving the system are obtained for a year of production in one hectare of apple orchard. Therefore, they must be corrected using the factors for the functional unit (one tonne of export and local apples) shown in Table III-13. For visual purposes, these factors are illustrated in Figure III-8. The units are ha·year·ton^{-1} of export and local apples, and thus correspond to an indicator of the land competition aspect discussed in the description of LCIA methods (section III.1.2).

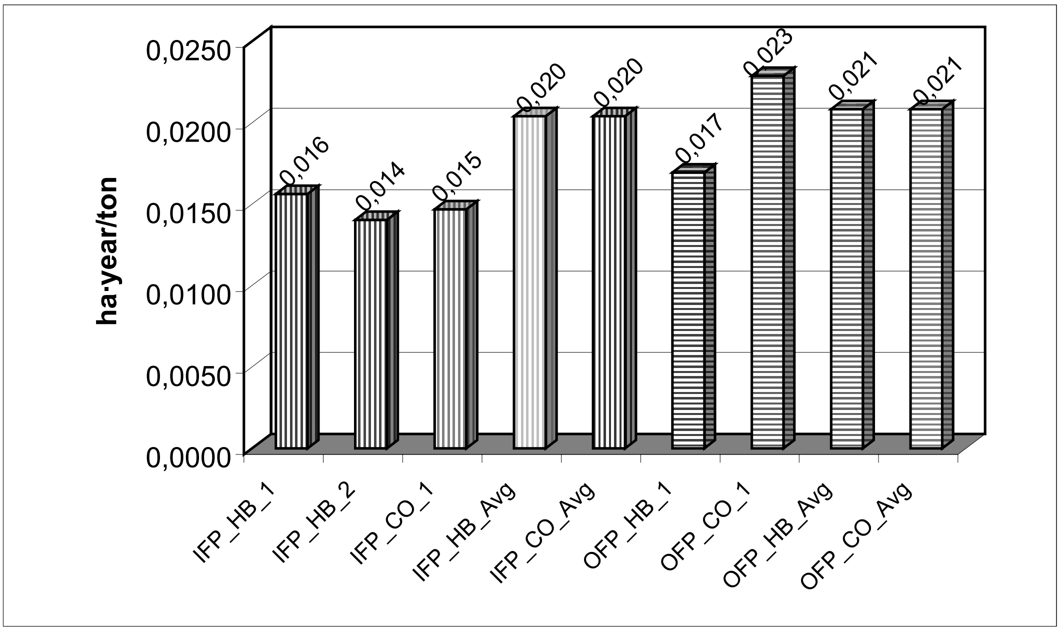


Figure III-8: Land competition indicator for the different systems in the study.

It must be noted that IFP systems (vertical pattern in Figure III-8) have in general lower values for land competition than OFP ones, i.e.: they produce more apples in less surface. This is not a general rule, though, and Heather Gregory (OFP_HB_1) has a similar value for land competition than IFP orchards. Actually, the reference IFP land competition value is in the range of OFP sites. This implies that all of the IFP orchards participating in the study had higher yields than the reference.

The land competition factor has an obvious effect on the LCA results, as systems with lower productivity and pack-out will be charged more for their impacts.

The causes and sources of the environmental impacts of apple production are deeply explored in the following sections, where the relative contributions of different field operations and different inputs to each impact category are analysed. In common LCA practice, the relative contribution of each life cycle stage to the overall impacts would be given at this point. In the present study, most impacts are caused during the "production" stage, in the field, and in order to gain more information from the LCIA graphs, the contributions of different environmental aspects have been grouped into "Field operations" and "Items". The aspects considered in each of these groupings are shown in Table III-34.

Table III-34: Environmental aspects considered in the "Field operations" and "Items" groupings considered in the life cycle impact analysis.

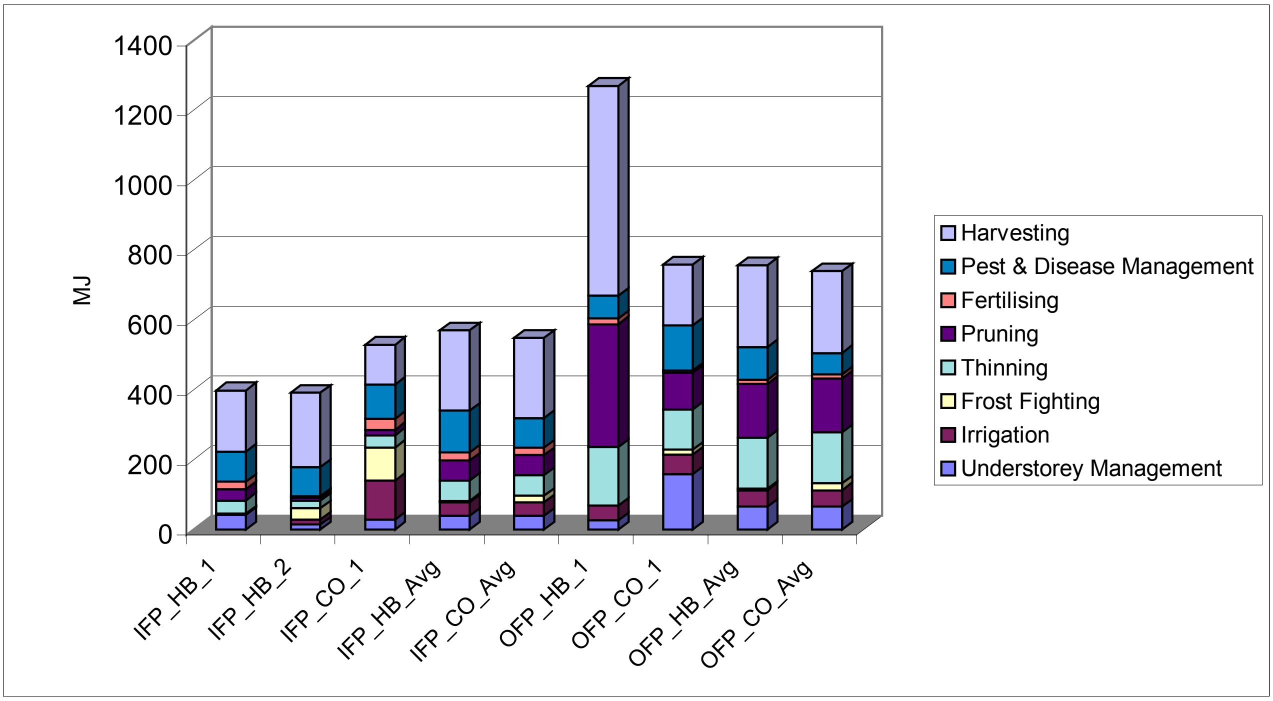
Field operation	***Aspects included***
Understorey Management	▪ Herbicide production and transportation ▪ Herbicide field emissions ▪ Machinery production and maintenance ▪ Energy production and emissions in field operations
Irrigation	▪ Energy production and emissions in field operations
Frost Fighting	▪ Machinery production and maintenance ▪ Energy production and emissions in field operations
Thinning	▪ Plant growth regulators production and transportation ▪ Plant growth regulators field emissions ▪ Machinery production and maintenance ▪ Energy production and emissions in field operations
Pruning	▪ Machinery production and maintenance ▪ Energy production and emissions in field operations
Fertilising	▪ Fertiliser production and transportation ▪ Fertiliser field emissions ▪ Machinery production and maintenance ▪ Energy production and emissions in field operations
Pest & Disease Management	▪ Insecticides, fungicides and calcium products production and transportation ▪ Insecticides and fungicides field emissions ▪ Machinery production and maintenance ▪ Energy production and emissions in field operations
Harvesting	▪ Machinery production and maintenance ▪ Energy production and emissions in field operations

Item	***Aspects included***
Herbicides	▪ Herbicide production and transportation ▪ Herbicide field emissions
Pesticides	▪ Insecticides, fungicides, plant growth regulators and calcium products production and transportation ▪ Insecticides, fungicides and plant growth regulators field emissions
Fertilisers	▪ Fertiliser production and transportation ▪ Fertiliser field emissions
Machinery	▪ Machinery production and maintenance
Energy	▪ Energy production and emissions in field operations

The rationale for the "field operations" groupings is that the production stage of the life cycle has been the main consideration of this study (cradle-to-gate), and these groupings characterise the major detail in this stage. Furthermore, when grouped by "items" this helps in determining the relative importance of aspects from the agricultural LCA that have been the matter of discussion in the literature, especially in the case of machinery and the production of agro-chemicals (both pesticides, herbicides and fertilisers).

