An environmental systems analysis of greenhouse horticulture in the Netherlands

- the tomato case -

Jacomijn Pluimers

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Stellingen

1. Veel milieu-indicatoren bevatten impliciete keuzen die onvoldoende duidelijk worden gemaakt.
   (dit proefschrift en Van den Bergh en Verbruggen in Ecological Economics 29 (1999) 61-72)

2. Het formuleren van systeemgrenzen in modelstudies is een toepassing van het gezegde "bezint eer ge begint".
   (dit proefschrift)

3. Kosteneffectieve vermindering van de milieudruk door de tomatenteelt kan alleen dan worden bepaald als de heterogeniteit van die sector wordt meegenomen.
   (dit proefschrift)

4. Normalisatie zoals deze wordt toegepast in de levenscyclusanalyse is een ondoorzichtige manier van wegen.
   (dit proefschrift en Heijungs et al., 1992. Milieugerichte levenscyclusanalyses van producten, Handleiding. Centrum voor Milieukunde Leiden)

5. Het besluit om bosaanwas mee te laten tellen bij de bepaling van de emissiereductie van broeikasgassen is kortzichtig.

6. Acteren is spelen met je leven.
   (Stanislavski, 1985. Lessen voor acteurs 1. International Theatre Bookshop, Amsterdam)

7. De uitdrukking "geen bericht is goed bericht" geldt niet voor gebruikers van mobiele telefoons.

Stellingen bij het proefschrift:
An environmental systems analysis of greenhouse horticulture in the Netherlands – the tomato case.

Jacomijn Pluimers, Wageningen, 7 november 2001

C'est le temp que tu as perdu pour ta rose
qui fait ta rose si importante……
Tu deviens responsable pour toujours de ce
que tu as appprivoisé. Tu es responsible de
ta rose.

Antoine de Saint-Exupéry, Le Petit Prince

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In May 1996 I started the work presented in this thesis. I remember my difficulties with the decision whether or not to start a PhD: four years seemed an incredible long time to spend on the environmental problems related to greenhouse horticulture. In the end, I did the job in five years and with a focus only on the tomato cultivation. In these five years I have learned a lot about carrying out research in an multidisciplinary group, environmental systems analysis, horticulture, writing, computers and myself.

I never could have done this work all by myself. It is a result of the enjoyable co-operation of a many-sided multidisciplinary team. I would like to thank my (co-) promotors Leen Hordijk, Hugo Challa, Carolien Kroeze en Evert Jan Bakker. Leen, thank you for teaching me (often with striking examples) the basics of environmental systems analysis. Your proficiency in keeping the overview and summarising discussions (in which we had to learn each other's scientific vocabulary) were a valuable input. Hugo, thank you for introducing me into horticulture. You stimulated me to critically review what we did and what the results indicated. I have learned a lot of your critical scientific approach. Carolien, as a daily supervisor you were an important support. You encouraged me with your positive thinking. Thank you for the valuable brainstorm sessions and teaching me some basics of working in science. Evert Jan, thank you for your help in developing the "core" of the model (the TCG) and the programming in Delphi, when Excel became too slow! That was a very nice co-operation!

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1 Introduction

1.1 Background to the study

Greenhouse horticulture in the Netherlands is generally considered to be of social and economic importance. The sector produces vegetables, cut flowers and pot plants. By far the majority of greenhouses in the Netherlands are glasshouses. The total area of greenhouses has increased during the last decade to about 10,000 hectares in 1999 (Table 1.1), reflecting the relatively high profitability of greenhouse production. The annual value of the production in greenhouses is about seven billion Dutch guilders (NLG: NLG 1= EUR 0.45), or 20% of total agricultural production (Table 1.1). Eighty per cent of the greenhouse products is exported (LTO, 1998). There are 57,500 full-time jobs in this sector and an additional 60,000 jobs in the related agribusiness (Productschap Tuinbouw, 2000).

Greenhouse horticulture has been criticised for many years. In the eighties, the tomatoes from the Netherlands were called 'wasserbomben' (German for waterbombs) illustrating the aversion against the industrial production method and its tasteless products. In addition, people perceive the production in greenhouses as a relatively polluting activity. Environmental organisations (e.g. Muilerman et al., 1993), but also horticultural organisations (LTO, 1995, 1998) are concerned about the environmental problems caused by the production in greenhouses due to high inputs of fertilisers, fossil fuels (mainly natural gas) and chemical biocides. Moreover, artificial substrates and packing material are increasingly used, resulting in a substantial waste stream.

Table 1.1 *Area, production and employment in greenhouse horticulture, horticulture and total agriculture in the Netherlands in 1999*

	Area (ha)	Production (NLG)	Employment (persons per year)	References
Total agriculture 1)	± 2 million	39 billion	216 000	Anonymous (2001)
Horticulture 2)	144 421	14.9 billion	106 400	Productschap Tuinbouw (2000)
Greenhouse horticulture	10 708	9.5 billion	57 500	
Contribution of greenhouse horticulture to total agriculture	0.5%	20%	26%	

1) including horticulture, arable farming, dairy farming and animal husbandry

2) including vegetable production, floriculture, bulb production and tree cultivation

The concern about the environment has resulted in a growing number of environmental policy measures since the end of the 1980s. Initially, environmental policy was based on many different laws and regulations, including the Pollution of Surface Waters Act (Roos-Schalij et al., 1994), the Environmental Management Act (VROM, 1996) and the agreements on energy and crop protection between growers organisations and the government. Buurma et al. (1993) concluded that 34% of the greenhouse farms would get into financial problems by 2000 as a result of these environmental policies. In 1997 a new agreement, 'Greenhouse Horticulture and the Environment', was reached on the so-called 'integral environmental task' (IMT). In the IMT, general environmental aims are translated into operational and measurable targets for the sector for the period 1995-2010 (LNV, 1997). Hietbrink et al. (1999) concluded that the IMT will have large consequences for the financial-economic position of many greenhouse farms and that only less than 50% will probably achieve all environmental targets.

There are many strategies for reducing the environmental impact of greenhouse horticulture in the Netherlands. These include technical options that can be applied at the farm level and those applied at the regional or national level. An example of the latter is the reconstruction of greenhouse areas. The implementation of these options requires investments, an important consequence for a sector that faces increasing competition from southern European countries and from countries outside Europe. Besides reducing the environmental impact of production in greenhouses, the sector (represented by the agriculture and horticulture organisation LTO) aims to improve its competitiveness and sustainability and the quality of the products as well as the quality of the production process. Furthermore, the sector aims to maintain employment in horticulture and the quality of the landscape (LTO, 1995, 1998).

Alternatives that lead to more sustainable greenhouse horticulture in the Netherlands should consider both environmental and economic aspects. There is, however, no single unique definition of what sustainable greenhouse horticulture entails, and if there were one it would undergo constant change in response to changing economic climates and environmental concerns. In general, definitions of sustainable development include protecting the interests of present and future generations as well as the consideration of both ecological and socio-economic aspects. The Dutch Ministry of Agriculture, Nature Management and Fisheries defined the objective of sustainable agriculture as follows: *"Sustainable agriculture has an environmental and a socio-economic aspect. The environmental aspect implies the maintenance and development of the environment as a natural resource. The socio-economic aspect implies that agricultural policy contributes to the promotion of the standard of living and socially acceptable living and working conditions."* (Boer et al., 1992)

Obviously, there is a potential conflict between the environmental impact of greenhouse horticulture and the economic importance of this sector. This thesis focuses on the assessment of possibilities to reduce the environmental impact of greenhouse horticulture in the Netherlands, including the economic consequences. In section 1.2 I give an overview of the environmental impact of greenhouse horticulture in the Netherlands and government policy for this sector. Next, I discuss the research that has been carried out into the environmental impact of greenhouse horticulture in the Netherlands (section 1.3). Finally, I indicate the deficiency in knowledge on the possibilities for reducing the environmental impact of greenhouse horticulture and specify what will be studied in this thesis (section 1.4 to 1.6).

1.2 Greenhouse horticulture and the environment

The most important activities in Dutch greenhouse horticulture that lead to environmental impacts are the use of fossil fuel, chemical biocides, fertilisers and water, the use of artificial substrate and the use of assimilation light (Table 1.2). Further, greenhouses are considered to affect landscape values. Below, I discuss some of these activities in more detail and describe the policies that have been formulated for greenhouse horticulture in the Netherlands to reduce the environmental impact.

Table 1.2 *Inputs in and emissions from greenhouse horticulture in the Netherlands and their impact on the environment*

Inputs and activity	Environmental pressure	Environmental impact
- use of fossil energy	- emission of CO_2, C_xH_y, SO_2, NO_x, CH_4, N_2O, CO, etc.	- climate change, acidification, smog, depletion of fossil fuel
- use of chemical biocides	- emissions of toxic and persistent substances	- dispersion of toxic elements: human toxicity and eco-toxicity
- use of fertilisers	- emission of nutrients	- eutrophication
- use of water	- ---	- desiccation
- production of waste	- disposal of waste	- soil, water and air pollution
- use of assimilation light	- radiation of light during the night	- nuisance
- building of greenhouses	- ---	- landscape impairment

The combustion of fossil fuel in greenhouse horticulture contributes to the depletion of fossil resources as well as to air pollution. The total annual energy consumption is about 140 PJ, of which 85% is from natural gas (Bakker et al., 2000). Combustion of natural gas results in the emission of carbon dioxide (CO_2), which contributes to global warming. The total CO_2 emission from Dutch greenhouse horticulture is about 7.9 million tonnes CO_2 per year, which is more than 4% of the total CO_2 emission in the Netherlands (Bakker et al., 2000). The use of fossil fuels also results in emissions of methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and hydrocarbons (C_xH_y), contributing to global warming, acidification and/or tropospheric ozone. An agreement (included in the above-mentioned IMT) has been drawn up which aims at an energy-efficiency improvement (amount of energy used per unit of product) of 50% by 2000 and 65% by 2010 relative to 1980 (LNV, 1997). The target for 2000, however, has not been reached; in 1999 the energy efficiency improvement was 43%, which is 7% below the target for 2000 (Bakker et al., 2000). This means that extra effort is needed to achieve the target for 2010. Additionally, a policy target has been set for the use of renewable energy: a 10% share of total energy use in 2020 (VROM, 1999). For greenhouse horticulture the policy target is a 4% share in 2010 (LNV, 1997). Furthermore, legislation on the emissions of NO_x has been formulated for burners and cogeneration installations (Hirsch Ballin, 1992).

The use of chemical biocides results in the emission of toxic substances to water, soil and air. In 1995, 823 tonnes of active ingredients were used in Dutch greenhouses (Brouwer and Bruchem, 1999), which is more than 6% of the total biocide use in the Netherlands. The emission of biocides to the air not only results in air pollution, but is also an important indirect source of the contamination of surface water. Direct inputs of biocides to surface water via condensation water and drainwater only account for a few per cent of the contamination (Kraay et al., 1996). An official agreement formulated on biocide use in Dutch agriculture from 1992 focused on the reduction of emissions of biocides to soil, water and air and aimed at a reduction in annual use by 2000 relative to 1984-88 (Gabor, 1991). In the 'Greenhouse Horticulture and the Environment Agreement' new targets were formulated for use and for different emission routes in 2010 (LNV, 1997). These targets are a reduction in use and emission to the atmosphere of 88% and 72% for vegetable production and floriculture respectively, and a reduction of emissions to soil and surface water of 75% and 95% all relative to the 1984-1988 situation (Table 1.3).

Nitrogen leaching and the emission of nitrogen (N), phosphorus (P) may result in the eutrophication of the environment. The total losses of nitrogen to soil and surface water from Dutch greenhouse cultivation are about 4000 tonne per year (Sonneveld, 1996; LNV, 2000). The total phosphorus emission to soil and surface water is about 900 tonne per year (LNV, 2000). The average fertiliser application rate in Dutch greenhouse horticulture is 759 kg N and 150 kg P per hectare (Brouwer and Bruchem, 1999). This is high compared with the average fertiliser use per hectare in Dutch agriculture. The highest amounts of fertilisers are applied in vegetable production under glass (on average 1026 kg N and 225 kg P per hectare). Policy targets have been set for the reduction of nitrogen and phosphate emissions to the environment by the year 2000 and 2010 (Table 1.3). To reach these targets of recirculation of drain water on the farm has been made compulsory for cultivation on substrate and on soil in the Third Policy Document on Water Management (VenW, 1994).

Disposal of waste results in pollution of water, soil and air and in the depletion of resources. Greenhouse horticulture produces about 400 tonnes of waste per year, equivalent to 23% of the waste from agriculture and about 0.5% of the total amount of waste produced in the Netherlands (Harmelen et al., 1999). The use of artificial substrate is an important source of waste. Use of substrate also includes the use of foil to wrap up the substrate and to cover the soil. Screen materials for energy saving, climate control and darkening may also contribute to waste, depending on the type of material used. Waste also includes crop residues, prunings and unsold products. The Memorandum on Prevention and Re-use of Waste (VROM, 1988) contains several activities to reduce the amount of waste that is landfilled. These include prevention, re-use and useful application of waste.

Supplementary light (assimilation light) is used in several crops to increase yield and product quality, and also for socio-economic reasons, such as providing a continuous supply to the market and continuity in labour requirements. In 1998 supplementary light was used on 13% of the greenhouse area (Bakker et al., 2000). The use of supplementary light at night disturbs nocturnal animals and neighbours (Wolters and Elings, 1998). The Nuisance Act states that the light intensity at boundary of the property must be less than 4 lx (VROM, 1996).

Table 1.3 *The relative contribution of horticultural activities to total Dutch activities causing environmental problems and the environmental policy formulated for greenhouse horticulture*

Activities and emissions	Total in the Netherlands	Total for agriculture	Total for greenhouse horticulture	References	Policy with respect to horticulture (LNV, 1997)
Energy use (PJ)	3024	166	140	RIVM, 1999	Energy efficiency improvement of 50% by 2000 and 65% by 2010 relative to 1980 and 4% of energy from renewables by 2010
Use of natural gas (m^3)	$47 * 10^9$	$5.0 * 10^9$	$4.5 * 10^9$	Bakker et al., 2000	
CO_2 emission (kt CO_2)	$186 * 10^3$	$8.2 * 10^3$	$7.9 * 10^3$	RIVM, 1999; Bakker et al, 2000	
Total GHG emissions (kt CO_2-eq)	$240 * 10^3$	$25.8 * 10^3$	$7.9 * 10^3$	RIVM, 1999	
Biocide use (tonne active ingredient)		12 700	823	Brouwer and Bruchem, 1999; Harmelen et al., 1999	For vegetables: 65% reduction in annual use and emission reduction to the air by 2000 and 88 % reduction in annual use and emission reduction to the air by 2010 relative to 1984-88. For floriculture: 64% reduction in annual use and emission reduction in the air by 2000 and 72 % reduction in annual use and emission reduction in the air by 2010 relative to 1984-88. For all sectors: >75% reduction of emissions to soil water by 2000 and 2010 and 90% to 95% reduction of emissions to surface water
N surplus (kt N)		636	4	RIVM, 1999; LNV, 2000	70 % reduction of emissions of N and 75% of P by 2000 relative to 1985, and 95% reduction of emissions of N and P by 2000 relative to 1985.
P surplus (kt P)		61	0.9	RIVM, 1999; LNV, 2000	
N use (kg N/ha)		246	756	Brouwer and Bruchem, 1999	Recirculation for cultivation on substrate.
P use (kg P/ha)		48	155	Brouwer and Bruchem, 1999	
Waste production (kt)	56 550	1 715	395	Harmelen et al., 1999	The memorandum covers prevention of waste (5%), re-use of waste (35%) and useful application of waste (25%). The rest (35%) is incinerated or landfilled.
Area with assimilation light (ha)	-	-	1 300	Bakker et al., 2000	Light intensity on gardens less than 4 lx. Use of sidewall screen and dark period in 2000 (Environmental Management Act)

1.3 Research on greenhouse horticulture and the environment

Many studies have attempted to quantify the environmental impact of greenhouse horticulture, and the possibilities for reducing this environmental impact. In this section I give a selected overview of relevant literature and set out the scope of this thesis.

Most studies aimed at the *quantification of the environmental impact* of greenhouse horticulture in the Netherlands have focused on one single activity or on one environmental problem (Table 1.4). For instance, the use of energy and related CO_2 emissions by greenhouse horticulture in the Netherlands is reported annually by the Agricultural Economics Research Institute (see e.g. Velden et al., 1995 and Bakker et al., 2000). Research into the environmental impact of biocide use in greenhouses has concentrated on the emissions of biocides to the atmosphere (Baas et al., 1992; Baas et al., 1996; Leendertse et al., 1997) and emissions by drainage and condensation water (Runia et al., 1996; Staay and Douwes, 1996).

Research into the emissions of nutrients has mainly focused on the emissions of nitrogen (N) and phosphorus (P) to the soil and surface water. These studies are often based on nutrient mass balances (Sonneveld, 1996; LNV, 2000). One of the few studies on the production of waste is a study by the National Reference Centre (IKC, 1995) describing the sources and the amounts produced.

One of the few studies that focus on the integrated environmental impact of production in greenhouses is an environmental life cycle analysis (LCA) by Nienhuis and Vreede (1994a, 1994b). It quantifies the environmental impact of the production of tomatoes and roses following a cradle-to-grave approach. This approach implies the identification and quantification of emissions and materials and energy consumption that affect the environment at all stages of the entire product life cycle. However, Nienhuis and Vreede did not include the environmental impact of the use of biocide in their analysis.

Table 1.4 *Selected overview of studies on the quantification of the environmental impact of greenhouse horticulture in the Netherlands.*

QUANTIFICATION OF ENVIRONMENTAL IMPACT		
Subject	Reference	Selected content and findings
Energy use and emissions of CO_2	Bakker et al., 2000	- Annual report on developments in the greenhouse sector in energy use, energy efficiency, emission of CO_2 and the application rate of reduction options. In 1999 energy- efficiency improved due to a decrease in energy use (-2%) and an increase in production (+3%).
	Vermeulen, 1996	- Analysis of the use of energy and CO_2 emissions in the sector by interviews. Focus on the method of CO_2 fertilisation in greenhouses. Vermeulen concludes that a heat buffer is most frequently used.
Biocide use and emissions of biocides	Vernooy, 1992a	- Analysis of the variation in biocide use on greenhouse farms. Farms with highest biocide use range apply 6 times more biocides than farms with lowest use range.
	Baas et al., 1996	- Analysis of the risks of biocide emission from greenhouses in the atmosphere. Large uncertainties in the estimates of emissions of biocides into the atmosphere.
	Woittiez et al., 1996	- Woittiez et al. identified the use and emissions in the policy reference year for the multi-year agreement on crop protection and distinguished between the emissions to soil, water and air.
	Runia et al., 1996	- Analysis of the leaching of biocides into surface waters from greenhouse soils. All biocides applied could be determined in the surface water.
	Leendertse et al., 1997	- Development of an environmental indicator for the environmental impact of biocide emissions into the atmosphere.
Use of fertilisers and emissions of nutrients	Vernooy, 1992b	- Analysis of the emission of nutrients to the environment. Vernooy concludes that about 30% of water use and 50% of nutrient use can be saved by recirculation of drainwater.
	Sonneveld, 1993 and 1996	- Sonneveld analyses the emissions of nutrients at the farm and sector levels by using nutrient mass balances.
	VEK adviesgroep, 1994	- Analysis of the amount of waste water from greenhouse horticulture in the Netherlands and the possibilities for connection to the sewer.
	LNV, 2000	- Overview of the estimated emission of eutrophying compounds by greenhouse horticulture in the Netherlands from nutrient concentration measurements in water and nutrient balances
Production of waste	IKC, 1995	- Overview of waste production by agriculture in the Netherlands
More than one environmental aspect considered	Nienhuis and Vreede, 1994a, b	- Environmental life cycle analysis of tomato production and rose production in greenhouses in the Netherlands. Comparison of production with recirculation of drain water and with free-drainage systems.

Research into the *possibilities for reducing the environmental impacts* of greenhouse horticulture has focused on either single environmental problems or several environmental problems simultaneously (Table 1.5). These studies include options to reduce the emissions of pollutants to the air, water and soil, but hardly any on all the environmental problems mentioned in section 1.2. The production of waste is often not included. Most of these analyses focus on the environmental and economic consequences of the application of emission reduction options. Some studies limit themselves to reduction options that are obligatory by law (e.g. Buurma et al., 1993; Balthussen et al., 1996) while others also include other available (technical) reduction options (e.g. Muilerman et al., 1993) and the reconstruction of the whole greenhouse area (e.g. Bouwman et al., 1996). Furthermore, there are studies that primarily focus on economic developments in the sector but also analyse the environmental consequences. Alleblas and Mulder (1997), for example, studied the optimal distribution of greenhouse areas over the Netherlands for the economic performance of the sector and additionally analysed the environmental impact of this optimal distribution.

The above illustrates that several studies have been carried out on the quantification of the reduction of the environmental impact of greenhouse horticulture in the Netherlands, also including the economic consequences of emission control. However, those studies paid relatively little attention to the interactions between reduction options. Such interactions occur especially when an option that reduces a specific environmental problem influences, as a side effect, another environmental problem. The complexity of these interactions may increase as the number of combinations of reduction options rises. Ignoring these interactions may lead to sub-optimal solutions for environmental problems. Furthermore, the cost-effectiveness of reduction options has not been discussed in any of the above-mentioned studies, whereas this is an important aspect in the evaluation of reduction options.

In identifying options to reduce the environmental impact of greenhouse horticulture in the Netherlands, this thesis specifically examines important interactions between reduction options and their cost-effectiveness in solving multiple environmental problems. This is a complex task that requires an integrated approach. Environmental systems analysis may prove to be a valuable tool for carrying out such an integrated analysis. In the following section I give a brief overview of this methodology.

Table 1.5 *Selected overview of studies on the possibilities for reducing environmental problems caused by Dutch greenhouse horticulture and their economic consequences*

POSSIBLITIES FOR REDUCING ENVIRONMENTAL IMPACTS		
Subject considered	Literature	
Use of energy (natural gas and electricity)	Uffelen and Vermeulen, 1994	- Analysis of the effect of energy reducing options on gas use and additional annual costs. The authors concluded that investing in combi-condensers is profitable and that energy screens have great technical potential to reduce energy use, but may not be profitable for all cultivations.
	Zwart, 1996	- Zwart analysed the prospects of energy saving options in greenhouse horticulture and concluded that the application of combined heat and power and alternative cladding material resulted in the highest reduction in energy use.
	Velden et al., 1996	- Analysis of the potential application rate of energy reducing options. The authors concluded that the technical potential is high, but the individual horticultural firms have limited financial means.
	Lange and Dril, 1998	- Analysis of the contribution of renewable energy to total use in 2010 in greenhouses (scenario analysis). The contribution varied from <1% at low energy costs to about 10% at high energy costs.
Use and emissions of biocides	Esch et al., 1996	- Analysis of the financial consequences of options that reduce the emissions of biocides to the atmosphere. They concluded that the use of screens and advanced spraying techniques are relevant options to reduce these emissions.
Use and emissions of nutrients	Haskoning, 1990	- Haskoning analysed the emissions of N and P to surface water from greenhouse horticulture enterprises in the Netherlands. Among the reasons for differences in emissions were differences in cultivation method, nutrient management, and quality of irrigation water.
More than one environmental aspect considered	Verhaegh et al., 1990 included[1]: energy, nutrients, biocides and waste	- The authors quantified the environmental impact by greenhouse horticulture in the province of South Holland and analysed the possibilities for their reduction and the additional costs involved (period 1990-2000). They concluded that the costs would increase depending on the type of farm.
	Buurma et al., 1993 included: energy, nutrients and biocides	- Analysis of the economic implication of environmental policy targets for reduction options at the farm level by 2000. They concluded that the investments costs will exceed NLG 300 000 per farm and that 34% of the greenhouse firms may encounter financial problems in achieving the targets.
	Muilerman et al., 1993 included: energy, nutrients, biocide and waste	- An overview of technical options that can be applied to reduce the environmental impact and quantified the amount of reduction for each option.

(*Table continued on next page*)

Table 1.5 *(Continued)*

More than one environmental aspect considered	Balthussen et al., 1996 included: energy, nutrients and biocides	- The authors analysed the economic and environmental consequences of the voluntary agreement on greenhouse horticulture and the environment for 2010 and concluded that large reductions in use and emissions could be achieved without causing a rise in the number of farms with financial problems. The targets for energy-efficiency and biocide use can be achieved.
	Bouwman et al., 1996 included: energy, nutrients, biocides, assimilation light	- Analysis of the reduction in environmental pressure by building new greenhouses on new locations (reconstruction of the greenhouse sector) and the costs involved. They concluded that a reconstruction can reduce the energy use by 35%, has no effect on biocide use and may reduce the emissions of nutrients. Total investment costs may be about NLG 800 000 /ha.
	Alleblas and Mulder, 1997 included: energy, nutrients, biocide and landscape	- The authors analysed the economical optimal distribution of greenhouses within the Netherlands and analysed the environmental effect of this optimal distribution. They concluded that the optimal distribution would raise energy efficiency and reduce emissions of nutrients.
	Hietbrink et al., 1999 included: energy, nutrients, biocide	- Analysis of the economic and environmental consequences of the agreement on greenhouse horticulture and the environment. They concluded that more than 50% of the firms will achieve the environmental targets by 2010.

[1]) included indicates which of the following themes are considered: energy use, biocide use, nutrient use and related emissions, and the production of waste.

1.4 Environmental systems analysis

Environmental systems analysis is a tool for studying environmental issues. The nature of environmental problems requires integrated studies in which knowledge of different disciplines is combined (Huggett, 1993). Although environmental systems analysis covers a broad spectrum and is applied differently for each analysis, it does have some general features. First of all, the aim is to help decision-makers to find solutions to complex environmental problems. This is achieved by describing the problem systematically and gaining insight in the consequences of alternatives. The effect of alternatives or decisions is evaluated (Quade and Miser, 1995).

Systems analysis itself is not new. Initially, systems analysis was conceived as an integrated framework whereby complex systems, involving several disciplines, could be studied (Dent and Anderson, 1971). The increase in complexity and scale of technical systems, and the development of computers were the prime movers that gave rise to system design methodologies (Wilson, 1984; Rotmans, 1998). Systems analysis has also been used in agriculture to facilitate farm management decisions (Dent and Anderson, 1971). In greenhouse horticulture growth factors can be controlled in far more detail than in agriculture in the open field. Examples of such factors are temperature, humidity, CO_2 concentration in the air and light. There are many possible ways to control the system, and thus the decisions on what to do for an optimal yield are more complex than in agriculture. Examples of the use of systems analysis in greenhouse horticulture are the analysis of energy saving options by Zwart (1996) and the management of the production of pot plants by Leutscher (1995).

Several methods of systems analysis have been described in the literature (Wilson, 1984; Checkland, 1979; Quade and Miser, 1995). Although each author has his or her own approach, the general procedure consists of three phases (Figure 1.1). These are:

1. the formulation phase, in which the problem is defined and objectives are selected,
2. the research phase, in which facts are established, data are collected and alternatives are listed, and
3. the evaluation and presentation phase in which alternatives are compared and ranked, results are interpreted and conclusions are presented.

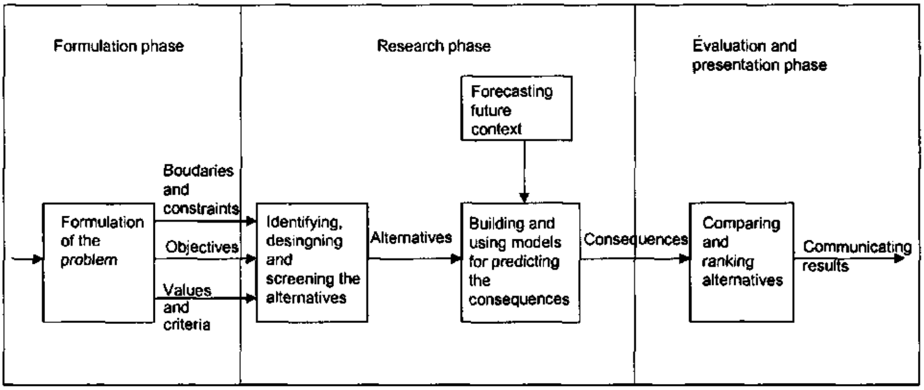

Figure 1.1 *The procedure of systems analysis following Quade and Miser (1995)*

An important component of environmental systems analysis is the development and application of models. Wilson (1984) defines a model as an "*explicit interpretation of one's understanding of a situation, or merely of one's ideas about that situation. A model can be expressed in mathematics, symbols or words, but it is essentially a description of entities, processes or attributes and the relationships between them.*" Modelling is a helpful tool for gaining insight into the problem or system behaviour and it can be used to compare and rank alternatives.

Environmental problems concern the problematic relation between human society and the natural environment. Environmental problems include socio-economic and ecological elements. Models developed for environmental systems analysis purposes, therefore, need to integrate knowledge from natural sciences and from economic sciences. Figure 1.2 illustrates the relation between society and the natural environment. The flows of energy and material from the ecological system to the socio-economic system are the resources used as an input to the economic processes. Other flows are into the natural environment and consist of emissions and waste from economic processes. Integrated models include an economic subsystem and an ecological subsystem and combine economic objectives, such as maximising welfare at minimum costs, with objectives for the natural subsystems, such as minimising the environmental impact (Braat and Lierop, 1987).

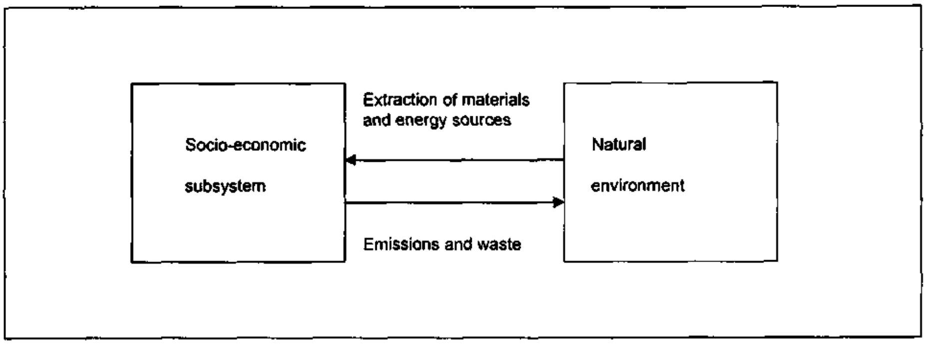

Figure 1.2 *Simplified model of the relation between society and natural environment (based on Braat and van Lierop, 1987)*

A systems analysis can be carried out at different spatial scales, depending on the purpose of the study. The well known study by Meadows et al. (1972) was the first systems analysis on a global scale (see also Bruijn, 1999). An example of an integrated environmental model at continental scale is the RAINS model (Regional Acidification and Simulation model) (Alcamo et al., 1990) that has been developed to analyse transboundary air pollution in Europe. The model includes emission calculations of acidifying and eutrophying compounds, cost-calculations for emission reduction, atmospheric processes and environmental impact calculations. An example of a national scale (or sectoral) model is the DRAM model (Dutch Regional Agricultural Model) (Helming, 1997). This model analyses the impact of changes in agricultural policy and techniques for agriculture in the Netherlands, including employment and income on the one hand and the emissions of nutrients, biocides and heavy metals on the other hand (Boer et al., 1992).

A wide range of tools is available for use in environmental systems analysis. Box 1.1 contains some examples of partly overlapping tools that can be used in environmental systems analysis, either singly or as a mix of tools. Some tools are applied in certain phases of the study, for example a sensitivity analysis is carried out in the research phase when the model performance is analysed. Other tools are used during the whole procedure, such as environmental indicators.

1.5 Purpose of the study and research questions

A major challenge facing the greenhouse horticulture sector in the near future is to reduce the environmental impacts of its activities. It is a complex problem involving different environmental problems and their economic consequences. This study investigates the possibilities for reducing the environmental impact of greenhouse horticulture in the Netherlands and its consequences, using the methodology of environmental systems analysis. The overall objective of the study is:

> *to identify technical options to reduce the environmental impact of greenhouse horticulture in the Netherlands and to evaluate their cost-effectiveness.*

Additionally, I will discuss the usefulness of environmental systems analysis as a method to evaluate these cost-effective reduction options.
As we have seen, greenhouse horticulture in the Netherlands is a very heterogeneous sector. The diversity of crops and cultivation methods, the diversity of environmental problems to which greenhouse horticulture contributes and the wide range of available reduction options all add to the complexity of the analysis. For this reason, I have chosen to focus the analysis on tomato cultivation. Such a case study can provide insight into the complexity of the different environmental problems and the possibilities to reduce the integrated environmental impact. Tomato cultivation was chosen because tomato is an important crop in the Netherlands about which many information and good statistics are available. It was anticipated that knowledge gained from studying tomato cultivation could be used to increase our understanding of greenhouse production in the Netherlands in general.

To identify technical options for reducing the environmental impact of greenhouse horticulture in the Netherlands and evaluate their cost-effectiveness I formulated the following sub-goals;

1. To identify the system boundaries and the input, output and processes that have to be taken into account when analysing the environmental impact of tomato cultivation in the Netherlands.
2. To develop a model that quantifies the environmental impact of tomato cultivation in the Netherlands and that can be used to evaluate the effects of combinations of options to reduce the environmental impact.
3. To explore the model to obtain insight in the model behaviour.
4. To analyse the cost-effectiveness of options to reduce the environmental impact of tomato cultivation in the Netherlands, with a special focus on strategies to meet the current environmental policy targets.
5. To discuss the possibilities of extrapolating the results for tomato cultivation to total greenhouse horticulture in the Netherlands

The first four sub-goals are in line with the procedure of environmental systems analysis used in this thesis. In the next section this procedure is further explained.

Box 1.1 *Overview of some tools that can be applied in environmental systems analysis*

Environmental indicators

An indicator is a parameter or a value derived from a parameter providing information about the environment. An indicator can be descriptive or normative. A descriptive indicator reflects actual conditions, such as the state of the environment or the environmental pressure (e.g. amount of CO_2 emissions). A normative indicator compares actual conditions with a reference condition (e.g. an index of acid deposition related to a critical load) (Opschoor and Reijnders, 1991; Bakkes et al., 1994). Two main requirements for indicators are 1) the indicator must have a broad significance, and 2) the indicator must be simple. Other examples of criteria that can be considered when selecting an indicator are described by Liverman et al. (1988). This tool can be used in the problem identification step (quantification of the problem) and the model development step (to quantify the environmental impact and/or to quantify the effect of reduction options).

Environmental life cycle analysis

This tool is a quantitative method to evaluate the environmental impact associated with a product process or activity. It includes all environmental problems that result from the emissions released during the whole life cycle, from cradle to grave. This tool is explicitly used to compare products (with the same function) and to explore where in the production chain most emissions occur and where emission reduction measures can be applied (Heijungs et al., 1992; SETAC, 1993). This tool can be used in the problem definition step as well as in the model building step.

Substance flow analysis

This tool can be used to analyse the flows of a single substance through the economy and the environment and identifies where any hazardous accumulations or emissions occur. It can be used to analyse and evaluate measures related to substance management (Bouman, 2000). This tool may be applied in the problem definition and model building step.

Sensitivity analysis

A sensitivity analysis is a systematic inventory of the changes in model results as a consequence of changing the values of the parameters or input variables used in the model (Heuberger and Janssen, 1994). This tool can be used to analyse the sensitivity of the model results to values of model parameters and is used in model building and systems analysis.

Uncertainty analysis

In an uncertainty analysis, as in a sensitivity analysis, the impact of changing the values of the parameters or input variables on the model results is analysed. It differs from a sensitivity analysis in that the change in values is based on an uncertainty range of these values. This tool can be used in the systems analysis step of the analysis (Morgan et al., 1990).

Box 1.1 *Continued*

Cost-effectivity analysis

This tool analyses the costs and effects of, for example, environmental policy. The cost-effectivity of an option can be defined as the relation between the costs and the amount of emission reduction (Janse and Wit, 1996). A reduction option is said to be efficient if its costs are justified in terms of its effects. Or, in other words, a cost-effective option achieves any given effect at the least possible costs (Zylicz, 1995). The tool can be used to evaluate the economic consequences of alternatives and it is used in the research and evaluation phase of the analysis.

Optimisation analysis

Cost-effectivity analysis frequently includes an optimisation analysis. This is a systematic method for finding the least expensive way to achieve a certain objective. In an optimisation analysis an object function is maximised or minimised under defined constraints (Tietenberg, 1994). This tool can be used in the research and evaluation phase.

Multi-criteria analysis

Multi-criteria analysis is an evaluation methodology for problems in which different criteria are taken into account. These criteria may have different units (e.g. kg CO_2 and kg NO_x), which means that they are not easily compared or combined. Multi-criteria methods account for the fact that certain criteria may be considered more important than others (e.g. the reduction of greenhouse gas emissions can be considered more important than the reduction of acidifying compounds). Many different multi-criteria methods are available (Paruccini, 1994; Ministry of Financial Affairs, 1986). One of the easiest way of summarising or evaluating a set of criteria is by adding up all the criteria, after having multiplied each of them by their own weighting factor, which reflects the preference of the decision makers. This weighted-sum method is most commonly used as multi-criteria method (Andreoli and Tellarini, 2000; Ministry of Financial Affairs, 1986). Multi-criteria analysis can be used in the evaluation phase of the analysis.

Scenario analysis

Every systems analysis study looks to the future since it deals with the consequences of decisions not yet taken and alternatives not yet adopted. A scenario is an outline of a probable or desirable development or situation. Scenario analysis typically results in a set of answers to WHAT IF questions illustrating the consequences of a range of alternative decisions (Schwarz, 1997). In scenario analysis the future is explored by using models and different scenarios. This tool can be used in the research phase of the analysis.

1.6 Research procedure

The systems analysis procedure in this thesis is based on Wilson (1984) and Checkland (1979) and consists of six steps (Figure 1.3).

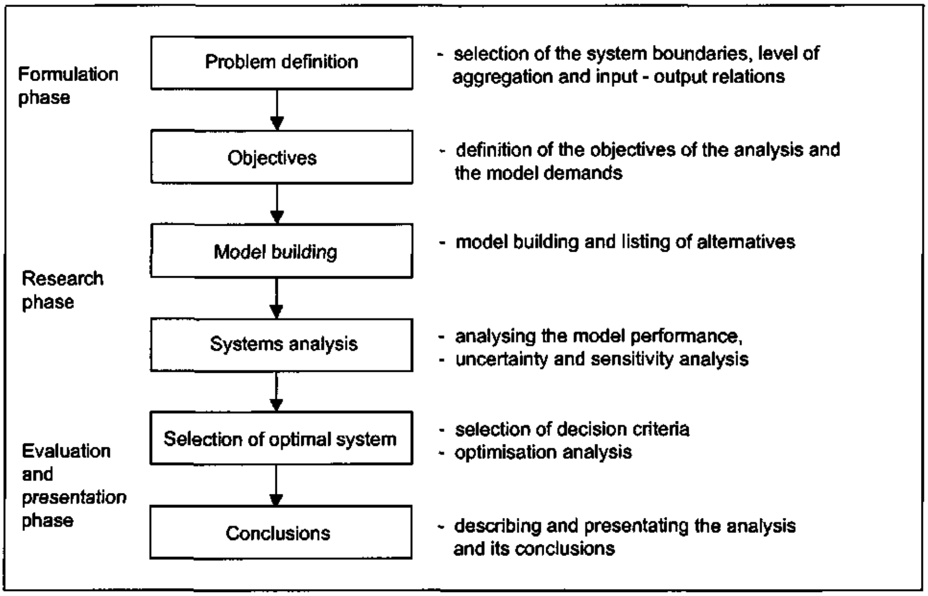

Figure 1.3 *The six steps of the procedure of environmental systems analysis used in this thesis (based on Wilson (1984) and Checkland (1979))*

The procedure starts with the formulation of the problem, the definition of the system boundaries and the level of aggregation, the systems inputs, outputs and their relationship. This step (partly) comprises the first sub-goal of this thesis (Chapter 2). Then, the objectives one hopes to achieve are classified and selected (Chapter 1 and 5). After that, the model is built. The model is mathematically described and alternatives (in this study the technical farm-level options to reduce the environmental impact) are identified (Chapter 3). This step covers the second sub-goal. After the model is built the model system is analysed. This can be done by analysing the model performance and by carrying out a sensitivity analysis (Chapter 4). This step deals with the third sub-goal. Next, an optimisation analysis is carried out for which first decision criteria are defined. The model is used and the responses to the reduction options are ranked and evaluated (Chapter 5). This step deals with the fourth sub-goal. The procedure ends with documentation of the overall analysis and presentation of the results and conclusions (all chapters).