Energy consumption

a)



b)

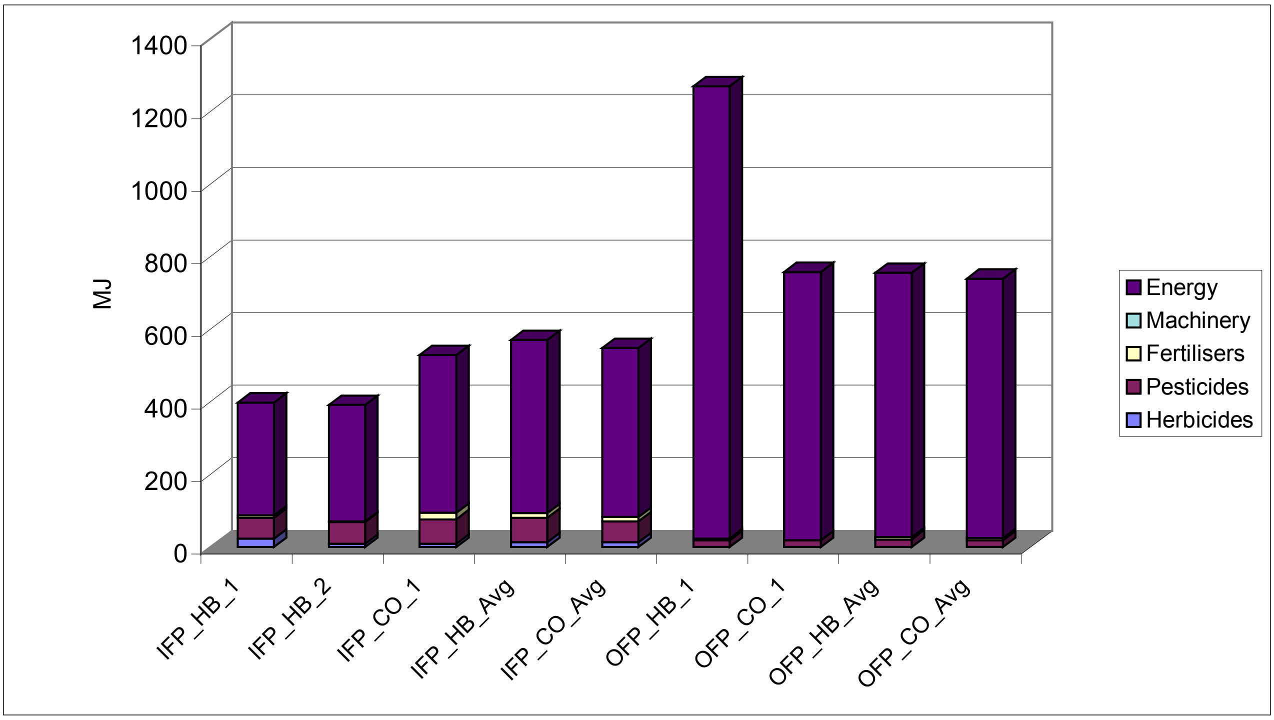


Figure III-9: a) Energy consumption in different field operations. b) Energy consumption by different input items. Results refer to 1 ton of apples of export or local quality.

Firstly, Figure III-10 shows the systems consuming more energy, and the sources of energy consumption. As it will be seen in the following paragraphs, energy consumption determines the system's contributions to impact categories, and that is why this is explained first. What first comes into sight from the figure is that organic systems always have higher energy consumption than IFP systems. This could already be anticipated from Table III-13, which shows the higher values for fuel and electricity consumption from field operations in OFP than in IFP.

Figure III-9 a) gives an interesting picture of the most energy-consuming field operations in apple production, both in IFP and OFP. It is noticeable how the share of energy consumption for pruning and thinning is relatively higher in organic systems, due to the reasons explained in the text in section III.2.1 (see also Table III-7 and Table III-8). It is interesting to note how pruning and thinning particularly have a greater share of the energy consumption in organic systems than in integrated ones, as was explained in section III.2.1.

From Figure III-9 b) it is obvious that direct energy consumption by field operations is the main cause of energy consumption (70-75% in IFP and 83-90% in OFP), while only machinery and pesticide production (the latter only in IFP systems) have a further relevant contribution to energy consumption. Consequently, the profile of the contributions by the different sites to the impacts mainly caused by direct energy consumption (see Figure III-16 for eco-toxicity through soil and Figure III-17 for photochemical oxidants formation) follow exactly the same pattern as energy consumption.

Of all the producers participating in the study, Ms. Heather Gregory (OFP_HB_1) is the one with the highest energy consumption, due to the extraordinary use of hydra-ladders for pruning, thinning, and harvesting. The energy consumption for understorey management in Mr. Dan Harlan's farm (OFP_CO_1) is also noticeable, and can be explained by the intensive mowing of the orchard; also the fact that the engine of the tractor is of a higher cc rating than usual partly explains this higher contribution.

The contribution of pesticides production to energy consumption is noteworthy, particularly in integrated systems, where it represents from 11% to 18%. Also energy consumption related to machinery production is relevant, and contributes 7% to 15% to total consumption.

Global Warming

Figure III-10 b) shows that the highest contributions to global warming come from energy related emissions (chiefly CO_2). Therefore, those sites consuming more energy (in general: OFP orchards, but particularly OFP_HB_1, Heather Gregory's orchard, see Table III-13 in page 66and Figure III-9) have higher contributions to this impact. The intensive use of machinery (particularly hydra-ladders), in OFP systems is the main reason for this higher energy consumption. Nevertheless, a highly relevant contribution from fertilisers is also observed in Figure III-10 b) for IFP sites, coming from the N_2O emissions generated by mineral fertilisers. The bigger proportion of urea consumption in reference IFP sites renders their nitrous oxide emissions higher than other IFP producers (N_2O emissions per kg N in fertiliser are higher in urea than CAN, see Table III-15 in page 75). CH_4 emissions, on the other hand, only cause 2-3.5% of global warming in most systems. It is interesting to note how the use of different inputs may have such an influence on the results, due to their different emission factors.

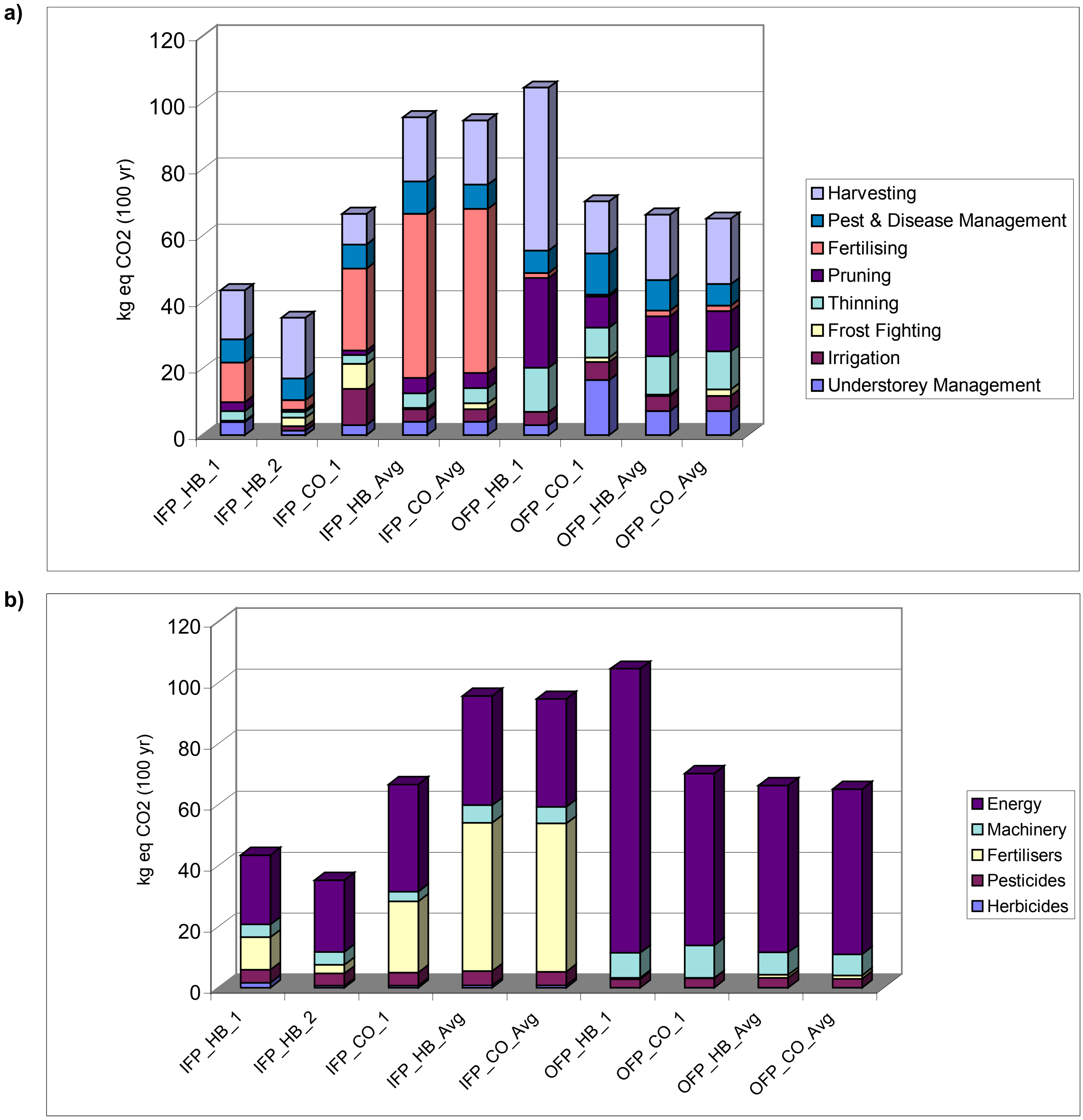


Figure III-10: a) Contribution to Global Warming by different field operations. b) Contribution to Global Warming by different input items. Results refer to 1 ton of apples of export or local quality.

Also CO_2 emissions caused by machinery production and maintenance are relevant, with contributions of ca. 8-15% in OFP systems. The contribution from machinery production is higher in OFP because machinery use is more intensive. Besides, mulch-mowers and mowers are intensively used in organic systems; the inefficiency in the use of such machines (their useful life is short) is one of the main reasons for this high contribution. Mulch-mower production is the cause of between 30% and almost 50% of the machinery production contribution to global warming in OFP orchards. OFP_CO_1 represents the extreme case, because Dan Harland uses the mulch-mower almost 50% more than the other organic systems. The higher rate of Dan Harland's tractor is also an explanation for some of the contribution from machinery production in his orchard to global warming.

CO_2 emissions from pesticide manufacture also cause around 5-11% of global warming in IFP.

To summarise, it can be said that there is no clear difference between organic and integrated systems respect the contributions to global warming. In general, contributions in OFP due to E consumption (and to a lesser extent machinery production) are higher, but these are easily overcome by fertiliser-related emissions (chiefly N_2O) depending on the type of fertiliser used in IFP.

Human Toxicity through Air

This impact category is dominated by energy-related emissions (see Figure III-11 b), in next page). In OFP, more than 90% of the impact is caused by direct energy consumption, while IFP systems also have a relevant contribution from pesticide emissions to air. Again, OFP_HB_1's huge fuel consumption is the reason why this system shows the highest contribution to the impact category. The other OFP systems have a contribution to human toxicity through air that is in the range of IFP systems (with lower contributions from IFP_HB_1 and IFP_CO_1).

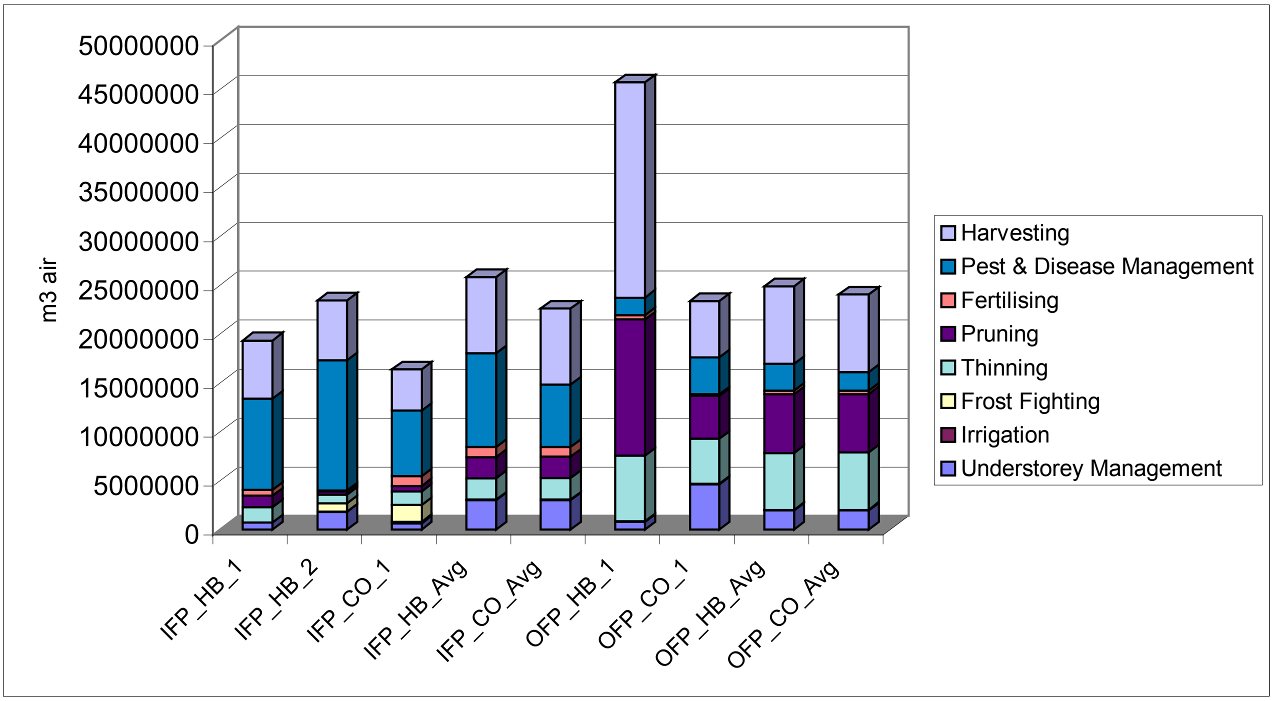
Benzene emissions are the main cause of impact related to energy, with a contribution of almost 80% to the total impact in OFP systems. As these emissions come from tractor and hydra-ladder use, they should be regarded with suspicion because of the reasons discussed in section III.2.8. It must be noted that benzene emissions are 40% higher for petrol than for diesel (2.84 mg benzene MJ^{-1} for diesel and 3.93 mg benzene MJ^{-1} for petrol) according to the database used (BUWAL 1996).

Lead emissions to air are also relevant for human air toxicity. These are also energy-related emissions, and come not only from direct energy consumption, but also from pesticide, machinery, and fertilisers production.

In IFP, pesticide emissions to air play a relevant role as well. These are more important in IFP_HB_2 due to emissions of Diazinon (20% of impact) and Azinphos-methyl (12%). Air emissions of Amitrole also have a significant contribution in IFP_HB_2, IFP_HB_Avg and IFP_CO_Avg, where this herbicide is used. These agro-chemicals are mainly emitted to air through volatilisation once they reach soil or plant's surface.

Again, it can be stated as a conclusion for impacts on human toxicity coming from air that there are no clear differences between organic and integrated systems. The different contributions from each system come from particular producer's practices, rather than generic characteristics of such systems. As in the case of global warming, the contributions in organic systems due to energy consumption are higher, but pesticide emissions counteract IFP's lower energy use. Particular producer's practices that determine this impact category are the efficiency in machinery use and the election of agro-chemicals. Indeed, Heather Gregory's intensive hydra-ladder use is the main reason for her huge contribution to human toxicity. In IFP, the use of amitrole, diazinon and azinphos-methyl causes higher contributions in the systems where they are used.

a)



b)

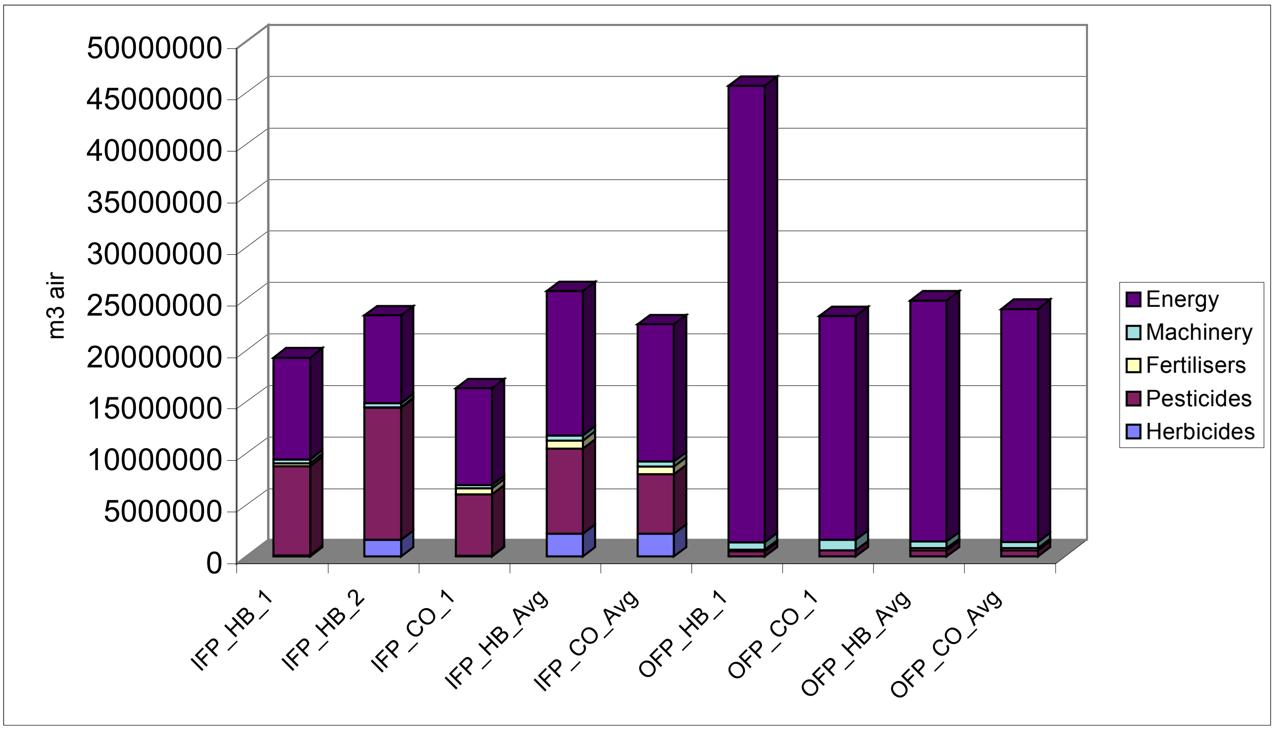


Figure III-11: a) Contribution to Human Toxicity Air by different field operations. b) Contribution to Human Toxicity Air by different input items. Results refer to 1 ton of apples of export or local quality.

Human Toxicity through Water

As opposite to Human Toxicity through air emissions, the water component of Human Toxicity is clearly dominated by agro-chemicals emissions to groundwater and surface water, and thus only IFP systems have a relevant contribution to this impact in Figure III-12.