The definition of system boundaries and system components depends on the purpose of the study. This study focuses on the present greenhouse horticulture in the Netherlands and analyses the environmental impact on an annual basis. The spatial boundaries and particularly the processes that need to be considered, are not easily defined, in particular not for the sector's contribution to global warming, acidification and eutrophication Therefore, an analysis is carried out on the selection of the system boundaries and model components with respect to these three environmental problems (Chapter 2).

The environmental issues included in the analysis are global warming, acidification, eutrophication, dispersion of toxic compound and the production of waste. These environmental problems were mentioned in the literature as most important environmental problems associated with greenhouse horticulture in the Netherlands. The problems of depletion of the ozone layer, smog formation and depletion of fossil fuels are not included in this study, because from the literature (CBS, 1997a; RIVM, 1999) I concluded that the role of agriculture in ozone depletion and smog formation is relatively small. Depletion of fossil fuels is not explicitly accounted for, because this analysis focuses primarily on environmental quality issues rather than on depletion of natural resources. The analysis of energy use and the associated emissions of e.g. CO_2 indirectly refer to depletion issues.

In environmental science a distinction is made between the pressure on the environment caused by human activities and the resulting environmental impact. Environmental pressure indicators can be used to quantify the potential impact of certain emissions to the environment. For instance, the total emissions of greenhouse gases from a sector expressed in CO_2-equivalents can be used to quantify the potential contribution of this sector to global warming and related climate change. Throughout this thesis, the environmental impact of greenhouse horticulture is analysed by using mainly environmental pressure indicators, although the term environmental impact is used.

An important first step is to define the aggregation level of the study. Cost-effective reduction options can be analysed at the farm level as well as at the national or sectoral level. Although environmental policy is formulated at the national or sectoral level, practical decisions about the application of technical reduction options, for example, are made by growers. Options at national level require more regional or national organisation. In this analysis I focus mainly on options that are applied by individual growers, the so-called on-farm options. I will analyse the consequences of these on-farm options at the national level (for the tomato case this is the total area of tomato cultivation in the Netherlands).

The choice of the model structure and model elements depends on the purpose of the analysis. Only processes or relations should be incorporated that are relevant to the problem. The model presented here should be able to describe, for instance, the environmental impact of greenhouse horticulture and tomato cultivation in such a way that the consequences of alternatives (reduction options) can be quantified. These consequences include not only environmental effects, but also economic consequences such as additional costs and changes in production. There are many different types of alternatives, from changes in cultivation practices to the application of technical reduction options. This study focuses on the technical reduction options that are presently available.

As indicated before, there are interactions between the processes and the emissions contributing to different environmental problems. As a result, reduction options may have side effects and consequently may affect more than one environmental problem. An example for greenhouse horticulture is soil disinfection by heating the soil using steam. The purpose of this technique is to reduce the use of chemical biocides. A side effect is that the use of natural gas increases, and as a result the emissions of CO_2. Other options may simultaneously reduce emissions of other gases. In this study I try to include all of the relevant side effects to calculate the environmental effect of the reduction options.

Systems analysis studies are typically performed to help decision-makers find the best solution to a complex problem. The decision-maker is the user or client of the analysis and its conclusions. The study presented in this thesis may assist policy makers in formulating environmental policies for greenhouse horticulture in the Netherlands. It may be interesting for decision-makers at the Ministry of Agriculture, Nature Management and Fisheries and at agricultural or environmental organisations. The analysis will, for instance, provide information on cost-effective ways to achieve the policy targets for greenhouse horticulture as set by the government.

2 Quantifying the environmental impact of production in agriculture and horticulture in the Netherlands: which emissions do we need to consider?

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Abstract

This study focuses on the environmental impact of agricultural production. The aim of the study is to identify the most important sources of greenhouse gases, acidifying and eutrophying compounds in Tomato Cultivation, Greenhouse Horticulture and Total Agriculture in the Netherlands. Within each of these three sectors we distinguish two systems. The System Agriculture (System A) includes the first-order processes of the agricultural production chain and the System Industry (System I) includes some second-order processes. Results indicate that, in general, System A emissions exceed System I emissions. However, in some cases emissions from System I are relatively high compared to System A emissions, and need to be considered when quantifying the total environmental impact of agricultural production. For example, acidifying emissions from the production of electricity and rock wool (both second-order processes) contribute by almost 25 % to the total acidifying emissions from System Greenhouse Horticulture A+I.

2.1 Introduction

Agricultural production in the Netherlands contributes to various environmental problems. Well-known environmental problems caused by agriculture are often related to specific activities and sectors. Dutch greenhouse horticulture, for example, is associated with relatively large emissions of the greenhouse gas carbon dioxide (CO_2) resulting from the combustion of natural gas. At the level of the total agricultural sector, on the other hand, the emissions of acidifying ammonia from animal waste are usually considered a major contributor to environmental problems.

Several studies have been published on the environmental impact of agricultural production in the Netherlands. These studies differ in their choice of system boundaries. Sometimes system boundaries are related to economic sectors at a national scale (e.g. RIVM, 1997). In this way, emissions from fuel combustion in farms are assigned to agriculture, while emissions from power plants are assigned to the energy sector. Other studies on the environmental impact of agriculture focus on the whole production chain of, for instance, a particular crop by using the methodology of environmental life cycle analysis (LCA) (Nienhuis and Vreede, 1994a, b; Wegener Sleeswijk et al., 1996). LCA is a tool for assessing the environmental impact of a product (Heijungs et al., 1992). A feature of LCA is that it aims to cover the entire life cycle, from cradle to grave, and to include all relevant environmental problems related to the product analysed.

Formulation of system boundaries is part of the first step in environmental systems analysis (Table 2.1) (Checkland, 1979; Wilson, 1984). Usually, environmental systems analysis deals with policy-making and aims at finding solutions to complex problems that arise in society by describing the system and analysing alternatives to the system. When defining system boundaries both spatial and temporal aspects need to be taken into account. The definition of system boundaries depends partly on the focus and purpose of the study. When studying an economic sector, one may chose to define sub-sectors to describe the most important aspects of a heterogeneous sector. Temporal boundaries indicate whether the analysis focuses on the present situation or also includes past or future trends. In this study we focus on system boundaries within the present horticultural and agricultural production chain (Figure 2.1).

Table 2.1 *The methodology of systems analysis in six steps as described by Wilson (1984) and Checkland (1979)*

Step 1	In the first step the problem is defined. The system boundaries, level of aggregation and input-output relations are described.
Step 2	In the second step the objectives of the analysis are clarified and the model demands are appointed.
Step 3	During the third step the system is synthesised, i.e. a model is built, system functions are listed and alternatives to the current situation are collected.
Step 4	The system is analysed by using the model developed in the third step. Uncertainties are deduced and the performance is compared with the objectives.
Step 5	In the fifth step the optimum system is selected. The decision criteria are described and the consequences are evaluated.
Step 6	During the last step the whole analysis and its conclusions are described.

When analysing the emissions of pollutants related to the agricultural sector, ideally one would aim for a full LCA approach for all products of the agricultural sector. However, this is not feasible because of the complexity and heterogeneity of the agricultural sector and the amount of data and time needed for such an analysis. The question then is what parts of the production chain have to be described to analyse a certain environmental problem related to agricultural production, without performing full LCAs for all the products involved. In other words: what are the system boundaries and how can we decide which inputs, outputs and processes have to be taken into account and which can be ignored? This study aims to contribute to an answer to this question.

We focus on three sectoral aggregation levels in this study. Our primary interest is the analysis of the environmental impact of the greenhouse horticultural sector in the Netherlands, resulting in recommendations to policy makers. The greenhouse horticultural sector is a relatively heterogeneous sector, both in terms of economic activities and environmental impacts. Rabbinge and Ittersum (1994) formulated guidelines to cope with tensions between aggregation levels. They recommend including the next lower and next higher aggregation level in the systems analysis in order to determine the relation between the aggregation levels. In our study, therefore, we will analyse system boundaries for Greenhouse Horticulture (primary focus), Tomato Cultivation (a level lower) and Total Agriculture (a level higher).

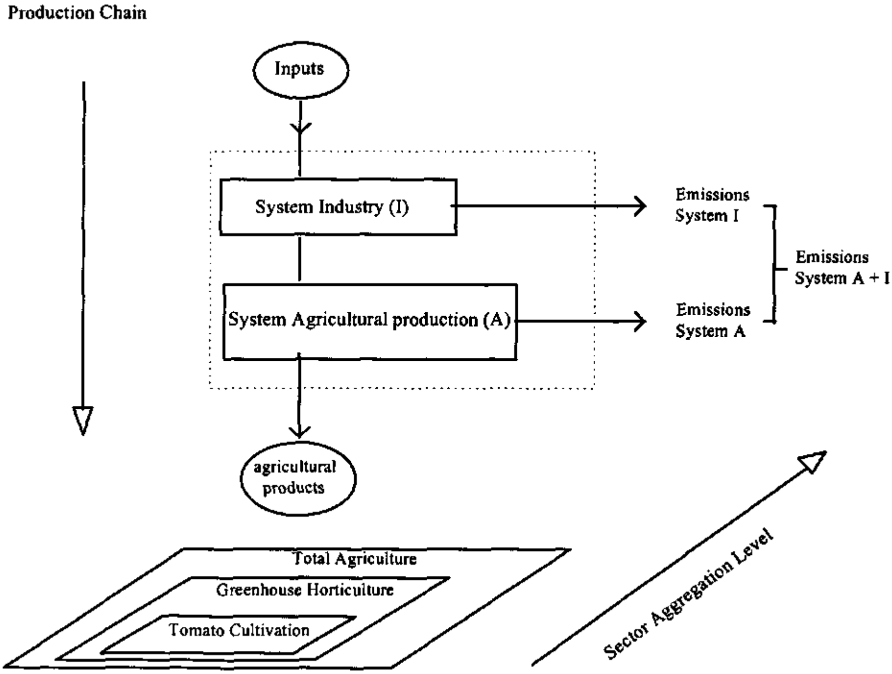

Figure 2.1 *Overview of System A(griculture) and System A+I(ndustry) and the three aggregation levels: Sector Tomato Cultivation, Sector Greenhouse Horticulture and Sector Total Agriculture*

The aim of this study is to identify the most important present-day emissions of greenhouse gases, acidifying compounds and eutrophying compounds related to agricultural production in the Netherlands. For this purpose we will estimate emissions resulting from activities within the agricultural sector (i.e. first-order processes) as well as answer the question whether emissions due to the production of the most important inputs to the agricultural sector, such as fertilisers, biocides and electricity (second-order processes) need to be taken into account. We will include the most important greenhouse gases (carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)), acidifying compounds (sulphur dioxide (SO_2), nitrogen oxide (NO_x) and ammonia (NH_3)), and eutrophying compounds (nitrogen (N) and phosphorus (P)).

2.2 Methodolgy

In this section we describe the different systems included in the analysis (system definition), present the method for calculating the emissions (calculation of emissions and environmental impact) and list the source of emission data or data used for the calculation of the emissions (data collection).

System definition: System A and System A+I

The agricultural sector is studied here at three different aggregation levels (Tomato Cultivation, Greenhouse Horticulture and Total Agriculture). At each of these levels two different systems are distinguished: System Agriculture and System Agriculture+Industry (Table 2.2, Figure 2.1). Basically, System A (Agriculture) includes the inputs and outputs of the agricultural production system in a strict sense (first-order processes). System I (Industry) includes the production of electricity, fertilisers, biocides and rock wool, which we consider second-order processes. The inputs and outputs of System A consist of direct production factors and emissions resulting from the use of these direct production factors, which include fossil fuels, fertilisers, biocides and rock wool. The inputs to System I include indirect production factors and the outputs consists of fertilisers, biocides, rock wool and electricity, and the related emissions. Thus in total we will consider six systems: System Tomato Cultivation A and A+I, System Greenhouse Horticulture A and A+I, and System Total Agriculture A and A+I (Table 2.2). We will also quantify indirect N_2O emissions resulting from nitrogen use in agriculture. These emissions are described in the IPCC emission calculation method (IPCC, 1997) and it is known that they account for about one third of the total agricultural N_2O emissions worldwide (Mosier et al., 1998).

Table 2.2 *Description of the systems studied: System Tomato Cultivation Agriculture (A) and Agriculture and Industry (A+I), System Greenhouse Horticulture A and A+I and System Agriculture A and A+I*

	Tomato Cultivation	Greenhouse Horticulture	Total Agriculture
System A	Environmental impact from use of gas, fertilisers, biocides and rock wool	As Tomato Cultivation, but Greenhouse Horticulture includes both soil and rock wool cultivation	Environmental impact from fuel use and cogeneration in farms, soils and lifestock sheds
System A+I	As System A but including the environmental impact of the production of electricity, fertilisers, biocides and rock wool (System Industry)	As Tomato Cultivation	As System A but including the environmental impact of the production of electricity, fertilisers, biocides and rock wool (System Industry)

Calculation of emissions and environmental impact

We analysed the emissions of CO_2, CH_4 and N_2O (greenhouse gases), SO_2 (acidifying gas), NO_x and NH_3 (acidifying gases and eutrophying gases), NO_3 and PO_4 (eutrophying compounds). Most of the emissions were either estimated by using emission inventory data from the literature or calculated as a function of agricultural activities and the emission factors (Table 2.3 and 2.4):

$$\text{EMISSION} = f\,(\text{ACTIVITY, EMISSION FACTOR}) \qquad (1)$$

Activities in System A include use of energy, biocides and fertilisers (nitrogen and phosphorus). In System A the production of manure and processes resulting in ammonia emissions from lifestock sheds are also included. System I describes the production of electricity, fertilisers, biocides and rock wool.

For each of the compounds considered, the integrated impact of emissions is calculated as (Heijungs et al., 1992) (Table 2.5):

$$\text{IMPACT} = \text{EMISSION} * \text{CLASSIFICATION FACTOR} \qquad (2)$$

In this analysis we use as classification factors the Global Warming Potentials (GWPs) defined by the IPCC (1997), and acidification and eutrophication potentials as described by Heijungs et al. (1992) (Table 2.5). The GWP is an index of cumulative radiative forcing between the present and some chosen later time horizon caused by a unit mass of gas emitted now, expressed relative to the reference gas CO_2 (1 kg CO_2) (Houghton et al., 1995). Heijungs et al. (1992) describe classification factors for substances contributing to acidification and eutrophication expressed in SO_2-equivalents and PO_4-equivalents, respectively.

Table 2.3 *Activity data for the calculation of the emissions from Tomato Cultivation, Greenhouse Horticulture and Total Agriculture in the Netherlands as used in Eq 1*

Activity	Value	Reference
Tomato Cultivation [1]		
- Gas use	$8.79 * 10^8$ m^3	KWIN, 1993
- Electricity use	$1.25 * 10^8$ kWh	Nienhuis and Vreede, 1994a
- Fertiliser N use	1 733 tonne N	Nienhuis and Vreede, 1994a
- Fertiliser P use	409 tonne P	Nienhuis and Vreede, 1994a
- Rock wool use	12.8 ktonne	Berg and Lankreijer, 1994; CBS, 1996
- Biocide use	11.3 tonne	CBS, 1996; CBS, 1997b
Greenhouse Horticulture [2]		
- Gas use	$4.3 * 10^9$ m^3	Velden et al., 1995
- Electricity use	$9.2 * 10^8$ kWh	Velden et al., 1995
- Fertiliser N use in soil cultivation	4 259 tonne N	Poppe et al., 1995; CBS, 1996
- Fertiliser N use in rock wool cultivation	4 500 tonne N	Poppe et al., 1995; CBS, 1996
- Fertiliser P use in soil cultivation	868.6 tonne P	Poppe et al., 1995; CBS, 1996
- Fertiliser P use in rock wool cultivation	924.9 tonne P	Poppe et al., 1995; CBS, 1996
- Rock wool use	25.2 ktonne	IKC, 1995
- Biocide use	704 tonne	Poppe et al., 1995
Total Agriculture [3]		
- Electricity use	9 PJ	CBS, 1997a
- Fertiliser use N	412 ktonne N	Kroeze, 1994
- Fertiliser use P	60 ktonne P	CBS, 1997a
- Biocide use	5 812 tonne	CBS, 1997b
- Rock wool use	25 200 tonne	IKC, 1995; CBS, 1996

[1] Area Sector Tomato Cultivation is 1 505 ha (CBS, 1996)

[2] Area Sector Greenhouse Horticulture is 10 144 ha (CBS, 1996)

[3] Area Sector Total Agriculture is $2*10^6$ ha (Kroeze, 1994)

Data for Tomato Cultivation and Greenhouse Horticulture

The emissions from Tomato Cultivation and Greenhouse Horticulture are estimated using Equation 1. This requires input data on activities and related emission factors. These data are listed in Table 2.3 and 2.4 respectively.

For the production of fertilisers and biocides (both activities in System I) we distinguished between energy-related and process-related emissions (Table 2.4). Process-related emissions are released during the chemical production process. Energy-related emissions are related to the production of energy used in the chemical process. We assumed that all electricity used in the production of fertilisers and biocides is produced by a coal-fired power plant and used the same emission factors as for electricity production (Table 2.4). This assumption can be considered a worst case scenario because in practice electricity is produced from a mix of fuels.

For Greenhouse Horticulture we distinguished between cultivation on soil and rock wool. Using the area of vegetables, ornamentals, soil and rock wool (CBS, 1996) and fertiliser use on vegetables and ornamentals (Poppe et al., 1995), we estimated total fertiliser use in these two cultivation methods (soil and rock wool).

Table 2.4 *Emission factors as used in Eq 1 for the calculation of the emissions from Tomato Cultivation, Greenhouse Horticulture and Total Agriculture in the Netherlands*

Emission factors related to activities in System A		
Activity	Emission factor	Reference
Gas use		
- CO_2	1.776 kg/ m^3 natural gas	IPCC, 1997; Boersema et al., 1986
- N_2O	7.20 * 10^{-5} kg/ m^3 natural gas	IPCC, 1997; Boersema et al., 1986
- NO_x	1.42 * 10^{-3} kg/ m^3 natural gas	IPCC, 1997; Boersema et al., 1986
- CH_4	9.5 * 10^{-5} kg/ m^3 natural gas	Berdowski et al., 1993
Fertiliser use in soil cultivation in greenhouses		
N fertiliser use		All emission factors are estimated from the studies by Mosier, et al. ,1998; Daum and Schenk, 1996; Sonneveld, 1993 and Postma, 1996
- N_2O	0.03 kg N_2O-N/kg N	
- NO_x	0.025 kg NO_x-N/kg N	
- NO_3	0.35 kg NO_3-N/kg N	
P fertiliser use		
- PO_4	0.2 kg PO_4-P/kgP	
Fertiliser use in rock wool cultivation in greenhouses		
N fertiliser use		All emission factors are estimated from the studies by Mosier, et al., 1998; Daum and Schenk, 1996; Sonneveld, 1993 and Postma, 1996
- N_2O	0.01 kg N_2O-N/kg N	
- NO_x	0.025 kg NO_x-N/kg N	
- NO_3	0.1 kg NO_3-N/kg N	
P fertiliser use		
- PO_4	0.1 kg PO_4-P/kgP	
Emission factors related to activities in System I		
Activity	Emission factor	Reference
Electricity production		
- CO_2	0.834 kg/kWh	IPCC, 1997; McInnes, 1996
- CH_4	9.0 * 10^{-6} kg/kWh	IPCC, 1997; McInnes, 1996
- N_2O	1.26 * 10^{-5} kg/kWh	IPCC, 1997; McInnes, 1996
- NO_x	1.35 * 10^{-3} kg/kWh	IPCC, 1997; McInnes, 1996
- SO_2	3.9 * 10^{-4} kg/kWh	IPCC, 1997; McInnes, 1996
Fertiliser production		
N fertiliser		
Process related emissions		
- N_2O	2.7 * 10^{-2} kg/kg N	Kroeze and Bogdanov, 1997
- NO_x	1.58 * 10^{-3} kg/kg N	Biewinga and Bijl, 1996
- NH_3	3.72 * 10^{-3} kg/kg N	Biewinga and Bijl, 1996
Energy related emissions[1]		
- CO_2	2.5 kg/kg N	All emission factors are estimated from France and Thompson, 1993 IPCC, 1997; McInnes, 1996
- CH_4	2.7 * 10^{-5} kg/ kg N	
- N_2O	3.78 * 10^{-5} kg/ kg N	
- NO_x	8.1 * 10^{-3} kg/ kg N	
- SO_2	1.13 * 10^{-2} kg/ kg N	
P fertiliser		
Process related emissions		
- NO_x	1.53 * 10^{-3} kg/kg P	Hoogenkamp, 1992
- P	4.0 * 10^{-3} kg/kg P	Bøckman et al., 1990
Energy related emissions [2]		
- CO_2	0.705 kg/kg P	All emission factors are estimated from France and Thompson, 1993 IPCC, 1997 + McInnes, 1996
- CH_4	7.6 * 10^{-6} kg/ kg P	
- N_2O	1.06 * 10^{-5} kg/ kg P	
- NO_x	2.28 * 10^{-3} kg/ kg P	
- SO_2	3.18 * 10^{-3} kg/ kg P	

(Table continued on next page)

Table 4 *(continued)*

Activity	Emission factor	Reference
Biocide production[3]		
- CO_2	4.77 kg/kg a.i.	All emission factors are estimated
- CH_4	$5.15 * 10^{-5}$ kg/ kg a.i.	from
- N_2O	$7.2 * 10^{-5}$ kg/ kg a.i.	France and Thompson, 1993;
- NO_x	$1.50 * 10^{-2}$ kg/ kg a.i.	IPCC, 1997 and McInnes, 1996
- SO_2	$2.15 * 10^{-2}$ kg/ kg a	
Rock wool production		
- CO_2	0.168 kg/kg rock wool	Kaskens et al., 1992
- SO_2	$1.92 * 10^{-3}$ kg/kg rock wool	Kaskens et al., 1992
- NO_x	0.02 kg/kg rock wool	Kaskens et al., 1992
- NH_3	$1.2* 10^{-3}$ kg/kg rock wool	Kaskens et al., 1992

[1] Energy related emissions from N fertiliser production are based on an energy use of 27 MJ/kg N (Melman et al.,1994)

[2] Energy related emissions from P fertiliser production are based on an energy use of 7.6 MJ/kg P (France and Thompson, 1993; Melman et al.,1994)

[3] These are energy related emissions from biocide production are based on an energy use of 51.5 MJ/kg active ingredient (Melman et al.,1994)

Data for Total Agriculture

The estimated emissions from the Total Agricultural sector are based mainly on studies by the National Institute for Public Health and the Environment (RIVM) (RIVM, 1996, 1997; Spakman et al., 1997b; Hoek, 1994). In some cases the estimated emissions are based on additional assumptions.

RIVM uses a definition for agriculture that is almost identical to System A described here. The only exception is indirect emissions of N_2O from soils, which RIVM assigns to agriculture (our System A) but are assigned to System A+I in the present study. The System A estimates for greenhouse gases, acidifying gases and eutrophying compounds are mostly based on RIVM studies (Hoek, 1994; Kroeze, 1994; RIVM, 1996; Spakman et al., 1997b). The only additional assumption for System A is that 2.5% of the fertiliser N use is emitted as NO_x, while total fertiliser N use in the Netherlands was 412 kt N in 1990 (Kroeze, 1994).

The emissions for System I include emissions released during the activities of the production of electricity, fertilisers, biocides and rock wool (Table 2.3 lists the associated activity levels). The emission factors associated with these activities in System I are the same as for Tomato Cultivation and Greenhouse Horticulture (Table 2.4).

Table 2.5 *Classification factors used in Eq2 for emissions of greenhouse gases (in CO_2-eq), acidifying gases (in SO_2-eq) and eutrophying compounds (in PO_4-eq)*

Environmental theme	Compounds	Classification factor	References/ notes
Global warming	CO_2	1 kg = 1 CO_2-eq	over 100 years: from IPCC, 1997
	CH_4	1 kg = 21 CO_2-eq	
	N_2O	1 kg = 310 CO_2-eq	
Acidification	SO_2	1 kg = 1 SO_2-eq	from Heijungs et al., 1992
	NO_x	1 kg = 0.7 SO_2-eq	NO_x = mainly/average NO_2
	NH_3	1 kg = 1.88 SO_2-eq	
Eutrophication	NO_x	1 kg = 0.13 PO_4 -eq	from Heijungs et al., 1992
	NH_3	1 kg = 0.35 PO_4 -eq	NO_x = mainly/average NO_2
	NO_3	1 kg = 0.10 PO_4 -eq	
	N	1 kg = 0.42 PO_4 -eq	
	PO_4	1 kg = 1 PO_4 -eq	
	P	1 kg = 3.06 PO_4 -eq	

2.3 Results

The estimated emissions related to specific activities within System A and System I for the three aggregation levels are presented in Table 2.6.

Results for Tomato Cultivation

Total greenhouse gas emissions from Tomato Cultivation are mainly from System A (Figures 2.2 and 2.3a). CO_2 emissions have by far the highest share in total greenhouse gas emissions from System Tomato Cultivation A+I. CO_2 emissions resulting from combustion of natural gas in System A account for 90% of the total emission of greenhouse gases in System A+I. Production of electricity in System I is the second largest source of greenhouse gas emissions by CO_2 emissions. The emissions of NO_x from System A are about half of total NO_2 emissions, but are relatively small compared with CO_2 emissions.

Tomato Cultivation System I provides a considerable proportion of total acidifying emissions from System A+I (about 30%). NO_x emissions make up 90% of total acidifying emissions from System A+I. Most of this NO_x results from the use of natural gas in System A. Other sources of NO_x emissions are rock wool production and production of electricity, which are both assigned to System I, and from the use of N fertiliser, which is assigned to System A (Table 2.6). SO_2 and NH_3 are only emitted in System I and are relatively moderate contributors to acidifying emissions in Tomato Cultivation.

Eutrophying emissions from System A account for 84% of total eutrophying emissions from Tomato Cultivation. The use of fertiliser (N and P) in System A accounts for almost half of total eutrophying emissions in System A+I. The use of natural gas accounts for about 37% of total eutrophying emissions in System A+I. Eutrophying emissions from System I can mainly be attributed to the production of rock wool and electricity and only consist of N compounds.

Results for Greenhouse Horticulture

Total greenhouse gas emissions from Greenhouse Horticulture consist mainly of CO_2 from System A (Figures 2.2 and 2.3b). The most important source of these emissions is the combustion of natural gas (Table 2.6). Production of electricity results in almost one-tenth of total greenhouse gas emissions in System A+I. As for the System Tomato Cultivation, N_2O is the second greenhouse gas of importance and is emitted in both System A and I in equal proportions.

For acidification, the use of natural gas is also an important source of emissions (about 60%). Other activities of interest contributing to acidification result from the production of electricity (SO_2 and NO_x) and the production of rock wool (NO_x). Most of the emissions of eutrophying compounds to the environment are included in System A (90% of total emissions). Gas use and use of nitrogen fertilisers have about equal shares in emissions of nitrogen compounds from System A (Table 2.6). When expressed in kg N or P the emissions of phosphorus compounds are not as high as the emissions of nitrogen compounds from System A, but due to differences in classification factors (Table 2.5) the total impact of emissions of phosphorus is relative high in System A (Table 2.6).

Table 2.6 *Results for Systems Tomato Cultivation, Greenhouse Horticulture and Total Agriculture A and I*

	Tomato Cultivation				Greenhouse Horticulture				Total Agriculture			
	System A		System I		System A		System I		System A		System I	
Greenhouse Gases	kt	kt CO_2-eq	kt	kt CO_2-eq	kt	kt CO_2-eq	kt	kt CO_2-eq	kt	kt CO_2-eq	kt	kt CO_2-eq
CO_2												
- gas use/fuel use in agriculture	1560	1560	0	0	7672	7672	0	0	8600	8600	0	0
- electricity production	0	0	104	104	0	0	767	767	0	0	1918	1918
- fertiliser N/P production	0	0	5	5	0	0	23	23	0	0	1787	1787
- biocide production	0	0	<<1	<<1	0	0	3	3	0	0	28	28
- rock wool production	0	0	2	2	0	0	4	4	0	0	4	4
TOTAL	1560	1560	111	111	7672	7672	797	797	8600	8600	3737	3737
CH_4												
- gas use/energy use	<1	1.8	0	0	<1	8.6	0	0	2	42	0	0
- manure	0	0	0	0	0	0	0	0	505	10605	0	0
- electricity production	0	0	<<1	<<1	0	0	<<1	<1	0	0	<1	<1
- fertiliser N/P production	0	0	<<1	<<1	0	0	<<1	<<1	0	0	<1	<1
- biocide production	0	0	<<1	<<1	0	0	<<1	<<1	0	0	<1	<1
TOTAL	<1	1.8	<<1	<<1	<1	8.6	<<1	<1	507	10647	<1	<1
N_2O												
- gas use/energy use	<<1	20	0	0	<1	96	0	0	<1	93	0	0
- fertiliser use	<<1	8	0	0	<1	84	0	0	20	6293	0	0
- lifestock sheds	0	0	0	0	0	0	0	0	8	2573	0	0
- electricity production	0	0	<<1	<1	0	0	<1	4	0	0	<1	9
- fertiliser N/P production	0	0	<<1	15	0	0	<1	73	0	0	6	1705
- indirect soil emissions [1])	0	0	<<1	8	0	0	<1	84	0	0	<1	<1
- biocide production	0	0	<<1	<<1	0	0	<<1	<<1	0	0	17	5301
TOTAL	<<1	28	<<1	23	<1	180	<1	161	28	8959	23	7015
Total greenhouse gas emissions		1590		134		7861		958		28206		10754

(Table continued on next page)

Table 2.6 *(continued)*

	Tomato Cultivation				Greenhouse Horticulture				Total Agriculture			
	System A		System I		System A		System I		System A		System I	
Acidifying Gases	t	t SO_2-eq	t	t SO_2-eq	t	t SO_2-eq	t	t SO_2-eq	kt	kt SO_2-eq	kt	kt SO_2-eq
SO_2												
- gas use/energy use	0	0	0	0	0	0	0	0	0	0	0	0
- electricity production	0	0	49	49	0	0	358	358	0	0	0.9	0.9
- fertiliser N/P production	0	0	21	21	0	0	105	105	0	0	0.7	0.7
- biocide production	0	0	<1	<1	0	0	15	15	0	0	0.1	0.1
- rock wool production	0	0	25	25	0	0	48	48	0	0	0.1	0.1
TOTAL	0	0	95	95	0	0	526	526	0	0	1.8	1.8
NO_x												
- gas use/energy use	1248	873	0	0	6134	4294	0	0	9	6	0	0
- fertiliser use	143	100	0	0	720	504	0	0	10	7	0	0
- electricity production	0	0	169	118	0	0	1242	869	0	0	2.8	2
- fertiliser N/P production	0	0	18	13	0	0	92	64	0	0	0.9	0.6
- biocide production	0	0	<1	<1	0	0	11	7	0	0	0.1	0.1
- rock wool production	0	0	256	179	0	0	504	353	0	0	0.5	0.4
TOTAL	1391	973	443	310	6854	4798	1849	1293	19	13	4.3	3.1
NH_3												
- fertiliser use	0	0	0	0	0	0	0	0	118	222	0	0
- lifestock sheds	0	0	0	0	0	0	0	0	82	153	0	0
- fertiliser N/P production	0	0	7	12	0	0	33	61	0	0	5.1	9.6
- rock wool production	0	0	15	29	0	0	30	57	0	0	0.3	0.6
TOTAL	0	0	22	41	0	0	63	118	200	375	5.4	10.2
Total acidifying emissions		973		446		4798		1937		388		15

Table 2.6 *(continued)*

	Tomato Cultivation				Greenhouse Horticulture				Total Agriculture			
	System A		System I		System A		System I		System A		System I	
Eutrophying emissions	t N or P	t PO_4-eq	t N or P	t PO_4-eq	t N or P	t PO_4-eq	t N or P	t PO_4-eq	kt N or P	kt PO_4-eq	kt N or P	kt PO_4-eq
N												
- gas use /energy use (NO_x)	374	162	0	0	1840	793	0	0	3	1	0	0
- fertiliser use (NO_x)	43	19	0	0	216	94	0	0	3	1	0	0
- fertiliser use (NH_3)	0	0	0	0	0	0	0	0	97	41	0	0
- fertiliser use (NO_3)	173	73	0	0	1941	815	0	0	426[2]	179[2]	0	0
- electricity production (NO_x)	0	0	51	22	0	0	373	161	0	0	<1	<1
- fertiliser N/P production (NO_x+NH_3)	0	0	11	5	0	0	54	23	0	0	8	3
- biocide production (NO_x)	0	0	<1	<1	0	0	3	1	0	0	<1	<1
- rock wool production (NO_x+NH_3)	0	0	89	39	0	0	176	74	0	0	<1	<1
TOTAL	590	254	151	65	3997	1702	606	259	529	222	8	3
P												
- fertiliser use (PO_4)	38	115	0	0	359	1098	0	0	71[2]	217[2]	0	0
- fertiliser P production	0	0	2	5	0	0	7	22	0	0	<1	1
TOTAL	38	115	2	5	359	1098	7	22	71	217	0	1
Total eutrophying emissions		369		70		2800		281		439		4

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[1] N_2O formation in remote soils and waters induced by agricultural N after volatilisation or leaching

[2] from RIVM (1996) indicated as total N and P to soil (excluding NO_x and NH_3 emissions)

Results for Total Agriculture

For the sector Total Agriculture the greenhouse gas emissions from System I amount to about one-third of the total emissions (Figures 2.2 and 2.3c). These System I emissions include CO_2 and N_2O from the production of electricity, fertiliser and rock wool and indirect soil emissions. The production and use of fertiliser are the most important sources of N_2O, with about equal contribution from emissions included in System A (mainly soils and livestock sheds) and System I (mainly industrial production of fertiliser and indirect soil emissions) (Table 2.6).

The greenhouse gases CO_2 and CH_4 have about an equal share (about 30%) in total emissions from System A+I, while N_2O accounts for 40% of total greenhouse gas emissions (Figure 2.2). Emissions of CO_2 are mainly from fuel use within the agricultural sector (System A). Emissions of CH_4 are almost entirely from animal production systems, which is also included in System A.

Most of the acidifying emissions estimated for System A+I are included in System A (96%). In other words, electricity production and industrial production of fertilisers and rock wool are relatively small sources of acidifying compounds compared to the emissions from animal production systems.

The eutrophying emissions from System A also account for more than 95% of total emissions. These emissions are mainly from the use of fertilisers and from animal manure.

Tomato Cultivation versus Greenhouse Horticulture

The results for Tomato Cultivation and Greenhouse Horticulture show several similarities (Figure 2.3). For instance, in both sectors gas use and related CO_2 emissions are relatively high and in both sectors CO_2 is most important greenhouse gas. Both Tomato Cultivation and Greenhouse Horticulture contribute to acidification, mainly through emissions of NO_x from gas use, use of fertilisers and production of electricity and rock wool. And for both sectors it was found that SO_2 and NH_3 are only emitted from System I.

On the other hand, the Tomato Cultivation and Greenhouse Horticulture sectors differ with respect to the use of electricity (Figure 2.3). Use of electricity and related NO_x emissions in Tomato Cultivation are, on an area basis, lower than the average electricity use in Greenhouse Horticulture. This is caused mainly by use of supplementary lighting in cut flower production. Nevertheless, total NO_x emissions in System A+I per hectare are higher in Tomato Cultivation because of rock wool production for Tomato Cultivation in System I (see below).

Another difference is related to the use of rock wool. In the Netherlands, virtually all tomatoes are cultivated on rock wool and almost none in soil. Of the total greenhouses, however, about 35% of the total area under glass is cultivated on rock wool and about 65% in soil (CBS, 1996). These differences are reflected in the relative contribution made by rock wool production to System I emissions and fertiliser use to System A emissions. The use of rock wool is often combined with the recirculation of water and nutrients, which results in lower losses of N and P to the environment per kg fertiliser used. However, use of N and P are relatively high for Tomato Cultivation so that, per hectare, emissions resulting from production of fertilisers are higher for Tomato Cultivation than for Greenhouse Horticulture (Figure 2.3).