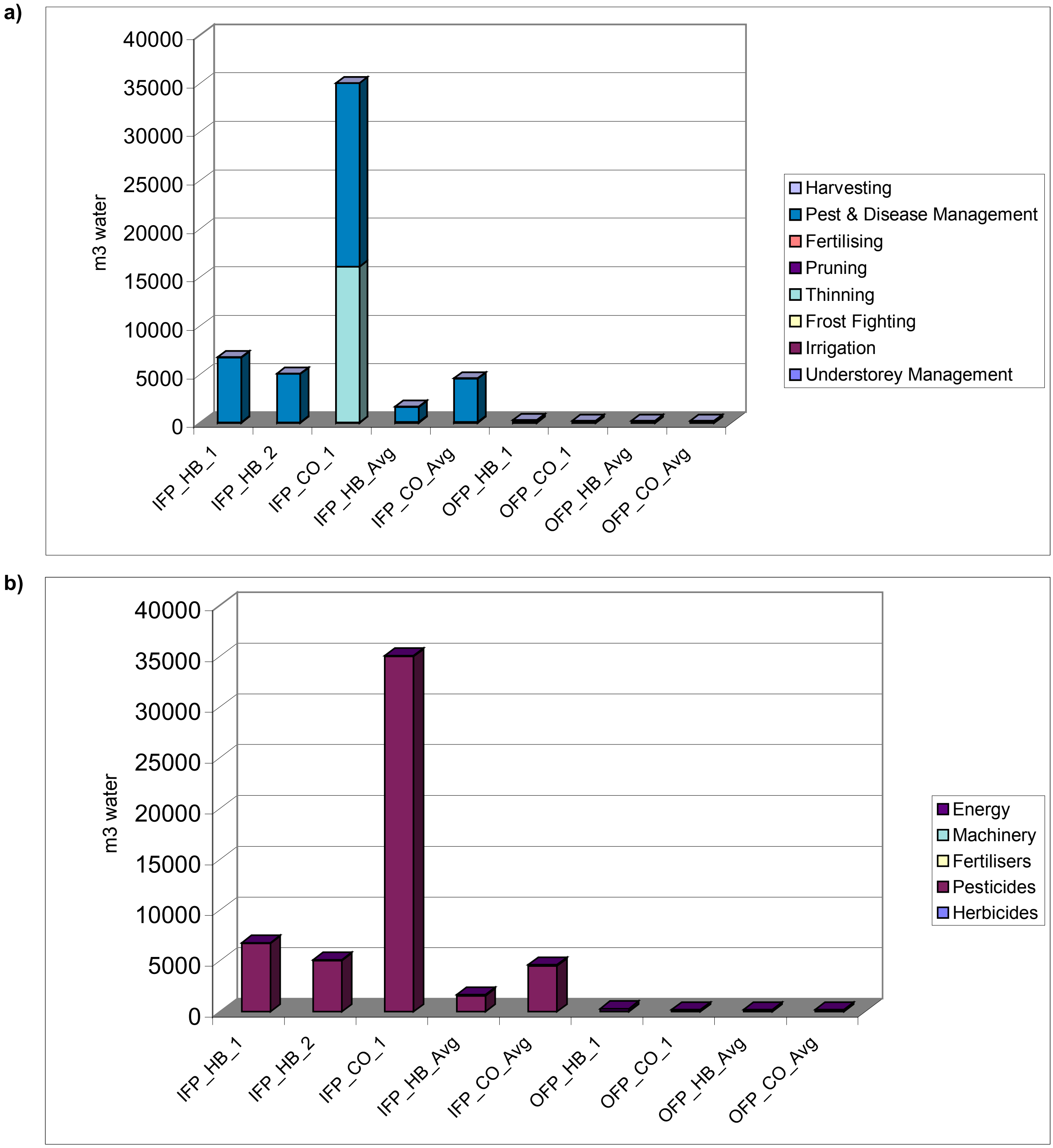


Figure III-12: a) Contribution to Human Toxicity Water by different field operations. b) Contribution to Human Toxicity Water by different input items. Results refer to 1 ton of apples of export or local quality.

The model applied to calculate pesticide fractions heavily influences the results, and particularly the soil type considered in IFP_CO_1 is crucial in determining pesticide fraction to groundwater. As it can be easily seen in Figure III-12, the Bennies' orchard has an impact around 5 to 20 times bigger than the rest of IFP systems, and the soil type considered in PESTRISK model to determine the fraction of pesticide that leaches to groundwater mainly causes this. This result should be looked at with suspicion, because of the uncertainty in the election of the soil type for PESTRISK (only a general reference to the soil being “a gravel” was available, and no specific values of texture could be used to better estimate the soil type to be used in PESTRISK). The most relevant emissions from the Bennies’ orchard are carbaryl (used for thinning, and causing above 50% of the impact) and cyprodinil.

The differences in other IFP systems come from different pesticide use. In IFP_HB_1, for instance, the higher contribution comes from the use of the insecticide Alsystin (a.i.: Triflumuron), which causes around one fourth of Human Toxicity through water emissions in that system. In IFP_CO_Avg, it is interesting to see that emissions to groundwater are also relevant (Triadimefon, Tebufenozide), possibly due to the soil type again. Indeed, it is noticeable that Triadimefon and Tebufenozide emissions to groundwater present a significant contribution to Human Toxicity through water in IFP_CO_Avg and not in IFP_HB_Avg, even though its use is smaller in Central Otago than in Hawke’s Bay (see Table III-13). Lufenuron and Chlorpyrifos are also very relevant in IFP_HB_1 and IFP_HB_2, while Chlorpyrifos and Tebufenozide are some of the highest contributors in the reference systems.

Contributions in OFP, which are negligible compared to IFP’s, are dominated by energy-related emissions to air (NMVOC, Hg and heavy metals, amongst others). These are mainly due to direct energy consumption, but also related to machinery production.

In summary, the system type determines Human Toxicity through water: integrated systems have always a significantly bigger impact (between 5 and 200 times bigger) than organic systems. Nonetheless, the results present huge variability depending on the site’s conditions, chiefly the soil type, and to a certain extent the active ingredients chosen for pest and disease management.

Human Toxicity through Soil

Again, this impact category is clearly dominated by pesticide emissions in IFP systems, which have contributions up to 2,500 and 5,000 times bigger than organic orchards (when compared to IFP_CO_1) to human toxicity through soil. In this case, mainly the election of active ingredient and timing of application affect the results, because no soil conditions were taken into account in the modelling of the fraction that remains in soil.

As it can be seen in Figure III-13, the highest contributions to human toxicity through soil appear in IFP_CO_1 and IFP_HB_2 (The Bennies and Rue Collin), and come mainly from three substances:

- Ziram, which causes 91.8% of the impact in the Bennies’ orchard and 85.6% in Rue Collin’s; this fungicide is intensively used in these two orchards (compare the dose with those in reference systems in Table III-13; Diana Gillum does not even use this substance). The main reasons for its high contribution to human toxicity through soil are that it is usually applied late (January), and its degradation rate is not very fast (half-life = 30d).
- Azinphos-methyl, which is only used in Rue Collin’s (IFP_HB_2) orchard, increases its contribution to human toxicity through soil in 5.9%. Even though the degradation rate is fast (half-life=10d), this insecticide is applied very late (in March), and so there is not much time left for microbial degradation.

- Metiram, causing 4.7% of the impact in IFP_CO_1 and 3.3% in IFP_HB_2; again, this fungicide is only used in these systems and in IFP_CO_Avg (where a much smaller dose is applied). The main reason of metiram's high contribution is the high dose applied, as it is applied early and its degradation rate is not very slow (half life =20d). On the other hand, its toxicity effect is particularly high (see the characterisation factor in Table III-33, page 98).