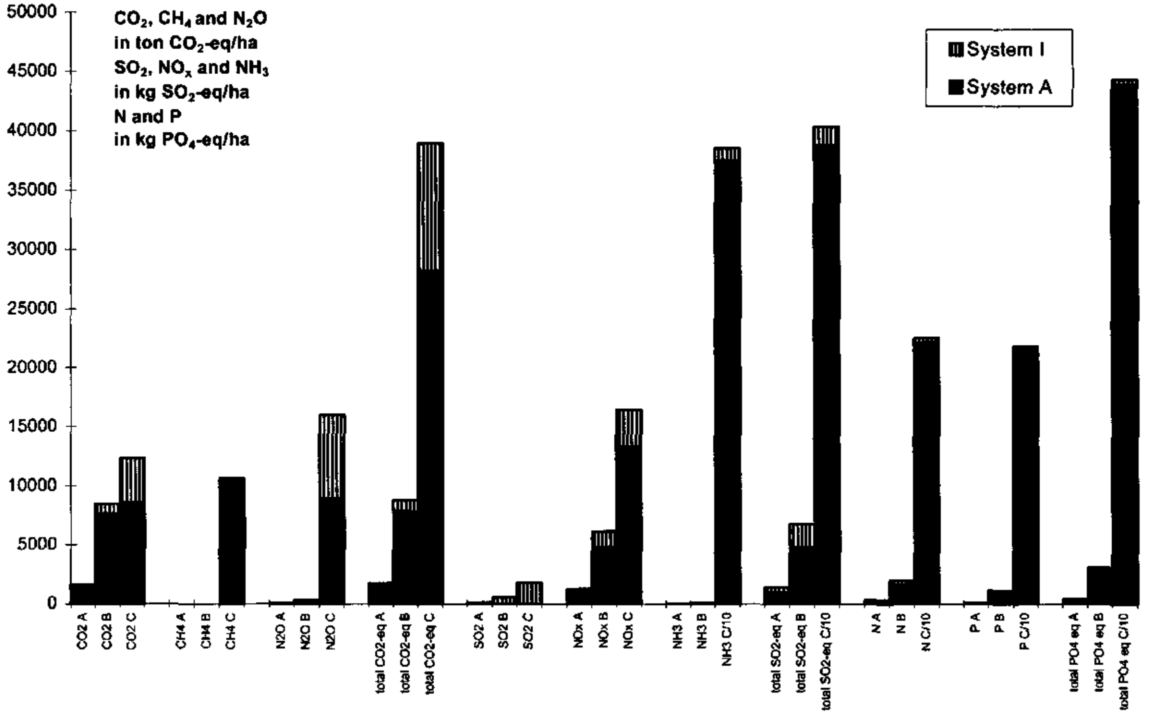

Figure 2.2 *Emissions of greenhouse gases (CO_2, CH_4 and N_2O, and total CO_2-eq), acidifying compounds (SO_2, NO_x and NH_3 and total SO_2-eq) and eutrophying compounds (N and P, and total PO_4-eq) from A: Tomato Cultivation; B: Greenhouse Horticulture and C: Total Agriculture. Units are listed in the figure. For Total Agriculture, emissions of NH_3, SO_2-eq, N, P and PO_4-eq have been divided by 10*

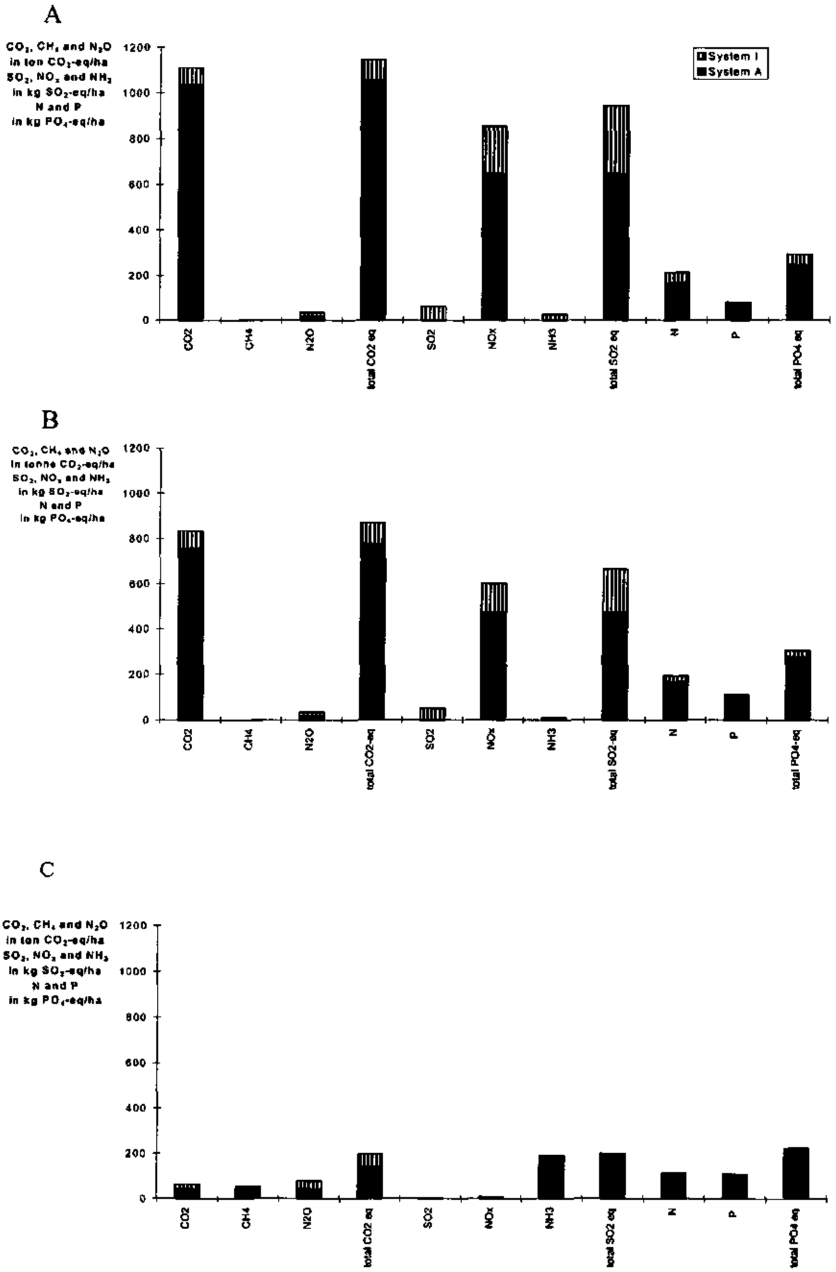

Figure 2.3 *Emissions of greenhouse gases (CO_2, CH_4 and N_2O, and total CO_2-equivalents) acidifying compounds (SO_2, NO_x and NH_3 and total SO_2-equivalents) and eutrophying compounds (N and P and total PO_4-equivalents) per hectare from processes in System A and System I for A: Tomato Cultivation, B: Greenhouse Horticulture and C: Total Agriculture in the Netherlands*

Tomato Cultivation and Greenhouse Horticulture versus Total Agriculture
We observed two important differences between agricultural production in greenhouses and the total Dutch agricultural sector. The first relates to the relative importance of the compounds emitted form the different sectors. While in Tomato Cultivation and Greenhouse Horticulture CO_2 is by far the most important greenhouse gas, emissions from Total Agriculture also include considerable amounts of other greenhouse gases, such as CH_4 and N_2O. These are emitted from animal production systems and fertilised soils (Figure 2.2). Secondly, we observed large differences in areal emissions from different sectors. For instance, expressed per hectare, greenhouse gas emissions from Total Agriculture (Figure 2.3) are considerably lower than emissions from Tomato Cultivation and Greenhouse Horticulture. Acidifying emissions in Total Agriculture are mainly from NH_3 emissions from animal husbandry, while in both Tomato Cultivation and Greenhouse Horticulture NO_x plays the most important role in acidification due to the use of energy. Eutrophying emissions in sector Total Agriculture are relatively high and can be fully ascribed to System A, while in Tomato Cultivation and Greenhouse Horticulture emissions of N in System I are considerable.

2.4 Discussion and conclusion

We investigated emissions of greenhouse gases, acidifying gases and eutrophying compounds from horticulture and agriculture in the Netherlands at three different aggregation levels: Tomato Cultivation, Greenhouse Horticulture and the Total Agricultural sector. We estimated emissions for these sectors including (System Agriculture + Industry) and excluding (System Agriculture) including second-order processes, which are defined as the production of electricity, fertilisers, biocides and rock wool (System Industry). We also addressed the question of what sources to include in an environmental systems analysis.

Discussion
To calculate emissions we used what we consider to be the best data available. Nevertheless, calculated emissions are subject to uncertainty. In this study no sensitivity or uncertainty analysis has been carried out to analyse the sensitivity of the calculated emissions to uncertainties in assumptions and methods used. Some emission factors are commonly used and widely accepted, for example emission factors described by the IPCC (IPCC, 1997). Other emission factors, however, were not available from the literature and have been estimated based on information in the literature, as are the emission factors for eutrophying and acidifying compounds related to fertiliser (N and P) use. Also the classification factors used, such as Global Warming Potentials (GWPs), Acidifying and Eutrophying Potentials are surrounded with uncertainties. GWPs are commonly used and accepted as classification factor for greenhouse gases (IPCC, 1997). The classification factors for calculating the PO_4-equivalents of eutrophying emissions are less widely used and are based on several assumptions (Heijungs et al., 1992). PO_4-equivalents are used in LCA studies to indicate the gross effect of eutrophication irrespective of the location of the emissions. However, eutrophication is an environmental problem with typically local effects and the eutrophication potentials for different compounds may change when

considering eutrophication as a local problem. Despite these limitations the data presented here may be the best presently available and serve the purpose of the study.

We assumed some aspects to be irrelevant for our analysis for several reasons. For instance, we did not quantify emissions from transport, such as transport of fertilisers and rock wool from production plant to greenhouse or farm. We assumed that these emissions are relatively small because fertilisers, biocides and rock wool are produced in the Netherlands (Nienhuis and Vreede, 1994a). For the same reason, emissions during the transport of natural gas were ignored. In addition, we only focused on first- and second-order processes and we did not consider capital equipment, like machinery or greenhouse construction. The results of an LCA study of tomato production in the Netherlands indicate that for the environmental problems considered here (global warming, acidification and eutrophication) first- and second-order processes are the most important contributors to the total impact (Nienhuis and Vreede, 1994a). Further, Nienhuis and Vreede (1994a) concluded from the LCA of Dutch tomato production that the production of capital equipment has little influence on the total impact. We assume that this holds for Greenhouse Horticulture and Total Agriculture as well.

We focused our analysis on three environmental problems: climate change, acidification and eutrophication. The analysis of the effects of the choice of system boundaries and system components is most interesting for these three problems because of the interrelations between human activities and the emissions. For example, an activity such as gas use results in the emissions of CO_2, a greenhouse gas, and NO_x, a compound contributing to the problems of acidification and eutrophication. For the emission of toxic biocides and the production of waste this is different. For example, the environmental effect of biocides are mainly related to the direct toxic effects caused by the use of biocides (System A) (Reijnders, 1991).

Table 2.7 *The contribution by different activities to total emissions in Tomato Cultivation: a comparison of the results of this study with the results of a life cycle analysis of Dutch tomato production by Nienhuis and Vreede (1994a)*

Environmental problem and Activity	Contribution by the activity to total emissions (in %)	
	Results of this study	Results as described by Nienhuis and Vreede (1994a)
Greenhouse Gases		
- use of natural gas	92%	91%
- production of electricity	6%	5%
- others	2%	4%
Acidifying Compounds		
- use of natural gas	61%	52%
- production of electricity	12%	20%
- others	27%	28%
Eutrophying Compounds		
- use of fertilisers	47%	42%
- production of P fertiliser	1%	16%
- use of natural gas	37%	22%
- production of electricity	5%	5%
- others	10%	15%

In the analysis we assumed that all electricity was produced by coal-fired power plants. In reality, part of the electricity is produced in gas- or oil-fired power plants. However, in this analysis we were searching for major contributors to environmental problems and the assumption of a coal-fired power plant seems to be justified. Further, the use of emission factors for a coal-fired power plant increases the possibilities for comparing results with many other countries where coal is the most important fuel. We ignored the possibility that electricity can be produced by cogeneration at the farm. Comparing with coal-fired power plants, cogeneration may result in lower emissions of CO_2 and higher emissions of NO_x. Cogeneration is only used for 8% of the total greenhouse area, mainly in cut flower and pot plant cultivation (Velden et al., 1997).

We compared our results for Tomato Cultivation with the results of the LCA of Dutch tomato production executed by Nienhuis and Vreede (1994a). Table 2.7 shows that there is a good agreement between our estimated greenhouse gas emissions related to System A and those calculated by Nienhuis and Vreede (1994a). Our estimates of the contribution made by natural gas and electricity to total greenhouse gas emissions largely agree with the estimates of Nienhuis and Vreede; for acidification there is a reasonable agreement. The total contribution made by emissions from natural gas and electricity production to total acidification agree well (73% versus 72%). However, the contribution made by natural gas in our study is higher than in the study by Nienhuis and Vreede (61% versus 52%). This may be caused by differences in emission factors. The relative contributions from different processes, such as use of fertilisers, combustion of natural gas, production of electricity and production of fertilisers to eutrophication differ only in the contribution of P emissions during the production of P fertilisers. This difference can be explained by differences in emission factors (Hoogenkamp, 1992; Bøckman et al, 1990). In other words, the results of this study of the Tomato Cultivation sector are, in general, in good agreement with the results of the complete LCA of tomato cultivation for the three environmental problems.

Conclusions

For Tomato Cultivation (System Tomato Cultivation A and A+I) the emissions related to activities in System A reflect about 92, 69 and 84% of the System A+I emissions for the greenhouse gases and acidifying and eutrophying compounds respectively (Table 2.8). Including the emissions during the production of electricity, fertiliser and rock wool does not influence the results of the analysis of greenhouse gas emissions to a great extent. However, the production of rock wool and electricity contribute to one-fifth of the total emission of acidifying compounds, a contribution that cannot be ignored. Our conclusion, therefore, is that a study on the impact of tomato cultivation would need to take into account: (1) CO_2 emissions from gas use and electricity, (2) NO_x emissions from use of gas and fertilisers, and from production of electricity and rock wool, and (3) N and P emissions from fertiliser use (Table 2.8).

Table 2.8 *Sources of emissions of greenhouse gases, acidifying gases and eutrophying compounds that contribute to at least 90% of the total present-day emissions from three agricultural sectors (Tomato Cultivation, Greenhouse Horticulture and Total Agriculture) in the Netherlands*

Environmental Problem	Source of Emission[1]	Contribution to total emissions from sector (in %)[2]
Tomato Cultivation		
Greenhouse Gases	CO_2 from gas use (A)	90%
	CO_2 from electricity production (I)	6%
Acidifying Gases	NO_x from gas use (A)	62%
	NO_x from rock wool production (I)	13%
	NO_x from electricity production (I)	8%
	NO_x from fertiliser use (A)	7%
Eutrophying Gases	NO_3 and PO_4 from fertiliser use (N and P) (A)	47%
	NO_x from gas use (A)	37%
	NO_x + NH_3 from rock wool production (I)	9%
	NO_x from electricity production (I)	5%
Greenhouse Horticulture		
Greenhouse Gases	CO_2 from gas use (A)	87%
	CO_2 from electricity production (I)	9%
Acidifying Gases	NO_x from gas use (A)	64%
	NO_x from electricity production (I)	13%
	NO_x from fertiliser use (A)	7%
	SO_2 from electricity production (I)	5%
	NO_x from rock wool production (I)	5%
Eutrophying Gases	NO_3 and PO_4 from fertiliser use (N and P) (A)	65%
	NO_x from gas use (A)	26%
	NO_x from electricity production (I)	5%
Total Agriculture		
Greenhouse Gases	CH_4 from manure (A)	27%
	CO_2 from energy use (A)	22%
	N_2O from fertilised soils (A)	16%
	N_2O indirect emissions (I)	14%
	N_2O from lifestock sheds (I)	7%
	N_2O in fertiliser production (I)	4%
Acidifying Gases	NH_3 from fertiliser use (manure) (A)	55%
	NH_3 from lifestock sheds (A)	38%
Eutrophying Compounds	P from fertiliser use (A)[3]	50%
	N from fertiliser use (A)[3]	41%

[1] letter between brackets () indicates whether source is included in System Agricultural Production (A) or System Industry (I)

[2] from Table 2.5

[3] from RIVM, 1996; indicated as total N and P to soil (is excluding NO_x and NH_3 emissions)

For the Greenhouse Horticulture sector (System Greenhouse Horticulture A and A+I) the emissions included in System A represent about 89% of the greenhouse gas emissions, about 71% of the acidifying emissions and about 90% of the eutrophying emissions of System A+I (Table 2.8). If production of electricity is considered as well as System A activities, this will include almost 90% of acidifying emissions (Table 2.8). Our conclusion is that a study on the impact of the Dutch greenhouse horticultural sector would need to take into account: (1) CO_2 from gas use and electricity production, (2) NO_x from gas use, electricity production, fertiliser use and rock wool production, and (3) N and P from fertiliser use (Table 2.8).

For the Total Agricultural sector (System Agriculture A and A+I) the emissions included in System A represent more than 90% of total (A+I) acidifying and eutrophying emissions (Tables 2.8). Thus, assigning emissions from the production of electricity, fertiliser and rock wool does not influence the results of the analysis to a great extent for acidification and eutrophication. For greenhouse gas emissions, however, we estimated that the additional System A+I sources increase the System A greenhouse gas emissions by almost one-third (Tables 2.6). This is mainly due to indirect emissions of N_2O in aquatic systems and remote terrestrial systems as a result of nitrogen volatilisation or leaching, and N_2O production in industrial fertiliser production. Our conclusion is that a study on the impact of the Dutch agricultural sector would need to take into account: (1) CH_4 emissions from animal waste (2) CO_2 emissions from fuel use in the sector, (3) sources of N_2O from fertilised soils, indirect emission, fertilisers production and lifestock sheds, (4) NH_3 emissions from animal production, and (5) nitrate and phosphate inputs to soils and surface waters. Most of these sources are included in System A (Table 2.8).

Although this analysis has been carried out for three specific agricultural sectors, we may draw some more general conclusions. First, we illustrated that without performing a complete LCA it seems possible to identify the most relevant processes that need to be taken into account when describing the environmental impact of agricultural production on a sectoral level. In other words, expert judgement and limited data could be used to define the most important sources of emissions related to agricultural production. We would like to underline that the choice of system boundaries largely depends on the purpose of the study and the envisaged users of the results (e.g. policy-makers or growers/farmers). Furthermore, we showed that a profound study of the definition of system boundaries is worthwhile and leads to greater insight into the system. We found that System I emissions can be relatively high compared with System A emissions. If we had restricted our study to System A emissions, in some cases we would have overlooked up to 30% of the total System A+I emissions. These results also imply that options to reduce the total environmental impact of an agricultural sector may include the application of reduction options in System I.

3 Environmental systems analysis of Dutch tomato cultivation under glass I: Model description

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Abstract

Dutch greenhouse horticulture contributes to several environmental problems, including global warming, acidification, eutrophication, dispersion of toxic substances and problems related to waste disposal. The overall aim of this study is to analyse the possibilities for reducing these environmental impacts as far as they are caused by Dutch tomato cultivation. We use the methodology of environmental systems analysis. This chapter describes a model for quantifying the environmental impact of Dutch tomato cultivation, which can be used to evaluate the effect of combinations of technical options to reduce the environmental impact. The model includes 22 groups of technical options to reduce emissions.

3.1 Introduction

Dutch greenhouse horticulture contributes to different environmental problems as a result of high inputs of energy, chemical biocides, fertilisers and water (Poppe et al., 1994). These inputs are used to obtain high production levels. Greenhouse horticultural production contributes to air pollution through emissions of greenhouse and acidifying gases (Muilerman et al., 1993; Velden et al., 1995), eutrophication through emission of nutrients (Sonneveld, 1993) and dispersion of toxic substances through emissions of biocides into the environment (Kraay et al., 1996). Furthermore, artificial substrates and packing material are increasingly used and result in a considerable amount of waste.

Environmentally safe production is one of the challenges greenhouse horticulture will face in the near future. It is, however, a complex problem concerning both environmental and economic aspects. Therefore, a study of the environmental impact of Dutch greenhouse horticulture and the exploration of feasible alternatives requires a multi-disciplinary problem-solving approach, such as environmental systems analysis (Checkland, 1979; Wilson, 1984).

The general aim of our overall study was to identify technical options to reduce the environmental impact of greenhouse horticulture in the Netherlands and to evaluate their cost-effectiveness. Therefore, we passed through the different stages of a systems analysis (Box 3.1). Environmental systems analysis has evolved to deal with complex problems that arise in public and private enterprises and organisations (Quade and Miser, 1995). The methodology includes the development and application of integrated models to gain insight into interactions within systems. Systems analysis can provide an insight into the consequences of different strategies.

Box 3.1 *The 6-step methodology of systems analysis as described by Checkland (1979) and Wilson (1984)*

1 Problem definition	The first step is the problem definition. This also includes a clear definition of the system by listing the system inputs, outputs and their relations, and the system boundaries.
2 Choosing objectives	The objectives of the analysis are described and the related model structure for simulation and optimisation are defined.
3 System synthesis	The model is built, system functions are listed, alternatives are collected and subsystems are delineated. This step requires a creative research attitude.
4 Systems analysis	During this step the system is analysed; computations are carried out to explore consequences of various alternatives. The model developed during the previous step is used. The results from model calculations are examined for sensitivity to changes in parameters and changes in assumptions, and the system performances are compared with the objectives of the analysis.
5 Selecting the optimum system	Decision criteria are described in the fifth step. The consequences are evaluated and rejected systems are documented.
6 Planning for action	During the last step the whole analysis is documented and the plans for further action to solve the complex problems are formulated. Recommendations for change and evidence for the recommendations are described.

The Dutch greenhouse sector consists of about 13,000 nurseries that differ with respect to cultivation (crop), cultivation practice, size, extent of modernisation, etc., which all influence the environmental impact. To simplify the analysis we focus on Dutch tomato cultivation. Tomato is an important vegetable crop in Dutch greenhouse horticulture about which information and good quality statistics are readily available. The methodology and model that we developed for Dutch tomato cultivation can be used in further research to analyse other crops or cultivation practices in Dutch greenhouse horticulture.

Our aim was to develop a model that quantifies the environmental impact of tomato cultivation in the Netherlands and that can be used to evaluate the effect of combinations of options to reduce the environmental impact. No such model is yet available. In the following, we defined the elements and boundaries of the system to be analysed by describing the most important activities and emissions that give rise to environmental problems. We formulated environmental indicators to quantify the environmental impact. Further, we reviewed the technical options to reduce the environmental impact of Dutch tomato cultivation. This chapter in fact describes the first three steps of the environmental systems analysis of Dutch tomato cultivation (Box 3.1). In Chapter 4 and 5 (Pluimers et al., submitted II and III) the results of the analysis of different reference situations are presented (steps 4, 5 and 6 of the analysis).

3.2 Problem definition and system overview

3.2.1 Environmental impact of tomato cultivation in the Netherlands

In this study, the method of systems analysis described by Checkland (1979) and Wilson (1984) was used. This method consists of several steps (Box 3.1): problem definition, description of the objectives of the analysis, synthesis and analysis of the system, selection of the optimum system and documentation of the study and its recommendations. As a first step, we present an overview of the environmental impact of Dutch tomato cultivation.

The most important activities in Dutch tomato cultivation leading to environmental problems are the use of fossil energy, fertilisers and water, chemical biocides and the disposal of waste (Figure 3.1). These activities result in emissions of environmental pollutants contributing to global warming, acidification, eutrophication, dispersion of toxic substances and accumulation of waste. The activities concerned are briefly discussed below.

The use of fossil fuels in tomato cultivation contributes to global warming and acidification. Natural gas is the most important source of energy in Dutch tomato cultivation (Nienhuis and Vreede, 1994a). The combustion of natural gas for heating and CO_2 fertilisation in greenhouses gives rise to emissions of carbon dioxide (CO_2), contributing to global warming, and emissions of nitrogen oxides (NO_x), resulting in acidification. The combustion of fossil fuels also results in emissions of methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and hydrocarbons (C_xH_y), contributing to global warming, acid rain and smog formation.

In tomato cultivation relatively large amounts of fertilisers are used (Poppe et al., 1994). The use of fertilisers results in the emissions of nitrogen and phosphate, mainly into ground and surface water, which contributes to the problem of eutrophication. Fruit vegetable production under glass (mainly tomato, cucumber and sweet pepper) may use about 1500 kg to 2000 kg N per hectare per year (Sonneveld, 1996). This amount is high in comparison with the fertiliser use per hectare in Dutch agriculture (usually less than 500 kg N/ha/y). Furthermore, the industrial production of fertilisers is highly energy intensive and results in emissions of, among others, N_2O, NO_x, NH_3, CO_2 and SO_2 (Hoogenkamp, 1992; Montfoort, 1995).

Crop protection can be provided by biological control and/or the application of chemical biocides. Biological control is increasingly used in the Netherlands, especially in the cultivation of greenhouse fruit vegetables. However, chemical biocides are still widely used. The use of chemical biocides results in the emission of toxic substances into water, soil, and atmosphere. The emission routes of biocides are various and include emission by air (Woittiez et al., 1996), condensation water (Bor et al., 1994), drain or drainage water and leaching to groundwater (Runia et al., 1996). The emission of biocides into the air is the most important emission route in greenhouses (Woittiez et al., 1996). When cultivation takes place in soil (and not in substrate) biocides may leach to surface and groundwater. The emissions of biocides and the impact on the environment depend on the chemical characteristics of the biocides used (Leendertse et al., 1997).

Tomato cultivation also leads to the production of waste. In the Netherlands, tomatoes are mainly cultivated on rock wool (Bakker, 1993), an artificial substrate made from basalt rock. The advantage of rock wool is that water and nutrients can easily be reused and emissions of nutrients to soil, ground, and surface water are diminished. Furthermore, cultivation on rock wool has resulted in higher production levels. However, the introduction of artificial substrates increases the amount of waste (IKC, 1995): Foil is used to wrap the substrate and cover the ground. In addition, the production of rock wool results in emissions of CO_2, SO_2, NH_3, and NO_x (Kaskens et al., 1992). Screen material for energy saving, climate control and light regulation (shading) may also result in waste production, depending on the type of material used. In addition, organic waste is produced consisting of crop residues, plant material removed by pruning and unsold products.

3.2.2 System boundaries

The formulation of the system boundaries is part of the first step of the environmental systems analysis and indicates which processes are included in the analysis. We focused on the five most important environmental problems related to Dutch tomato cultivation under glass: global warming, acidification, eutrophication, dispersion of toxic compounds and the production of waste. For each of these environmental themes we analysed system boundaries in order to select the most important processes that lead to emissions.

In Chapter 2 (Pluimers et al., 2000) we identified the most important sources of greenhouse gases, acidifying and eutrophying compounds in tomato cultivation in the Netherlands. We distinguished two systems: 'Agricultural Production', including the first-order processes of the agricultural production chain, and 'Industry', including some second-order processes (Figure 3.1). The processes included are the use of natural gas and fertilisers for Agricultural Production and the production of electricity, fertilisers, biocides and rock wool for Industry. For both systems we quantified Dutch emissions of carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (NO_2), nitrogen oxide (NO_x), sulphur dioxide (SO_2), nitrate (NO_3) and phosphate (PO_4) and we identified which compounds from which activities contribute to the environmental problems of global warming, acidification and eutrophication. The results indicated that for tomato cultivation in the Netherlands the most important emissions are: CO_2 emissions from the use of natural gas and the production of electricity, NO_x emissions from the use of natural gas and fertilisers, and from the production of electricity and rock wool, and emissions of NO_3 and PO_4 from fertiliser use.

In addition to these emissions, we included the impact of biocide emissions and the waste production in our analysis. The dispersion of biocides is directly related to their use because most important environmental effects of biocides depend almost entirely on their use (Reijnders, 1991). Therefore we excluded emissions of toxic compounds during the production of biocides, although severe environmental incidents have occurred in this process. No concise indicator exists for the production of waste, which may contribute to different environmental problems during storage or transformation. It is too complex a task to analyse all the emissions resulting from the disposal and treatment of waste. In this analysis we dealt with waste production as one single environmental problem.

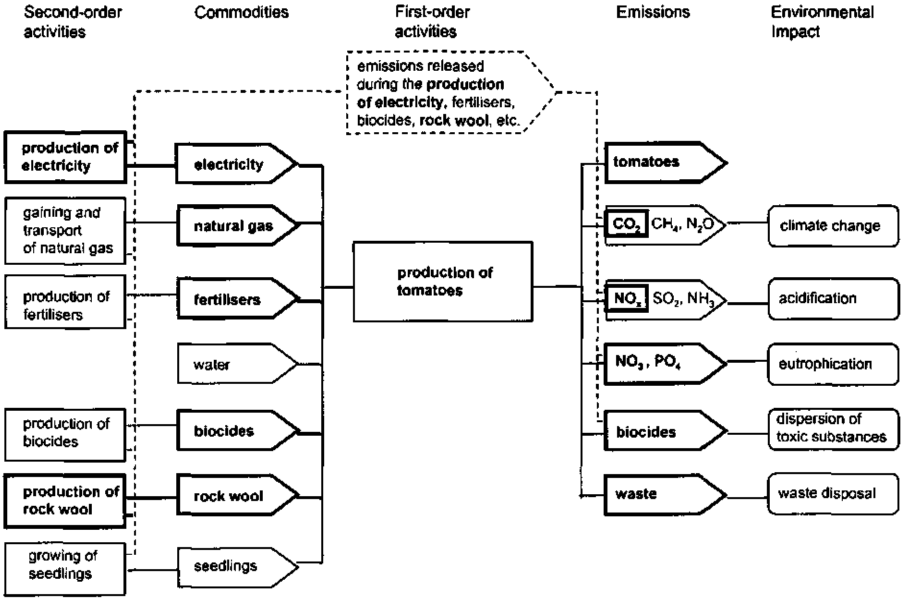

Figure 3.1 *Schematic overview of tomato cultivation in the Netherlands*
The bold elements are included in the system analysis. The dotted line indicates emissions released during second-order processes. The pentagon figures ⬠ *indicate first-order processes and emissions during first-order processes.*

In conclusion, a study on the impact of tomato cultivation on global warming, acidification, eutrophication, dispersion of toxic compound and the disposal of waste would need to take into account: CO_2 emissions from the use of natural gas and the production of electricity, NO_x emissions from the use of natural gas and fertilisers, NO_x emissions from the production of electricity and rock wool, NO_3 and PO_4 emissions into soil and surface water from the use of fertilisers, emissions of biocides from applications in greenhouses and the production of waste during cultivation (Figure 3.1).

3.3 Model formulation

3.3.1 Mathematical formulation

We developed a model to estimate the effect of combinations of reduction options on the environmental impact of Dutch tomato cultivation (Box 3.2). The method applied is often referred to as the 'emission factor' approach, since for each activity an emission factor is identified reflecting the emissions per unit activity (Spakman et al., 1997a). Both the activity levels and the emission factors can be influenced by reduction options. The environmental impact of the emissions depends on the total amount emitted per time unit (year) and the environmental impact factor of the compounds. In the following, the calculation procedure is described in more detail.

We described in total 22 different groups of reduction options (Table 3.1). Within each group there is a set of options that are mutually exclusive. For example, group 'screens' includes three different energy screens: a movable screen, a fixed energy screen and a double screen. Simultaneous application of these screens is not sensible and they are considered to be mutually exclusive. A combination of options (J) consists of one or no option (j) from each group.

The effect of reduction options is frequently quantified as a fraction of the activity levels or emission factors, independent of the absolute level of the activities or emissions (see for examples publications (Velden et al., 1995; KWIN 1997; Uffelen and Vermeulen, 1994). The so-called reduction factor of an option (rf) is defined as the fraction by which the level of activity or emissions is reduced (Equation 1 and 2 in Box 3.2). Applying the principle of a reduction fraction to simultaneous application of reduction options leads to a multiplicative model. We adopted this principle in our model.

The activity A is calculated from the combination of options applied (J) and the activity level in the reference situation (A_{ref}) (Table 3.2). There are some options that lead to a decrease in the level of one activity but to an increase in the level of another activity. For example, the use of rock wool for two years (instead of one year) is an option for reducing the amount of waste produced. However, a side effect is an increase of gas use, because reuse implies that rock wool has to be disinfected to prevent pests and diseases by steaming the rock wool, for which gas is used. X_α in the model represents the extra activity caused as a side effect by an option to reduce another activity (Equation 1 Box 3.2). This is an absolute value (not multiplicative but additive) and independent of the amount of gas used for heating or CO_2 fertilisation. It is an additional amount of gas use that is not affected by the application of options.

Box 3.2 *Mathematical formulation of the model*

Activity levels

$$A_\alpha = A_{\alpha,ref} * \prod_{j \in J}(1 - rf_{\alpha,j}) + \sum_{j \in J} X_{\alpha,j} + X_{\alpha,ref} \tag{1}$$

Emissions

$$E_{\varepsilon,\alpha} = A_\alpha * F_{\varepsilon,\alpha} * \prod_{j \in J}(1 - (rf_{\varepsilon,\alpha,j})) \tag{2}$$

$$E_\varepsilon = \sum_\alpha E_{\varepsilon,\alpha} \tag{3}$$

Impact 1)

$$M_{\mu,\varepsilon} = E_\varepsilon * IF_{\mu,\varepsilon} \tag{4}$$

$$M_\mu = \sum_\varepsilon M_{\mu,\varepsilon} \tag{5}$$

Costs

$$C = \sum_{j \in J}(CI_j + CO_j) + CV \tag{6}$$

where

$$CI_j = I_j * r * [1 - (1 + r)^{-d_j}]^{-1}$$

$$CO_j = I_j * o_j$$

$$CV = (Y_{ref} - Y) * P_{tom} - \sum_\alpha (A_{\alpha,ref} - A_\alpha) * P_\alpha$$

Yield

$$Y = Y_{ref} * \prod_{j \in J}(1 - rf_{y,j}) \tag{7}$$

α = index for type of activity: use of natural gas, electricity, biocides (fungicides, insecticides, greenhouse cleaning agent and other biocides (rest group), fertilisers (N fertiliser and P fertiliser), water use (rainwater and tap water), use of substrate (rock wool) and production of waste (inorganic and organic waste).
ε = index for type of pollutant emitted: CO_2 from gas use, NO_x emissions from the use of gas and fertilisers and from the production of electricity and rock wool, NO_3 and PO_4 from fertilisers .
μ = index for type of environmental impact considered: climate change, acidification, eutrophication, dispersion of toxics and production of waste.
j = index for reduction option (see Table A.1 Appendix 3.I)
J = set (combination of options); a subset of all available options, but including no more than one option from each of the 22 groups listed in Table 3.1.
ref = assumptions for reference situation (in this chapter: zero case)
A_α = level of activity α (in unit activity/ha/year)
$A_{\alpha,ref}$ = level of activity α in reference situation (in unit activity/ha/year)
C = total annual costs of reduction options (NLG/ha/year)
CI_j = annual investment costs of option j (NLG/ha/year)
CO_j = fixed operation costs of option j (NLG/ha/year)
CV = variable costs of all applied options (NLG/ha/year)
d_j = lifetime of option j (years)
E_ε = total emission of compound ε (in kg of compound ε /ha/year)
$E_{\varepsilon,\alpha}$ = emission of compound ε due to activity α (in kg of compound ε /ha/year)
$F_{\varepsilon,\alpha}$ = emission factor F for compound ε related to activity α (kg/unit activity)
$IF_{\mu,\varepsilon}$ = impact factor IF for environmental problem μ due to emissions of compound ε (impact unit/kg of compound ε)
Ij = investment costs of option j (NLG/ha)
M_μ = total impact μ (impact unit/ha/year)
$M_{\mu,\varepsilon}$ = impact μ for emissions of compound ε (impact unit/ha/year)
o_j = fixed percentage of investment for maintenance of option j (fraction/year)
P_α = price of activity α (NLG/ unit activity)
P_{tom} = tomato price (NLG/kg)
r = interest rate (fraction/year)
$rf_{\alpha,j}$ = reduction factor for activity α by option j (fraction)
$rf_{\varepsilon,\alpha,j}$ = reduction factor for emissions ε due to activity α by option j (fraction)
$rf_{y,j}$ = reduction factor for yield by option j (fraction)
$X_{\alpha,j}$ = extra activity α due to application of option j (in unit activity/ha/year)
$X_{\alpha,ref}$ = extra activity α in reference situation (in unit activity/ha/year)
Y = yield of tomatoes per year (kg/ha/year)
Y_{ref} = yield of tomatoes per year in reference situation (kg/ha/year)

1) This equation is not used for the calculation of the environmental impact of the emissions of biocides

Appendix 3.I describes all reduction options and their reduction factors (rf), as well as extra activities X_α (gas use and use of electricity) induced by the reduction option.

We calculated the emission (E) as a function of the activity (A_α), the emission factor ($F_{\varepsilon\alpha}$) and the options applied (Equation 2 and 3 Box 3.2). The emissions are calculated for the compounds ε, which are CO_2, NO_x, NO_3 and PO_4, biocides and organic and inorganic waste. The emissions can be abated by combinations of reduction options, which in the model are treated in the same way as the reduction of activity levels. The reduction factors apply to the emission of compound ε to a certain activity A_α ($rf_{\varepsilon,\alpha}$). The emission factor $F_{\varepsilon\alpha}$ indicates the quantity of emission in kg compound per unit activity A_α for a certain compound ε. For biocide use, the emission factor indicates the fraction of the biocide that is emitted (Equation 2 Box 3.2).

The emissions of compounds ε have their impact (M) on the environment (Equation 4 and 5 of Box 3.2). The integrated environmental impact of different emissions on one environmental problem is quantified by using impact factors (or classification factors) (Heijungs et al., 1992). The impact factor for environmental problem μ reflects the relative contribution of a compound ε to the environmental problem μ related to a reference compound. In this way, the emissions of different eutrophying compounds can be expressed in terms of phosphate equivalents (PO_4-eq) by using the nutrification potentials (Heijungs et al., 1992). The environmental impact of biocides is calculated in a different way (see 3.3.4).

The annual costs of the reduction options include investment costs, operating costs and variable costs (Equation 6 Box 3.2) (Klaassen, 1991; VROM, 1998). We calculated the annual investment costs by using interest rate (r) and the economic lifetime (d) of the reduction option. Operating costs may include maintenance, insurance and administrative costs. Variable costs depend on the reduction in tomato yields due to the application of the reduction options and the savings or costs due to a reduction or increase in activities. The tomato yield can be influenced by reduction options, for example by light reduction due to the application of an energy screen. Although there may be more factors influencing the yield, here only the effect of light reduction on yield is taken into account. We ignored the possible reduction in product quality, which is more uncertain and difficult to quantify, although it may affect the economic value of the tomatoes.

To analyse the cost-effectiveness of combinations of reduction options we calculated the effect of all possible combinations of options from the groups described in Table 3.1 and Appendix 3.I. The number of possible combinations increases rapidly as the number of groups rises. For this reason, we developed a so-called technical coefficient generator (TCG) (Ven, 1996) which generates all possible combinations of options and, for each combination, calculates the resulting activity levels, emissions, environmental impact and costs, according to the equations described in Box 3.2. For each environmental problem considered we analysed the efficiency of combinations of options. A combination of options is considered to be efficient if no other combination of options exists that results in a lower or equal environmental impact M_μ at lower or equal costs for the environmental problem μ considered. The efficient combinations of options form the basis for the optimisation analysis (Chapter 5).

Table 3.1 *Overview of the group of technical options to reduce the environmental problems caused by Dutch greenhouse cultivation. The individual options per group are described in Appendix 3.I.*

Name of the group	Description of the group
Condensers	- exploit the latent heat present in the exhaust gases of a boiler or a combined heat and power engine, so that the efficiency of heat production is increased.
Screens	- screens that decrease energy loss through the greenhouse roof
Wall insulation	- techniques that are applied to insulate greenhouse walls
Roof insulation	- different materials which are applied on the glass and result in a reduction of energy loss
CO_2 supply method	- use of heat buffer or pure CO_2 to reduce the use of natural gas for additional CO_2 application for fertilisation, when there is no heat demand in the greenhouse.
NO_x emission reduction	- a techniques that reduce the emission of NO_x during gas combustion
Temperature management	- different techniques or control options to reduce gas use for heating, such as lowering the average temperature and use of special climate computers
Construction change	- a change in construction or a technical application to decrease heat loss and biocide emission through window panes
Spraying technique	- a change in spraying techniques which increases spraying efficiency and therefore reduces the amount of biocides applied and/or the emission of biocides to the air
Resistant crop varieties	- use of crop varieties which are more resistant to certain pests or diseases
Biological control and scouting	- crop protection by using of natural enemies (biological control) and regular checking of the crop for pests and diseases (scouting)
Greenhouse hygiene	- wearing clean shoes and clothes
High-pressure cleaner	- a technique for cleaning the greenhouse (from inside) by using only (hot) water under high pressure
Mechanical roof cleaner	- a technique for cleaning greenhouse roofs from the outside using only water
Sources of irrigation water	- a plan to change the source of irrigation water which influences the quality of the irrigation water and consequently reduces the amount of drain water emitted into the environment
Sewage treatment	- draining water to the sewer instead of draining to surface water
Drain water cleaning	- cleaning drain water in a water purification plant/system
Recirculation of drain water	- reducing the emission of eutrophying compounds by collecting and reusing drain water
Drain water disinfection	- a technique for disinfecting drain(age) water which is reused as irrigation water, this technique is applied simultaneously with recirculation
Change of substrate use	- a change of type of substrate or cultivation method influencing the amount of substrate used
Composting	- a technique for converting organic waste to usable compost
Reduction of foil waste	- reducing the amount of foil waste by recycling plastic foil or using biodegradable foil

3.3.2 Emissions and emission factors

Emission factors indicate the amount of a component ε emitted per unit of activity (Appendix 3.II). The following compounds were included in this study: CO_2, NO_x, NO_3, PO_4, biocides and waste. The emission factors for CO_2 and NO_x due to combustion of gas and coal (electricity) are based on IPCC (1997), Boersema et al. (1996) and McInnes (1996). Emission factors for NO_x emissions during the production of rock wool are from Kaskens et al. (1992). The production of waste is based on DLV (1991) and IKC (1995). The waste products taken into account are rock wool, plastic foils and organic material (mainly crop residues at the end of the growing season).