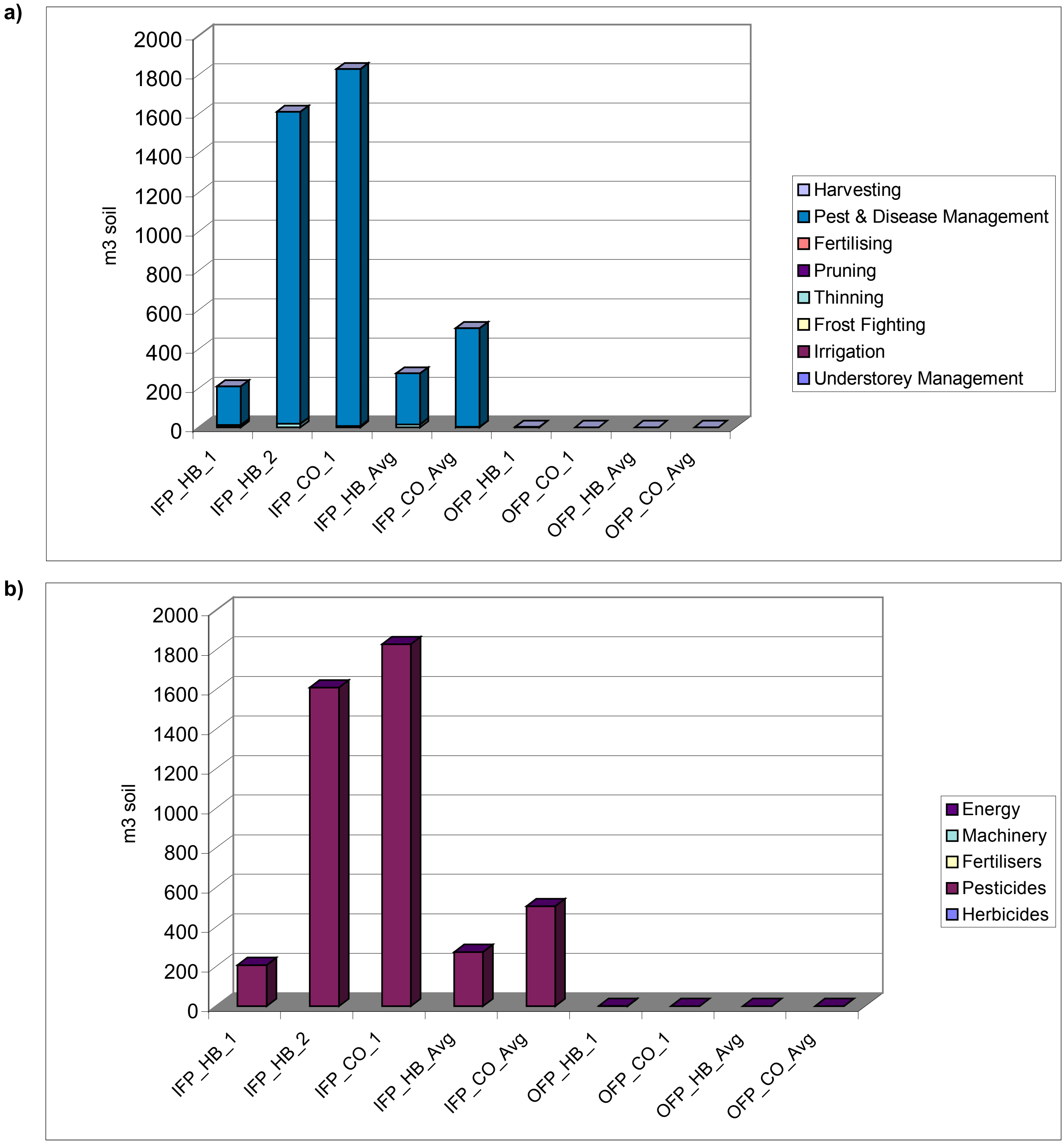
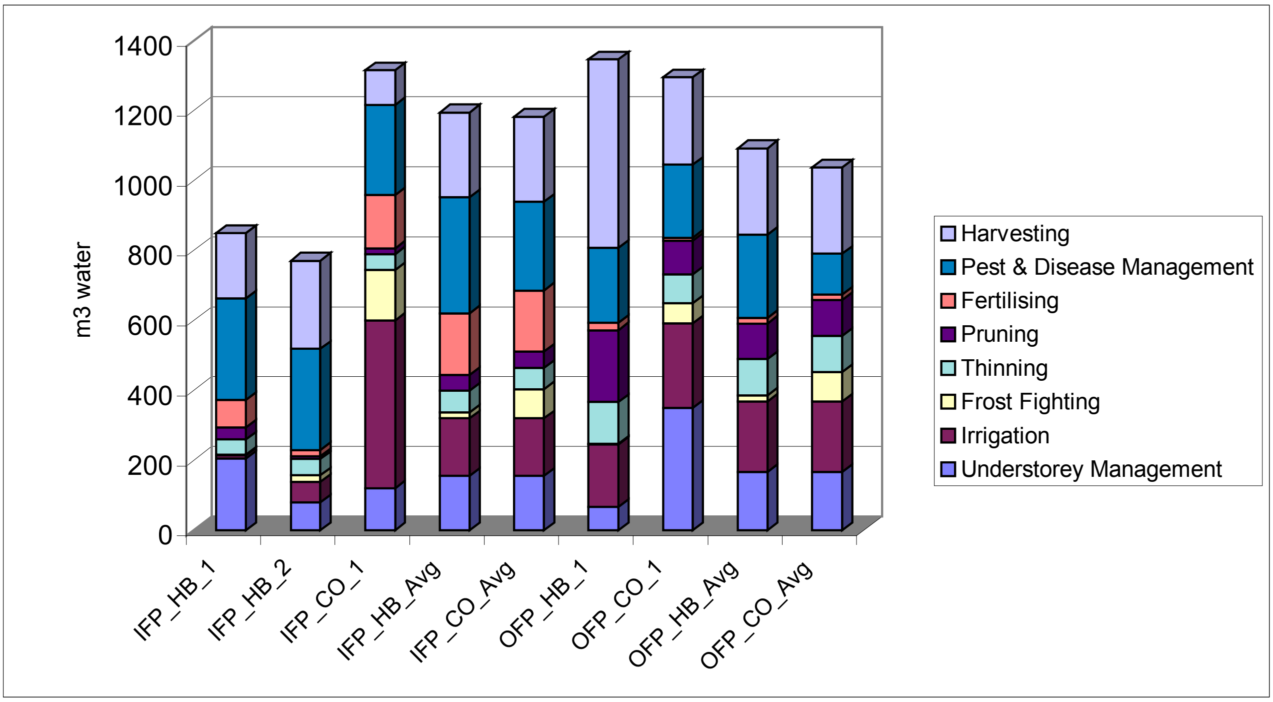


Figure III-13: a) Contribution to Human Toxicity Soil by different field operations. b) Contribution to Human Toxicity Soil by different input items. Results refer to 1 ton of apples of export or local quality.

It must be noted that the pesticide effects in soil's toxicity would not probably be so relevant if the whole orchard life cycle was assessed, because only the pesticide fraction remaining after the orchard's elimination stage would be taken into account.

Ecological Toxicity through Water. Chronic effects

a)



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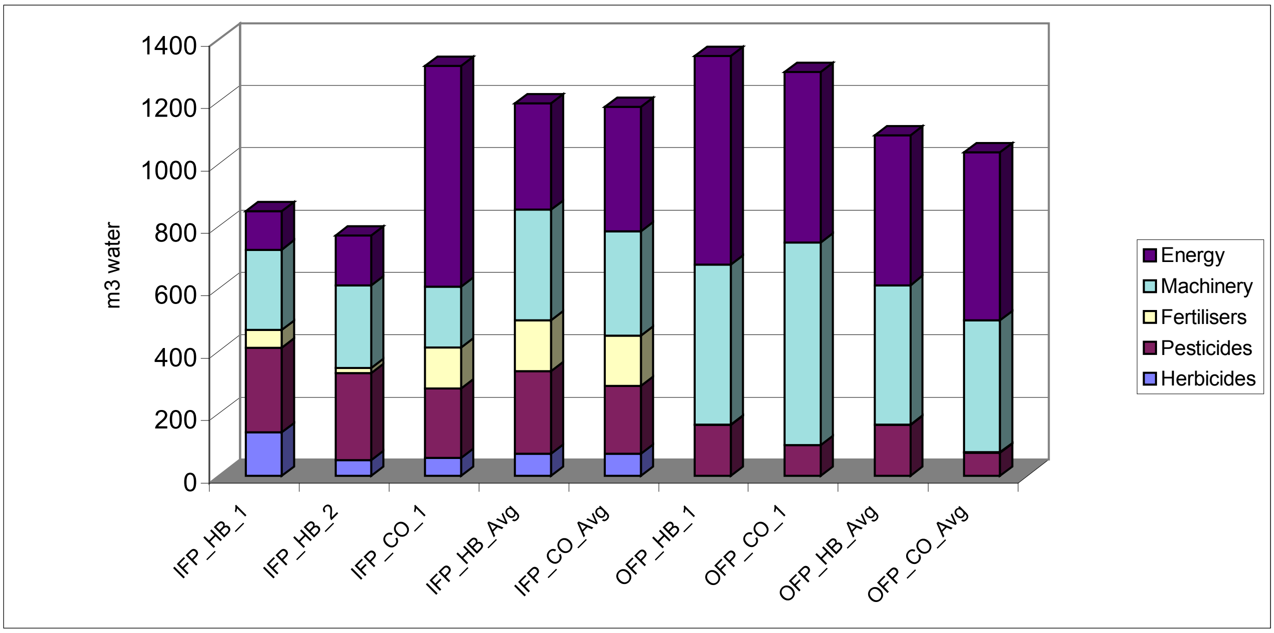


Figure III-14: a) Contribution to Ecological Toxicity Water (Chronic) by different field operations. b) Contribution to Ecological Toxicity Water (Chronic) by different input items. Results refer to 1 ton of apples of export or local quality.

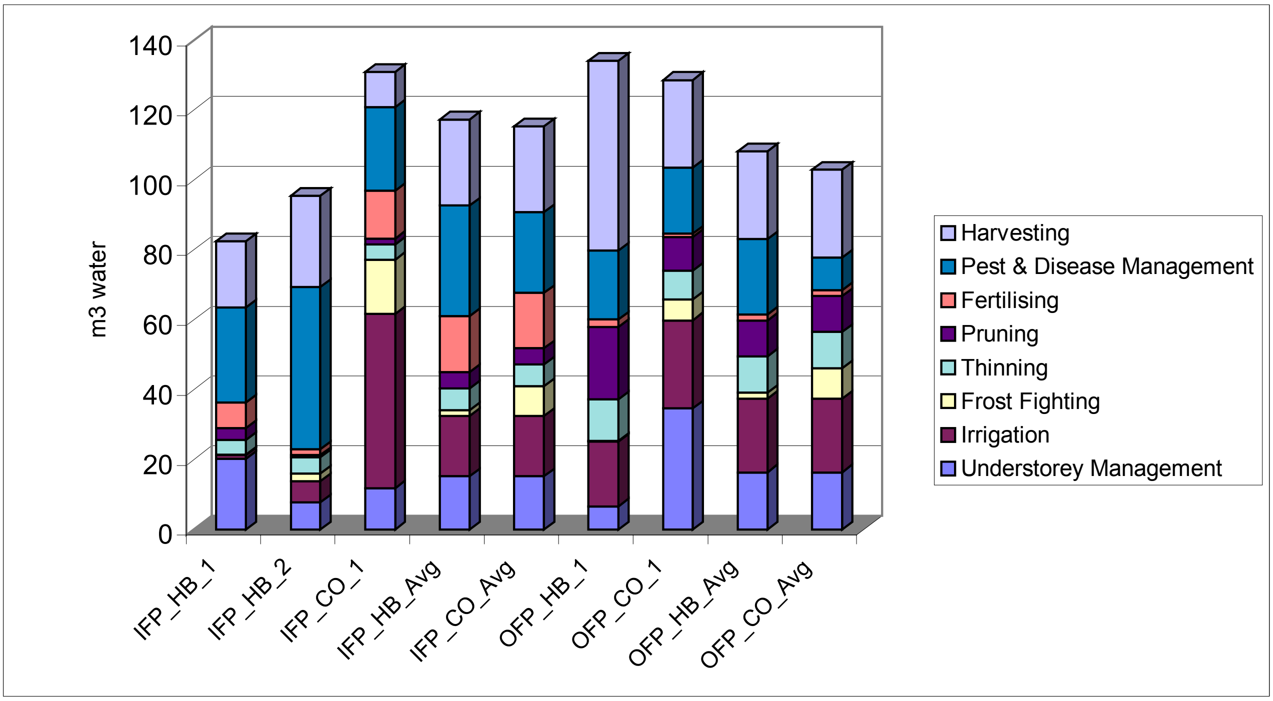
No relevant differences between organic and integrated systems can be observed in Figure III-14. Only the systems IFP_HB_1 and IFP_HB_2 do have a sensitively lower contribution to the chronic effects on ecological toxicity through water. As it can be noted in both Figure III-14 a) and b), a wide variety of sources produce this impact: the reason is that the substances mostly affecting this impact category are heavy metals emitted to water (Fe, Cu, Cd), which are emitted in the production processes of machinery, pesticides, fertilisers and herbicides. Also direct energy consumption and production of fuels is an important source of heavy metals emissions to water. In this sense, the use of electricity for irrigation has a rather strong effect on heavy metals emissions, and this is the cause for the high contribution of the Bennies orchard (IFP_CO_1) to this impact category. Indeed, it can be noted in Table III-13 that their electricity consumption (for irrigation and frost fighting) is around 5 times bigger than any other orchard. Copper emissions to water caused by electricity production in New Zealand are an order of magnitude higher than the emissions from diesel or petrol; in the case of iron, electricity emissions are three times bigger than petrol' and over 5 times bigger than diesel emissions. The use of copper substances as fungicides has a small contribution to the overall impact in the systems where they are used (only 0.01% of the copper reaching soil is considered to run-off to surface water, see section III.2.3).