The emission of nitrogen from fertiliser use in tomato cultivation on rock wool with recirculation of water and nutrients occurs in different compounds. Crop products (tomatoes) and crop residues remove approximately 50-60% of the nitrogen and phosphorus applied. Emissions to the environment occur along different routes: with drain water into surface water (sluice water) (NO_3) and into the atmosphere (N_2, N_2O, NO_x and NH_3). As concluded in Chapter 2 we considered in this analysis the emissions of NO_x into the atmosphere and the emission of NO_3 and PO_4 into surface water as result of the use of fertilisers. Drain water is reused (recirculation), but because of an increase in salinity, drain water is discharged now and then into surface water. The small root volume in substrate cultivation increases the plant's sensitivity to the salinity of irrigation water. The percentage of the nitrogen input that is recirculated and reused is estimated to be 20-30%. The emission of N through the discharge of water is estimated to be 10%, based on Sonneveld (1996) and Bouwman et al. (1996). Nitrification and denitrification result in emissions of N_2, N_2O and NO_x. Denitrification is difficult to estimate for substrate cultivation. Daum and Schenk (1996) measured the emission in the cultivation of cucumbers on substrate and concluded that about 13% (3-20%) of the nitrogen input was denitrificated and resulted mainly in the emission of N_2 and NO_x. For phosphate we estimated an emission of 10% of the applied phosphorus into surface water (Sonneveld, 1996; 1997).

As mentioned before, most important emission routes of biocides are by air (for soil and rock wool cultivation) and by drainage water (in soil cultivation) (Leendertse et al., 1997). Following the methodology of Leendertse et al. (1997) we only considered emission by air in this study, because we assumed that all tomatoes are cultivated on rock wool and that drain water is recycled. The emission of biocides into the atmosphere through window panes or chinks varies between 1 and 40% of the amount applied (Woittiez et al., 1996). The emission factors are from Woittez et al. (1996) and Baas et al. (1996) (Appendix 3.II). They estimated the emission factors on the basis of the vapour pressure of the active ingredient(s) of the biocide and the method of application. We only included the vapour pressure and do not consider the method of application, because the application method is one of the options. The emission factors for biocides are relatively uncertain, but although the use of a classified emission factor based on vapour pressure is a very rough approach to the actual situation, it still represents the best knowledge available for this analysis.

3.3.3 Emission index

An emission index indicates the impact of a compound on a specific environmental problem relative to the compound in which the environmental pressure is quantified. We used emission indices to estimate the overall effect of emissions of different compounds on a specific environmental problem. The pollutants considered in this model contribute to different environmental problems. For global warming and acidification we considered only one compound for each (CO_2 and NO_x) and therefore we did not need an emission index. For eutrophying compounds (NO_x, NO_3 and PO_4) we used the nutrification potentials as described by Heijungs et al. (1992). By using the nutrification potentials we quantified all eutrophying compounds in kg PO_4-equivalents (Table 3.2). For waste we simply assumed that the environmental impact is related to the sum of organic and non-organic materials in kilograms.

Table 3.2 *Emission indices for eutrophying compounds (Heijungs et al. (1992))*

Environmental theme	Compound	Impact factor
Eutrophication	NO_x	0.13 kg PO_4-equivalents/kg NO_x emitted
	NO_3	0.1 kg PO_4-equivalents/kg NO_3 emitted
	PO_4	1 kg PO_4-equivalents/kg PO_4 emitted

3.3.4 Environmental impact by biocides

For the evaluation of the environmental impact of biocide emissions several biocide characteristics are relevant. The most important chemical/physical characteristics of biocides related to their environmental impact are their persistency, toxicity and tendency to bind on organic material and soil particles (Mensink et al., 1995). We describe two approaches to estimate the environmental impact of biocide use. The first approach (Approach I in Box 3.3) considers the environmental impact from emissions to the atmosphere and soil and is adopted from Leendertse et al. (1997). This approach was used in the analysis. The second approach shows the potential hazard of the use of biocides (Approach II in Box 3.3) and was used in a sensitivity analysis described in Chapter 4. In this way we hoped to get more insight in the validity of the two different approaches.

The first approach by Leendertse et al. (1997) focuses on the emission of biocides (E_β) into the atmosphere. The emitted biocides are deposited on soil and surface water. Leendertse et al. assume that each biocide is exposed to decomposition in the atmosphere for 12 hours before it is deposited. The fraction remaining after 12 hours (Q_β) depends on the half-life (DT_{50}) of the biocide (Equation 8c Box 3.3). We, like Leendertse et al. (1997), did not consider spatial aspects of emissions, because this is influenced by many factors on a lower scale than adopted in this study and which are, moreover, difficult to quantify.

The environmental impact depends on the amount deposited and the toxicity of the active ingredient (Equation 8a Box 3.3). Therefore, the deposition is divided by the maximum allowable concentration (MAC) of a biocide for water organisms (Leendertse et al., 1997). Leendertse et al. chose the MAC for water organisms because these organisms are most sensitive to biocides (Leendertse, 1998). The MAC of biocides is calculated by using the method of the United States Environmental Protection Agency (USEPA) (Leendertse, 1998). The unit of the environmental impact of biocides is expressed in 10^3 m^3, which indicates the amount of water polluted by more than the allowable concentration for biocide β due to the use of biocide β. We considered the environmental impact of all biocides as an additive phenomenon (Equation 8 Box 3.3).

Box 3.3 *Alternative calculation for the impact M of biocides: two approaches*

Approach I: Environmental impact related to air emission of biocides

Total impact of biocide use $$Ma = \sum_{\beta} Ma_{\beta} \tag{8}$$

where

Impact of biocide β $$Ma_{\beta} = D_{\beta} / MAC_{\beta} \tag{8a}$$

Total deposition of biocide β from air to soil and surface water $$D_{\beta} = E_{\beta,a} * Q_{\beta} \tag{8b}$$

Fraction available after 12 hours $$Q_{\beta} = e^{-ct} \tag{8c}$$
$$c = -\ln 0.5 / DT50_{\beta}$$

where
$DT50_{\beta}$ = half-life of biocide β (hours)
D_{β} = total deposition of biocide β to soil and surface water by air emission (kg/ha/year)
$E_{\beta,a}$ = emission of biocide β to the air (kg/ha/year)
MAC_{β} = the Maximum Allowable Concentration for biocide β (mg/l)
Ma = impact of total biocide use due to air emission (10^3 m^3/ha/year)
Ma_{β} = impact of biocide β due to air emission (10^3 m^3/ha/year)
Q_{β} = fraction of biocide β available after 12 hours (fraction)
t = 12 (hours)

Approach II: Environmental impact related to use of biocides (indication of the potential hazard)

Total impact of biocide use $$Mu = \sum_{\beta} Mu_{\beta} \tag{9}$$

where

$$Mu_{\beta} = A_{\beta} * Q_{\beta} / MAC_{\beta} \tag{9a}$$

where
A_{β} = use of biocide β per year (kg/ha/year)
Mu_{β} = biocide-use score for biocide β (10^3 m^3/ha/year)
Mu = total score for biocide use (10^3 m^3/ha/year)
MAC_{β} = the Maximum Allowable Concentration for biocide β (mg/l)
Q_{β} = fraction of biocide β available after 12 hours (fraction)

In the alternative approach (Approach II Box 3.3), the environmental impact is related to the use of biocides (Equation 9 Box 3.3). In contrast to the first approach the total amount (A_β) applied is considered and not the amount emitted into the atmosphere. We considered the fact that if a biocide degrades rapidly the impact will be lower than if it degrades slowly. We calculated the amount remaining after 12 hours according to Leendertse et al. (1997) (Equation 8c Box 3.3) and divided the amount available after 12 hours by the maximum allowable concentration (MAC) of a biocide for water organisms. The potential hazard of the environmental pollution (the impact score) is described as the amount of water polluted by more than the permissible concentration for biocides β. The total potential hazard of biocide application is the sum of all the impact scores of the individual biocides used.

The estimation of the values of the half-life of biocides is based on the reactivity of the agent with OH radicals in the atmosphere (Atkinson, 1988; Kwok and Atkinson, 1995) and is according to the method of the Centre of Agriculture and Environment (CLM) (Leendertse et al., 1997). When data were not available at the CLM we used values from Tomlin (1995). Otherwise we estimated the half-life to be 50 hours, based on Leendertse et al. (1997).

Besides these two approaches, other methods exist for evaluating the environmental impact of the use of biocides (Mensink et al., 1995). An example of such a method, which could have been used in our model, has been developed by Huijbrechts (1999). Huijbrechts developed a method to calculate the toxicity potentials of emitted substances for environmental life cycle analysis purposes by adapting the USES 2.0 model (Uniform System for the Evaluation of Substances) developed by the RIVM (1998). Huijbrechts distinguishes between four impact categories: aquatic ecotoxicity, terrestrial ecotoxicity, sediment ecotoxicity and human toxicity. The resemblance between Huijbrechts and the methods we used are (1) the fact that the spatial context of emissions and depositions is not taken into account; the outcome, therefore, lacks any relation to a particular area, and (2) the sum used to estimate the environmental risk, which is the amount emitted divided by the No Effect Concentration. One important difference is that we only used the aquatic ecotoxicity, while Huijbrechts estimates the environmental impact for four impact categories.

We focused on the two approaches and did not use the method described by Huijbrechts for three reasons:

- For our analysis the calculation should not be too complex. However, it should include the most important aspects, which are the emission into the atmosphere, which is considered to be the most important emission, and the environmental impact on the aquatic system, because this ecosystem is assumed to be most sensitive to biocides.
- The method should give insight in the potential impact and should indicate the effect of applying abatement options. In other words, the method should show the effects on the reduction or change in use of biocides and the reduction in emissions.
- Our method will only be used to analyse biocide use in greenhouse horticulture; there is no need in this study to compare the results with the use of biocides in other agricultural sectors.

3.4 Model parameters related to reduction options

In this section we describe the options parameters. First, we describe reduction options that mainly affect the use of natural gas and the emission of NO_x from gas use. Then we present biocide options, which reduce either the amount of biocides used or the amount of biocides emitted into the atmosphere. Further, we describe the methods for reducing the emission of nutrients and finally we focus on options influencing the production or disposal of waste.

From each reduction option we required information on the reduction fractions for activities (rf_α in Box 3.2 Equation 1) and/or emissions ($rf_{\varepsilon,\alpha}$ in Box 3.2 Equation 2), and for possible extra activities (X_α in Box 3.2 Equation 1), and information on cost parameter values to calculate the annual cost. These cost parameters are investment costs (I in Box 3.2 Equation 6), fraction of the investment costs (o in Box 3.2 Equation 6) representing annual operation costs, and lifetime of the option (d in Box 3.2 Equation 6). All values refer to a situation in which the option is not applied. Some of the options considered have a twofold effect. They may, for example, reduce the use of natural gas as well as the use of biocides or they may reduce one activity or emission but meanwhile increase another. The adverse effect of an option on an activity is described by a negative reduction fraction (= increase). For an overview of all reduction options and their assumed impact on the activities and or emissions and the associated costs we refer to Appendix 3.I Table A2 and A3.

3.4.1 Energy related options

The energy options analysed affect the consumption of natural gas or the emission of NO_x. This effect is due to better insulation, increase in the efficiency of heat production, a change of temperature management or a reduction of NO_x by changing the burner. For calculating the costs of insulation material we assumed that the greenhouse has an area of 1 ha and wall surface of 1757 m^2 (Uffelen and Vermeulen, 1994). For more information about the reference situation see section 3.3.2.

Condensers

Condensers are used to increase the efficiency of heat production. The reduction in gas use ranges from 4% to more than 12%. We distinguished three types of condensers, which differ in the method of heat exchange (Appendix 3.I gives a more detailed description of each option). The reduction factors for gas use and the values of cost parameters are all according to Uffelen and Vermeulen (1994) and correspond with the values described in KWIN (1993).

Screens

Screens are applied horizontally under greenhouse roofs to reduce heat losses. The option group screens consists of fixed, movable and double screens. The reduction in gas use achieved by these options range from 5 to 25%. The reduction depends on crop and cultivation practice. The lower the average annual gas use the higher the annual reduction fraction. Movable screens and double screens can also be used to reduce biocide emission into the air. The effect of (horizontal) screens on gas use is based on KWIN and Uffelen and Vermeulen (KWIN, 1997; Uffelen and Vermeulen, 1994). Information about the gas use reduction and light reduction effect of a fixed screen and a movable screen are from Uffelen and Vermeulen (1994) and are typically for tomato cultivation. A fixed screen is only used for 6 weeks during the winter period (KWIN, 1997) and therefore the annual light-loss effect is ignored. After this period the fixed screen is disposed as waste. We estimated the total amount of waste produced per year to be 1200 kg (we assumed that the material has the same weight as dot foil (see section wall insulation)). A movable screen (of single and double isolating material) is permanently available and can be opened and closed throughout the year. Uffelen and Vermeulen (1994) assumed that a single movable screen is used in tomato cultivation night and day for 6 weeks and during the night for 18 weeks. We estimated that 25% (10-40%) of the reduction in gas use is achieved by a double screen based on KWIN (1997). Light reduction due to application of a double screen is about 9% (3-15%) on an annual basis (KWIN, 1993). The extra waste produced by using screens is estimated to be 1900 kg per 6 years and 3800 kg per 7 years for a movable and double screen respectively. We assumed that screens weigh one and a half times more than dot foil. We estimated the cost of a double screen to be the sum of the cost of a single moveable screen and the cost of a second layer of screen material (Uffelen and Vermeulen, 1994).

Movable and double screens may, as a side effect, reduce the emission of biocides to the atmosphere if the screens are closed during and shortly after application of biocides. Staay and Douwes (1996) measured the effect of screening (during application and for 12 hours after application) on biocide losses in condensation water and concluded that emissions to condensation water can be reduced by 80 to 90%. We estimated a 60% reduction in biocide emissions to the atmosphere by screening based on the research by Esch et al. (1996).

Wall insulation

Different techniques can be used to insulate the wall of the greenhouse. The options we analysed are movable wall screens (applied vertically), double glass in the wall, two types of foils (plane foil and 'dot' foil) and coated double glass. Reduction of gas use by these options varies from 0.4% to 8%. A movable screen can be opened and closed, double glass is permanent and foils are mainly used for a certain period during cultivation. All information about movable wall screens and double glass is from Uffelen and Vermeulen (1994). The extra production of waste from a movable screen was estimated to be 180 kg per 5 years (in line with the estimate for horizontally applied screens).

Parameters for estimating gas use reduction obtained by applying plane and dot foils and coated double glass are based on KWIN (1997). The method for calculating gas use reduction is according to Uffelen and Vermeulen (1994). For plane and dot foils we assumed that they are used during 6 weeks of the cultivation period and that consequently light reduction can be ignored. The light reduction due to application of double coated glass is based on the reduction value per m^2 wall (KWIN, 1997) and is converted to a value for a one hectare greenhouse according to Uffelen and Vermeulen (1994). The use of dot foil and plane foil results in 625 kg waste per 4 years and 225 kg waste per year, respectively (Genap, 1998). The costs of plane foil used for one year (NLG 0.15/m^2 wall and NLG 1.00/m^2 wall installation costs (NLG: NLG 1= EUR 0.45)) and coated double glass are based on KWIN (1997). The costs of dot foil were obtained from Genap (1998) on which we included annual costs of installation based on KWIN (1997) (NLG 1.00/m^2 wall).

Roof insulation

Glasshouse roofs can be insulated by using coated glass or double glass. These options result in a gas use reduction of 20 to 35%. Information about the reductions in gas use and light obtained by using single coated glass is derived from Out and Breuer (1995). The additional costs of coated single glass are derived from KWIN (1997) and Bouwman (1999). Information about the costs and reduction fraction of gas use from double glass is derived from Velden (1996). The fraction of light reduction is given in KWIN (1997). A problem related to double glass is that water condensation is reduced, which results in higher humidity encouraging the growth of fungi. We did not quantify this effect by raising fungicide use, but note this problem related to the application of double glass.

CO_2 application method

Each year CO_2 fertilisation in Dutch tomato cultivation accounts for the combustion of 70,000 m^3 gas per ha (KWIN, 1997). To reduce gas consumption for this purpose a heat buffer can be installed, or pure CO_2 can be applied. All options within the group reduce total gas use by around 10%. Information on the two sizes of heat buffers included in our analysis (with volumes of 80 m^3 and 100 m^3) is derived from Uffelen and Vermeulen (1994). The costs of pure CO_2 are from KWIN (1997) (The costs of tank rent and pure CO_2 are NLG 450 per month and 25 cents per kg CO_2, respectively). Potential effects of the use of pure CO_2 instead of exhaust gases on tomato production is not taken into account. We estimated that the use of pure CO_2 reduces the consumption of natural gas by 10%.

NO_x emission reduction

The combustion of natural gas releases NO_x. The NO_x emission can be reduced in two ways. The first one is to prevent the formation of NO_x by improving the combustion processes (this is done in a low-NO_x burner). The second option is to remove NO_x from exhaust gases, for example by adsorption techniques (Wypkema, 1991). We only considered the reduction of NO_x emissions during combustion using low-NO_x burners, resulting in a potential reduction in NO_x emission of 40%. This reduction percentage and the costs are based on Balthussen et al. (1996).

Temperature management

Gas use can not only be reduced by insulation, but also by changing climate management. We included the effects of reducing average temperatures, abandoning the use of a minimum tube temperature and the method of temperature integration.

We analysed the effect of reducing of the average temperature by one and two degrees. Information about the reduction in gas use and effects on tomato production are derived from Uffelen and Vermeulen (1994). We assumed that a lower average greenhouse temperature results in lower fungicide use (because fungi flourish better at higher temperatures) and estimated the effect to be 3% and 6% for one and two degrees reduction. Furthermore, a lower temperature may result in lower evaporation of the biocide, which in turn may result in lower emissions of biocides into the air (Esch et al., 1996). Hence, we estimated an air emission reduction of 1% per degree temperature reduction. Further, we analysed the effect of climate management by temperature integration and the effect of eliminating the use of a minimum heating pipe temperature. Temperature integration can be achieved by using the Econaut climate programme (developed by Hoogendoorn Automatisation). The effect of the Econaut on gas use reduction and costs are obtained from Voogt (1999) and Rijsdijk (1998).

A minimum heating pipe temperature might stimulate crop production, possibly due to increased transpiration and hence increased uptake of water and nutrients. The effect of cancelling the use of a minimum tube temperature on gas use is based on Bakker (1998) and Esmeijer (1998). We estimated a reduction in total tomato production of 1.5 % on an annual basis due to a decreased uptake of water and nutrients by the crop caused by a reduced transpiration.

A general comment on energy saving options is that we did not include the effect of reduced gas use on the CO_2 level in the greenhouse. Most of the reduction in gas use will occur in periods of intensive gas combustion for heating. In these periods the CO_2 concentration will be adequate (Uffelen and Vermeulen, 1994).

3.4.2 Biocide related options

We analysed greenhouse construction options and biocide application methods which reduce emission levels of biocides and options which reduce the amount of biocides used, such as biological control, the use of resistant plants, greenhouse hygiene, high pressure water cleaner and mechanical cleaning of greenhouse roofs.

Construction options
The construction of the greenhouse affects the amount of biocide used and biocide emitted into the atmosphere. We analysed several construction options, including the use of strips around window panes, greenhouses without windows and the use of insect netting. These options partly result in lower biocide emissions (1-80%) and partly in a decrease in the use of insecticides (50%). The use of strips around window panes reduces the emission of biocides into the air and, because of the better insulation it reduces gas use (Esch et al., 1996). The effect of strips on gas use and the related costs are obtained from Esch et al. (1996).

Information on costs and assumed reduction fractions for the activities and emissions for a greenhouse without windows is derived from Esch et al. (1996). The assumptions made by Esch et al. (1996) for a greenhouse without windows include: a 2% reduction in gas use, a reduction in the use of insecticides (same effect as netting: see below), an estimated 4-5% increase in tomato production due to an increase in the amount of light (fewer construction elements) and an additional use of electricity of 480,000 kWh per ha for ventilation and dehumidification.

Insect netting may also reduce the number of insects in the greenhouse. The effect of netting is examined by Roosjen et al. (1995). Their results indicated that the number of insects is considerably reduced when insect netting is used to cover the windows. White fly populations were reduced by 85%, red spider mite by 90%, the plant-louse by 80% and thrips by 50%. The relation between decreased number of insects and a decrease in use of insecticides is not obvious. We tentatively estimated a reduction of 50% of the use of insecticides due to application of insect netting. We derived the costs of application of insect netting from Vollebregt and Hermsen (1995).

Spraying technique

The choice of the spraying technique for biocide application may influence both the amount of biocides used and the amount emitted to the atmosphere and soil. The reduction in use varies from 5 to 25%; emissions to the air are reduced by 5% and to the soil by 50%. Electrostatic spraying, for instance, results in a relatively good contact of biocides on the crop, resulting in less use of biocides. In addition, the better application results in less deposition on the soil (especially interesting for soil cultivation) (Esch et al., 1996). The LVM (Low Volume Mister) results in high emissions to the air (low volume but small drops). For total greenhouse horticulture in the Netherlands the emission reduction to the air by changing application technique is estimated to be 10-20% (Esch et al., 1996). Balthussen et al. (1996) summarise the effect of other spraying techniques as being 20% emission reduction and 20% reduction of biocide use. In view of the different values in the literature we estimated the reduction in use achieved by using the most suitable application method to be 5% for the biocides groups fungicides, insecticides, greenhouse cleaning and rest group. We assumed no reduction in air emissions.

The tunnel technique for biocide application (Balthussen et al.,1996) is not taken into account in this study because it is mainly used in tablet cultivation (e.g. in pot plant cultivation). Reduction in biocide use and emissions and the costs of this option are described in Esch et al. (1996).

Os et al. (1994) investigated the removal of biocides from greenhouse air by suction. The technique is not efficient and it does not have any effect on emission to the atmosphere (Os et al., 1994). For this reason we did not consider this option in the analysis.

Resistant crop varieties

Improved resistance against pests and diseases is another option for reducing the amount of biocides needed. Balthussen et al. (1996) estimated a reduction in biocide use of 5% by using resistant plants. An example of the effect of improved resistance with tomato cultivation was the introduction of plants resistant to the tomato mosaic virus (LNV, 1990). The use of resistant crops increases costs by 10-25% (Balthussen et al.,1996). Based on this percentage we estimated the additional costs of resistant crops to be NLG 3160 per ha per year.

Biological control and scouting

We included the option of biological control as practised in integrated pest management, which implies that chemicals are also used for crop protection. This is done in such a way that biological predators are not affected (CBS, 1994). Scouting includes inspecting the crop for pests and diseases, using 'catch-plates' to monitor the population of insects in the greenhouse. Balthussen et al. (1996) estimated the reduction in biocide use obtained by adopting biological control and scouting methods to be 5-10%. We estimated fungicide and insecticide use reduction to be 15% and the reduction in use of greenhouse cleaning and the rest group to be 5%. The costs of biological control and scouting are based on Balthussen et al. (1996) and KWIN (1993) (NLG 13,000 per ha per year). The total annual costs (NLG 26,000 per ha per year) also include extra labour costs.

Greenhouse hygiene improvement

Improved hygiene may include different measures, resulting in a decrease in biocide use (about 10 to 20% for different biocide groups). The project group of the Multi-Year Agreement on Crop Protection (MJPG) lists measures that growers can apply to improve greenhouse hygiene (IKC, 1996). This list includes moving crop residues, cleaning of glass and fixtures, clothes and boots for visitors, disinfecting shoes, removing the weeds, a new application of substrate a year and clean planting material. Balthussen et al. (1996) estimated the total effect of these measures to be 20 % reduction in fungicide use and a 10% reduction in the use of insecticides and acaricides. Based on this we used a reduction fraction of 20% for the use of fungicides and 10% for the use of insecticides and the rest group. We tentatively estimated that the extra costs are NLG 1000 per ha per year.

High-pressure cleaner

A high-pressure cleaner can be used to disinfect the greenhouse during change of cultivation. In the analysis we included a high-pressure cleaner, which heats the water used to 150°C. The annual costs are derived from KWIN (1997). We estimated that this high-pressure cleaner reduces the use of chemical biocide of the greenhouse cleaning group by 80%.

Mechanical roof cleaner

Mechanical roof cleaners reduce the amount of chemical used for greenhouse cleaning. Balthussen et al. (1996) estimated a reduction of about 75%. We considered two options in this analysis: 1) investing in a mechanical roof cleaner installation, and 2) cleaning by contractors. Costs of both options are based on KWIN (1997). The investment costs of the installation depend on the rate of automation (NLG 40,000-110,000). We estimated the investment costs of an installation to be NLG 80,000. The costs of contracting out are NLG 25,000 per ha per year.

3.4.3 Nutrient emission reduction options

As described in section 3.3.2 emissions of nutrients to surface water occur despite the use of water recirculation. Changing the source of irrigation water may decrease the sluice fraction. Further, emissions of nutrients into the environment can be decreased by a connection to the sewer or by sluice water cleaning.

Source of irrigation water

As described in section 3.3.3 (emission and emission factors for the reference situation) we assumed that the reference situation includes water recirculation. However, 100% recirculation is not possible due to an increase in water salinity, which differs per crop depending on the crop's sensitivity to salinity and water quality. Water salinity rises because the input of some minerals is higher than the uptake by the crop, resulting in reduced production. The main elements of concern are Sodium (Na) and Chloride (Cl), because they appear abundantly in the water but are only taken up by the plants in low quantities (Sonneveld, 1996). The concentration in the nutrient solution is much higher than the concentration taken up by the plant because tomatoes need irrigation water with a relatively high EC (electronic conductivity) value to yield quality fruit (Sonneveld, 1996). Another reason why 100% recirculation is not always achieved is that growers are afraid that recirculation of drain water will spread (root) diseases.

The sluice fraction is directly related to the quality of irrigation water. Tomatoes are relatively tolerant of salinity. The minimum sluice fraction for tomato cultivation varies between 0 and 24% depending on the quality of the irrigation water (Haskoning, 1990). The higher the proportion of tap water in the irrigation water (which consists in our study of rainwater and tap water) the higher the sluice fraction. The quality of the tap water in the Netherlands varies from region to region. Reducing the amount of tap water used will reduce the sluice fraction and consequently reduce the emission of nutrients into surface water. The rainwater basin in the reference situation (500m^3) provides about 50-60% of total water use per year (KWIN, 1997; Bouwman, 1996).

The options considered for reducing the salinity of irrigation water lead to a reduction in nutrient emissions of 7 to 50%. We considered in our analysis: increasing the volume of the rainwater basin by 1000 m^3 and by 4000 m^3, increasing rainwater use by using a joint basin or ground store, the use of unsalted tap water and the use of osmosis water (inverse osmosis). An extra basin of 1000 m^3 raises the contribution of rainwater to total water use to 70% (KWIN, 1997) and results in an emission reduction of 5 to 10% (Balthussen et al., 1996). An extra basin of 4000 m^3 increases the proportion of rainwater in total water use from about 50% (in the reference situation) to 95% (KWIN, 1997). Based on this increase, we estimated the emission of nutrients to surface water to be 50% of that in the reference situation. The costs of an extra rainwater basin of 1000 m^3 and 4000 m^3 are derived from Bouwman et al. (1996) and from KWIN (1997), respectively.

A joint basin or joint water storage in the ground require the involvement of other greenhouse enterprises. The emission reduction for both options is estimated to be 50% (we assumed the same effect as the addition of an extra 4000 m^3 basin) (Anonymous, 1997). Information about ground storage of rainwater is derived from Persoon (1998).

Desalinisation of tap water also results in lower sluice fractions. We estimated an emission reduction of 30% (we assumed the same effect as the addition of an extra 4000 m^3 basin). Information about cost parameters was obtained from KWIN (1997). For an inverse osmosis installation we assumed an emission reduction of 30% and derived information about costs from KWIN (1997). For all options influencing irrigation water quality we assumed no effect on the use of fertilisers as a consequence of reduced emissions of nutrients.

Sewage treatment

Having sewage treated in public facilities instead of discharging it to surface water may reduce the emission of nutrients by sluice water. The reduction in nutrient inputs to surface water is estimated to be 10-20%, assuming 60% efficiency of the sewage treatment plant (Balthussen et al., 1996; VEKadviesgroep, 1994). Costs are based on Balthussen et al. (1996) and depend on the distance to an existing sewer (internal or external connection). Sewage charges are not included.

Drain water cleaning

Sluice water (and sewage water) can also be cleaned at a purifying plant (Haskoning, 1990). The purifying plant may be a local or regional facility. We assumed a reduction of

95% in the discharge of nutrients to surface water from the use of a purifying plant (Haskoning, 1990). The costs of sluice water cleaning are from Haskoning (1990).

Recirculation of drain water
Drain water is recirculated to reduce the emission of eutrophying compounds to ground and surface water. Recirculation has been compulsory since November 1996. In addition to reducing the emission of nutrients, recirculation results also in a decrease in use of water and nutrients. We estimated the reduction to be 30% of nutrient use, 70% of nutrient emission and 4000 m^3 less water used per hectare per year, all based on Sonneveld (1996). The costs of recirculating drain water are from Bouwman et al. (1996).

Drain water disinfection
Drain water is always disinfected when it is recirculated. In our analysis of a zero case situation (Chapter 4) we assumed drain water is recirculated and disinfected; nevertheless, we discuss here the effect of drain water disinfection. Several techniques are available, some of which result in extra gas use and/or extra electricity use. We estimated for all techniques a nutrient use reduction of 7% and a nutrient emission reduction of 30%. Because this option is only applied in combination with recirculation, we assume that total emission reduction by recirculation and drain water disinfection is about 80%. The costs of the different techniques are from KWIN (1993).

3.4.4 Options to reduce waste production

Waste is a term designating a range of waste products. We distinguished between organic waste, rock wool waste and foil waste (mainly plastics). We describe three groups of options for reducing the amount of (final) waste produced. The options affect the disposal of organic waste or the amount and disposal of inorganic waste (rock wool and foil waste). In our study, we considered a change in substrate use, composting organic waste and reducing foil waste.

Change of substrate use
There are several options for reducing the use of substrate. We considered duration of the use, a change in the cultivation method and changing the substrate material. The substrate may be used for more than one year. We considered the situation in which rock wool is used for three years instead of one year. The effect of this option on waste production (rock wool and foil) and costs are based on IKC (1993). In addition to using the substrate for a longer period, we analysed a V-cultivation system where less rock wool and foil is used per ha (the so-called V-system). We estimated the reduction in the use of rock wool to be 40% and the reduction in foil waste to be 20%. These estimates and associated costs are according to IKC (1993). Clay granulates can be used instead of rock wool. They last much longer and the rock wool waste is eliminated. Foil waste is reduced by 37.5% (IKC, 1993). The additional costs of using clay granulates instead of rock wool are derived from IKC (1993). Many alternatives for rock wool are available, including perlite, cocos, peat, glass wool, agrofoam and oasis (IKC, 1993). Analysing all these possibilities in relation to cultivation method and time of use would be too exhaustive. We chose the three

options described here because we believe they cover the range of possibilities for substrate use.

Composting

In the reference situation organic waste is removed from the glasshouse to a waste disposal unit. We analysed the option of composting organic waste on individual farms and at regional facilities. The estimated reduction fraction of organic waste for both options is 85% based on NCB Tilburg (1996). The estimated additional costs for on-farm composting are minus NLG 500 per ha greenhouse per year, based on NCB Tilburg (1996). IKC (1995) gives an overview of the costs of regional composting (NLG 42-73 per tonne organic waste). Based on this we estimated the costs to be NLG 75.50 per tonne organic waste. The additional costs related to the reference situation are minus NLG 3000 per hectare per year.

Reduction of foil waste

Foil waste can be reduced by recycling or preventing the production of waste by using biodegradable foil instead of the regular non-biodegradable type. We estimated that recycling reduces foil waste by 80%. The costs of recycling foil are derived from Balthussen et al. (1996) and are relative to the reference situation. The use of biodegradable foils is still in the investigative phase. Costs and reduction fractions are from Linden (1999). We assumed that the use of biodegradable foils increases the amount of organic waste by 20%.

3.5 Discussion and Conclusion

We developed a model that quantifies emissions of environmental pollutants related to Dutch tomato cultivation under glass and calculates the consequences of the application of combinations of technical options for reducing the environmental impact. In the following, we discuss our model approach and restrictions and briefly discuss some model uncertainties.

Model approach

We developed a model that quantifies all relevant emissions from tomato cultivation in the Netherlands contributing to the environmental problems of global warming, acidification, eutrophication, dispersion of toxic biocides and production of waste. The emissions are quantified by using the emission factor approach (Spakman et al., 1997a; IPCC, 1997). In this approach emissions are calculated as a function of a certain activity and accompanying emission factors. The reduction options analysed may effect the activity levels or the emission factors. The costs of the reduction options are calculated as annual costs per hectare tomato cultivation. The model enables us to analyse the cost-effectiveness of combinations of technical options that can be applied at the farm level.

A new element in our approach is an integrated analysis of all relevant environmental problems related to Dutch tomato cultivation, an analysis of the impact of technical options at the farm level on these problems and an analysis the cost-effectiveness of combinations of options. In Chapter 2 we analysed which emissions need to be considered when analysing the environmental impact of Dutch tomato cultivation

(Pluimers et al., 2000). The results of that study are used to define the system boundaries. Consequently, we considered in our model system the emissions of off-farm activities for the production of electricity and rock wool as well as the emissions of on-farm activities (see Figure 3.1). Further, we analysed the effect of technical options on all relevant environmental problems. For example, the use of a movable screen primarily saves gas, but it also affects the emissions of biocides to the air, the production of waste and yield of tomatoes. All these interrelations are taken into account. Finally, we analysed the cost-effectiveness of combinations of options. A combination of options is considered cost-effective if no other combination of options exists which result in an equal or higher reduction of the environmental impact at the same costs.

Several studies have been carried out to analyse possibilities for reducing the environmental impacts of agriculture in the Netherlands. The Dutch Council for Agricultural Research (NRLO), for example, has reviewed some models to analyse possibilities for sustainable agriculture (NRLO, 1992). None of these models are specific for Dutch greenhouse horticulture. Examples of sector-based studies are those by Ven (1996) and Jansma et al. (1994), which analyse the possibilities of a more environmental friendly production in which economic effects are taken into account for Dutch dairy farming and flower bulbs, respectively. Although the aim of these two studies is comparable to ours (to estimate the environmental impact and to analyse reduction strategies), the modelling approach is different. This is because greenhouse horticulture differs largely from cultivation in the open field, resulting in other environmental problems and other possibilities for managing these problems.

There are many studies focussing on the environmental impact of Dutch greenhouse horticulture and the possibilities to reduce this impact. Most of these studies have been used for the development of our model (Muilerman et al., 1993; Uffelen and Vermeulen, 1994; Vollebregt and Hermsen, 1995; Balthussen et al., 1996). None of these studies, however, focuses on the cost-effectiveness of combinations of options in relation to the overall environmental impact.

We mention two studies that are interesting for our analysis. First, the environmental life cycle analysis by Nienhuis and de Vreede (1994a) in which they quantify the total environmental impact (from cradle to grave) of one kilogram of tomatoes cultivated in the Netherlands. Their conclusion that most important emissions are released during the cultivation phase in greenhouses more or less supports our choice of the system boundaries (Pluimers et al., 2000). Second, the analysis of the costs and environmental effects of a reconstruction of the greenhouse sector by Bouwman et al. (1996). This study gives an overview of the possible reduction of the environmental impact of greenhouse horticulture for a combination of reduction options. It does not indicate the cost-effectiveness of these options or combination of options and this is one of the reasons why our approach, as discussed above, is new.

We used a multiplicative approach to calculate the effect of combinations of reduction options on activity or emission levels. Uffelen and Vermeulen (1994) also use a multiplicative approach in their calculations of the farm economic consequences of the application of energy saving options in greenhouse horticulture. Their method for calculating gas use, however, is more complex and makes use of the energy use program developed by the Research Station for Floriculture and Glasshouse Vegetables. With this program they calculated the effect of an energy saving option on the total energy demand in a greenhouse. The multiplicative approach to calculate the total reduction in energy use is also used in other studies, for example Bouwman et al. (1996) and Velden (1996). We also applied this approach to the calculation of non-energy related activity or emission levels.

Model uncertainties

We distinguish two types of model uncertainties. These are uncertainties in the model form and in values of model parameters (see also Hordijk et al. (1999)). Uncertainty in model form relates to the structure of the model and the relations described in the model. The parameter uncertainty relates to the assignment of values to parameters and variables of the model.

The most important uncertainty in our model structure is likely to be our description of the environmental effects of biocide use and emission (adapted from (Leendertse et al., 1997)). In our approach we only focused on emission to the atmosphere because we assumed that this emission route is most important. A study by Bor et al. (1994) illustrates that less than 50% of the amount applied in a greenhouse could be traced. Other uncertainties in the biocide impact approach are related to decomposition in the air, unknown deposition effects or the combined effect of biocides. It would have been too complex to consider all these aspects in this analysis. We emphasise that the approach used is not necessarily correct, but that it represents the best known method to quantify the environmental impact of biocide use in greenhouse horticulture. In Chapter 4 we analyse the sensitivity of model results to the use of different methods to describe the impact of biocides on the environment.

The uncertainties in parameter values are discussed for different types of values. Values for activity levels are well described in various statistical overviews (CBS, 1994; KWIN, 1997). The uncertainty of the values of the emission factors, however, depends on the type of emission factor. Emission factors related to natural gas use are well know and documented (IPCC, 1997). Emissions related to fertiliser use are either unknown or uncertain, which corresponds with the number of factors that influence the emissions. Further, there are uncertainties in the reduction factor values for reduction options. The reduction attained by an option is largely dependent on the growers' knowledge and experience, the (geographic) location of the farm, position and age of the farm, etc. We did not consider these aspects and assumed that options are applied at best available knowledge. This assumption may affect the results presented in Chapter 5, which may be considered too optimistic if best available knowledge is not available. In Chapter 4 we describe a sensitivity analysis to quantify the effect of variation of parameter values and assumptions on model structure on model results.

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Appendix 3.I Overview and explanation of reduction options considered in this study

Table A.1 *Overview of options (j) for reduction of environmental problems related to Dutch tomato cultivation (The groups are described in Table 3.1)*

Group	Options	Description of option
Condensers	single condenser	a condenser with one heat exchange circuit on a separate single net
	retour condenser	a condenser with one heat exchange circuit on the retour net to the boiler
	combi-condenser	a condenser with two heat exchanging circuits
Screens	fixed screen	this screen is fixed and used for 6 weeks during the winter period
	moveable screen	this screen can be opened and closed throughout the year
	double screen	as movable screen, but made of a double screen material
Wall insulation	screen	a movable wall screen which can be opened and closed throughout the year
	double glass	double instead of single glass in the wall
	foil	an plastic isolating material which is fixed and can be used for a certain period
	dot foil	as foil, but insulation material consists of two plastic layers
	double glass coat	as double glass, but one glass contains a isolating coating
Roof insulation	coated glass	coated glass reduces thermal emission
	double glass	double instead of single glass in roof
CO_2 supply method	heat buffer 80m^3 and heat buffer 100m^3	short-term heat storage in a tank - saves gas use by saving heat produced in a period with heat surplus for a period with heat demand
	pure CO_2	pure CO_2 from industry used instead of CO_2 derived from natural gas
NO_x emission reduction	low-NO_x burner	a burner with lower emission of NO_x per m^3 natural gas is used
Temperature management	T 1 degree lower	reduction of average temperature by one degree
	T 2 degrees lower	reduction of average temperature by two degrees
	no minimum pipe T	no use of minimum pipe temperature (which is done to stimulate evaporation)
	Econaut	a climate computer program to save energy by temperature integration
Construction change	strips around window panes	strips around window panes to reduce lost of heat and biocide emission into the air
	no windows	a greenhouse without windows, using ventilation pumps to settle humidity
	netting in window panes	nets in window panes to reduce the population of insects inside the greenhouse
	netting and strips	including nets and strips in window panes
Spraying technique	electrostatic spraying	a biocide spraying technique resulting in more equal dispersion on the crop
	advanced technique	a biocide spraying technique resulting in a lower emission to the atmosphere
Resistant crop varieties	resistant crop varieties	use of resistant crop varieties
Biological control and scouting	biocontrol and scouting	use of biological control (use of natural enemies and bacteria) and scouting the crop for pests and diseases (local application of biocides)
Greenhouse hygiene	greenhouse hygiene	increasing greenhouse hygiene by several actions: for example wearing clean shoes and clothes
High- pressure cleaner	high-pressure cleaner	a cleaning technique using a high-pressure water jet
Mechanical roof cleaner	own roof cleaner	investing in own cleaner
	roof cleaning by contract	cleaning is done by other firm (by wages)

Table A.1 *(continued)*

Group	Options	Description of option
Source of irrigation water	extra basin of 1000 m^3	is extra basin of 1000 m^3
	extra basin of 4000 m^3	is extra basin of 4000 m^3
	joint water basin	a joint basin with other firms
	unsalted tap water	unsalted tap water (reduce water salinity)
	reverse osmosis	reverse osmosis to reduce water salinity
	ground store	extra water storage in the ground
Sewage treatment	internal sewage connection	connection to sewage is internal (depends on situation)
	external sewage connection	connection to sewage is external
Drain water cleaning	local level	cleaning of drain water at local level
	regional level	cleaning of drain water at regional level
Recirculation	recirculation	recirculation of drain water
Drain water disinfection	heating	heating of drain water to 90 degrees
	ozonisation	use of ozone to clean water
	HD_UV	UV radiation under high pressure
	LD_UV	UV radiation under low pressure
	iodine	use of iodine for disinfection
	biofilter	use of a sand filter to disinfect drain water
Change of substrate use	multi year use of rock wool	using rock wool for three years
	multi year use + V-system	reduces the amount of rock wool used per ha
	clay granulates	using expanded clay (granulates) instead of rock wool reduces waste production
Composting	at the farm level	composting of organic waste at the farm
	at the regional level	disposing of organic waste at regional composting plant
Reduction of foil waste	recycling	recycling of plastic foils outside nursery
	bioplastics	use of biological degradable ground foil

Table A.2 *Reduction factors (rf) for options applicable in tomato cultivation for reducing activities (*rf_α*) or emissions (*$rf_{\varepsilon,\alpha}$*)and their side effects on activities (*X_α*). The unit is a fraction relative to the reference case (See for explanation Box 2).For an explanation of the type of options we refer to Table A.1*

Group	Options	rf_α α = gas use	$rf_{\varepsilon,\alpha}$ ε = NO_x α = gas use	rf_α α = use of electricity	rf_α α = use of fungicide	rf_α α = use of insecticide	rf_α α = use of greenhouse cleanings	rf_α α = use of rest biocides	$rf_{\varepsilon,\alpha}$ ε = biocide emissions into the air
Condenser	single condenser	0.044	0	0	0	0	0	0	0
	return condenser	0.098	0	0	0	0	0	0	0
	combi-condenser	0.125	0	0	0	0	0	0	0
Screen	fixed screen	0.082	0	0	0	0	0	0	0
	moveable screen	0.167	0	0	0	0	0	0	0.6
	double screen	0.25	0	0	0	0	0	0	0.6
Wall insulation	screen	0.007	0	0	0	0	0	0	0
	double glass	0.05	0	0	0	0	0	0	0
	foil	0.0048	0	0	0	0	0	0	0
	dot foil	0.011	0	0	0	0	0	0	0
	double glass coat	0.08	0	0	0	0	0	0	0
Roof insulation	coated glass	0.2	0	0	0	0	0	0	0
	double glass	0.35	0	0	0	0	0	0	0
CO_2 supply method	heat buffer 80 m^3	0.11	0	0	0	0	0	0	0
	heat buffer 100 m^3	0.11	0	0	0	0	0	0	0
	pure CO_2	0.1	0	0	0	0	0	0	0
NO_x emission	low-NO_x burner	0	0.4	0	0	0	0	0	0
Temperature management	T 1 degree lower	0.076	0	0	0.05	0	0	0	0.01
	T 2 degrees lower	0.16	0	0	0.06	0	0	0	0.02
	no minimum pipe T	0.1	0	0	0	0	0	0	0
	Econaut	0.08	0	0	0	0	0	0	0
Construction change	strips around window panes	0.015	0	0	0	0	0	0	0.01
	no windows	0.02	0	0	0	0.5	0	0	0.8
	netting in window panes	0	0	0	0	0.5	0	0	0
	netting and strips	0.015	0	0	0	0.5	0	0	0.01
Spraying technique	electrostatic spraying	0	0	0	0.05	0.05	0.05	0.05	0
	advanced technique	0	0	0	0.05	0.05	0.05	0.05	0
Resistant varieties	resistant crop varieties	0	0	0	0.05	0.05	0.05	0.05	0
Biological control and scouting	biological control and scouting	0	0	0	0.15	0.15	0.05	0.05	0
Hygiene	greenhouse hygiene	0	0	0	0.2	0.1	0	0.1	0
High-pressure cleaner	high-pressure cleaner	0	0	0	0	0	0.8	0	0
Mechanical roof cleaner	own roof cleaner	0	0	0	0	0	0.75	0	0
	by contract	0	0	0	0	0	0.75	0	0
Source of irrigation water	extra basin of 1000 m^3	0	0	0	0	0	0	0	0
	extra basin of 4000 m^3	0	0	0	0	0	0	0	0
	joint water basin	0	0	0	0	0	0	0	0
	unsalted tap water	0	0	0	0	0	0	0	0
	reverse osmosis	0	0	0	0	0	0	0	0
	ground store	0	0	0	0	0	0	0	0
Sewage treatment	internal sewage connection	0	0	0	0	0	0	0	0
	external sewage connection	0	0	0	0	0	0	0	0
Drain water cleaning	at local level	0	0	0	0	0	0	0	0
	at region level	0	0	0	0	0	0	0	0
Recirculation	recirculation	0	0	0	0	0	0	0	0
Drain water disinfection	heating	0	0	0	0	0	0	0	0
	ozonisation	0	0	0	0	0	0	0	0
	HP_UV	0	0	0	0	0	0	0	0
	LP_UV	0	0	0	0	0	0	0	0
	iodine	0	0	0	0	0	0	0	0
	biofilter	0	0	0	0	0	0	0	0
Change of substrate use	multi year use of rock wool	0	0	0	0	0	0	0	0
	multi year use + V-system	0	0	0	0	0	0	0	0
	clay granulates	0	0	0	0	0	0	0	0
Composting	at the farm level	0	0	0	0	0	0	0	0
	at the regional level	0	0	0	0	0	0	0	0
Reduction of foil waste	recycling	0	0	0	0	0	0	0	0
	bioplastics	0	0	0	0	0	0	0	0

Table A.2 *(continued)*

Group	options	rf_α α = use of nutrients	$rf_{\varepsilon,\alpha}$ ε = nutrient emissions into water α = use of nutrients	rf_α α = use of water	rf_α α = organic waste production	rf_α α = rock wool waste production	rf_α α = foil waste production	X_α α = extra gas use	X_α α = extra use of electricity
Condenser	single condenser	0	0	0	0	0	0	0	0
	return condenser	0	0	0	0	0	0	0	0
	combi-condenser	0	0	0	0	0	0	0	0
Screen	fixed screen	0	0	0	0	0	-0.22	0	0
	moveable screen	0	0	0	0	0	-0.07	0	0
	double screen	0	0	0	0	0	-0.12	0	0
Wall insulation	screen	0	0	0	0	0	0.008	0	0
	double glass	0	0	0	0	0	0	0	0
	foil	0	0	0	0	0	-0.02	0	0
	dot foil	0	0	0	0	0	-0.014	0	0
	double glass coat	0	0	0	0	0	0	0	0
Roof insulation	coated glass	0	0	0	0	0	0	0	0
	double glass	0	0	0	0	0	0	0	0
CO_2 supply method	heat buffer 80 m^3	0	0	0	0	0	0	0	0
	heat buffer 100 m^3	0	0	0	0	0	0	0	0
	pure CO_2	0	0	0	0	0	0	0	0
NO_x emission	low-NO_x burner	0	0	0	0	0	0	0	0
Temperature management	T 1 degree lower	0	0	0	0	0	0	0	0
	T 2 degrees lower	0	0	0	0	0	0	0	0
	no minimum pipe T	0	0	0	0	0	0	0	0
	Econaut	0	0	0	0	0	0	0	0
Construction change	strips around window panes	0	0	0	0	0	0	0	0
	no windows	0	0	0	0	0	0	0	480000
	netting in window panes	0	0	0	0	0	0	0	0
	netting and strips	0	0	0	0	0	0	0	0
Spraying technique	electrostatic spraying	0	0	0	0	0	0	0	0
	advanced technique	0	0	0	0	0	0	0	0
Resistant varieties	resistant crop varieties	0	0	0	0	0	0	0	0
Biological control and scouting	biological control and scouting	0	0	0	0	0	0	0	0
Hygiene	greenhouse hygiene	0	0	0	0	0	0	0	0
High-pressure cleaner	high-pressure cleaner	0	0	0	0	0	0	0	0
Mechanical roof cleaner	own roof cleaner	0	0	0	0	0	0	0	0
	by contract	0	0	0	0	0	0	0	0
Source of irrigation water	extra basin of 1000 m^3	0	0.075	1000	0	0	0	0	0
	extra basin of 4000 m^3	0	0.5	2000	0	0	0	0	0
	joint water basin	0	0.3	2000	0	0	0	0	0
	unsalted tap water	0	0.3	1000	0	0	0	0	12000
	reverse osmosis	0	0.5	1000	0	0	0	0	0
	ground store	0	0.5	1000	0	0	0	0	0
Sewage treatment	internal sewage connection	0	0.6	0	0	0	0	0	0
	external sewage connection	0	0.6	0	0	0	0	0	0
Drain water cleaning	at local level	0	0.95	0	0	0	0	0	0
	at region level	0	0.95	0	0	0	0	0	0
Recirculation	recirculation	0.3	0.7	4000	0	0	0	0	0
Drain water disinfection	heating	0.07	0.3	0	0	0	0	3000	2100
	ozonisation	0.07	0.3	0	0	0	0	0	4500
	HP_UV	0.07	0.3	0	0	0	0	0	3000
	LP_UV	0.07	0.3	0	0	0	0	0	300
	iodine	0.07	0.3	0	0	0	0	0	0
	biofilter	0.07	0.3	0	0	0	0	0	0
Change of substrate use	multi year use of rock wool	0	0	0	0	0.6	0	6000	0
	multi year use + V-system	0	0	0	0	0.4	0.2	4500	0
	clay granulates	0	0	0	0	1	0.375	6000	0
Composting	at the farm level	0	0	0	0.85	0	0	0	0
	at the regional level	0	0	0	0.85	0	0	0	0
Reduction of foil waste	recycling	0	0	0	0	0	0.8	0	0
	bioplastics	0	0	0	-0.2	0	0.625	0	0

Table A.3 *Cost parameters (I_j, d_j, o_j) used for the calculating of annual costs of reduction options applicable in tomato cultivation and their effect on production (rf_y). For explanation of the type of options we refer to Table A.1*

Group	Individual option	Investment (I_j) in NLG	Lifetime (d_j) in years	Fixed costs (o_j) as fraction of the investment	Production effect (rf_y) as fraction of the production
Condenser	single condenser	24000	7	0.01	0
	return condenser	60000	7	0.01	0
	combi-condenser	61000	7	0.01	0
Screen	fixed screen	13300	1	0.05	0
	moveable screen	163000	7	0.05	0.0285
	double screen	225280	6	0.05	0.09
Wall insulation	screen	41600	5	0.05	0.00473
	double glass	66000	10	0.05	0.01625
	foil	2375	1	0	0
	dot foil	6225	4	0.3	0
	double glass coat	12300	14	0.05	0.024
Roof insulation	coated glass	195030	14	0.005	0.108
	double glass	850000	10	0.05	0.16
CO_2 supply method	heat buffer 80 m^3	70000	14	0.02	0
	heat buffer 100 m^3	85000	14	0.02	0
	pure CO_2	36900	1	0	0
NO_x emission	low-NO_x burner	5000	14	0.01	0
Temperature management	T 1 degree lower	0	-	0	0.1
	T 2 degrees lower	0	-	0	0.22
	no minimum pipe T	0	-	0	0.015
	Econaut	12500	3	0.1	0
Construction change	strips around window panes	6500	7	0.005	0
	no windows	1500000	10	0.05	-0.04
	netting in window panes	70000	5	0.02	0
	netting and strips	73000	5	0.02	0
Spraying technique	electrostatic spraying	9000	7	0.05	0
	advanced technique	30000	6	0.02	0
Resistant varieties	resistant crop varieties	3157	1	0	0
Biological control and scouting	biological control and scouting	26000	1	0	0
Hygiene	greenhouse hygiene	1000	1	0	0
High-pressure cleaner	high-pressure cleaner	10000	10	0.05	0
Mechanical roof cleaner	own roof cleaner	80000	12	0.03	0
	by contract	25000	1	0	0
Source of irrigation water	extra basin of 1000 m^3	25000	8	0.03	0
	extra basin of 4000 m^3	30000	6	0.05	0
	joint water basin	80500	7	0.015	0
	unsalted tap water	64000	7	0.015	0
	reverse osmosis	170000	7	0.05	0
	ground store	60000	7	0.02	0
Sewage treatment	internal sewage connection	9000	10	0.02	0
	external sewage connection	30000	20	0.01	0
Drain water cleaning	at local level	31000	1	0	0
	at region level	24800	1	0	0
Recirculation	recirculation	38000	10	0.015	0
Drain water disinfection	heating	60000	6	0.015	0
	ozonisation	70000	6	0.0142	0
	HP_UV	70000	6	0.0175	0
	LP_UV	30000	6	0.0275	0
	iodine	50000	6	0.019	0
	biofilter	30000	10	0.05	0
Change of substrate use	multi year use of rock wool	-13000	1	0	0.02
	multi year use + V-system	-20550	1	0	0.02
	clay granulates	-10050	1	0	0.02
Composting	at the farm level	-500	1	0	0
	at the regional level	-3000	1	0	0
Reduction of foil waste	recycling	1015	1	0	0
	bioplastics	25400	1	0	0.005

Appendix 3.II: Emission factors used in the calculation of the emissions related to the production of tomatoes in the Netherlands

Table B.1 *Emission factors for emissions (per compound) due to the use of natural gas, electricity and fertilisers (with and without recirculation of drain water), rock wool production and biocide use. See text for literature references*

Activity	Compound or compound characteristics		Emission factor
Gas use	CO_2		1.776 kg /m^3 natural gas
	NO_x		1.42 * 10^{-3} kg /m^3 natural gas
Electricity use	CO_2		0.834 kg/kWh
	NO_x		1.35 * 10^{-3} kg / kWh
Fertiliser use (recirculation)			
N use	NO_x		0.025 kg NO_x-N/ kg N
	NO_3		0.1 kg NO_3-N/ kg N
P use	PO_4		0.1 kg PO_4-P/ kg P
Fertiliser use (free drainage)			
N fertiliser use	NO_x		0.025 kg NO_x-N/ kg N
	NO_3		0.4 kg NO_3-N/ kg N
P fertiliser use	PO_4		0.3 kg PO_4-P/ kg P
Rock wool production	NO_x		0.02 kg NO_x-N/ kg rock wool
Biocide use	Vapour pressure (mPa)		
	very high	> 10	0.40
	high	1 – 10	0.32
	mean	0.1 – 1	0.15
	low	0.01 - 0.1	0.08
	very low	< 0.01	0.02

4 Environmental systems analysis of Dutch tomato cultivation under glass II: Exploring the model system

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Abstract

In this Chapter we explore the model developed to analyse options for reducing the environmental impact of Dutch tomato cultivation and to gain insight into the model system. The analysis shows that the cost-effective combinations of options as selected by the model for different environmental problems frequently include combi-condensers, heat buffers, most options from the alternative temperature management group, electrostatic spraying techniques and several crop protection options (resistant varieties, biological control, greenhouse hygiene and high-pressure cleaners), all options from the change of substrate groups, composting at the regional level and all options from the foil waste reduction group. A sensitivity analysis shows that the model is relatively sensitive to including or excluding nitrogen oxide as an eutrophying compound, the price of natural gas and the emission factors for biocide emissions to the air.

4.1 Introduction

Dutch greenhouse horticulture contributes to a number of environmental problems. These environmental problems are largely caused by emissions of carbon dioxide (CO_2) from the combustion of natural gas and production of electricity, emissions of nitrogen oxides (NO_x) from the combustion of natural gas and the use of fertilisers, and from the production of electricity and rock wool, and emissions of nitrate (NO_3) and phosphate (PO_4) from fertiliser use (Chapter 2 (Pluimers et al., 2000)). Moreover, the use and emissions of toxic biocides and the production of waste contribute to environmental problems (Chapter 3 (Pluimers et al., submitted I)).

Concern about the environment has led to the adoption of several environmental policy plans for the horticultural sector by the Dutch government. As a result, growers are faced with an increasing number of environmental policy measures, which require monetary investments (Balthussen et al., 1996; Buurma et al., 1993; EZ, 1992; Muilerman et al., 1993). In 1997, several Dutch ministries and horticultural organisations drew up the 'Greenhouse horticulture and the Environment' agreement. This includes agreed targets for energy efficiency in Dutch greenhouse horticulture, reduction of the emissions and use of pesticides, the emission of nutrients, the production of waste and the use of supplementary lighting between 1995 and 2010 (LNV, 1997). It is, however, as yet not clear what the most cost-effective way is to achieve these goals simultaneously.

The overall aim of this study is to identify technical options to reduce the environmental impact of greenhouse horticulture in the Netherlands and to evaluate their cost-effectiveness. This study is carried out using the methodology of environmental systems analysis. This methodology is applied in a series of steps which include the building and application of the modeland the analysis of the consequences of different strategies (Checkland, 1979; Wilson, 1984). In Chapters 2 and 3 we described the results of the first three steps of the environmental systems analysis, consisting of (I) the problem definition, description of the system and system boundaries, (II) objectives of the analysis and (III) model approach. In this chapter we focus on the fourth step: the analysis of the model system. In the next chapter (Chapter 5 (Pluimers et al., submitted III)) we will complete the analysis with an optimisation analysis at the national level.

The aim of the present study is to explore the model as described in Chapter 3 to gain insight into the model behaviour. We explored the model for a so-called 'zero case', which is a reference situation describing tomato production under glass in which no options to reduce the environmental impact are applied. For the zero case we analysed reduction options with respect to their cost-effectiveness in reducing environmental problems. We chose the zero case situation as a basis for the model exploration because the present real-world situation is too complex to analyse the model behaviour, and because the different options in the model can interact and therefore all possible combinations should be considered. As an additional benefit, the analysis of the zero case may give a better indication of the most cost-effective strategy for tomato cultivation in the Netherlands. We also present results of a sensitivity analysis.

When exploring the models behaviour we examined different methods for multi-criteria analysis of the various environmental problems. The model can be used to identify the reduction of pollution in Dutch tomato cultivation that can be achieved at minimal costs. However, as described in Chapter 3, tomato cultivation contributes to a number of environmental problems, which are not easily compared. We investigated the overall environmental impact of the sector in two ways. First, by analysing the impact of emission reduction options for each individual environmental problem and using this as a basis for an overall evaluation, without attempting to quantify the overall impact on the environment. Alternatively, we used a more integrated approach by expressing the total environmental impact in terms of one generic environmental indicator. In this way, we could evaluate the efficiency of options while considering the total environmental impact of the sector. We applied different methods to weigh environmental problems for the analysis of the cost-effectiveness of combinations of options to reduce total environmental impact. We used five different multi-criteria methods to evaluate the effects of these methods on the results.

4.2 Methodology

4.2.1 Model description

Our model calculates the environmental impact (M) of tomato cultivation under glass and the effect of the application of combinations (J) of reduction options (j) on the environmental impact M. A short summary of the model follows below. For a detailed description we refer to Chapter 3.

The model input consists of different activities (A) related to tomato cultivation, which result in emissions (E) of polluting compounds (ε). The activities included are the use of natural gas, fertilisers, biocides, the production of electricity and rock wool, and the production of waste. The emissions are calculated using an emission factor (F) approach (Spakman et al., 1997a). The environmental problems (μ) considered are global warming, acidification, eutrophication, dispersion of toxic compounds (biocides) and the production of waste. The model includes all important sources of pollutants resulting from activities at the farm level, as well as from the production of inputs (electricity and rock wool) (Pluimers et al., 2000). The emissions are quantified in kilograms CO_2 for global warming, in kilograms NO_x for acidification and in kilograms waste for the problem of waste production. The emissions of eutrophying compounds are expressed in PO_4-equivalents, using classification factors from Heijungs et al. (1992). The impact of the emission of biocides (Ma) is quantified using the biocide-air-emission score as described by Leendertse et al. (1997).

The model includes 58 technical options (j) to reduce emissions of pollutants, either by reducing the amount emitted or by reducing the activity levels. The 58 options are arranged in 22 groups. Each group includes a number of options, which are not applicable simultaneously in the greenhouse. The 22 groups are: condensers, screens, wall insulation, roof insulation, CO_2 supply method, temperature management, NO_x emission reduction, change in greenhouse construction, spraying technique, resistant tomato varieties, biological control and scouting, greenhouse hygiene, mechanical roof cleaners, high-pressure cleaners, recirculation of drain water, drain water disinfection, sewage treatment, source of irrigation water, drain water cleaning, change in substrate use, composting, and reduced use of plastic foils.

The costs of applying reduction options (C) are quantified as annual costs (NLG: NLG 1= EUR 0.45)) per hectare. The costs are the sum of the annual investment costs (CI), the operational costs (CO) and variable costs (CV). The annual investment costs are a function of the total investment (I), the lifetime (d) of an option and the interest rate (r). The operational costs include maintenance, insurance and administrative costs. The variable costs consist of the savings or costs due to reduction or increase in activity levels, for example savings or increase in gas use, and the effect of options on the tomato yield.

4.2.2 Five methods for summarising the environmental impact

Our model quantifies the impact of tomato cultivation on the environment in terms of emissions of different pollutants to the environment. These compounds contribute to different environmental problems. In this chapter we explore different ways to evaluate the overall environmental impact of different strategies on the environment. This can be done using multi-criteria analysis.

A multi-criteria analysis performs an overall evaluation on the basis of different criteria (Ministry of Financial Affairs, 1986), which may be kg CO_2-equivalents, kg waste, etc. These criteria have different units, which means that they cannot be summed. Moreover, in a multi-criteria analysis weights are assigned to the different criteria (Ministry of Financial Affairs, 1986) (Box 4.1).

Several methods of multi-criteria analysis are available (Ministry of Financial Affairs, 1986; Soest et al, 1997; Goedkoop, 2000). Some of these include many types of criteria (economic, social, environmental, etc.) and result in one overall value (Andreoli and Tellarini, 2000). In this way the alternatives examined can be ranked and the analysis results in one single optimal solution. In this chapter, we restricted the multi-criteria analysis to the different environmental problems and did not include economic criteria. The reason for this was that we aimed to obtain insight into the possible reduction of the environmental impact by tomato cultivation at different costs (the cost-effectiveness of environmental reduction options). This type of multi-criteria analysis in which all environmental criteria are summarised is common in life cycle analysis (LCA) (Heijungs et al., 1992; Kortman et al., 1994; Lindeijer, 1996). To determine a cost-effective reduction of the total environmental impact of tomato cultivation we analysed the effect of the use of five different multi-criteria methods (Table 4.1). For each multi-criteria method we determined the cost-effective combinations of options and compared the results.

Box 4.1 *Multi-criteria methods applied in the analysis to compare overall environmental impact*

Method for multi-criteria analysis based on emission levels or environmental impact as used in Distance to target, NSAEL, Panel and Marginal costs method

Normalisation procedure 1 $Mn_\mu = M_\mu / N_\mu$

Valuation $M = \sum_{\mu \in u} (Mn_\mu * W_\mu)$

M = total environmental impact (unit depending on weighing method)
M_μ = total impact for environmental problem μ (impact unit /ha/year)
Mn_μ = normalised impact for environmental problem μ (fraction)
u = set of environmental problems
μ = index for type of environmental problem considered: climate change, acidification, eutrophication, dispersion of toxics and production of waste.
W_μ = valuation factor for environmental problem μ (see Table 4.3)
N_μ = normalisation factor for environmental problem μ (impact unit/year) (see Table 4.2) For Marginal cost method $N_\mu = 1$

Method for multi-criteria analysis based on activity levels (α) including normalisation and valuation as used in the MPS method

Normalisation procedure 2 $Mn_\alpha = \dfrac{N_{max} - A_\alpha}{(N_{max} - N_{min})}$

Valuation[1] $M_{mps} = \sum_{\alpha \in u} (Mn_\alpha * W_\alpha)$

[1]) to make the score of the environmental impact comparable with the other scores we calculate M as :

$$M = M_{max} - M_{mps}$$

α = index for type of activity included in the weighing: energy use, biocide use and N and P use. The energy use is calculated as function of the gas use and use of electricity (see Table 4.4). Biocide use and N and P use are according Chapter 3
A_α = activity level (in kg/ha/y) (see Chapter 3 for detailed description)
M_{mps} = score using MPS weighing method (unitless)
M_{max} = maximum achievable score (unitless)
M = converted environmental impact score using MPS weighing method (unitless)
Mn_α = normalised impact for activity α (fraction)
N_{max} = upper boundary of the target value (kg/ha/y) (see Table 4.2)
N_{min} = lower boundary of the target value (kg/ha/y) (see Table 4.2)
W_α = valuation factor for activity α (see Table 4.2)
u = set of activities

Table 4.1 *Five different methods of multi-criteria analysis applied in the study, using two different normalisation procedures (see text, Box 4.1 and Table 4.2) and five different valuation methods (Table 4.3)*

Method of multi-criteria analysis	Normalisation procedure [2])	Normalisation values based on [2]):	Valuation based on [3]):
I. Distance to target	Procedure 1	'European region'	Distance between an environmental target and the actual situation
II. NSAEL[1])	Procedure 1	'Dutch territory'	The excess factor of current emissions relative to a NSAEL[1])
III. Panel	Procedure 1	'Dutch territory'	Experts' view
IV. Marginal costs	No normalisation	-	The marginal costs of emission reduction
V. MPS	Procedure 2	'practice in tomato cultivation'	Greenhouse sector's view

[1]) NSAEL = No Significant Adverse Effect Level
[2]) See Table 4.2
[3]) See Table 4.3

A multi-criteria analysis is usually performed in two steps (Box 4.1). The first step is normalisation, in which the effect scores (emissions or environmental impact scores) are related to some starting point. Normalisation provides an insight into the significance of the various environmental effect scores (or emissions) generated by the system. In addition, the normalisation results in dimensionless values for the different environmental scores, so that these different scores can be compared. The second step in the multi-criteria analysis is the valuation, where we assigned weights to the different environmental problems (Lindeijer, 1996).

In the five multi-criteria methods we used two different procedures for normalisation (Box 4.1). Procedure 1 is generally used in LCA. In this procedure, the normalised score is calculated by dividing the effect scores (M_μ) by those of a certain reference area (N_μ see Box 4.1). The resulting normalised values have the same (or no) dimension and reflect the relative shares of the calculated damages to the reference. We applied this procedure in three of the five multi-criteria methods. The second normalisation procedure we applied is presently used by the Dutch greenhouse sector (Environmental Project for Ornamental Plants (MPS) (See Box 4.1). This normalisation results in a value that illustrates the distance between the environmental performance of a farm and the goal of 'adequate environmental performance', for which an upper (N_{min}) and lower (N_{max}) boundary are determined by the sector in co-operation with farmers (Stiching Milieukeur, 1998). In this procedure, the higher the normalised score the better. This is contrary to the first normalisation procedure, where lower normalised scores are better. We applied this procedure in one of the multi-criteria methods used.

Table 4.2 *Values used in the normalisation procedure 1 and 2 as described in the text, Table 4.1 and Box 4.1*

Normalisation procedure 1		
Normalisation values based on total emissions from Europe (Blonk, 1997)		
Environmental problem (μ)	Nμ	Unit
Global warming	$6.5 * 10^{12}$	kg CO_2-eq/y
Acidification	$5.6 * 10^{10}$	kg SO_2-eq/y
Eutrophication	$1.9 * 10^{10}$	kg PO_4-eq/y
Pesticide use	$4.8 * 10^{8}$	kg active ingredient/y
Normalisation values based on total emissions from Dutch territory (Blonk, 1997)		
Environmental problem (μ)	Nμ	Unit
Global warming	$2.1 * 10^{11}$	kg CO_2-eq/y
Acidification	$9.2 * 10^{8}$	kg SO_2-eq/y
Eutrophication	$1.1 * 10^{9}$	kg PO_4-eq/y
Aquatic toxicity	$8.9 * 10^{12}$	m^3/y
Waste production	$8.8 * 10^{9}$	kg waste /y

Normalisation procedure 2			
Normalisation values for tomato cultivation as defined by MPS (Stiching Milieukeur, 1998) based on activity levels (A) in Dutch tomato cultivation			
Activity (α)	N_{min}	N_{max}	Unit
Energy use	21500	24500	GJ/ha/y$^{1)}$
Biocide use	5	15	kg active ingredient/ha/y
N use	1000	3000	kg/ha/y
P use	300	750	kg/ha/y

$^{1)}$ These units differ from the units of Mμ. The energy use is calculated as: gas use x $35,17.10^{-3}$ + electricity use x 9.10^{-3}. Biocide use, N and P use are calculated by the model.

Valuation is usually the second step in the multi-criteria analysis, although sometimes no normalisation takes place. In the valuation the impact scores or normalised impact scores are multiplied by weighing factors (Wμ, see Table 4.3) and then summed (Box 4.1). In each multi-criteria method we applied a different set of weighing factors.

Below, we describe the five different multi-criteria methods that we applied in this study (See also Tables 4.1 to 4.3 and Box 4.1).

I. In the Distance to target method we combined a normalisation procedure 1 with a valuation method based on the difference (distance) between an environmental target and the actual situation. The larger the distance to a defined environmental target, the more serious an environmental problem is considered to be and the higher the weighing factor (used in the valuation procedure) is. The weighing factors are the same as those used in the Eco-Indicator 95 methodology as described by Goedkoop (1995). The target values used by Goedkoop (1995) to calculate the weighing factors are based on an analysis of the damage to ecosystems and human health caused by an environmental pressure at the European scale. The weighing factors reflect the amount by which the emissions or effects should be reduced to result in an ecosystem impairment of less than 5% (Table 4.3). Normalisation procedure 1 is used in our Distance to target method (Box 4.1). The normalised score is calculated by dividing the impact scores by the European emissions (Europe excluding the former USSR) (Blonk, 1997) (Table 4.2) and reflects the relative contribution of the sector or hectare of tomato cultivation to the total environmental impact of Europe.

Table 4.3 *Values for the valuation factor (Wμ (Box 4.1) and Wα (Box 4.1)) used in the five different multi-criteria methods: (1) Distance to target method, (2) No-significant-adverse effect levels (NSAEL) method, (3) Panel method, (4) Marginal costs method, (5) MPS method*

(I) Distance to target (Goedkoop, 1995)		
Environmental problem (μ)	Wμ	Criterion on which the target value is based
Greenhouse effect	2.5	0.1° C per decade, 5% ecosystem impairment
Acidification	10	5% ecosystem impairment
Eutrophication	5	rivers and lakes, impairment of an unknown number of aquatic ecosystems
Pesticide use	25	5% ecosystem impairment
Waste production	no value available	--
(II) NSAEL (Kortman et al., 1994)		
Environmental problem (μ)	Wμ	Comments
Global warming	0.8	NSAEL dependent on scenario
Acidification	5.5	probably a maximum estimate
Eutrophication	2.5	probably a maximum estimate
Aquatic toxicity	0.6	weight based on small database of concentration data
Waste production	no value available	--
(III) Panel (Kortman et al., 1994)		
Environmental problem (μ)	Wμ	
Global warming	20.35	
Acidification	14.95	
Eutrophication	16.25	
Ecotoxicity	16.75	
Waste production	no value available	
(IV) Marginal costs (Bleijenberg and Davidson, 1996)		
Environmental problem (μ)	Wμ	
Global warming	0.10 NLG/kg CO_2	
Acidification	10.00 NLG/kg NO_x	
Eutrophication	9.50 NLG/kg PO_4	
Dispersion of toxic compounds	$6 * 10^{-10}$ NLG/m^3	
Waste production	1.60 NLG/kg waste	
(V) MPS weighing method (Stiching Milieukeur, 1998)		
Activity (α)	Wα	
Energy use	30	
Biocide use	40	
N use	10	
P use	10	

II. In the NSAEL (No Significant Adverse Effect Level) method we combined normalisation procedure 1 with a valuation procedure in which the excess factor of current emissions relative to a No Significant Adverse Effect Level (NSAEL) is an indicator for the harmfulness or seriousness of an environmental effect (Table 4.3). The NSAEL is defined as the level at which structural changes to ecosystems caused by an environmental pressure do not occur, or where the effects are considered acceptable. We used the excess factors developed by Kortman et al. (1994) in the valuation procedure. The excess factors relate to the Dutch area and the Dutch situation in the period 1988-1990. The normalisation values relate to the Dutch territory and agree with Kortman et al. (1994) (Table 4.2).

III. In the Panel method we combined normalisation procedure 1 with a valuation procedure in which the weighing factors are based on experts' views on the impacts on the environment (Table 4.3). Lindeijer (1996) argues that this valuation method can be seen as the most purely subjective one since there is direct communication with individuals or groups. The weighing factors used here are derived from Kortman et al. (1994) (Table 4.3). The normalisation used follows the first procedure. The normalisation values relate to the Dutch territory (Table 4.2).

IV. In the Marginal costs method the valuation uses the marginal costs of emission reduction in the Netherlands, based on Dutch policy targets. We calculated the total environmental impact by multiplying the emissions or impacts scores by the marginal costs derived from Blijenberg and Davidson (1996) and Soest et al. (1997) (Table 4.3). In this method no normalisation procedure is used (Table 4.1).

V. In the MPS method (from the Environmental Project for Floriculture (MPS)), in contrast with the methods discussed above, the environmental impact score is directly related to the activity levels on the farm. The activities considered in the valuation include energy use (use of gas and electricity), biocide use, use of N and P fertiliser, and the production of waste. The resulting MPS score lies between 0 and 100. This method uses the second normalisation procedure as described above. The normalisation quantifies the distance between the environmental performance of a farm and the goals of 'adequate environmental performance' as defined by the sector in co-operation with farmers. For the MPS normalisation we used the 'adequate environmental performance' targets set for tomato cultivation in the Netherlands (Stiching Milieukeur, 1998). The weighing values are also determined by the sector in co-operation with farmers (Stiching Milieukeur, 1998). For waste the value of the weighing factor is related to waste management practices (the rate of separate collection of different types of waste). Because our model does not include this waste management practice, but calculates how much waste has been produced, we did not consider this aspect in the calculation of the integrated environmental score. For this reason the maximum achievable MPS score in our analysis is 90. In the original MPS method a high score indicates a better situation (less environmental impact), while high scores in the other multi-criteria methods indicates a high environmental impact. For reasons of comparison we converted the MPS score by subtracting it from the maximum score (90) (Box 4.1).

The values used in the different normalisation and valuation procedures are listed in Table 4.2 and 4.3, respectively. The normalisation values (Nμ) sometimes have different units than the units of the values provided by the model output (Table 4.2). For global warming and eutrophication the units of the normalisation values are the same as for the model results (CO_2-eq and PO_4-eq, respectively). For acidification we converted the model output NO_x emissions to SO_2-equivalents using the classification factors described by Heijungs et al. (1992). For the environmental problems related to the use of biocide different normalisation values are available. We used normalisation values reflecting the biocide use (in kg active ingredient per year) or the volume of aquatic toxicity (quantified in m^3 per year). Both are also calculated by our model. The Distance to target, NSAEL and the Panel method do not have values for the production (disposal) of waste (Table 4.3) and so we did not consider waste in these multi-criteria methods. Consequently, the Marginal costs method is the only method in which we considered the production of waste.

4.3 Description of the 'zero case'

The model requires certain input information (see Box 3.2 and 3.3 in Chapter 3). The generic parameter values are given in Chapter 3. Other model inputs are specific to the reference situation to which the model is applied. These include activity levels (Table 4.4) and information on the costs of activities (Table 4.5). In this section we describe the information used for the analysis presented here.

As described above, the model calculates the environmental impact and costs of reduction options for a certain reference situation. The reference describes a situation with a specific tomato production (Y_{ref}) and specific activity levels ($A_{\alpha\ ref}$). In this chapter, we defined a reference situation in which virtually none of the options to reduce the environmental impact described in Chapter 3 are implemented. We refer to this hypothetical reference situation as the 'zero case'.

As described in the introduction we analysed the zero case to explore the model and to gain insight into the most cost-effective strategy for the tomato sector. We based the main zero case activity levels on tomato cultivation in the early 1990s. In the zero case, round tomato is cultivated in greenhouse type Venlo, using a high wire cultivation system, with a defined temperature regime (from the end of November to the beginning of January a night temperature of 18.5°C and a day temperature of 19.5°C, and from January to the beginning of November a night temperature of 18 °C and a day temperature of 18.5°C) and using natural gas as fuel in greenhouses (KWIN, 1993). Further, we assumed that the electricity used is produced in a coal-fired power plant. In the zero case rock wool is used as substrate for one year and is disposed as waste afterwards. The yield of tomatoes per hectare per year (Y_{ref}) in a Venlo type greenhouse under the cultivation practice described is given by Uffelen and Vermeulen (1994). The use of natural gas, when no reduction options are applied, in the early 1990s is according to Uffelen and Vermeulen (1994); the use of electricity is according to Nienhuis and Vreede (1994a) (Table 4.4).

In the zero case, water and nutrients are recirculated, and part of the drain water is discharged to surface water. Recirculation of water implies that water has to be disinfected. In the zero case water is disinfected by heating (KWIN, 1993). A basin of 500 m^3 is available to store rainwater, which is used for irrigation. If there is a water shortage, tap water is used. Water recirculation and disinfection and use of a basin to collect rainwater were not commonly applied in the early 1990s. Nevertheless, we included these options in the zero case and excluded them from the analysis of cost-effective combinations of options to reduce the environmental impact of tomato cultivation for the following reason. Recycling of drain water has been mandatory for substrate cultivation since November 1996 and the use of a rain water basin of 500 m^3 has been compulsary for substrate cultivation since November 1995 (Vollebregt and Hermsen, 1995). The use of nitrogen in tomato cultivation varies between 1000 kg N and 2000 kg N per ha per year (Sonneveld, 1993). The input of nitrogen and phosphorus fertilisers are according Nienhuis and Vreede (1994a), those of rock wool are according to Berg and Lankreijer (1994) and DLV (1991).