Consequently, the systems using more machinery (or using it more inefficiently) and consuming more energy have higher contributions to this impact category. As these parameters depend more on particular producers' practices than on agriculture type (organic or integrated), there are no consistent differences between these groups (IFP and OFP).

Ecological Toxicity through Water. Acute effects

The overall distribution of the sources for this impact is similar to the chronic effects on water eco-toxicity described above. In the case of acute effects, the absolute figures are lower (see Figure III-15) because of lower toxicity values in the short term (see Table III-33). Again, many substances affect this type of eco-toxicity: mainly heavy metal emissions to water (Fe, Cu, Cd), coming from machinery, pesticides, fertilisers and herbicides production (plus a small contribution to Cu emissions from copper pesticides' direct field emissions). The main difference with respect chronic eco-toxicity (Figure III-15) is that, as acute effects are included, new (biodegradable) substances appear as relevant contributors: cyanide and some pesticides. It must be noted, though, that they are never predominant in relation to heavy metals; the biggest single contribution comes from azinphos-methyl emissions, which cause 20% of the impact in IFP_HB_2. This further confirms that producer's practices, such as the election of active ingredients, do chiefly determine some environmental impacts of apple production. As in the case of chronic eco-toxicity through water, no clear distinction can be made between organic and integrated orchards.

a)



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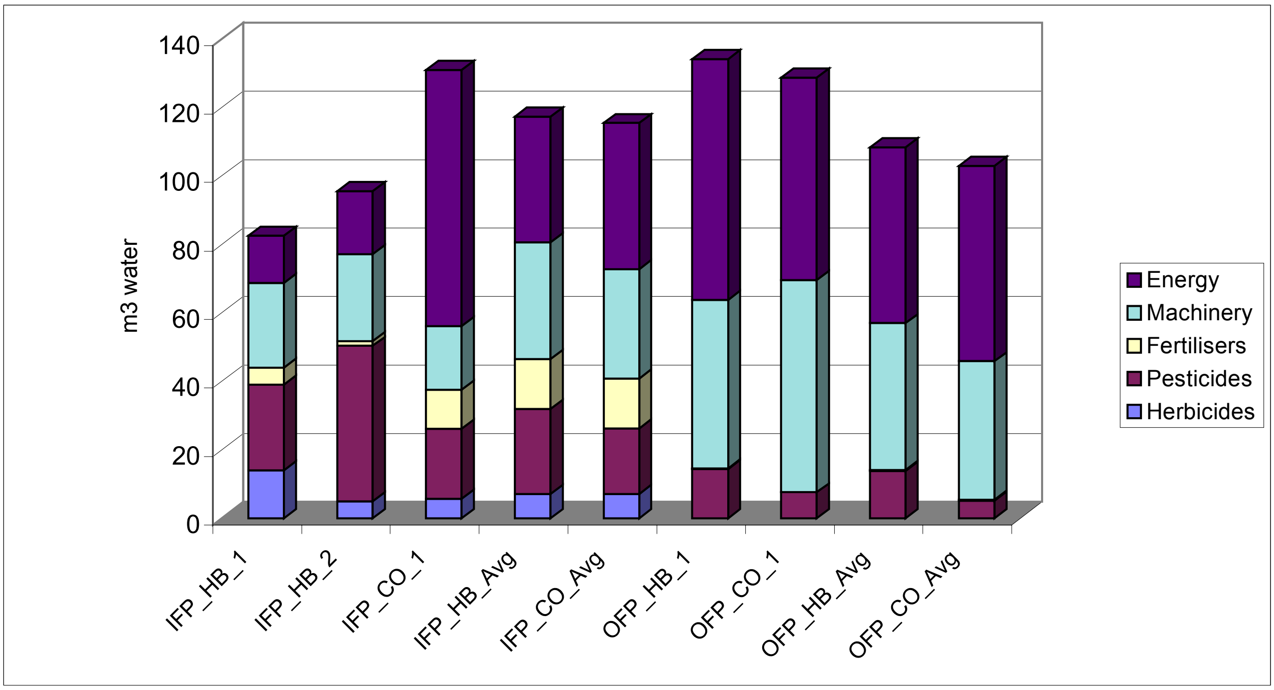
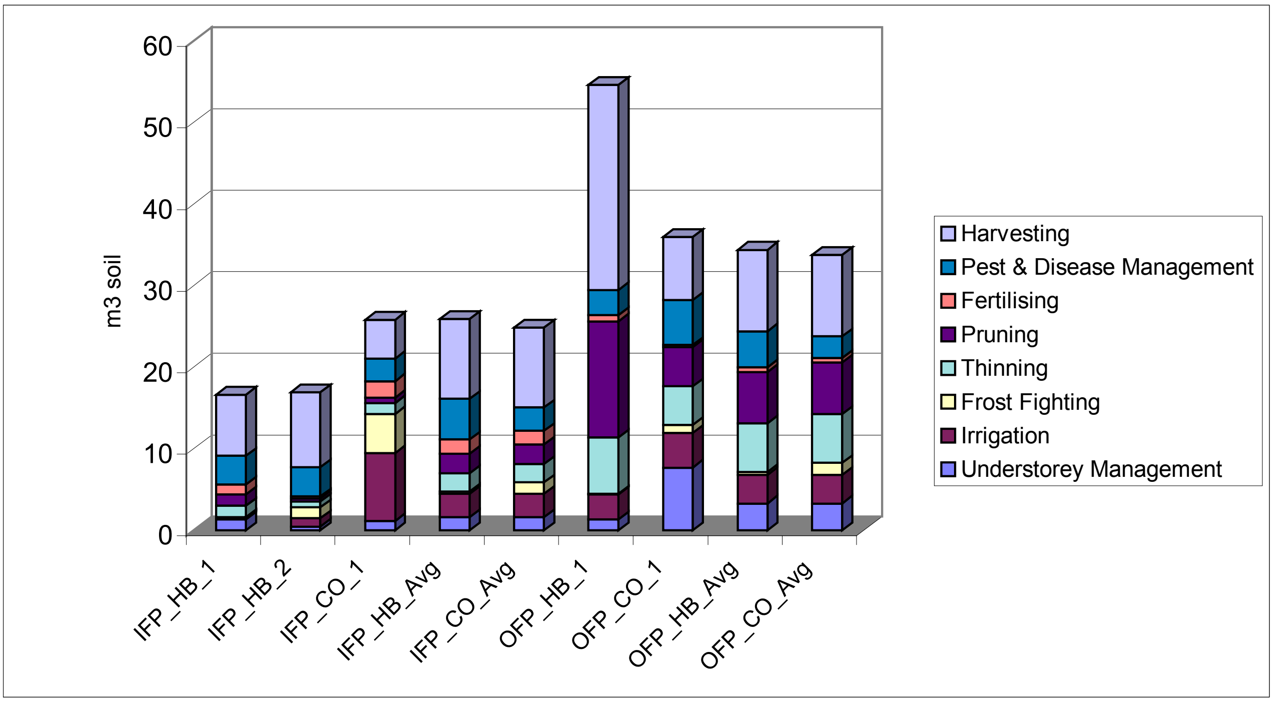


Figure III-15: a) Contribution to Ecological Toxicity Water (Acute) by different field operations. b) Contribution to Ecological Toxicity Water (Acute) by different input items. Results refer to 1 ton of apples of export or local quality.