Table 4.4 *Model input for the zero case1): yield (Y_{ref}) and activity levels (A_{α} and X_{α})*

Parameter	Value	Unit	References/remarks
Yield (Y_{ref})	490000	kg/ha/y	(Uffelen and Vermeulen, 1994)
ACTIVITIES (A_{α})			
Gas use	691000	m^3/ha/y	(Uffelen and Vermeulen, 1994)
Use of electricity	83200	kWh/ha/y	(Nienhuis and Vreede, 1994a)
N fertiliser use	1152	kg N/ha/y	(Nienhuis and Vreede, 1994a)
P fertiliser use	271	kg P/ha/y	(Nienhuis and Vreede, 1994a)
Rainwater use	6000	m^3/ha/y	(Nienhuis and Vreede, 1994a)
Tap water use	1000	m^3/ha/y	(Nienhuis and Vreede, 1994a)
Biocide use	77.3	kg/ha/y	(CBS, 1994)
Fungicide use:	12.2	kg/ha/y	(CBS, 1994, 1997b)
Propamocarb-hydrochloride	4.10	kg/ha/y	(CBS, 1994, 1997b)
Dichlofluanide	2.40	kg/ha/y	(CBS, 1994, 1997b)
Bitertanol	1.90	kg/ha/y	(CBS, 1994, 1997b)
Tolyfluanide	1.80	kg/ha/y	(CBS, 1994, 1997b)
Bupirimaat	2.00	kg/ha/y	(CBS, 1994, 1997b)
Insecticide use:	4.7	kg/ha/y	(CBS, 1994, 1997b)
Fenbutatinoxide	1.30	kg/ha/y	(CBS, 1994, 1997b)
Hexythiazox	0.50	kg/ha/y	(CBS, 1994, 1997b)
Dichloorvos	2.10	kg/ha/y	(CBS, 1994, 1997b)
Cyhexatin	0.40	kg/ha/y	(CBS, 1994, 1997b)
Oxamyl	0.40	kg/ha/y	(CBS, 1994, 1997b)
Greenhouse cleaning:	1.6	kg/ha/y	(CBS, 1994, 1997b)
Formaldehyde	59.1	kg/ha/y	(CBS, 1994, 1997b)
Rest biocide use:	1.2	kg/ha/y	(CBS, 1994, 1997b)
Ethefon	1.2	kg/ha/y	(CBS, 1994, 1997b)
Rock wool use	8500	kg/ha/y	(DLV, 1991)
Rock wool waste production	35000	kg/ha/y	(DLV, 1991)
Organic waste production	35000	kg/ha/y	(DLV, 1991)
Foil waste production	4500	kg/ha/y	(DLV, 1991)
EXTRA ACTIVITIES (X_{α})			
Extra gas use	3000	m^3/ha/y	For recirculation and disinfection (Chapter 3)
Extra electricity use	2100	kWh/ha/y	For recirculation and disinfection (Chapter 3)

1) See Chapter 3 for model description

Chemical biocides are used to protect the crop and prevent pests and diseases. The following biocide types are distinguished in the zero case: fungicides, insecticides, soil disinfection agents, greenhouse cleaning agents and a rest-group containing biocides which cannot be ascribed to the other groups (CBS, 1994). Reduction options may affect the use or emission of a certain group of biocide without affecting all biocides used. The assumptions on the use of biocides in the zero case are based on CBS (1994, 1997b), which describes the use of biocides in tomato cultivation in 1992 and in 1995 in the Netherlands. We assumed that the highest dosage of a biocide application in the statistics of 1992 and 1995 represents the use in the zero case situation of the early 1990s (Table 4.4). This can be viewed as a worst case situation.

The price of the activities (P_{α}) is described in Dutch guilders (NLG) per unit activity (Table 4.5). The price of natural gas ($P_{\text{natural gas}}$), fertilisers ($P_{\text{fertilisers}}$) and rock wool ($P_{\text{rock wool}}$) and the profit from the tomatoes produced (P_{tom}) are derived from KWIN (1997). The price of electricity ($P_{\text{electricity}}$) is from Bouwman et al. (1996). We estimated the price of biocides for each biocide group by calculating an average price for all biocides applied (in NGL per kg active ingredient). We used the price lists of two firms selling biocides to Dutch growers (Agrarisch Centrum Maurik, 1998; Kringkoop, 1998) and the Dutch Biocide Manual (Asselberg et al., 1996). Using the individual prices and the amounts of all biocides applied, we estimated the average price of fungicides ($P_{fungicide}$), insecticides ($P_{insecticide}$), greenhouse cleaning agents ($P_{greenhouse\ cleaning\ agents}$) and the rest-group biocides ($P_{rest\ biocides}$).

Table 4.5 *Tomato price (P_{tom}) and prices of activities (P_α) in the zero case[1])*

Parameter	Value	Unit	References
Tomato price (P_{tom})	1.46	NLG/kg	(KWIN, 1993)
(P_α):			
Gas price	0.261	NLG/m^3	(KWIN, 1993)
Electricity price	0.1	NLG/kWh	(Bouwman et al., 1996)
Fungicide price	252	NLG/kg	see text
Insecticide price	1250	NLG/kg	see text
Greenhouse cleaning price	1400	NLG/kg	see text
Rest group biocide price	115	NLG/kg	see text
Fertiliser price	12.3	NLG/kg N+P	(KWIN, 1993)
Rock wool price	0.50	NLG/kg	(KWIN, 1993)

[1]) See Chapter 3 for model description

4.4 Analysis of the zero case

We analysed the consequences of applying the reduction options (j) for the 'zero case'. In the following, we review the cost-effectiveness of each option in reducing environmental problems caused by Dutch tomato cultivation. First, we present results for the individual options. Second, we present an analysis of combinations of options for different environmental problems. Finally, we describe the cost-effectiveness of combinations of options in reducing the total environmental impact, using five different methods for environmental multi-criteria analysis.

4.4.1 Cost-effectiveness of single reduction options

The reduction options (j) were analysed with respect to their cost-effectiveness (CE), which we defined as the annual costs per kg emission reduction, per m^3 reduction in biocide-air-emission score or per kg waste reduction (Box 4.2). The annual costs, and consequently the cost-effectiveness, may have a negative value. This negative value indicates that benefits are higher than annual investment and operational costs. Note that the cost-effectiveness may change with the definition of the reference situation, because the higher the gas use, the higher the gas savings per percentage reduction. For this reason, the values of the cost-effectiveness (Table 4.6) should not be interpreted as fixed and valid for any given reference. The cost-effectiveness can be used to compare different reduction options.

Box 4.2 *Calculation method of the cost-effectiveness of single reduction options*

Cost-effectiveness $$CE_{j\mu} = \frac{C_j}{(M\mu_{\text{zerocase}} - M\mu_{\text{zerocase}+j})}$$

$CE_{j\mu}$ = Cost-effectiveness of option j regarding environmental problem μ (NLG/unit environmental problem)

C_j = Annual costs of options j (NLG/ha/y) (see Chapter 3 for detailed description)

$M\mu_{\text{zero case}}$ = Environmental impact of problem μ in the zero case (unit/ha/y)

$M\mu_{\text{zero case}+j}$ = Environmental impact of problem μ in zero case plus implementaition of option j (unit/ha/y)

We analysed the cost-effectiveness of single reduction options for each environmental problem (μ). For each environmental problem we only considered the options that are intended to reduce the environmental problem at stake. For example, extending the use of rock wool from one to three years is an option designed to reduce the amount of waste produced, but as a side effect increases emissions of CO_2 (due to extra gas use for steaming) and emissions of NO_x (an increase due to the use of gas for steaming and a decrease due to a reduction in rock wool production). Here, we only analysed the cost-effectiveness of waste reduction and ignored the impact of CO_2 and NO_x. In the analysis of combinations of options (section 4.2 and 4.3), however, we also considered the side effects. The appearance of such side effects is an important reason for using the method of environmental systems analysis.

Most of the options to reduce CO_2 emissions studied here involve a reduction in the amount of natural gas used. Our results indicate that all type of condensers, heat buffers, the termination of use of minimum pipe temperature, the use of an Econaut and strips are paying options (have net negative annual costs) to reduce use in gas for the zero case, because the annual savings in gas use are higher than the annual costs (Table 4.6). The options for reducing NO_x emissions are the same as for CO_2 reduction, but additionally include the implementation of a low-NO_x burner. Obviously, the same options as for CO_2 emission reduction yield a positive return.

Eutrophying emissions include NO_x, NO_3 and PO_4 compounds. For the analysis of the cost-effectiveness of options reducing eutrophication we focussed on options affecting NO_3 and PO_4 emissions only, because the NO_x emission reduction options have already been discussed above. None of the options affecting the emissions of NO_3 and PO_4 included in the option groups sewage treatment, source of irrigation water and drain water cleaning are paying options. Within these groups the most cost-effective options are the internal sewage treatment, extra water basin of 4000 m^3 and regional drain water treatment (Table 4.6).

Options to reduce emissions of biocide to the air either affect biocide use or the amount of biocide emitted. Paying options are mainly those that reduce biocide use and include electrostatic spraying techniques, the use of resistant crop varieties and the use of a high-pressure cleaner and mechanical roof cleaner. Strips around window panes are also paying due to savings on natural gas consumption (better insulation) rather than savings on biocide use.

Options for reducing the production of waste affect the annual consumption of rock wool and plastic and alternative ways of dealing with organic waste. The most cost-effective options are the V-cultivation system in which rock wool is used for more than one year, composting of organic waste on a regional scale and recycling of foil waste.

4.4.2 Cost-effective combinations of options for a selected environmental problem

For each environmental problem we analysed which combinations of options are cost-effective. A combination of options was considered cost-effective when no other combination of options exists which results in lower emissions at equal or lower costs, or equal emissions at lower costs. A so-called Technical Coefficients Generator (TCG) (Ven, 1996) was developed to create all possible combinations of options and to calculate the costs and emissions or impact scores related to the environmental problem concerned. A filter selects all cost-effective combinations of options for the environmental problem studied (Chapter 3). Table 4.7 lists all options that are considered in the analysis of cost-effective combinations of options per environmental problem (global warming, acidification, eutrophication and the dispersion of toxic biocides and options for reduction of waste). Further, it lists the options that are selected in one or more cost-effective combinations of options.

From some option groups just one option is selected in the cost-effective combinations of options (Table 4.7). For instance, cost effective combinations of options to reduce global warming, acidification and eutrophication always include a combi-condenser and a heat buffer (volume 80 m^3) but not the other condenser types and alternative CO_2 supply methods. Further, all types of screens appear in the selection of cost-effective combinations of options, as well as the use of foil, dot foil and coated double glass as wall insulation, all types of roof insulating options, strips around window panes and most temperature management options. Some options were not selected at all in the cost-effective combinations of options. Wall screens, double glass in wall and a reduction of average temperature by 1°C (T 1 degree lower) were not present in the set of cost-effective combinations of options to reduce global warming, acidification and eutrophication. This means that within the group of options there are other options which have a higher reduction potential at lower or equal costs. The no-windows option (a greenhouse without windows that can be opened) and a reduction of average temperature by 1°C are only selected in the cost-effective combinations of options to reduce biocide emissions into the air.

To reduce biocide emissions and production of waste the model selects other options than those selected for global warming, acidification and eutrophication in the cost-effective combinations. The movable screen appears in cost-effective combinations for biocides and waste, while fixed and double screens did not occur in cost-effective combinations. This is because a movable screen can be additionally used to reduce the emissions of biocides into the air. Furthermore, we observed that insect netting, alternative spraying techniques and mechanical roof cleaning by contractors were not selected in the cost-effective combination of options for biocide emissions. This corresponds well with their cost-effectiveness (CE), which is relatively low compared with the cost-effectiveness of the other options within the group (Table 4.6). Options that were selected in the cost-effective combinations of options for the reduction of waste include all types of change of substrate use and composting at the regional level and the options from the foil waste group.

Table 4.6 *Total annual costs (Cj) and cost-effectiveness (CE) 1) of individual options (j) per environmental problem (μ)*

Option group 2)	Option (j)	Total annual costs (Cj) in NLG/ha/y	CE for CO_2 emission in NLG/kg CO_2 reduction	CE for NO_x emission in NLG/kg NO_x reduction	CE for PO_4-eq emission in NLG/kg PO_4-eq reduction	CE for biocide air-score in NLG/m^3 reduction	CE for waste production in NLG/kg waste reduction
Condenser	return condenser	-5550.05	-0.05	-57.72	-443.98	-	-
	single condenser	-3085.71	-0.06	-71.47	-549.78	-	-
	combi-condenser	-10217.46	-0.07	-83.30	-640.80	-	-
Screen	fixed screen	240.22	0.00	2.99	22.97	-	-0.19
	moveable screen	29728.08	0.15	181.42	1395.53	0.13	-94.37
	double screen	79293.78	0.26	323.25	2486.51	0.33	-146.84
Wall insulation	screen	14620.37	1.70	2128.60	16373.85	-	-406.12
	double glass	15743.65	0.26	320.90	2468.46	-	-
	foil	16126.07	2.74	3423.90	26337.67	-	-132.72
	dot foil	35222.64	2.61	3263.34	25102.64	-	-602.10
	double glass coat	4848.47	0.05	61.77	475.12	-	-
Roof insulation	coated glass	65824.68	0.27	335.42	2580.17	-	-
	double glass	220516.22	0.51	642.11	4939.27	-	-
CO_2 supply method	heat buffer 80 m^3	-9947.83	-0.07	-92.17	-708.97	-	-
	heat buffer 100 m^3	-7828.38	-0.06	-72.53	-557.92	-	-
	pureCO_2	21816.90	0.18	222.34	1710.34	-	-
NO_x emission reduction	low-NO_x burner	656.48	-	1.67	-	-	-
Temperature management	T 1 degree lower	57741.09	0.62	774.29	5956.10	14.47	-
	T 2 degrees lower	128347.38	0.65	817.52	6288.65	16.08	-
	no minimum pipe T	-7304.10	-0.06	-74.44	-572.61	-	-
	Econaut	-8327.66	-0.08	-106.09	-816.06	-	-
Construction change	strips around window panes	-1424.29	-0.08	-96.77	-744.39	-0.36	-
	no windows	311383.71	-	-	-	0.88	-
	netting in window panes	15994.45	-	-	-	0.08	-
	netting and strips	14100.56	0.77	958.03	7369.45	0.07	-
Spraying technique	electrostatic spraying	-2412.72	-	-	-	-0.12	-
	advanced technique	2498.09	-	-	-	0.13	-
Resistant crops	resistant crop varieties	-1181.81	-	-	-	-0.06	-
Biological control and scouting	biocontrol and scouting	22593.69	-	-	-	0.38	-
Greenhouse hygiene	greenhouse hygiene	-136.18	-	-	-	-0.003	-
High-pressure cleaner	high-pressure cleaner	-64201.71	-	-	-	-760.43	-
Mechanical roof cleaner	own roof cleaner	-49039.40	-	-	-	-619.56	-
	by contract	-35055.00	-	-	-	-442.88	-
Source of irrigation water	extra basin of 1000 m3	5100.37	-	-	517.90	-	-
	extra basin of 4000 m3	7989.46	-	-	121.69	-	-
	unsalted tap water	17869.33	-	-	479.24	-	-
	reverse osmosis	13252.63	-	-	336.42	-	-
	joint water basin	41152.31	-	-	626.80	-	-
	ground store	12724.34	-	-	193.81	-	-
Sewage treatment	internal sewage connection	1521.27	-	-	19.13	-	-
	external sewage connection	3355.57	-	-	42.59	-	-
Drain water cleaning	at local level	33480.00	-	-	268.39	-	-
	at regional level	26784.00	-	-	214.71	-	-
Change of substrate use	multi year use of rock wool	1834.00	-0.17	19.62	150.92	-	0.09
	multi year use + V-system	-6711.50	0.84	-108.94	-837.96	-	-0.45
	clay granulates	5020.00	-0.47	31.09	239.13	-	0.14
Composting	at the farm level	-540.00	-	-	-	-	-0.02
	at the regional level	-3240.00	-	-	-	-	-0.11
Reduction of foil waste	recycling of foil	1096.20	-	-	-	-	0.30
	bioplastics	31009.00	-	-	-	-	-7.41 3)

1) See Box 4.2.

2) See Chapter 3 for a description

3) The negative value for the cost-effectiveness of bioplastics regarding the production of waste is due to the increase of organic waste in this option.

Table 4.7 *Overview of the options (j) included in the analysis of efficient combinations of options (J) per environmental problem (μ) and the options forming the set of efficient combinations of options. - = not included in the analysis; N.E. = included in the analysis but not selected by the model in efficient combinations (J); E = included in the analysis and selected by the model in one or more efficient combinations of options (J)*

Option group	Option (j)	Global warming	Acidification	Eutrophication	Biocide-air-emission score	Waste
Condenser	return condenser	N.E.	N.E.	N.E.	-	-
	single condenser	N.E.	N.E.	N.E.	-	-
	combi-condenser	E	E	E	-	-
Screen	fixed screen	E	E	E	N.E.	N.E.
	moveable screen	E	E	E	E	E
	double screen	E	E	E	N.E.	N.E.
Wall insulation	screen	N.E.	N.E.	N.E.	-	N.E.
	double glass	N.E.	N.E.	N.E.	-	N.E.
	foil	E	E	E	-	N.E.
	dot foil	E	E	E	-	N.E.
	double glass coat	E	E	E	-	N.E.
Roof insulation	coated glass	E	E	E	-	-
	double glass	E	E	E	-	-
CO_2 supply method	heat buffer 80 m^3	E	E	E	-	-
	heat buffer 100 m^3	N.E.	N.E.	N.E.	-	-
	pureCO_2	N.E.	N.E.	N.E.	-	-
NO_x emission reduction	low-NO_x burner	-	E	E	-	-
Temperature management	T 1 degree lower	N.E.	N.E.	N.E.	E	-
	T 2 degrees lower	E	E	E	E	-
	no minimum pipe T	E	E	E	-	-
	Econaut	E	E	E	-	-
Construction change	strips around window panes	E	E	E	E	-
	no windows	N.E.	N.E.	N.E.	E	-
	netting in window panes	N.E.	N.E.	N.E.	N.E.	-
	netting and strips	N.E.	N.E.	N.E.	E	-
Spraying technique	electrostatic spraying	-	-	-	E	-
	advanced technique	-	-	-	N.E.	-
Resistant crops	resistant crop varieties	-	-	-	E	-
Biological control and scouting	biocontrol and scouting	-	-	-	E	-
Greenhouse hygiene	greenhouse hygiene	-	-	-	E	-
High-pressure cleaner	high-pressure cleaner	-	-	-	E	-
Mechanical roof cleaner	own roof cleaner	-	-	-	E	-
	by contract	-	-	-	N.E.	-
Source of irrigation water	extra basin of 1000 m^3	-	-	E	-	-
	extra basin of 4000 m^3	-	-	N.E.	-	-
	unsalted tap water	-	-	E	-	-
	reverse osmosis	-	-	E	-	-
	joint basin	-	-	N.E.	-	-
	ground store	-	-	N.E.	-	-
Sewage treatment	internal sewage treatment	-	-	N.E.	-	-
	external sewage treatment	-	-	N.E.	-	-
Drain water cleaning	at local level	-	-	N.E.	-	-
	at regional level	-	-	E	-	-
Change of substrate use	multi year use of rock wool	N.E.	N.E.	N.E.	-	E
	multi year use + V-system	E	E	E	-	E
	clay granulates	N.E.	N.E.	E	-	E
Composting	at the farm level	-	-	-	-	N.E.
	at the regional level	-	-	-	-	E
Reduction of foil waste	recycling of foil	-	-	-	-	E
	bioplastics	-	-	-	-	E

The costs of efficient combinations of options and the resulting emissions are presented in Figures 4.1 to 4.5. In all figures we see that some cost-effective combinations of options have net negative costs. This means that for those combinations the annual savings on inputs, such as use of natural gas, exceed the annual costs of the implementation of reduction options. The shape of the curve is more or less the same for the different environmental problems.

The maximum reduction that can be achieved by combinations of the reduction options differs per environmental problem analysed (Figure 4.1 to 4.5). The emissions of CO_2 are about 1300 tonnes per ha per year in the unabated zero case (Figure 4.1). The model results indicate that these emissions could be reduced to about 430 tonnes CO_2 per ha per year, which corresponds to a reduction of 67% relative to the unabated zero case (Figure 4.1). The annual gas consumption is then about 20 m^3 per m^2 and the production of tomatoes is 28.5 kg per m^2 as opposed to 69.4 m^3 per m^2 and 49 kg per m^2 in the unabated case (Table 4.4). This reduction in tomato production is caused by a decrease in temperature and light in the greenhouses. The energy-efficiency improvement target for Dutch greenhouse horticulture in 1995 has been set at 50% in the so-called 'Multi-Year Agreement for Energy' (EZ, 1992). This is the percentage of gas used per kg of tomato production compared with the reference year of 1980 (56.2 m^3 per 24.1 kg tomatoes in 1980 (Uffelen and Vermeulen, 1994)). The combination of options resulting in the maximum reduction of CO_2 emission (67% reduction from the unabated situation) results in an energy-efficiency improvement of 70% compared with 1980.

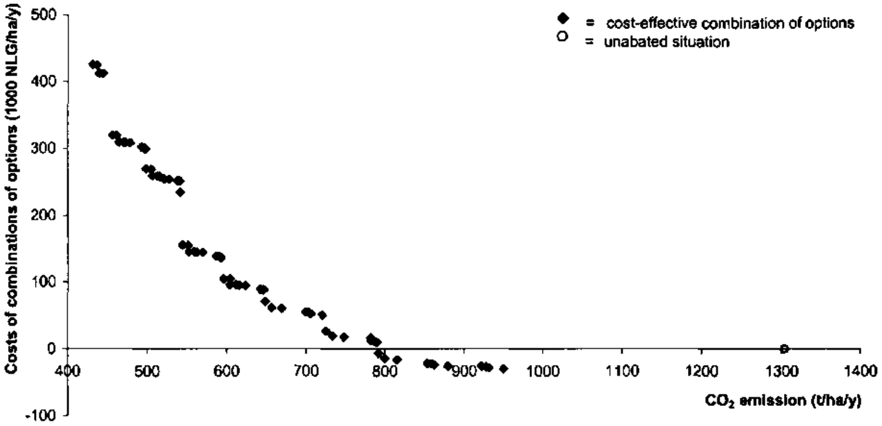

Figure 4.1 *The costs and resulting CO_2 emissions of cost-effective combinations of options to reduce CO_2 emissions from Dutch tomato cultivation*

For NO_x the model results indicate that emissions can be reduced from about 1364 to 386 kg per ha per year (Figure 4.2). This is a reduction of about 72% relative to the unabated zero case. This reduction is achieved by a decrease in gas use, lower NO_x emissions from gas combustion and the use of clay granulates instead of rock wool as substrate (as a result of which NO_x emissions during rock wool production are avoided). The associated tomato production is calculated to be about 28 kg per m^2. The energy-efficiency improvement relative to 1980 is then 68%. The options appearing in the cost-effective combinations of options are largely comparable to the options in the cost-effective combinations for CO_2 emissions, but additionally include the use of low-NO_x burners (Table 4.7).

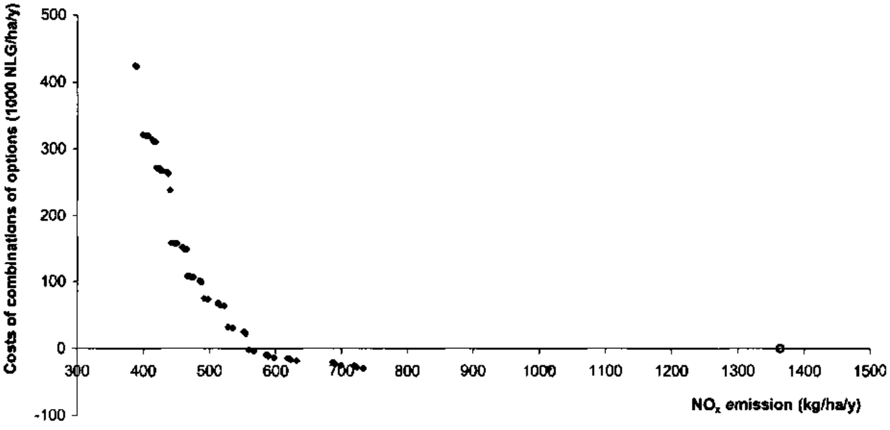

Figure 4.2 *The costs and resulting NO_x emissions of cost-effective combinations of options to reduce NO_x emissions from Dutch tomato cultivation*

Eutrophying emissions (NO_x, NO_3 and PO_4) could be reduced to 51.6 kg PO_4-equivalents according to the model results, which is a reduction of more than 83% relative to the zero case emission of 309 kg PO_4-equivalents (Figure 4.3). The reductions of NO_x, NO_3 and PO_4 emissions are 70%, 99% and 99%, respectively in this combination of options. N and P emissions into surface water are largely reduced by an internal sewage connection, an extra rain water basin of 4000 m^3 and regional treatment of drainage water. The production of tomatoes for this situation of maximal reduction of eutrophying emissions is about 28 kg per m^2.

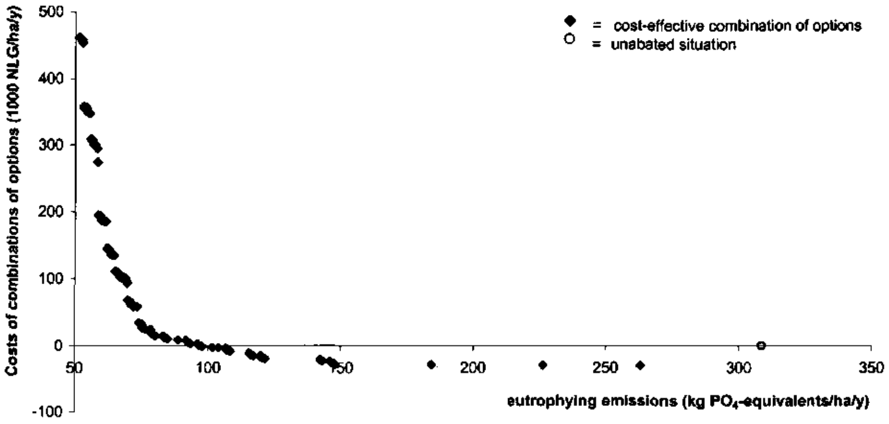

Figure 4.3 *Costs and resulting emission of eutrophying compounds of cost-effective combinations of options reducing eutrophying emissions from Dutch tomato cultivation*

The impact of biocide emissions into the atmosphere can be reduced from 395,315*10^3 m^3 to 10,719*10^3 m^3 per ha per year according to model results (Figure 4.4). This is a reduction of 97% compared with the zero case. The combinations of options with costs exceeding a maximum NLG 200,000 per ha per year all include the relatively expensive option of removing all windows (i.e. the no-windows option of the option group greenhouse construction). For a maximum reduction of biocide emissions, the biocide use is calculated to be about 12 kg per ha per year. Relative to the reference situation (77 kg per ha per year) this is a reduction of about 85%. Implementation of the combination of options for the maximum reduction in emissions of biocides to the air would reduce tomato production to almost 40 kg per m^2.

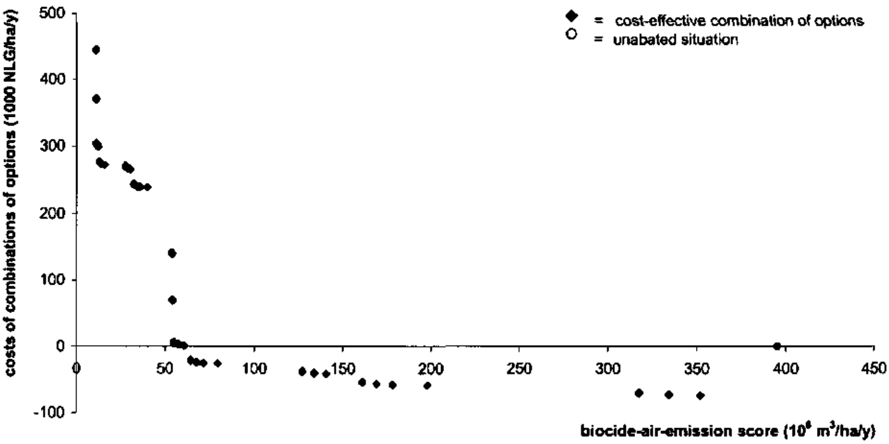

Figure 4.4 *Costs and resulting biocide air emission score of cost-effective combinations of options to reduce biocide use and emissions of biocides from Dutch tomato cultivation*

Most of the cost-effective combinations of waste reduction have negative costs (Figure 4.5). The lowest waste production that can be achieved by application of combinations of options is calculated to be 5812 kg per ha per year. This is a reduction of 92% compared with the zero case (74,500 kg organic and inorganic waste). The waste reducing options do not greatly affect the production of tomatoes (about 48 kg per m^2).

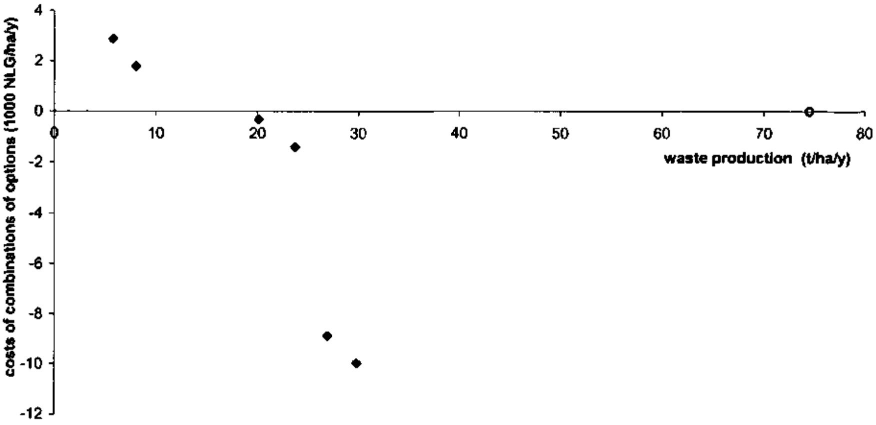

Figure 4.5 *Costs and resulting production of waste of cost-effective combinations of options to reduce the production of waste by Dutch tomato cultivation*

4.4.3 Using environmental multi-criteria methods to select overall cost-effective combinations of options

In the previous section we presented the cost-efficiency combinations of options to reduce the impact of tomato cultivation on a number of environmental problems. Our analysis showed that the options selected by the model differ for the different environmental problems. For instance, the options that were found cost-effective for global warming may be different from those selected for reducing the emission of biocides. There are also options that affect more than one environmental problem. This raised the question of which options are cost-effective for the overall environmental impact of tomato cultivation. To answer this we applied the five multi-criteria methods described earlier.

We analysed the efficiency of combinations of options for five different multi-criteria methods (Table 4.1). We included in this part of our analysis all options that were selected by the model in the set of cost-effective combinations of options in the analysis per environmental theme (see Table 4.7). The inefficient options (18 in total) were excluded from the analysis because they will not become cost-effective by applying a multi-criteria analysis. Figure 4.6 shows the costs of cost-effective combinations of options and their associated emission reductions using five different multi-criteria methods (Table 4.1).

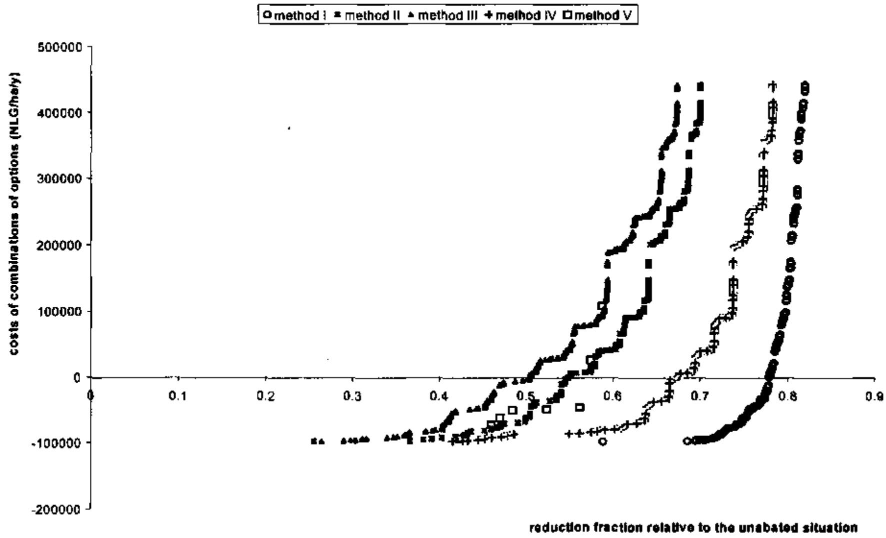

Figure 4.6 *Costs (C) of cost-effective combinations of options and the environmental score relative to the unabated zero case situation, calculated as* $(M_{zero\ case}-M_j)/M_{zero\ case}$*, using five multi-criteria methods (see Box 4.1):*
method I: Distance to target method
method II: No-significant adverse effect levels (NSAEL) method
method III: Panel method
method IV: Marginal costs method
method V: MPS method

The maximum reduction of the overall environmental impact calculated using the five multi-criteria methods ranges from 59% (MPS method) and 82% (Distance to target method) depending on the method used (Figure 4.6). The lowest reduction is calculated for the MPS method. This could be expected because the MPS method is based on reducing activity levels rather than the emissions. As a result, several options included in our analysis that reduce emissions but not activities have no effect. The results show that the maximum score in the MPS method (90) cannot be achieved by the options analysed.

The five multi-criteria methods resulted in different sets of cost-effective combinations of options. They differ with respect to the number of selected cost-effective combinations of options. The Distance to target, NSAEL, Panel, Marginal costs and MPS methods result in 130, 445, 499, 495 and 8 cost-effective combinations of options. Moreover, the combinations may consist of different options. The combinations of options selected by the model using the MPS method are all different from the combinations selected for the other four methods. The set of cost-effective combinations of options for the first four methods contain only two combinations that are identical for the four methods used. The sets of cost-effective combinations for the NSAEL and Panel methods have the most identical combination (279 out of 445 and 499 combinations are equal). In these two methods the same values for normalisation are used indicating that the choice of the normalisation method may largely determine the model's selection of options in cost-effective combinations of options.

Table 4.8 shows the extent to which each reduction option is selected in the set of cost-effective combinations of options resulting from the five multi-criteria analyses. We calculated the number of cost-effective combinations for which option was selected for six ranges of reduction costs. For example, 50% in Table 4.8 indicates that that option is selected in 50% of the combinations of options within that cost range.

Table 4.8 shows that some options are always selected by the model, regardless of cost-ranges and multi-criteria methods. These robust options include the combi-condenser, heat buffer (with a volume of 80m^3), high-pressure cleaner and composting at the regional scale. Low-NO$_x$ burners, improved greenhouse hygiene and to a lesser extent the use of double glass with coating as wall insulation were present in most of the cost-efficient combinations of options for the different multi-criteria methods. Some options were not or only rarely selected. These are the options to remove all windows (no-windows option) and the use of rock wool for more than one year. Further, we can see a shift towards more expensive options within groups with increasing reduction costs. For example, in the screen group the fixed screen is selected at relatively low costs (ranges I and II for most multi-criteria methods). When the reduction costs increase the movable screen is applied more frequently, while finally at highest costs (range VI) only the double screen appears in the cost-effective combinations of options. The pattern of this shift toward more expensive options with increasing reduction costs is largely the same for all multi-criteria methods. For some option groups the results differ per multi-criteria method used. Temperature management is an example. The option to lower the temperature in greenhouses by one degree appears in cost-effective combinations of options for the Distance to target and MPS methods, but not for the other methods.