Ecological Toxicity through Soil. Chronic effects

As in the case of chronic eco-toxicity through water, most eco-toxic chronic effects in soil do not come from agro-chemicals. Mainly energy-related emissions cause the impacts in all systems (see Figure III-16 b): cyanide emissions to water (74-86% of the impact) and benzene emissions to air (11-22%). Cyanide emissions are of the same order of magnitude for all energy vectors, and so the energy-related contributions are a profile of energy consumption in each system (see Figure III-9). The reason for the relatively higher contribution of cyanide emissions to water to eco-toxicity through soil is the effect factor for this substance, which according to the EDIP manual (Hauschild & Wenzel 1998) is $7.6 \cdot 10^{6}$ m^{3} soil · kg^{-1} (in front of orders of magnitude from10^{-1} to 10^{4} for pesticides; see Table III-33).

a)



b)

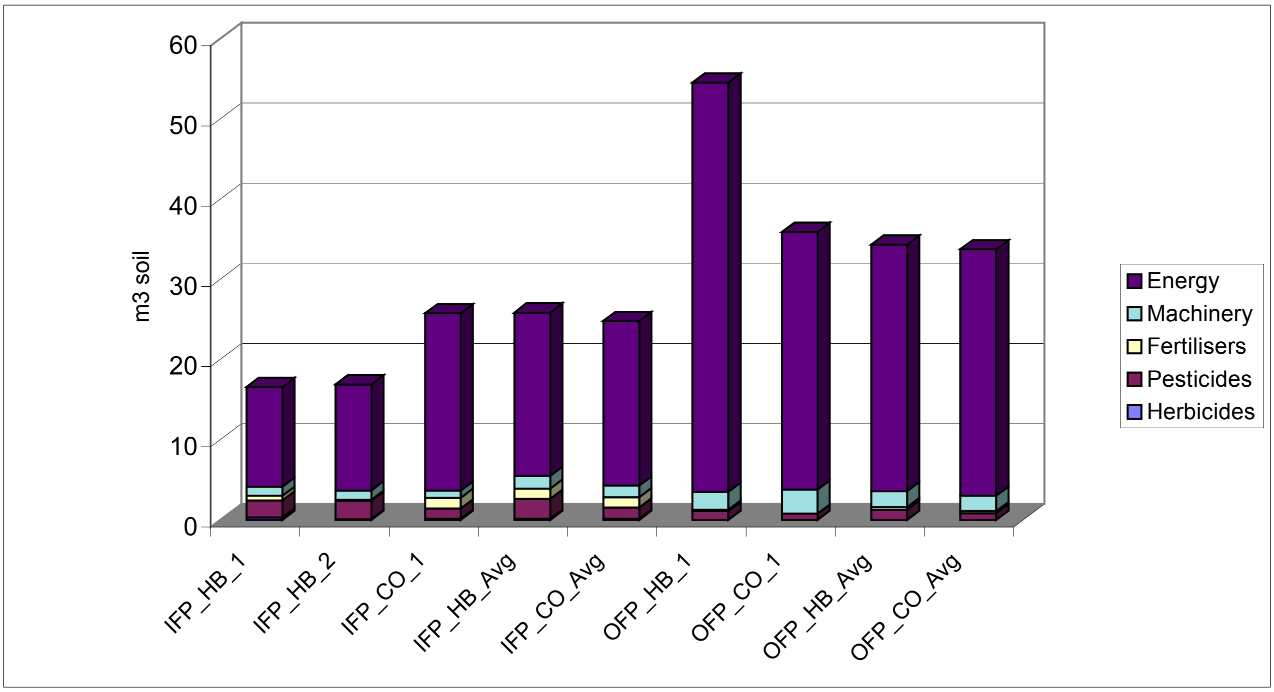


Figure III-16: a) Contribution to Ecological Toxicity Soil (Chronic) by different field operations. b) Contribution to Ecological Toxicity Soil (Chronic) by different input items. Results refer to 1 ton of apples of export or local quality.

In the case of agro-chemicals, their relevance is never high: in IFP_HB_2, 5.6% of the impact on soil eco-toxicity is produced by azinphos-methyl; in IFP_HB_Avg 4% is due to cyprodinil; and in IFP_HB_1 3.1% is due to cyprodinil. Again, pesticide soil emissions would play an even smaller role if the whole orchard life cycle was assessed: only the remaining fraction after 25-30 years would be considered, and this should be compared to the energy emissions from all these years.

Paradoxically, the higher energy consumption in all organic systems renders them more problematic on soil's chronic eco-toxicity effects, and all OFP sites have higher impacts than IFP sites.

Photochemical Oxidant formation

Clearly enough, this impact category is dominated by energy related emissions (see Figure III-17 b). NMVOC[20] cause most of the impact in all systems (65-75%) and CO emissions are relevant as well (17-34%). Figure III-17 a) is thus a picture of the relative energy consumption of each field operation (see Figure III-9) corrected for those types of energy with more NMVOC and CO emissions (see Table III-35). The higher NMVOC and CO emissions for petrol penalise those systems using more petrol than diesel, i.e.: OFP systems (because of the more intensive use of hydra-ladders). This difference has dramatic consequences on Heather Gregory's (OFP_HB_1) contribution to Photochemical Oxidants Formation.

Table III-35: NMVOC and CO emissions for Diesel, Petrol, and Electricity (kg/MJ).

	g/MJ	
	NMVOC	***CO***
Diesel	0.493	0.434
Petrol 97 unleaded	0.633	1.89
Electricity NZ	0.004	0.011
Electricity UCPTE	0.074	0.022

SOURCE: BUWAL (1996).

Due to the extraordinary mechanisation of field operations in OFP (mainly due to hydra-ladder intensive use for thinning and pruning), this impact category shows a consistently higher contribution from organic systems.

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[20] Non Methane Volatile Organic Compounds.

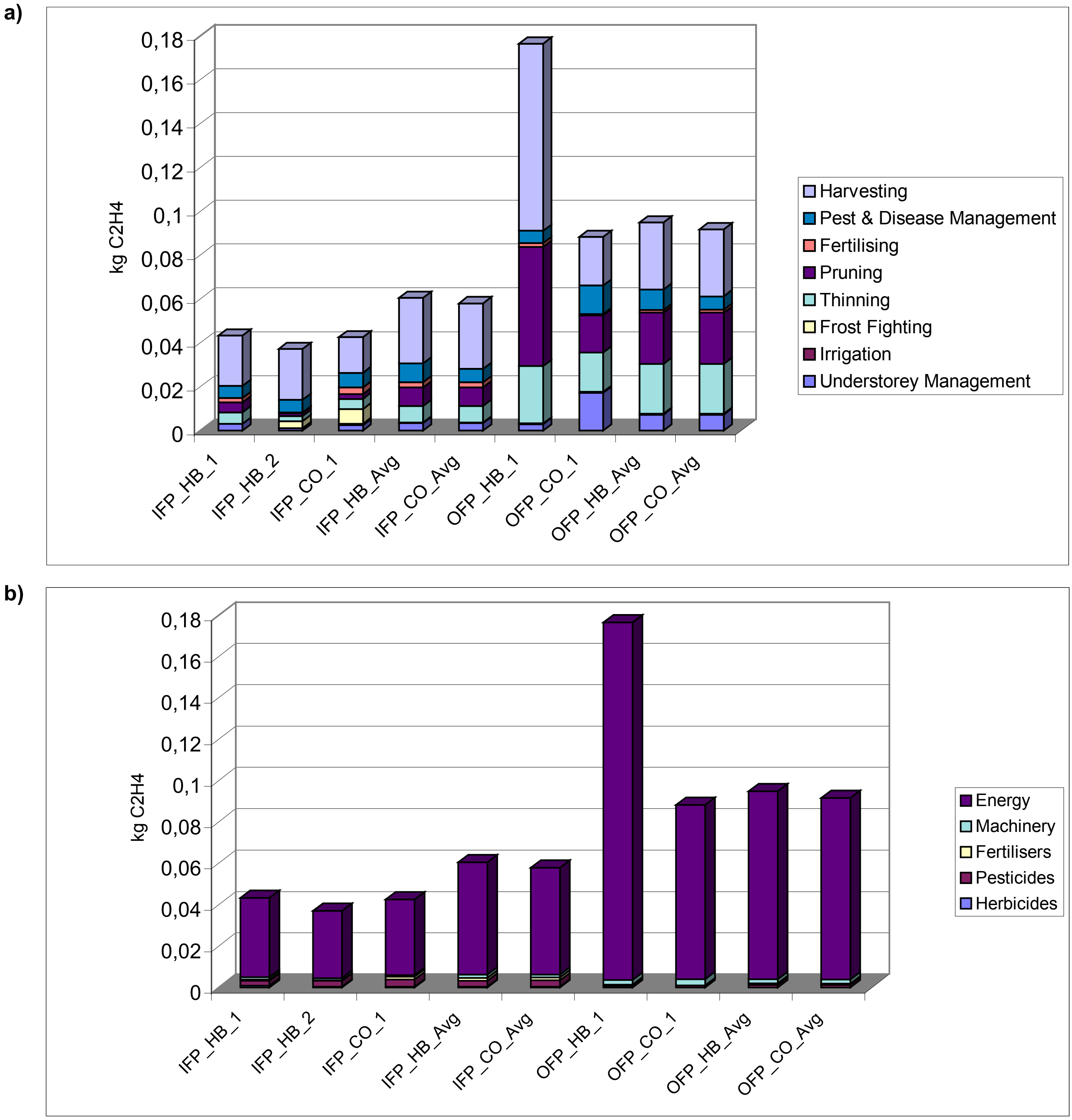

Figure III-17: a) Contribution to Photochemical Oxidant Formation by different field operations. b) Contribution to Photochemical Oxidant Formation by different input items. Results refer to 1 ton of apples of export or local quality.

Acidification

The two reference IFP systems show a clearly higher contribution to acidification than the other systems. 50% of their impact in this category is due to NH_3 emitted in the field from fertiliser use (see Figure III-18 a) and b); the higher use of urea together with the higher ammonia emissions in urea fertilisers (15% of total N, in front of 2% in CAN fertilisers) are the reason for this. Apart from the fertiliser-related ammonia emissions, nitrogen and sulphur oxides are the main cause of acidification in most systems. NO_x are mainly energy-related emissions, while SO_x are due to both direct energy consumption and to machinery and other inputs production (chiefly, machinery and pesticides).