Table 4.8 *The presence of reduction options in the set of efficient combinations of options (as a percentage of the number of the efficient combinations of options) resulting from five different methods for multi-criteria analysis. The percentages are tallied for ranges of costs of the reduction options: I) – 100,000-0 NLG/ha/y, II) 0-100,000 NLG/ha/y, III) 100,000-200,000 NLG/ha/y, IV) 200,000-300,000 NLG/ha/y, V) 300,000-400,000 NLG/ha/y, and VI) 400,000-500,000 NLG/ha/y. – indicates 0%.*

Group	Option	Distance to target method						NSAEL method						Panel method						Marginal cost method						MPS method		
		I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III
Condensers	combi-condenser	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Screens	fixed screen	63%	41%	-	-	-	-	54%	39%	-	-	-	-	57%	20%	-	-	-	-	41%	29%	-	-	-	-	-	-	-
	moveable screen	-	59%	27%	44%	58%	-	36%	45%	-	48%	-	-	35%	52%	17%	38%	-	-	37%	48%	10%	38%	-	-	-	-	-
	double screen	-	-	73%	56%	42%	100%	-	15%	100%	52%	100%	100%	-	28%	83%	63%	100%	100%	-	23%	90%	62%	100%	100%	-	-	-
Wall insulation	foil	6%	-	-	-	-	-	2%	2%	-	-	-	-	3%	-	-	-	-	-	1%	5%	2%	3%	-	-	-	-	-
	dot foil	16%	-	-	-	-	-	13%	6%	-	-	-	-	12%	4%	-	-	-	-	11%	13%	-	6%	-	-	-	-	-
	double glass coat	29%	100%	100%	100%	100%	100%	61%	89%	100%	100%	100%	100%	65%	96%	100%	100%	100%	100%	44%	71%	90%	88%	100%	100%	-	-	-
Roof insulation	coated glass	-	66%	100%	100%	-	-	3%	100%	100%	6%	-	-	16%	100%	83%	-	-	-	2%	100%	90%	9%	-	-	-	-	-
	double glass	-	-	-	-	100%	100%	-	-	-	94%	100%	100%	-	-	17%	100%	100%	100%	-	-	10%	91%	100%	100%	-	-	-
CO_2 supply method	heat buffer 80m^3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
NO_x emission reduction	low-NO_x burner	94%	100%	100%	100%	100%	100%	98%	100%	100%	100%	100%	100%	97%	100%	100%	100%	100%	100%	89%	97%	100%	98%	98%	100%	-	-	-
Temperature management	T 1 degree lower	-	-	-	6%	8%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100%	-
	T 2 degrees lower	-	-	-	94%	58%	100%	-	-	-	6%	69%	100%	-	-	14%	-	78%	100%	-	-	-	9%	70%	100%	-	-	100%
	no minimum pipe T	53%	72%	80%	-	33%	-	73%	92%	100%	91%	31%	-	82%	94%	85%	98%	22%	-	68%	89%	100%	89%	30%	-	-	-	-
	Econaut	47%	28%	20%	-	-	-	27%	8%	-	3%	-	-	18%	6%	2%	2%	-	-	32%	11%	-	2%	-	-	100%	-	-
Construction change	strips around window panes	35%	-	-	-	-	-	95%	81%	46%	73%	60%	-	100%	91%	58%	81%	69%	-	97%	93%	54%	83%	60%	5%	33%	-	-
	no windows	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	netting and strips	65%	100%	100%	100%	100%	100%	5%	14%	54%	19%	36%	100%	-	3%	39%	15%	28%	100%	3%	3%	46%	9%	37%	95%	67%	100%	100%
Spraying technique	electrostatic spraying	92%	100%	100%	100%	100%	100%	45%	47%	61%	49%	62%	67%	48%	56%	55%	53%	63%	59%	35%	45%	58%	46%	56%	65%	67%	100%	100%
Resistant crop varieties	resistant crop varieties	84%	100%	100%	100%	100%	100%	11%	18%	26%	20%	25%	29%	13%	20%	24%	19%	28%	27%	7%	14%	24%	16%	23%	35%	50%	100%	100%
Biological control and scouting	biological control and scouting	35%	100%	100%	100%	100%	100%	-	-	11%	-	9%	24%	-	-	8%	-	8%	23%	-	-	10%	-	9%	25%	67%	100%	100%
Greenhouse hygiene	greenhouse hygiene	100%	100%	100%	100%	100%	100%	98%	97%	93%	96%	96%	90%	100%	99%	95%	96%	98%	91%	99%	99%	94%	97%	96%	90%	100%	100%	100%
High-pressure cleaner	high-pressure cleaner	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Mechanical roof cleaner	own roof cleaner	98%	100%	100%	100%	100%	100%	39%	40%	43%	40%	45%	43%	41%	42%	39%	40%	45%	41%	38%	40%	44%	39%	42%	45%	83%	100%	100%
Source of irrigation water	extra basin of 1000 m^3	10%	17%	20%	25%	25%	29%	7%	12%	4%	8%	15%	10%	9%	18%	3%	16%	14%	-	6%	9%	2%	7%	7%	-	-	-	-
	extra basin of 4000 m^3	6%	31%	33%	31%	33%	29%	15%	28%	61%	35%	51%	57%	17%	28%	38%	33%	46%	50%	11%	18%	56%	29%	47%	65%	-	-	-
Sewage treatment	internal sewage treatment	80%	93%	80%	81%	83%	86%	81%	91%	93%	92%	93%	100%	73%	86%	82%	86%	95%	82%	49%	75%	94%	80%	86%	100%	-	-	-
Drain water cleaning	at regional level	-	14%	60%	56%	67%	57%	10%	28%	78%	45%	64%	100%	-	10%	55%	31%	43%	100%	6%	13%	68%	29%	54%	100%	-	-	-
Change of substrate use	multi year use of rockwool	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2%	-	-	-	-	-	-	-	-
	multi year use + V-system	90%	38%	7%	6%	-	-	31%	-	-	-	-	-	76%	52%	30%	29%	25%	-	17%	-	-	-	-	-	100%	100%	100%
	clay granulates	10%	62%	93%	94%	100%	100%	69%	100%	100%	100%	100%	100%	24%	48%	70%	71%	75%	100%	81%	100%	100%	100%	100%	100%	-	-	-
Composting	at the regional level	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	-	-	-
Reduction of foil waste	recycling	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	96%	100%	100%	100%	100%	100%	-		-

Table 4.9 *Relative weight (importance) of environmental problems relative to global warming for four multi-criteria analysis methods. The values of* W_μ/N_μ *are divided by the* W_μ/N_μ *of global warming (see Box 4.1 and Tables 4.1, 4.2 and 4.3)*

Multi-criteria method	Global warming	Acidification	Eutrofication	Biocide-air-emission score	Biocide use	Waste
I. Distance to target	1	464	684	- [1])	135417	-
II. NSAEL	1	1550	597	0.02	-	-
III. Panel	1	167	152	0.02	-	-
IV. Marginal Costs	1	70	95	$6*10^{-9}$	-	16

[1]) – means that this environmental problem is not considered in the multi-criteria method

Table 4.9 compares the relative weights as an overall weighing factor for four multi-criteria methods. The MPS was not included because this method largely differs from the other methods. The differences between the multi-criteria methods are due to the different valuation factors (W) and normalisation factors (N) used to calculate the overall environmental impact. From this overview we can see that, for example, acidification in the NSAEL method has a relative high weight compared with the other methods, the Distance to target method has a relatively high weight for biocide use and the Marginal costs method has a relatively low weight for emissions of biocides. These differences in overall weighing factor can explain some of the results of the different multi-criteria analyses in Table 4.8. For example, in the set of cost-effective combinations of options from the NSAEL method the low-NO_x burner and the options to reduce rock wool use both appear frequently. These are options that result in a lower NO_x emission (and consequently a lower score for acidification). Results from the Distance to target method show that options that reduce biocide use are frequently selected in all cost ranges, which agrees with its relatively high weight for biocide use.

Results from the five different multi-criteria analyses show that there are some robust options that are selected by all methods. However, the presence of less robust options in both the cost-effective combinations of options and the reduction of the overall environmental impact differs per multi-criteria method used. In other words, the results are sensitive to the multi-criteria method used. In the following section we present the results of a sensitivity analysis.

4.5 Sensitivity analysis

We analysed the sensitivity of our model results to selected assumptions on model structure and parameter values.

4.5.1 Sensitivity to alternative model structure

In building a model many assumptions need to be made about model structure. We analysed the impact of choices about model structure on model results. We investigated alternative approaches in the model for:

(1)The environmental impact of biocides; we used alternative indicators when calculating the impact because many uncertainties exist in the emissions of biocides from greenhouses, and environmental policy is not only based on emissions of biocides, but also on the use of biocides.

2) The environmental impact of eutrophying compounds by excluding NO_x from the calculations, because environmental policies do not always involve emissions of NO_x in the reduction of eutrophication.

(3)The overall impact of eutrophying compounds by using different approaches for calculating the total eutrophying emissions, because in environmental studies different methods are applied to quantify the impact of eutrophication.

(4)The system boundaries, because we concluded in Chapter 2 that some of the off-farm emissions should be considered, while in the environmental policy for the Dutch greenhouse sector these emissions are not considered.

Biocide impact indicator

The biocide-air-emission score included in our model quantifies the aggregated environmental impact of the biocides emitted into the air. The impact is calculated as a function of the amount emitted into the air, which depends on the amount applied and the vapour pressure of the active ingredient, the amount that degrades within 12 hours and the toxicity to water organisms (Chapter 3). This approach ignores emissions to soil and surface water, assuming they are less important (Leendertse et al., 1997). Indeed, most emissions of biocides that are lost from greenhouses are emitted to the air (Bor et al., 1994; Baas et al., 1996). However, there are also emissions of biocides to soil and water and their contribution to total emissions, and hence the total impact, is unknown. For this reason, we analysed the effect of applying two alternative biocide impact indicators. The first approach (biocide-use score) is based on biocide use instead of emissions and could be interpreted as an indicator for the total potential risk of biocides (Chapter 3). The difference with the approach we use (biocide-air-emission score) is that the impact of the total amount of biocides applied is taken into consideration, not only the amount emitted into the air. We estimated the potential risk as a function of the amount of biocide applied and the persistency and toxicity of the biocide (Chapter 3). The second approach (biocide use) simply sums the total use of biocides in kg active ingredient. The difference between this approach and our approach (biocide-air-emission score) is that the biocide use does not explicitly consider the amount emitted and the specific impact of biocides on the environment.

Table 4.10 *Model results (realised reduction in percentage relative to the zero case situation, the options selected and the related costs) for biocide emissions as calculated using our model and two alternative approaches for the biocide impact indicator (biocide air emission score, biocide-use score and biocide use). Results are shown for two cases: I) the cheapest combination of options, and II) the combination of options with maximal reduction*

Case	Our model: Biocide-air-emission score[1]	Alternative approach: Biocide-use score[2]	Alternative approach: Biocide use[3]
I) Cheapest combination of options	*Attained reduction*: 11 % *Options*[4] : strips around window panes and high-pressure cleaner *Costs*[5] : -65,762 NLG/ha/y	*Attained reduction*: 11% *Options*[4] : strips around window panes and high-pressure cleaner *Costs*[5] : -65,762 NLG/ha/y	*Attained reduction*: 65 % *Options*[4] : strips around window panes and high-pressure cleaner *Costs*[5] : -65,762 NLG/ha/y
II) Maximal achievable reduction	*Attained reduction*: 97 % *Options*[4] : moveable screen, T 2 degrees lower, no windows, electrostatic spraying, resistant crop varieties, biocontrol and scouting, greenhouse hygiene, high-pressure cleaner, own mechanical roof cleaner *Costs*[5]: 446,311 NLG/ha/y	*Attained reduction*: 65 % *Options*[4] : T 2 degrees lower, strips and netting, electrostatic spraying, resistant crop varieties, biocontrol and scouting, greenhouse hygiene, high-pressure cleaner, own mechanical roof cleaner *Costs*[5]: 111,384 NLG/ha/y	*Attained reduction*: 84 % *Options*[4] : T 2 degrees lower, strips and netting, electrostatic spraying, resistant crop varieties, biocontrol and scouting, greenhouse hygiene, high-pressure cleaner, own mechanical roof cleaner *Costs*[5]: 111,384 NLG/ha/y

[1] as used in our model and described in Chapter 3; attained from Leendertse et al. (1997)

[2] alternative approach described in Chapter 3

[3] alternative approach described in text

[4] options selected by the model (see Chapter 3 for a description of the options)

[5] annual cost of the combination of options (see Chapter 3 for a description of the calculation method)

Table 4.10 shows the effect of using the alternative biocide impact indicators for the calculated cheapest cost-effective combination of options and the combination of options with maximal reduction. The reduction achieved by the cheapest cost-effective combination of options (11%) is equal to the biocide-air-emission score and the biocide-use score, but higher (65%) for biocide use. The maximum reduction achieved is different for all three indicators (97%, 65% and 84%). The highest calculated maximum reduction is for the biocide-air-emission score. This can be explained by the fact that more options affect the emissions of biocides into the air (by affecting the biocide use and emissions) than the use of biocides only. These options include screens and changes in greenhouse construction. Further, Table 4.10 shows that the same combination of options results in a considerably lower reduction when using biocide use as the indicator than when using biocide-use score as the indicator. This indicates that the biocides remaining after the introduction of the reduction options are the more toxic and/or more persistent ones.

Eutrophication

We analysed the effect of changing the method of calculating the impact of eutrophication on the model results. In our model approach we considered NO_x, NO_3 and PO_4 as eutrophying compounds. The model selected 105 different combinations of options that are cost-effective in reducing eutrophication (Table 4.11). In an alternative approach we quantified the eutrophying impact of the emissions to surface and ground water of nitrate (NO_3) and phosphate (PO_4), but ignored the emissions to the air (NO_x emissions). What we see is that in the alternative approach the total number of cost-effective combinations was reduced to seven because our model includes only a few options that reduces emissions of NO_3 and PO_4 to ground and surface water. These are the options from the groups sewage treatment, source of irrigation water, and drain water cleaning (Table 4.11). The maximum reduction of eutrophying emissions that can be achieved in the alternative approach is much higher (99%) than when applying our standard approach (83%) (Table 4.11), or, in other words, the emissions of NO_x are more difficult to reduce by the options analysed than the emissions of NO_3 and PO_4. Thus, including or excluding NO_x as an eutrophying compound certainly affects the outcome of the model calculations.

Table 4.11 *Model results (realised reduction percentage, the options selected and the related costs) for eutrophication as calculated using our model and two alternative approaches (PO_4-equivalents excluding NO_x emissions, and eutrophying equivalents). The number of efficient combination of options and the results for the combination of options with maximal reduction are shown*

	Our model [1]	Alternative approach: PO_4-eq without NO_x [2]	Alternative approach: Eutrophying equivalents [3]
Number of combinations of options	105	7	107
Maximal achievable reduction	*Attained reduction*: 83 % *Options* [4]: combi-condenser, double screen, coated double glass as wall insulation, coated glass as roof insulation, heat buffer 80 m^3, low-NO_x burner, T 2 degrees lower, strips around window panes, internal sewage connection, extra basin of 4000 m^3, drain water cleaning at regional level, clay granulates as substrate. *Costs* [5]: 461,441 NLG/ha/y	*Attained reduction*: 99 % *Options* [4] : internal sewage connection, irrigation water ground store, drain water treatment at the regional level *Costs* [5]: 32,549 NLG/ha/y	*Attained reduction*: 85 % *Options* [4] : see standard score *Costs* [5]: 461,441NLG/ha/y

[1] As used in our model and described in Chapter 3; [2] alternative approach described in text; [3] alternative approach following Soest et al. (1997); [4] options selected by the model (see Chapter 3 for a description of the options); [5] annual cost of the combination of options (see Chapter 3 for the description of the calculation method)

Eutrophication impact indicator

Various methods can be used to quantify the overall eutrophying impact of different (eutrophying) compounds. In our model approach, the total eutrophying impact is quantified in PO_4-equivalents by using classification factors, which convert the emissions of eutrophying compounds to PO_4-equivalents (Chapter 3). Alternative classification factors are used in the literature, in which 1 kg P is equivalent to 10 kg N (Soest et al., 1997). We analysed the effect of applying this alternative approach on the calculated cost-effective combinations of options. The results of the model calculations show that the cost-effective combinations of options for our standard model approach and the alternative approach are almost equal. The alternative approach results in two more cost-effective combinations of options (107 instead of 105) (Table 4.11). Of these, only a few combinations (6 in total) are different for the two approaches. The differences for these six combinations are small and can be ascribed to the application of one or two different options. The total reduction that can be achieved is 87% for the alternative approach, which is slightly more than for the standard approach (83%), while the costs are the same (NLG 461,411 per hectare per year: Table 4.11).

System boundaries
Finally, we analysed uncertainty caused by the choice of system boundaries. In our model approach we included on-farm emissions as well as the emissions from the production of electricity (CO_2 and NO_x emissions) and rock wool (NO_x emissions), because these sources contribute considerably to the total emissions (Pluimers et al., 2000). In an alternative approach we only considered on-farm emissions and analysed the effect on the cost-effective combinations of options for CO_2 and NO_x emissions reduction. The number of cost-effective combinations of options for NO_x emissions is lower in the alternative model formulation (49 cost-effective combinations) than in the standard approach (64 cost-effective combinations). This difference is caused by the options affecting the emissions from rock wool production. In the alternative model formulation, changes in substrate use do not emerge in cost-effective combinations. The total NO_x reduction that can be achieved for the alternative system boundaries approach (thus including only on-farm emissions) is higher (75%) than in the current model (42%).

Conclusions for the sensitivity to alternative model structure
The results of the sensitivity analysis give no reason to adapt the model structure. However, some aspects should be considered while interpreting the results. The quantification of the environmental impact of biocide use by the biocide-air-emission score and the amount of biocide use result in different cost-effective combinations. This may be a reason to consider both criteria in an analysis of the environmental impact of tomato cultivation. The model results are not sensitive to the change in classification factors used for the calculation of PO_4-equivalent or P-equivalent emissions, but are sensitive to the inclusion or exclusion of NO_x as eutrophying compound: including NO_x gives a more complete picture of the eutrophying impact of tomato cultivation. Another aspect that influences the model results is the description of the system boundaries. We showed that off-farm emissions may be considerable.

4.5.2 Sensitivity to alternative parameter values

In addition to uncertainties in model structure, uncertainties in parameter values may also influence the model results. Our model includes more than 300 parameters most of which are related to the options (reduction fractions and cost parameters) (Chapter 3). We did not perform a systematic quantitative uncertainty analysis but instead performed a partial sensitivity analysis. We selected the following parameters, which in our opinion have an important impact on model results: (1) 12 emission factors ($F_{\varepsilon,\alpha}$) and (2) the gas price (P_α). The uncertainty in emission factors may affect the calculation of environmental impact of tomato cultivation and the cost-effectiveness of all reduction options analysed. The gas price influences the costs and benefits of the reduction options analysed and consequently their cost-effectiveness.

Emission factors

We analysed nine sets of alternative emission factors for emissions resulting from electricity production, gas use, fertilisers use, rock wool production and biocide use. These alternative sets are described in Table 4.12 and more or less reflect the uncertainties in the emission factors considered.

Table 4.12 *Emissions of CO_2, NO_x, PO_4-eq and biocides from Dutch tomato cultivation as calculated for alternative emission factors ($F_{\varepsilon,\alpha}$). Results for the reference (zero case) are quantified per hectare per year. Results for alternative cases show the % change relative to the zero case*

	CO_2	NO_x	PO_4-eq	Bcairsc [1]
Reference: zero case	1,303,684 kg	1,364 kg	309 kg	395,315 $*10^3$ m^3
Alternative cases[2]				
1 Electricity is produced in gas-fired power plant instead of coal-fired: $F_{CO2, electricity}$ -40%, $F_{NOx, electricity}$ -50%	-2%	-4%	-2%	-[4])
2 $F_{NOx, gas\ use}$ -25%	-	-18%	-10%	-
3 $F_{NOx, gas\ use}$ +25%	-	+18%	+10%	-
4 Emission factors for fertiliser use are lower $F_{NOx, fertiliser\ use} = 0$ $F_{NO3, fertiliser\ use} = 0$ $F_{PO4, fertiliser\ use} = 0$	-	-7%	-46%	-
5 Emission factors for fertiliser use are higher $F_{NOx, fertiliser\ use} = 0.10$ $F_{NO3, fertiliser\ use} = 0.20$ $F_{PO4, fertiliser\ use} = 0.20$	-	+21%	+55%	-
6 $F_{NOx, rock\ wool\ production}$ -99%	-	-12%	-7%	-
7 $F_{NOx, rock\ wool\ production}$ +100%	-	+13%	+7%	-
8 Emission factors for biocide air emission all low [3] Vapour pressure class and emission factors very high 0.35 high 0.30 average 0.10 low 0.05 very low 0.01	-	-	-	-13%
9 Emission factor for biocide air emission all high [3] Vapour pressure class very high 0.60 high 0.35 average 0.25 low 0.15 very low 0.05	-	-	-	+51%

[1]) Biocide-air-emission score (see text)

[2]) The percentage indicates the change in emission factor value

[3]) The emission factors for biocide use depend on vapour pressure (See Chapter 3)

[4]) - means no change relative to the zero case

In case 1 we investigated the impact of assumptions on electricity production. In our model electricity is produced in a coal-fired power plant and is a source of CO_2 and NO_x emissions. In the alternative case 1 we assumed that electricity is produced in a gas-fired power plant. This change does not have a large impact on the total emissions of CO_2 and NO_x from tomato cultivation. The main reason for this is that the emissions from the production of electricity are low compared with the total CO_2 and NO_x emissions from tomato cultivation (Chapter 2). For CO_2 emissions we analysed the impact of changing the emission factors for electricity production because the emission factor of CO_2 emissions from gas use is quite accurate.

The calculation of total emissions of NO_x, NO_3 and PO_4 is influenced by many emission factors. In cases 2 to 7 we explored the sensitivity of the model to several of these. A 25% change in the NO_x emission factor for natural gas (cases 2 and 3) have a considerable effect on total NO_x and eutrophying emissions (10% to 18% lower or higher than in the zero case). Similarly, changes in the NO_x emission factors for rock wool production (cases 6 and 7) on NO_x and eutrophying emissions is considerable. The emission factors for NO_x, NO_3 and PO_4 from fertiliser use are rather uncertain (Sonneveld, 1996). We analysed the effect of zero emissions (case 4) and relatively high emission factors (case 5) for those three compounds. The results indicate a considerable change in the calculated eutrophying emissions (about 50% lower or higher than the zero case) and the emissions of NO_x (Table 4.12).

The emission factors for biocide emissions to the air are based on their vapour pressure (Chapter 3). Woittiez et al. (1996) describe ranges of emission factors for five vapour pressure classes. We analysed the effect of using the lowest and the highest values for the emission factors on the calculated biocide-air-emission score (cases 8 and 9). The analysis indicates that these changes have a considerable effect on the calculated biocide-air-emission score. We point out that these emission factors are just one step in the calculation of the biocide-air-emission score and that other parameters such as toxicity and persistency may also be uncertain.

Gas price

The annual costs of several reduction options depend, among other things on the gas price. Those options that reduce the use of natural gas also save costs. In the Netherlands, growers benefit from a reduced tariff for natural gas used for greenhouse horticulture (0.261 NLG/m^3 natural gas in 1995 (Table 4.5)). This tariff includes a lower gas price, a lower tax and exemption from the regulating energy tax (Mega Limburg, 1999). We analysed the effect on CO_2 emissions of an alternative gas price on the cost-effectiveness of combinations of options. For the alternative case we used the price of natural gas for household consumers (0.55 NLG per m^3 natural gas). Figure 4.7 shows the results. Compared with Figure 4.1 (zero case) the costs of combinations of options in the alternative case are significant lower due to high savings from gas use. The number of cost-effective combinations of options is also lower. For the alternative gas price the option Econaut does not appear in the set of cost-effective combinations of options. Another difference is the use of strips, which are selected in all combinations of options in the high gas price alternative, but less in the zero case.

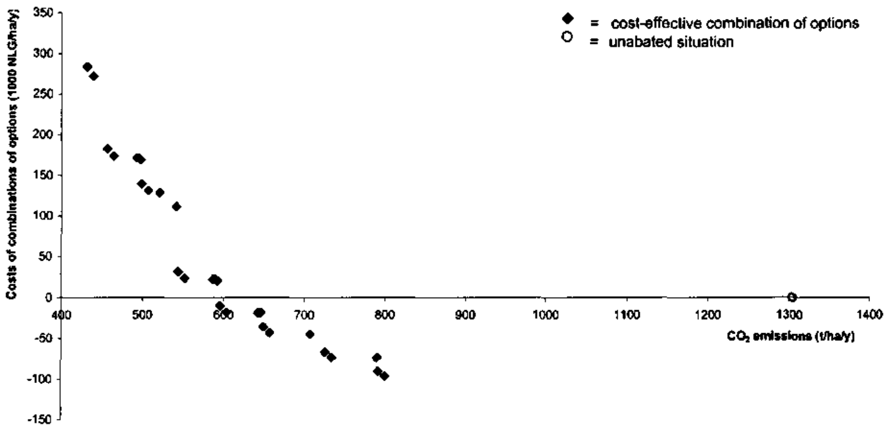

Figure 4.7 *Cost-effective combinations of options for CO_2 emission reduction at gas price = household consumers price (0.55 NLG/m^3 natural gas)*

4.6 Discussion and Conclusions

Cost-effective combinations of options for the zero case

We analysed a zero case to explore the behaviour of the model system described in Chapter 3. Our analysis of the cost-effectiveness of individual reduction options indicates that most of the profitable options are related to gas use reduction. These include all types of condensers and heat buffers, the use of an Econaut and strips around window panes. The cost-effectiveness of options is, however, no indicator that the model selects these options in cost-effective combinations. We analysed the effect of different combinations of reduction options on the reduction of global warming, acidification, eutrophication, dispersion of toxic biocides and the production of waste caused by tomato cultivation in the Netherlands. The results indicate that for the zero case considerable reductions of the environmental impact can be achieved at net zero costs.

We compared our results with the actual (1995) application rate of energy saving options in Dutch greenhouse horticulture. Our model selected combi-condensers and heat buffers in all cost-effective combinations of options. In 1995 the combi-condenser and heat buffer were indeed the most widely used energy saving options. Velden (1996) found that condensers are widely applied in the greenhouse sector (57% of the firms), but that other energy saving options were applied in only 10% of greenhouse enterprises. Moreover, Velden et al. (1997) show that heat buffers were present in 28% of the greenhouse vegetable firms. In our model results combi-condensers and heat buffers were selected in all cost-effective combinations of options. This is a result of the design of our model, which can only select options to be applied in all greenhouses, or none. In Chapter 5, we will analyse the 1995 situation in more detail while taking into account different farm types within the sector. Despite this aspect of model design and the fact that more criteria influence growers to apply options, the model seem to select the same options as the ones applied in the real greenhouse sector.

We included reduction options in our analysis that are presently available and applicable at the farm level. Nevertheless, there are more possibilities for reducing the environmental impact of Dutch tomato cultivation that we did not consider. At a higher aggregation level (large greenhouse areas) much attention is paid to the reconstruction of the greenhouse area (Bouwman et al., 1996; Alleblas and Mulder, 1997) and the use of district heating (Velden, 1996). Other possibilities to reduce the environmental impact include, for example, the use of renewable forms of energy, changing to biological production and changing to less energy demanding varieties of crops.

Model behaviour

The sensitivity analysis indicates that the biocide indicator used in our model is sensitive to variations in the amounts of biocides emitted, which are rather uncertain (Woittiez et al., 1996). The emission rate is just one assumption in the calculation of the environmental impact by emissions of biocides into the air. The analysis showed that the use of alternative methods for modelling biocide impact would result in a different set of reduction options and different reductions achieved. Nevertheless, we conclude that although the biocide air emission indicator has its shortcomings, it is a valuable tool because it provides insight into the impact of biocide on the environment. We point out that the biocide-air-emission score should be used as an indicator to compare alternatives, but not to quantify actual impact caused by emissions of biocides. Total use of biocides should also be considered as an indicator for the total potential environmental impact of biocides.

The model did not appear sensitive to the method for calculating the total eutrophying impact of different compounds. The model is sensitive to including or excluding NO_x emission as an eutrophying compound. The total emissions of NO_x from tomato cultivation are relatively uncertain and are influenced by many different activities.

Increasing the gas price from the current price (1995) for greenhouse horticulture to the tariff for households, changes the calculated reduction of the environmental impact at net zero cost and the cost-effectiveness of options. In addition, energy saving is more beneficial when gas prices are high, making it possible to implement more expensive emission reduction options at net zero costs. This corresponds with the results described by Ruijs et al. (1998) who analysed energy saving through financial instruments.

Many different multi-criteria methods are available to analyse the cost-effectiveness of environmental investments. We explored five different methods and compared their results. The results of the analysis show large differences in the number of cost-effective combinations of options as well as the combinations themselves. However, our results indicate that the use of multi-criteria analysis provides useful information on the robustness of the results. When analysing multiple targets a multi-criteria analysis is needed, but the choice of which method to use is subjective. For this reason, and because of the observed differences in the results of the five Multi-criteria methods, we recommend using preferably more than one method for MCA when the analysis is used as the basis for decision-making.

One multi-criteria method, the MPS method, needs further attention because Dutch growers are actually using this method. The disadvantage of this method is that it only focuses on the activity levels and does not take the emissions of pollutants into account. As a result, some reduction options (those which directly influence the emission rates) will not be considered cost-effective options when using this multi-criteria method. On the other hand, the fact that MPS uses activity levels rather than emissions leads to a simplified and transparent approach.

Model restrictions and model strengths

Our model is a deterministic and static model. Uncertainties are not explicitly accounted for in the model and dynamic aspects are not described. For example, no dynamic relation is described between the emissions and environmental impact, nor between the yield and the resulting tomato price (e.g. tomato demand, general production levels, etc.). Although the latter can be described in economic theory, it is too complex to be included in the present model. Further, the model does not describe future developments, calculates possibilities for a fixed reference year. To analyse future developments the reference should be adapted and options that will be available in future should be included in the model.

The annual emissions and effects (annual costs) of combinations of technical options are calculated for a (pre-)defined reference situation. It is possible to use the model for different reference situations. To apply the model to the sectoral level, a set of reference situations (reference hectares) needs to be described in such a way that it represents the total Dutch tomato cultivation sector (Chapter 5).

We analysed technical options to reduce the current environmental impact of tomato cultivation. We did not consider other cultivation techniques or practices such as planting and cultivation period, fertiliser amount, etc. We focussed on technical measures because the production method in Dutch greenhouses makes intensive use of technology and knowledge. Consequently, the model cannot yet answer questions about the effects of changing to other cultivation practices (for example changing to cultivation in soil or to biological cultivation methods). This model can only be used for current cultivation methods for analysing currently available on-farm techniques to reduce the environmental problems related to tomato cultivation.

The strength of the model is its capability to evaluate combinations of options to reduce the environmental impact by Dutch tomato cultivation, while taking into account both the different environmental problems and the cost-effectiveness of reduction options. If one wants to consider a set of different environmental problems at once, the most cost-effective investments can only be found by using multi-criteria analyses.

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5 Environmental systems analysis of Dutch tomato cultivation under glass III: Analysis at the national scale

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Abstract

We analysed cost-optimal strategies for tomato cultivation in the Netherlands to meet national environmental targets. We described this sector for the reference year 1995 by three farm types (Innovators, In-Betweens and Low-Costs), which differ in agricultural practices and the application of emission reduction options. We analysed cost-effective combinations of reduction options at the farm level. At the national level we analysed optimal area allocation of applying combinations of options while aiming at: 1) minimisation of the environmental impact at given constraints on the costs, or at 2) minimisation of the costs to achieve defined environmental targets. Our results indicate that the costs of achieving a set of environmental targets simultaneously are lower than those of achieving the targets individually; about 20% of the calculated environmental impact by Dutch tomato cultivation can be reduced at net zero cost. Targets for biocide emissions to the atmosphere and emissions of eutrophying compounds are most difficult to achieve.

5.1 Introduction

Horticultural production in Dutch greenhouses contributes to different environmental problems (Chapter 3 and 4 (Pluimers et al., submitted I and II)). The production system requires high inputs of fertilisers and energy (Poppe et al., 1995). In areas with a high density of greenhouses, production may give rise to substantial emissions of toxic substances (as a result of the use of biocides) and emissions of nutrients (Muilerman et al., 1993). In addition, Dutch tomato production contributes to the production of waste and to air pollution through emissions of greenhouse gases and acidifying gases.

Since the early 1990s, Dutch growers have been faced with various changes in environmental policy by the Dutch government. Concern about the environment has led to the adaption of several environmental policy plans. As a result, growers have to deal with regulations and legislation, which lead to considerable investments at the nurseries (Buurma et al, 1993; Balthussen et al., 1996). At the same time, vegetable growers face increased competition from other countries, especially from the Mediterranean region. The sector has taken action to strengthen its competitiveness and to reduce its contribution to environmental problems (LTO, 1998).

We investigated the possibilities for reducing the environmental impact caused by tomato cultivation in greenhouses in the Netherlands. The diversity of the environmental problems as well as the diversity of available abatement strategies makes the analysis rather complex. For this reason we used the methodology of environmental systems analysis which provides guidelines for dealing with environmental problems and analysing options for control or abatement (Checkland, 1979; Wilson, 1984). In Chapter 3 and 4 we described the first four steps of an environmental systems analysis of Dutch tomato cultivation. The first three steps were (1) problem definition, (2) description of the system and its boundaries (Chapter 2 (Pluimers et al., 2000)) and (3) the model approach (Chapter 3). The fourth step involved the analysis of the system, where we explored our model for a hypothetical zero case situation (Chapter 4). In Chapter 4 we analysed the theoretical optimal situation of a one hectare greenhouse for which none of the options analysed had been applied yet. This chapter focuses on the fifth step: the use of the developed model for optimisation analysis.

The purpose of this study is to analyse the cost-effectiveness of options to reduce the environmental impact of tomato cultivation in the Netherlands, with a special focus on strategies for meeting the current environmental policy targets. To this end, the diversity of nurseries, including the application of reduction options, is taken into account by defining farm types. In this chapter we present (1) an analysis of Dutch tomato cultivation at the national level, and (2) an optimisation analysis aimed at either minimising the costs of emission control, or minimising the environmental impact under given constraints on the costs of emission control. We used the model that we developed (Chapter 3) to explore the cost-effective strategies for reducing the environmental impact of Dutch tomato cultivation in the year 1995 by technical options. The optimisation analysis is based on linear programming. We performed the calculations for the year 1995. This year was selected because the required data were available. This paper may serve as an illustration how environmental systems analysis can be used to provide information that may assist decision makers in defining future policies for the sector.

5.2 Methodology

5.2.1 Introduction

We analysed optimal strategies for reducing the environmental impact of tomato production in the Netherlands in 1995. First, we described the situation in that year. We defined three farm types, that represent the sector, including some of the diversity in activity levels, emissions and the application of reduction options (section 5.3). Second, for each farm type we ran the model as described in Chapter 3. The output of the model includes cost-effective combinations of reduction options for each farm type (see section 5.4.1 for the results). Section 5.2.2 summarises the methodology for selecting these combinations of options, which is described in detail in Chapter 3. The third step includes an optimisation analysis at the national level, in which the cost-effective combinations of options for the three farm types are used as input. We analysed which combinations of options are to be applied in which farm types to meet environmental targets in a cost-optimal way. The optimisation approach is described in section 5.2.3.

5.2.2 Model approach

We developed a model to estimate the environmental impact of Dutch tomato cultivation under glass and to quantify the effect of the application of technical reduction options. In the following, we give a brief outline of the system and system description.

In Chapter 2 we analysed which activities and emissions need to be considered when analysing the environmental impact of tomato cultivation in the Netherlands (Pluimers et al., 2000). Using the results of that study, we formulated the main system elements and the system boundaries (Chapter 3). We included in our analysis the following emissions; emissions of carbon-dioxide (CO_2) from the use of natural gas and production of electricity, nitrogen-oxide (NO_x) emission from the use of natural gas and fertilisers and from the production of electricity and rock wool, and emissions of N (nitrogen) and P (phosphorus) compounds from the use of fertilisers. Further, we included biocide use and biocide emissions to the atmosphere and the production of waste.

We used indicators for each of the environmental problems. These indicators are kg CO_2 for climate change, kg NO_x for acidification, kg phosphate (PO_4)-equivalents for eutrophication (Heijungs et al., 1992) and kg of waste produced (and disposed). For the use and emissions of biocides we distinguished two indicators; the use of biocides (in kg active ingredients) and the biocide-air-emission score (in 1000 m^3). The latter is the sum of the biocide-air-emission score of each biocide applied and is calculated as a function of the amount of biocide used, the vapour pressure, the toxicity and the persistency of the compound (Leendertse et al., 1997).

The model quantifies the effects of combinations of technical options for reducing the environmental impact of tomato cultivation relative to a pre-defined reference situation. The so-called activities in this reference situation (the use of natural gas, biocides, N and P fertilisers, rock wool and electricity) form the basis for the calculations. The emissions of pollutants are calculated as a function of the activities and corresponding emission factors. Reduction options either reduce the activity levels or the emissions. Some options have a side effect on the tomato production level, on the activity levels (e.g. gas use) or on the emissions of other compounds. The costs of the reduction options are calculated as annual costs per hectare and include annual investment costs, which are calculated as a function of the investments, the lifetime of the option and the interest rate. Other costs are the annual operation cost and variable costs. The variable costs also include the effects of the options on gas use and tomato production.

The model contains 58 options for reducing emissions arranged in 22 groups. Within a group the options are mutually exclusive. Combinations of options are composed by selecting one reduction option from each of the 22 option groups. The model calculates for each possible combination of options the environmental impact and the annual costs for reducing the environmental impact for a certain reference situation. The model selects the cost-effective combinations of options. A combination of options is considered cost-effective if no other combination of options exists which reduces the environmental impact more at lower or equal costs.

We analysed for each individual environmental problem which combinations of options are cost-effective. We performed this analysis for each of the three farm types as described in section 5.3 and for each farm type we described a reference situation for 1995. Some of the farm types had already implemented reduction options in their reference situation. If an option (e.g. a fixed screen) has been applied in the reference situation, the model will not consider other options from that option group, even if it would be more cost-effective.

5.2.3 Optimisation analysis at the national scale

We used linear programming (LP) to analyse the options for reducing the environmental impact of Dutch tomato cultivation at a sectoral level. We analysed the options for minimising emissions in Dutch tomato production given certain constraints on the costs and for minimising the costs to achieve certain environmental targets (Box 5.1 and Table 5.1). The decision variables in the constraint equations, as well as in the objective function, are the areas (number of hectares) to which the different cost-effective combinations of options are applied for the different farm types. The constraint equations described in the model are the costs of the options applied (for type 1) or the emissions resulting from the application of combinations of options (for type 2) and constraint equations based on the total area of each farm type. For the latter we assumed that the total area of each of the farm types is constant, in other words it is not possible to shift from one farm type to another (Box 5.1).

The two above-mentioned types of optimisation are performed in two ways: for each single environmental problem, and for the integrated effect of all the problems considered (Box 5.1). The inputs of the LP model include the technical coefficients of the cost-effective combinations of options resulting from the model calculations described in section 5.2.2. For the analysis of a single environmental problem these

Box 5.1 *Optimisation approach for the analysis of cost optimal strategies to reduce the environmental impact of Dutch tomato cultivation on a sectoral level*

	Optimisation type 1: minimise environmental impact	**Optimisation type 2: minimise costs**
Optimisation for each single environmental problem	For each environmental problem several optimisations were carried out with different restrictions on the abatement costs (results in Figure 5.8 and 5.9)	For each environmental problem we analysed how the environmental target as described in Table 1 can be achieved at minimum costs (results in Figure 5.11a to e)
Integrated optimisation analysis for the combined effect of the environmental problems considered	The integrated environmental impact was quantified using 5 different methods for multi-criteria analysis. For each method several optimisations were carried out with different restrictions on the abatement costs (results in Figure 5.10)	As above, but for multiple environmental targets simultaneously. Additionally we minimised the costs without restrictions on the environmental impact (results in Figure 5.11f)

Optimisation type 1: minimise environmental impact

Object function:

$$\min\left(\sum_m X_m * M\mu_m + \sum_n X_n * M\mu_n + \sum_o X_o * M\mu_o\right)$$

Subject to:

$$\sum_m X_m * C_m + \sum_n X_n * C_n + \sum_o X_o * C_o \leq C_{target}$$

$$\sum_m X_m = 245$$

$$\sum_n X_n = 730$$

$$\sum_o X_o = 245$$

Optimisation type 2: minimise costs

Object function:

$$\min\left(\sum_m X_m * C_m + \sum_n X_n * C_n + \sum_o X_o * C_o\right)$$

Subject to:

$$\sum_m X_m * M\mu_m + \sum_n X_n * M\mu_n + \sum_o X_o * M\mu_o \leq M\mu_{target}$$

$$\sum_m X_m = 245$$

$$\sum_n X_n = 730$$

$$\sum_o X_o = 245$$

Indices m, n, o = indices for the combinations of options for Innovators, In-Betweens and Low-Costs farm types

Parameters

C_m, C_n, C_o = costs of the combination of options m, n and o

$M\mu_m, M\mu_n, M\mu_o$ = emission level or environmental impact score of environmental problem μ related to the application of combination m, n and o

Decision variables

X_m, X_n, X_o = number of hectares with combination m, n and o technical coefficients comprise the costs, activity levels and emission levels or environmental scores of the cost-effective combinations of options relating to the environmental problem at stake. Technical coefficients for the integrated analysis are the costs, activity levels and emission levels or environmental scores of combinations of options, which are cost-effective when taking into account all environmental problems simultaneously.

We used five different methods to quantify the overall environmental impact of tomato cultivation, which includes global warming, acidification, eutrophication, dispersion of toxic compounds or the use of biocides and, in one of the methods, the disposal of waste. We applied the Distance to target method as described by Goedkoop (1995), the No Significant Adverse Effect Level (NSAEL) method from Kortman et al. (1994), the Panel method described by Lindeijer (1996), the Marginal costs method from Blijenberg and Davidson (1996) and Soest (1997) and the MPS method as used in the Dutch greenhouse sector (Stichting Milieukeur, 1998). A more detailed description of these methods can be found in Chapter 4.

The environmental targets for the optimisation analysis (type 2) are mainly derived from the agreement Greenhouse Horticulture and the Environment (LNV, 1997). This includes agreed targets for energy efficiency, biocide use and biocide emissions, and emissions of N and P. Additionally, we derived targets for CO_2 emission reduction by Dutch greenhouse horticulture from the Dutch national policy plan for climate change (VROM, 1999). The targets used in the optimisation analysis are described in Table 5.1.