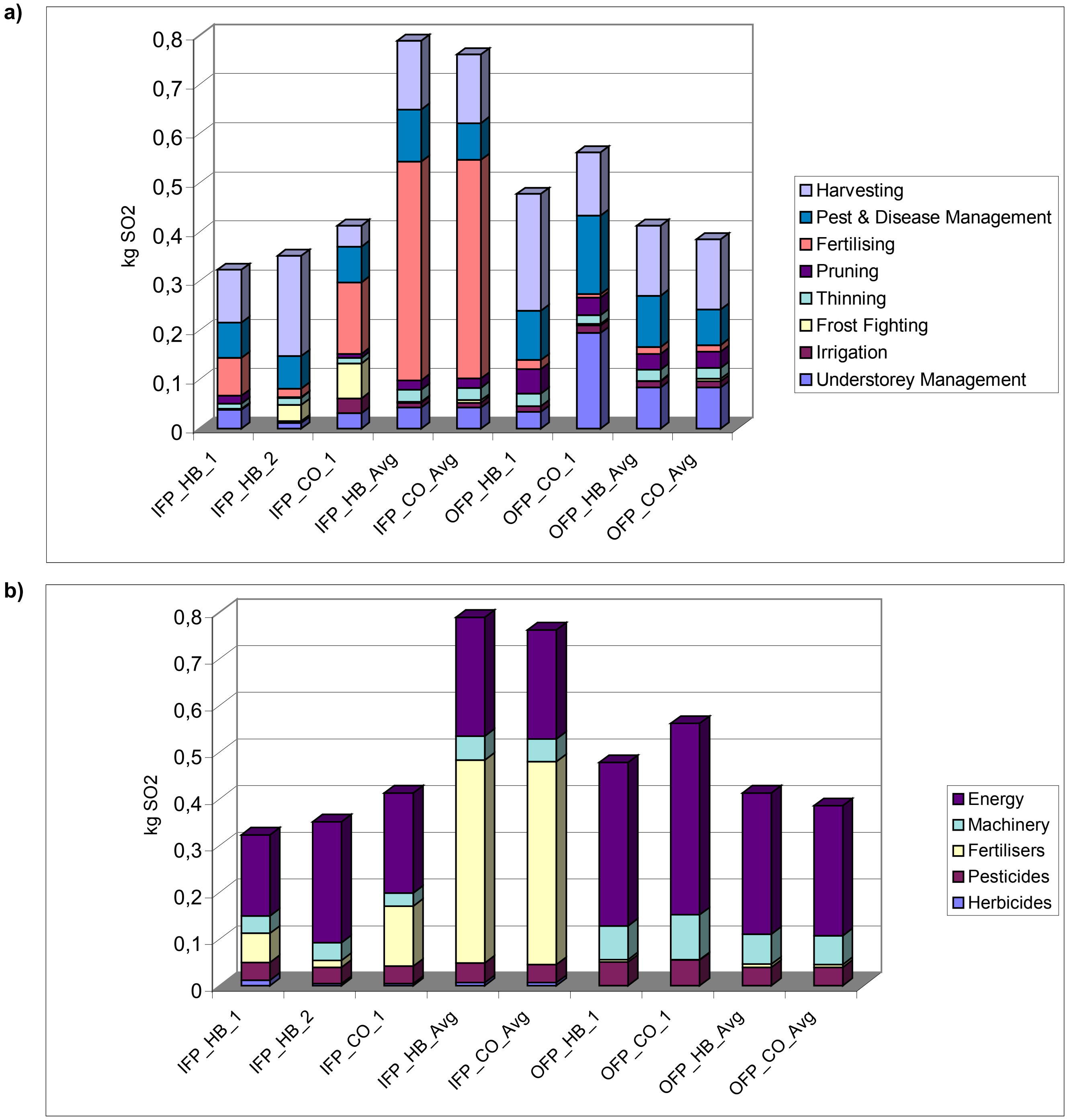

Figure III-18: a) Contribution to Acidification by different field operations. b) Contribution to Acidification by different input items. Results refer to 1 ton of apples of export or local quality.

Table III-36 shows the much lower NO_x emissions for petrol, which explain why OFP_HB_1 does not have a higher contribution in spite of its huge fuel consumption. SO_x emissions are thus the reason why there is a relevant contribution from machinery and pesticides production, even in organic systems (in OFP, mainly Kumulus/Thiovit production is relevant, which has the highest SO_x emissions per kg of all fungicides).

Table III-36: NO_x and SO_x emissions for Diesel, Petrol, and Electricity (kg/MJ).

	g/MJ	
	NO_x	***SO_x***
Diesel	1.42	0.119
Petrol 97 unleaded	0.008	0.143
Electricity NZ	0.075	0.047
Electricity UCPTE	0.256	0.627

SOURCE: BUWAL (1996).

In acidification, thence, there seems to be no clear difference between organic and integrated systems (see Figure III-18), in spite of organic system's higher energy consumption. The reasons are that petrol-related NO_x emissions are much lower than diesel's, and that mineral fertiliser's related ammonia emissions give higher contributions to orchards using urea as a nutrient source. Indeed, the election of fertiliser shows a strong influence on the results, and the IFP orchards that do not use urea have much lower contributions to acidification than those using it. Consequently, even though the Bennies use a high dose of CAN fertilisers to overcome their soil's low fertility, their contribution to acidification is much lower than the reference IFP systems', where urea is used as a source of nitrogen.

Nutrification

Special attention must be put to this impact category, because nitrate emissions from fertiliser leaching override all other emissions (see Figure III-19 a) and b). As the same average value was used for all systems, the variations are mainly due to system's productivity (Figure III-19 shows exactly the same profile as Figure III-8, where the values for the land competition indicator are given for all the systems). Consequently, it can be argued that Figure III-19 gives no additional information, and that a more detailed modelling of nitrate leaching is necessary before any conclusions can be drawn for the different orchards.

On the other hand, the comparatively higher NH_3 emissions in reference IFP systems contribute to this variation. As in the case of acidification, the type of fertiliser used and the dosage of nitrogen determine ammonia emissions. NO_x emissions have a small but noticeable contribution to nutrification as well.

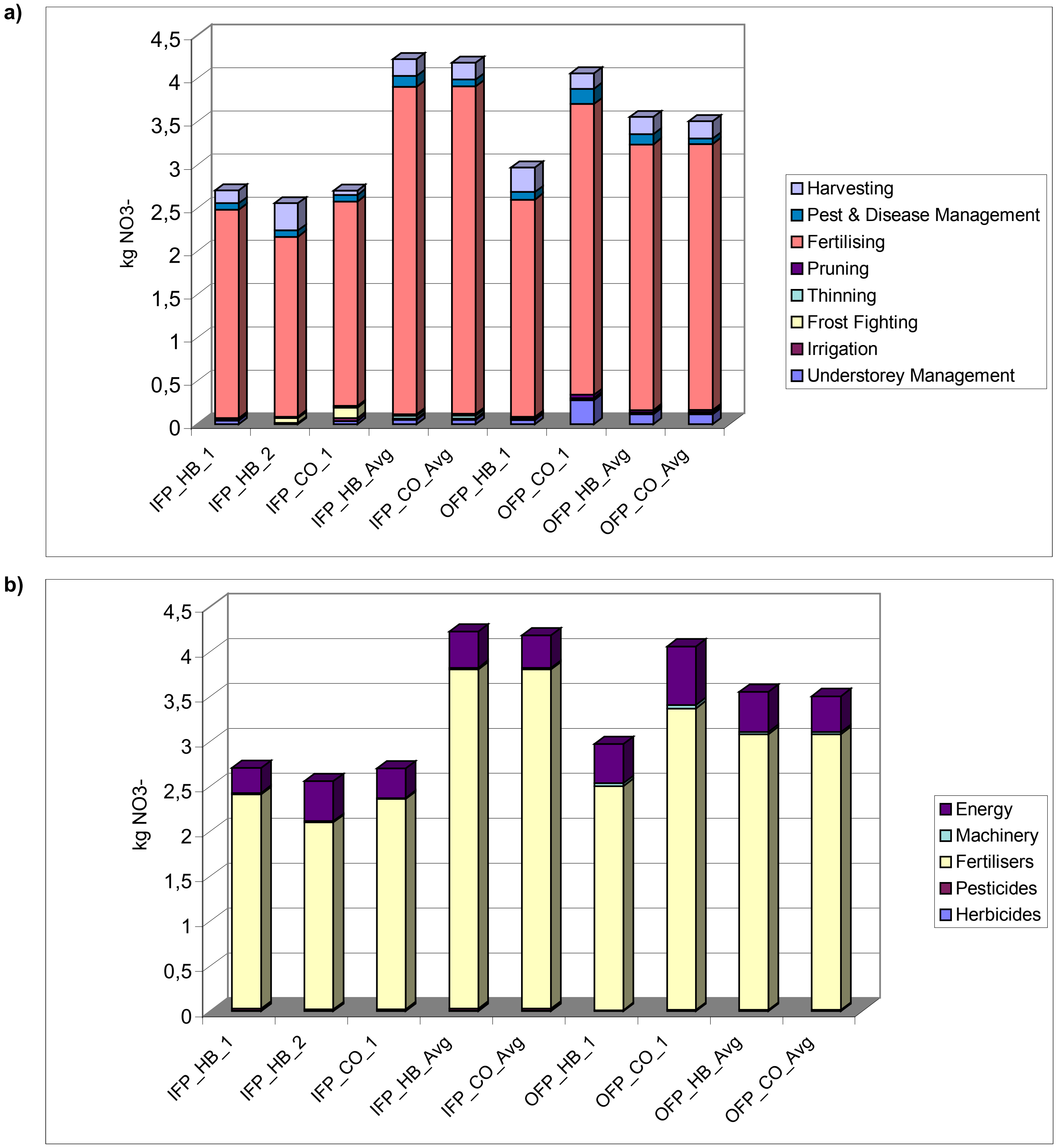

Figure III-19: a) Contribution to Nutrification by different field operations. b) Contribution to Nutrification by different input items. Results refer to 1 ton of apples of export or local quality.