Table 5.1 *Environmental targets used in optimisation type 1: minimise costs (Box 5.1)*

Environmental target for	Targets for tomato sector	Based on
Energy efficiency	65% energy efficiency improvement	Efficiency relative to 1980 situation [1]
Global warming	< 1.03 Gton CO_2 emission	2 Mton CO_2 reduction for greenhouse sector[2]. Share of tomato cultivation in greenhouse sector is 16.5%. Target for CO_2 reduction in tomato cultivation is therefore 24%
Eutrophication	$376.2*10^3$ kg PO_4-eq	20% reduction of eutrophying compound [3]
	$258.6*10^3$ kg PO_4-eq	45% reduction of eutrophying compound [3]
Biocide-air-emission score	$2290*10^6$ m^3	15% reduction [4]
	$1670*10^6$ m^3	38% reduction [4]
Biocide use	12186 kg active ingredient	15% reduction [4]
	8888 kg active ingredient	38% reduction [4]

[1] Energy efficiency described in Chapter 4 based on the Greenhouse Horticulture and Environment agreement (LNV, 1997).

[2] Based on Climate policy plan (VROM, 1999).

[3] Reduction of NO_x, nitrate and phosphate based the Greenhouse Horticulture and Environment agreement (LNV, 1997).

[4] Based on the reduction target for the emission of biocides to the atmosphere in the Greenhouse Horticulture and Environment agreement (LNV, 1997).

5.3 Description of the 1995 situation

5.3.1 Classification of farm types

Dutch tomato cultivation takes place on a variety of farms. The farms differ in size, age, production method, and in the application of technologies to reduce the environmental impact. All these aspects influence the levels of activities, the emissions of polluting compounds and the possibilities for abatement. Other than in Chapter 3 and 4 where the analysis was performed at farm level, we have not tried to describe Dutch tomato cultivation as one representative farm, but tried to take some of this heterogeneity into account by defining different farm types. The use of farm types enables us to describe the heterogeneous sector as a composition of homogeneous elements. For each homogenous element (that is, each farm type) we can use our model. In this way, we are able to include, for example, the application rate of reduction options in the analysis. For each farm type we described a reference situation, which was used as a basis for the model calculations (Table 5.2).

Table 5.2 *Yield*[1] *(Y_{ref}) and activity levels*[1] *($A_{\alpha\text{-}ref}$ and $X_{\alpha\text{-}ref}$) for the three farm types: Innovators, In-Betweens and Low-Costs in the reference situation of 1995 (see text for references)*

	Innovators	In-Betweens	Low-Costs	Unit
Yield (Y_{ref})	564000	470000	410000	kg/ha/y
ACTIVITIES ($A_{\alpha\text{-}ref}$)				
- Gas use	646000	590000	515000	m^3/ha/y
- Use of electricity	83200	83200	57600	kWh/ha/y
- N fertiliser use	3125	1152	2030	kg N/ha/y
- P fertiliser use	312	271	370	kg P/ha/y
- Biocide use	20.16[2]	9.09	11.15	kg/ha/y
Fungicide use	19.47	7.57	9.43	kg/ha/y
Propamocarb-hydrochloride	1.73	2.86	4.93	kg/ha/y
Dichlofluanide	-	0.17	0.09	kg/ha/y
Bitertanol	0.90	1.1	1.03	kg/ha/y
Tolyfluanide	1.64	2.23	2.98	kg/ha/y
Bupirimaat	0.50	1.21	0.40	kg/ha/y
Sulphur	14.70	-	-	kg/ha/y
Insecticide use	0.69	1.52	1.72	kg/ha/y
Fenbutatinoxide	0.24	0.48	0.52	kg/ha/y
Hexythiazox	-	0.11	0.09	kg/ha/y
Cyhexatin	0.41	0.54	0.88	kg/ha/y
Teflubenzuron	-	0.18	0.09	kg/ha/y
Buprofezin	0.04	0.06	0.08	kg/ha/y
Pirimicarb	-	0.15	0.06	kg/ha/y
Greenhouse cleaning	-	-	-	kg/ha/y
Rest biocide use	-	-	-	kg/ha/y
- Rock wool use	8500	3400	3400	kg/ha/y
- Rock wool waste production	35000	14000	14000	kg/ha/y
- Organic waste production	40250	35000	30000	kg/ha/y
- Foil waste production	4500	4500	4500	kg/ha/y
EXTRA ACTIVITIES ($X_{\alpha\text{-}ref}$)				
- Extra gas use	3000	9000	6000	m^3/ha/y
- Extra electricity use	2100	2100	0	kWh/ha/y

[1] See Chapter 3 for a detailed model description.

[2] This amount of biocide use is relatively high compared with the use in the other farm types because we consider the use of sulphur as a chemical fungicide.

Classifications of farms in Dutch greenhouse horticulture can be found in several studies. Spaan and Ploeg (1992), for example, described the heterogeneity of Dutch greenhouse horticulture in terms of farm styles and characterise the sector by idealised types, such as, 'Toppers', 'Followers' and 'Ancient Growers'. Hietbrink et al. (1995), on the other hand, distinguish several farm types in an explorative study of the development of the Dutch greenhouse sector to 2005 and include different types of growers, such as Innovators, Followers, Growers that will stop after some time, and Growers that are very careful in their investments. A comparable approach exists for the Dutch tomato sector (Verhaegh, 1998), in which a classification is based on the production costs and total production and includes Leading farms, Modern farms and Low-Costs farms.

We distinguished between three farm types: Innovators, In-Betweens and Low-Costs and based the description of these farm types on information about production levels, gas use and biocide use in tomato cultivation and the application of options reducing the environmental impact (Bouwman et al, 1996; Velden, 1996; Velden et al., 1996; Verhaegh, 1998; Vernooy, 1998). It should be noticed that farm types with the same name in other studies are not necessarily the same as those in our study. The three farm types are briefly described below.

Innovators

Innovators cultivate tomatoes in highly specialised and relatively new greenhouses (less then 5 years old). They apply the newest technologies and therefore need high capital investments. Innovators aim for high profits at high production rates, which they hope to obtain through a highly intensified cultivation method. They have high production levels and use high inputs of different production factors, such as energy. The size of the greenhouse is five hectares (250 m by 200 m).

In-Betweens

The farm type between the Innovators and Low-Costs (between the extremes) is defined as In-Betweens (the middle bracket). The growers of this farm type have modern greenhouses, but do not have the newest technologies like the Innovators. They follow technological developments, but implement them later than Innovators do. In-Betweens are careful with their investments. This farm type represents most of the tomato growers in 1995. The size of the greenhouse (two hectares; about 140 m by 140 m) is somewhat larger than the average greenhouse size in the Netherlands in 1995.

Low-Costs

For the Low-Costs the optimisation of natural processes with use of labour and skills (craftsmanship) is important. Less attention is paid to the newest farm technologies. Low-Costs farms have relatively old greenhouses (older than 10 years). They avoid high investments. The Low-Costs try to lower their costs by limiting the use of expensive production factors. Most of the labour is done by family members. The Low-Costs only apply the most commonly used options to reduce the environmental impact. The greenhouse size is one hectare (100 m by 100 m).

5.3.2 Defining the farm types

The three farm types have some common characteristics. In all farm types round tomato is cultivated in a greenhouse type Venlo, using a high wire cultivation system. The tomato plants are planted in December and cultivation continues until the end of November. The cultivation has a defined temperature regime (from the beginning of December to the beginning of January: night 18.5°C and day 19.5°C, and from the beginning of January to November: night 18 °C and day 18.5°C) and uses only natural gas as a fossil energy source. Further, we assumed that electricity is produced in a coal-fired power plant. Rock wool is used as substrate and is disposed as waste afterwards. A water basin of at least 500 m^3 is available to store rainwater for irrigation. Tap water is used if there is a water shortage.

For each farm type we described a 'reference situation' for 1995, as required by the model (see Chapter 3 and 4), based on the literature. We followed an iterative procedure for defining the reference situation for the three farm types, with respect to the activity levels, the options applied and the total area of each farm type. We made an attempt to describe the tomato sector in such a way that the total area, activity levels and tomato production as well as the application rate of reduction options are similar to the totals for Dutch tomato cultivation in 1995. For this we used data on the area of tomato cultivation (CBS, 1996), tomato production (CBS, 1996; Vernooy, 1998), the total use of gas and biocides (CBS, 1996; Vernooy, 1998) and the use of reduction options (Bouwman et al., 1996; Velden, 1996; Vernooy, 1998).

Table 5.2 gives an overview of the activity levels for the three farm types. The data used for the quantification of the activity levels and the assumptions about the options applied in the three farm types are mainly based on the study of Vernooy (1998). Vernooy describes the results of a statistical analysis of the use of energy and biocides during the period 1993-1996 in, among others, tomato cultivation. The analysis is based on a selection of 40 tomato farms. Vernooy did not define farm types. He analysed relations between farm size, gas use, use of biocides and tomato production. We used the relations described by Vernooy in the description of our farm types, e.g. the relation between farm size, the application of energy saving options, and the relation between gas use and production (Vernooy, 1998). In the following we describe the activity and yield levels ($A\alpha_{ref}$, $X\alpha_{ref}$ and Y_{ref}, see Chapter 3) for the three farm types. All activity and yield levels are listed in Table 5.2. The options applied in the different farm types in the reference situation are listed in Table 5.3. All parameters not mentioned in the text below have the same values as described in Chapter 3 and 4.

Table 5.3 *The options for reducing emissions as applied in the 1995 reference situation for the three farm types*

Innovators	In-Betweens	Low-Costs
combi-condenser	return condenser	biocontrol and scouting
double glass in wall	wall foil	multi year use of rock wool
heat buffer	biocontrol and scouting	
low-NO_x burner	improved greenhouse hygiene	
biocontrol and scouting	high-pressure cleaner	
improved greenhouse hygiene	multi-year use of rock wool	
high-pressure cleaner		
own mechanical roof cleaner		
extra water basin of 1000 m^3		

Innovators

Innovators have a relatively high level of tomato production at 56.4 kg/m^2 (Y_{ref}). The fertiliser use ($A_{N \text{ and } P\text{-use-ref}}$) is 3125 kg N and 312 kg P per hectare per year based on Nienhuis and Vreede (1994a) and assuming a linear relation between production and fertiliser use. The organic waste is 40,250 kg per hectare per year (DLV, 1991; Nienhuis and Vreede, 1994a). The intensive cultivation practice requires relatively large amounts of natural gas ($A_{gasuse\text{-}ref}$ = 64.6 m^3/m^2 (Vernooy, 1998)). Innovators use new greenhouses in which light intensity and insulation are improved. They have a combi-condenser, double glass as wall insulation, a heat buffer (with a total volume of 240 m^3) and a low-NO_x burner (Velden, 1996; Vernooy, 1998). In addition to the energy used for heating and CO_2 fertilisation, extra natural gas ($X_{gasuse\text{-}ref}$) and electricity ($X_{elect\ use\text{-}ref}$) are used for drain water disinfection (by heating) and recirculation of drain water (Bouwman et al., 1996). A water basin of 1000 m^3 is available to collect rainwater. Biological control and scouting, improved greenhouse hygiene, a high-pressure cleaner and a mechanical roof cleaner are used (partly based on (Vernooy, 1998)).

The assumptions about biocide use ($A_{biocide\ use}$) by Innovators is based on Vernooy (1998). Vernooy describes the use of biocides in the average dosage and in the application rate. The average dosage is calculated by dividing the total use of a certain biocide by the total tomato cultivation area. The application rate is calculated by dividing the total use of a certain biocide by the area on which that specific biocide is used. In cases where Vernooy found that a certain type of biocide is applied on more than 50% of the total tomato area this biocide is also used at the Innovators nurseries. The amount of biocides applied by Innovators is equal to the average dosage per hectare described by Vernooy (1998). Innovators use a relatively high dosage of fungicide (Table 5.2) because of the high application rates of sulphur. Vernooy, however, does not consider sulphur as a (chemical) fungicide. We quantified the rate of biocide use in such a way that the total use of the tomato sector corresponds with the data described by Vernooy (1998).

In-Betweens

In-Betweens have a tomato production (Y_{ref}) of 47 kg/m^2. The figures for production of organic waste is taken from Nienhuis and Vreede (1994a). Gas use for heating and CO_2 fertilisation ($A_{gas\ use\text{-}ref}$) is 59 m^3/m^2. Extra gas use ($X_{gasuse\text{-}ref}$) is required for drain water disinfection (by heating) and steaming rock wool to make it suitable for reuse; the amounts required are 3000 and 6000 m^3 natural gas per hectare (KWIN, 1994; IKC, 1993). Extra electricity ($X_{elect\ use\text{-}ref}$) is used for drain water disinfection and recirculation of drain water (pumps) (KWIN, 1994). In-Betweens apply a return condenser, foil as wall insulation material, biological control and scouting, improved hygiene and a high-pressure cleaner. Rock wool is used for a number of years which results in 14 tonnes of waste per hectare per year (IKC, 1995).

We assumed that In-Betweens use all biocides that are applied on 20% or more of the tomato cultivation area, according to Vernooy. The amount and the application rate of biocide used by In-Betweens is according to Vernooy.

Low-Costs

The production of tomatoes (Y_{ref}) by Low-Costs is 41 kg/m^2 and the amount of gas used ($A_{gas\ use\text{-}ref}$) is 51.5 m^3/m^2 (Vernooy, 1998). Rock wool is reused for a number of years. The extra gas use ($X_{gasuse\text{-}ref}$) for rock wool disinfection is based on IKC (1993). Low-Costs farms apply biological control and scouting and use all biocides listed by Vernooy (1998) that are applied on 20% or more of the area. The amount of biocide corresponds with the amount in the highest application dosage as described by Vernooy (1998).

Low-Costs do not recirculate drain water (based on Bouwman et al. (1996) who estimated that 40-50% of Dutch tomato growers recirculated drain water in 1995). The use of nitrogen and phosphorus is higher in free-drainage systems than in the drain water recirculation system. The fertiliser use is based on Nienhuis and Vreede (1994a) and Sonneveld (1996). The emission factors for nitrogen and phosphorus from fertiliser use in a free-drainage cultivation system are 0.4 kg N/kg N applied and 0.3 kg P/kg P applied. These estimates are based on Sonneveld (1996).

Costs of options

The costs of reduction options may differ per farm type, mainly as a result of the difference in farm size. For Low-Costs the costs are the same as in the zero case analysis (Chapter 4). The costs of some options applied in the farm type Innovators and In-Betweens are affected by the scale on which they are applied. For example, the investment costs per hectare of a condenser are lower for a greenhouse of five hectares than for a greenhouse of one or two hectares. Options from the following groups depend on the size of the nursery: condensers, CO_2 supply method, wall insulation, NO_x emission reduction, spraying technique and high-pressure cleaner, and for the individual options Econaut, internal sewage connection and own mechanical roof cleaner (Table 5.4). The costs of these options are according to Buurma et al. (1993) and Besseling (1991). The costs of wall insulation options were recalculated from Uffelen and Vermeulen (1994).

Table 5.4 *Investment costs (in NLG per hectare) of reduction options for Innovators, In-Betweens and Low-Costs (cost estimates for the latter are equal to those used in the zero case (see Chapter 3). Only those options are listed for which the costs depend on the scale of the farm (the farm type). All other cost estimates are as for the zero case (Chapter 3)*

Group	Individual option	Zero case/ Low-Costs	Innovators	In-Betweens
Condensers	single condenser	24000	6400	13000
	return condenser	60000	42400	49000
	combi-condenser	61000	43400	51500
Wall insulation	screen	41600	16720	26160
	double glass	66000	28400	44665
	foil	2375	1030	1605
	dot foil	6225	2700	4215
	double glass coat	12300	5320	8325
CO_2 supply method	heat buffer	70000	42000	65000
	pure CO_2	36900	33060	35400
NO_x emission reduction	low-NO_x burner	5000	1000	2500
Temperature management	T 1 degree lower	0	1)	1)
	T 2 degrees lower	0	1)	1)
	no minimum pipe T	0	1)	1)
	Econaut	12500	2500	6250
Spraying technique	electrostatic spraying	9000	1800	4500
	advanced technique	30000	6000	15000
Resistant crop varieties	resistant crop varieties	3157		
High- pressure cleaner	high-pressure cleaner	10000	2500	5250
Mechanical roof cleaner	own roof cleaner	80000	22000	55000
	by contract	25000	1)	1)
Source of irrigation water	extra water basin of 1000 m^3	25000	1)	1)
	extra water basin of 4000 m^3	30000	1)	1)
	unsalted	80500	1)	1)
	osmosis	64000	33000	55000
	joint water basin	170000	1)	1)
	ground store	60000	24000	40000
Sewage	internal sewage connection	9000	4000	9000
	external sewage connection	30000	1)	1)
Drain water disinfection	heating	60000	16000	32500
	ozonisation	70000	17000	37500
	HP_UV	70000	20000	42500
	LP_UV	30000	8000	17500
	iodine	50000	15000	30000
	biofilter	30000	9000	17500

1) investment costs as for zero case

5.3.3 Emissions from the three farm types

Emissions per hectare

The emissions for the reference situation for each farm type are given in Figure 5.1 and Table 5.5. We observed some interesting features when comparing farm types. The CO_2 emissions (and gas use) are higher for the Innovators than for the other two farm types. The NO_x emissions, however, are lower due to the application of a low-NO_x burner in this farm type. Emissions of eutrophying compounds are relatively high for the Low-Costs, who do not recirculate drain water. It is interesting to compare the biocide-air-emission score and the biocide use. Although the use of biocide by the Innovators is relatively high, the impact as described by the biocide-air-emission score is lower than the scores of the other farm types. This is caused by the high use of sulphur as fungicides, which has a relatively low impact on the environment compared with other biocides. The high amount of waste produced in the farm type Innovators can be explained by the fact that in this farm type rock wool is used for one year while in the other two farm types rock wool is used for a number of years.

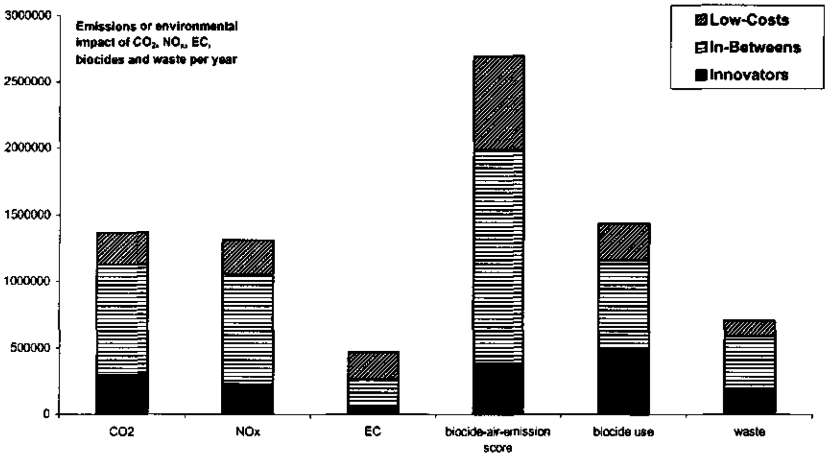

Figure 5.1 *Calculated annual emission levels for CO_2 (t/ha/y), NO_x (kg/ha/y) and eutrophying compounds EC (in kg PO_4-equivalents/ha/y), biocide-air-emission score (in 1000 m^3/ha/y), biocide use (in 0.01 kg/ha/y) and the production of waste (in 100 kg/ha/y)) for farm types Innovators, In-Betweens and Low-Costs in 1995, without additional control options implemented (reference case)*

Table 5.5 *1995 emissions in the reference situation for the three farm types as calculated in this study*

	Innovators	In-Betweens	Low-Costs
CO_2 in t/ha/y	1124	1135	973
NO_X in kg/ha/y	946	1127	1051
PO_4-eq in kg/ha/y	274	278	817
Biocide-air-emission score in 1000 m^3/ha/y	1571	2197	2879
Biocide use in kg/ha/y	20.2	9.1	11.2
Total waste in 100 kg/ha/y	798	542	485

Area and total emissions

The total area allocated to the three farm types in the Netherlands in 1995 was 20% for Innovators, 60% for In-Betweens and 20% for Low-Costs (Table 5.6). Based on these estimates, we calculated total emissions and environmental impact scores for Dutch tomato cultivation in 1995. Figure 5.2 illustrates that In-Betweens have the largest share of most emissions and activities; 61% of CO_2 emissions, 63% of NO_x emissions, 43% of the emissions of eutrophying compounds, 46% of biocide use, 60% of the biocide-air-emission score, and 58% of the waste production. The large contribution of In-Betweens to total emissions can be explained by its large area. Low-Costs farms account for a relatively high share of eutrophying emissions (43%), due to their high emissions per hectare caused by the free drainage system (Figure 5.1).

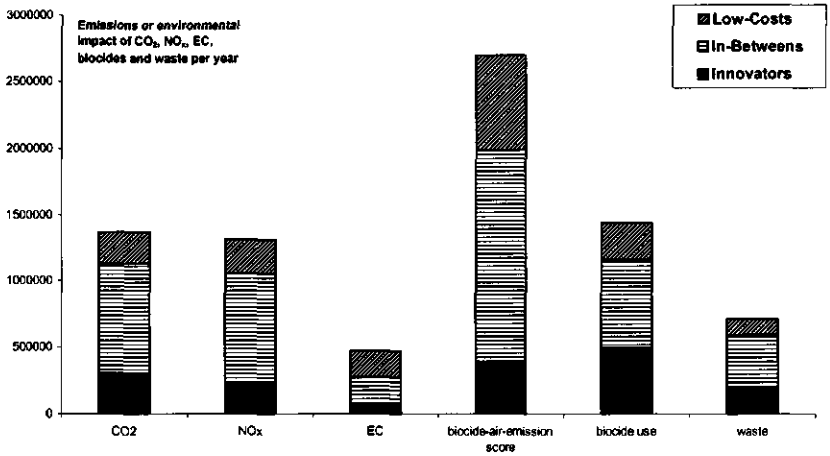

Figure 5.2 *Calculated emission levels for CO_2 (t CO_2/y), NO_x in (kg NO_x/y) and eutrophying compounds EC (kg PO_4-equivalents/y), biocide air emission score (1000 m^3/y), biocide use (0.01 kg/y) and the production of waste (100 kg/y) for total area of Dutch tomato cultivation in 1995, without additional control options implemented (reference case)*

Table 5.6 *Estimated distribution of farm types over total tomato cultivation area in 1995, based on Verhaegh (1998), Bouwman et al. (1996), Vernooy (1998) and Velden (1996)*

	Percentage of total area	Area in ha
Innovators	20%	245
In-Betweens	60%	730
Low-Costs	20%	245
Total area	100%	1220

5.4 Analysis of the 1995 tomato sector

5.4.1 Cost-effective combinations of options per environmental problem per farm type

For each of the three farm types we used our model (Chapter 3) to analyse the cost-effective combinations of options for the environmental problems considered. The results of each analysis are presented in Figures 5.3 to 5.7. These figures show the reductions achieved by cost-effective combinations of options, relative to the 1995 reference for the three different farm types. We quantified the environmental impact in terms of emissions and scores. Our model calculations indicate that the reduction that can be achieved by the application of technical options is in most cases smaller for the Innovators than for the other two farm types. This is due to the fact that Innovators had already adopted several reduction options in 1995. None of these options, however, influences the amount of waste disposed, so that Innovators can still reduce waste production considerably (see Figure 5.7). The Low-Costs have the highest reduction potentials because only a few options are applied in the 1995 reference for this farm type.

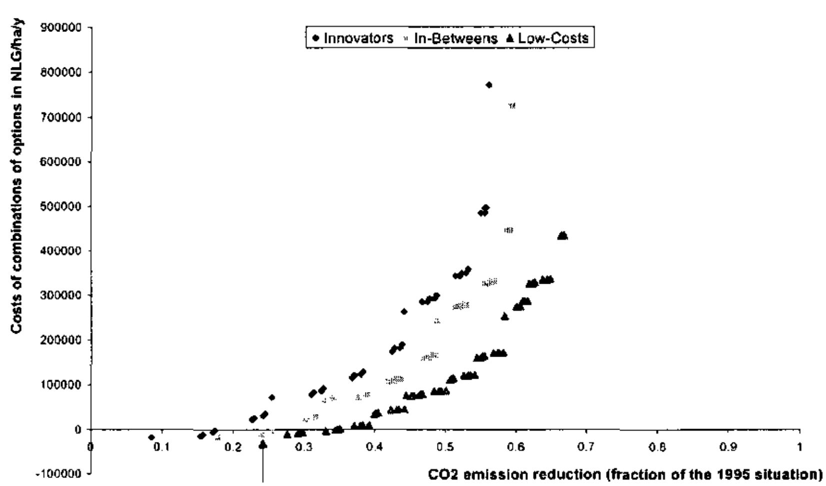

Figure 5.3 *The costs of efficient combinations of options for reducing CO_2 emissions and the reduction achieved as a fraction of the 1995 situation for the farm types Innovators, In-Betweens and Low-Costs (the arrow indicates the environmental target from Table 5.1)*

In some of the figures (Figure 5.3, 5.5 and 5.6) we included the environmental policy targets which were also used in the optimisation analysis (see section 5.3.2 and Table 5.1). For CO_2, we find that the target of 24% emission reduction can be achieved by In-Betweens and Low-Costs at net negative costs, while for the Innovators the additional costs of realising the target are about NLG 31,000 per hectare per year (Figure 5.3).

Similar results are obtained for the emissions of eutrophying compounds (Figure 5.5). The target of 38% reduction in biocide emissions can be realised by In-Betweens and Low-Costs at about NLG 12,000 and NLG 9000 per hectare per year respectively. The costs of achieving 38% emission reduction at the Innovators farms are similar. The next available cost-effective combination of options results in a 60% emission reduction and costs NLG 26,500 per hectare per year.

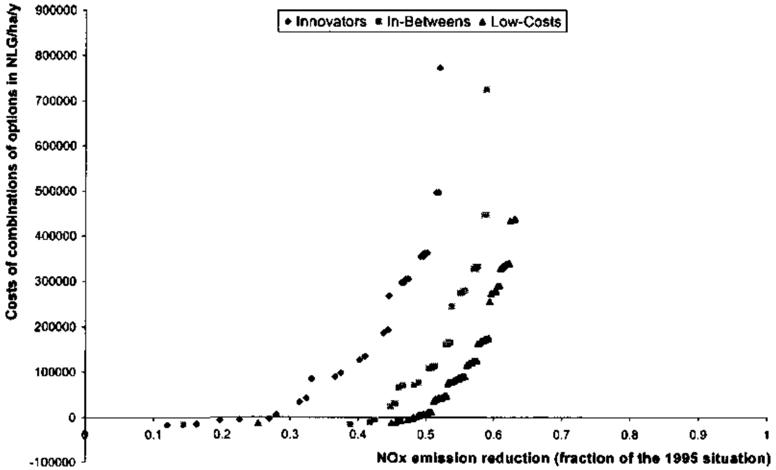

Figure 5.4 *The costs of efficient combinations of options for reducing NO_x emissions and the reduction achieved as a fraction of the 1995 situation for the farm types Innovators, In-Betweens and Low-Costs*

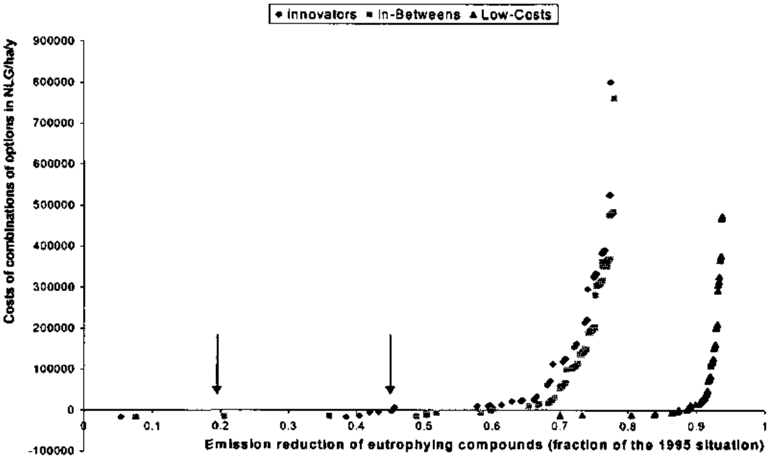

Figure 5.5 *The costs of efficient combinations of options for reducing emissions of eutrophying compounds and the reduction achieved as a fraction of the 1995 situation for the farm types Innovators, In-Betweens and Low-Costs (the arrows indicate the environmental targets from Table 5.1)*

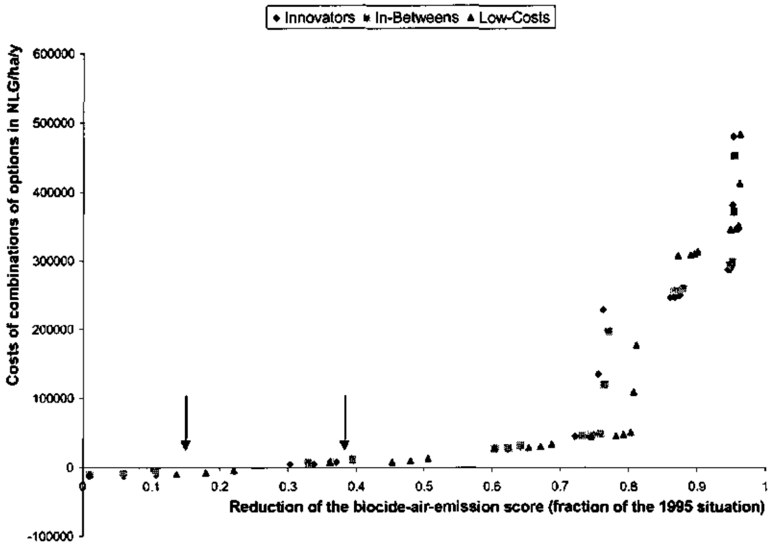

Figure 5.6 *The costs of efficient combinations of options for reducing the biocides-air-emission score and the reduction achieved as a fraction of the 1995 situation for the farm types Innovators, In-Betweens and Low-Costs (the arrows indicate the environmental targets from Table 5.1)*

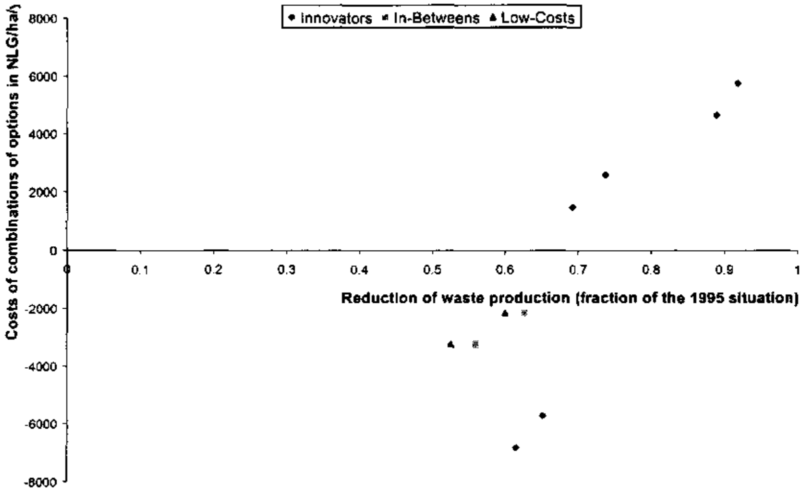

Figure 5.7 *The costs of efficient combinations of options for reducing waste production and the reduction achieved as a fraction of the 1995 situation for the farm types Innovators, In-Betweens and Low-Costs*

The options selected by the model in the cost-effective combinations differ per farm type. For CO_2, NO_x and eutrophying compounds all combinations for the In-Betweens and Low-Costs include a heat buffer, and those for Low-Costs include a combi-condenser. For the Innovators the options of the V-cultivation system using rock wool or the use of clay granulates as substrate are selected in all cost-effective combinations of options. For other option groups the cost-effective options for CO_2 emission control are similar for the three farm types and include different types of screens and roof insulation options, a temperature decrease in the greenhouse of 2°C, no minimum pipe temperature and the use of an Econaut and strips around window panes. Low-NO_x burners are used to achieve NO_x emission reduction. To reduce eutrophying emissions, the internal sewage connection, an extra water basin of 1000 or 4000 m^3 and the regional drain water cleaning are selected in the set of cost-effective combinations of options.

In the cost-effective combinations of options for reducing waste and biocide emissions to the air, the options that are selected are the same for the three farm types. For biocide air emissions all combinations include a movable screen, a decrease in greenhouse temperature (1° and 2 °C), electrostatic spraying techniques, and resistant crop varieties. For waste the selected options are composting on a regional level and recycling of plastic foil; for the Innovators the reuse of rock wool combined with the V-cultivation system and the use of clay granulates as substrate are cost-effective.

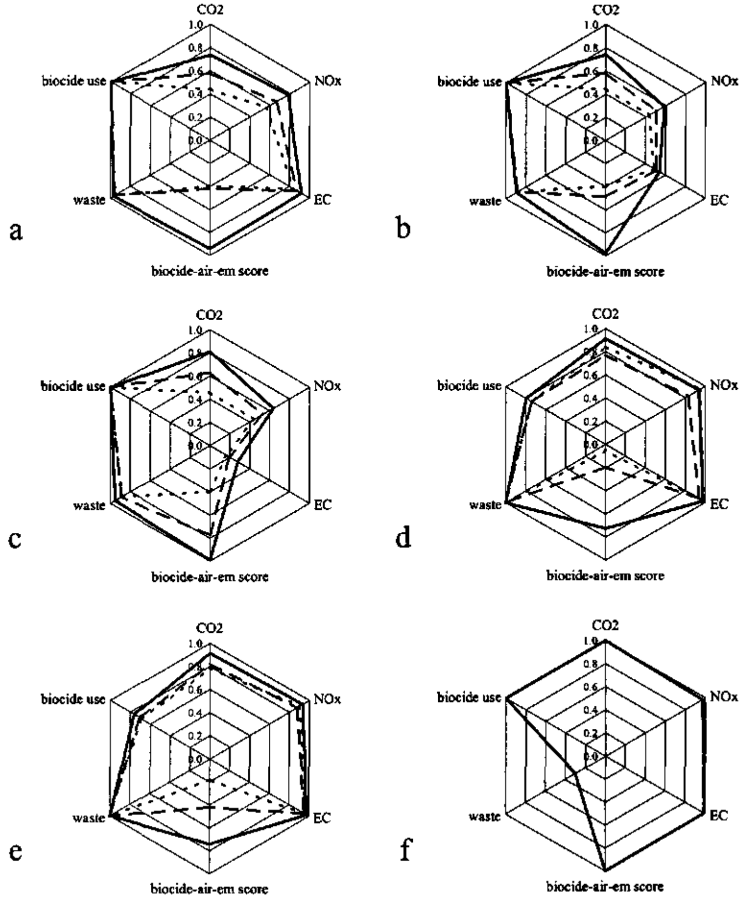

Figure 5.8 *Results of the optimisation analysis type 1: minimising the environmental impact (emissions or impact score) of tomato cultivation in the Netherlands for single environmental problems at different restrictions to the costs. The restrictions are zero (solid line), NLG 1.2 million (semi-dashed line) and NLG 3.6 million per year (dashed line). For each optimisation the consequences for all environmental problems are presented as the remaining fraction of the emissions of* CO_2*,* NO_x*, eutrophying compounds (EC), biocide emission into the air, biocide use and waste production relative to the reference situation of 1995.*

a minimising CO_2 *emissions* *d minimising biocide-air-emission score*
b minimising NO_x *emissions* *e minimising biocide use*
c minimising eutrophying (PO_4*-eq) emissions* *f minimising waste production*

5.4.2 Results of the optimisation analysis at the national scale

5.4.2.1 Optimisation type 1: Minimising environmental impact at given costs

Analyses per environmental problem

Figures 5.8a - e show the results of the optimisation analysis for three different cost restrictions and five different environmental problems. In each optimisation one environmental indicator is minimised, while the costs are restricted to NLG 0, 1.2 or 3.6 million per year for tomato cultivation in the Netherlands. These costs correspond with NLG0, 100,000, 300,000 per hectare per year, respectively, or 0%, 14% and 42% of the annual income of a tomato firm (IKC, 1995). It should be noticed that the optimal solutions for one environmental indicator affect the other environmental problems or emissions.

Figure 5.8a shows the results of minimising CO_2 emissions for three restrictions on costs. The figure shows that CO_2 emission can be reduced by 27%, 42% and 56% relative to 1995 for the three cost levels. These reductions all exceed the CO_2 emission reduction target (Table 5.1). The results furthermore indicate that, as a side-effect, emissions of NO_x and eutrophying compounds (EC) are reduced as well. Besides, the biocide-air-emission score is largely reduced for the cost restriction of NLG 1.2 and 3.6 million per year. This is due to the introduction of moveable screens, which reduce the gas use (and therefore the CO_2 emission) as well as emissions of biocides into the atmosphere. However, biocide use, as well as the emissions of eutrophying compounds and the production of waste, are not or only slightly affected by the CO_2 emission reducing options.

When the emissions of NO_x are minimised, the three cost restrictions result in 48%, 50% and 57% emission reduction (Figure 5.8b). These reductions and the reductions in emissions of eutrophying compounds are larger than for CO_2. The reason is that NO_x emissions are not only reduced by decreasing the gas use, but also by reducing the emissions from gas use directly (low-NO_x burner), the amount of fertiliser use and the use of rock wool. Reducing these activities and emissions affects the emissions of CO_2 and eutrophying compounds.

Emissions of eutrophying compounds can be reduced by 72% at zero costs (Figure 5.8c). The additional reductions achieved at increasing costs are relatively small. This can be explained by the effect of recirculating drain water, which results in a relatively large reduction in emissions compared to other options affecting the emissions of eutrophying compounds, such as the change of the source of irrigation water and cleaning of drain water.

The biocide-air-emission score, on the other hand, is reduced relatively little at zero costs (28%), but at NLG 1.2 and 3.6 million per year the additional reduction is relatively large at up to 95% (Figure 5.8d). Biocide use and emissions of CO_2 and NO_x are affected by the options for reducing biocide-air-emission score (mainly by the application of a movable screen). For biocide use we see similar results (Figure 5.8e).

For the reduction of waste we show only the optimisation result at zero costs because most of the combinations of options have net negative costs. At zero costs the maximum possible reduction that can be achieved by the options analysed in this study is reached

(70%) (Figure 5.8f). Higher costs will not result in a lower amount of waste production with the options considered in this study.

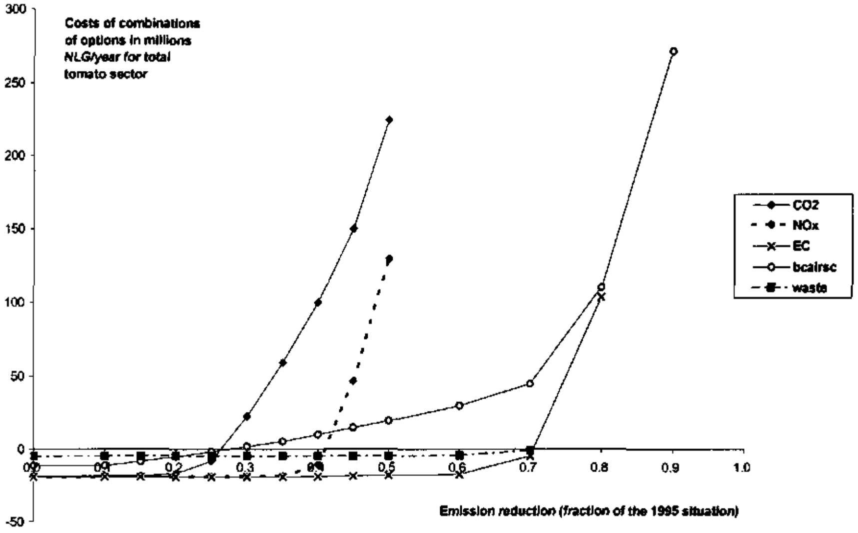

Figure 5.9 *Cost curves of emission reduction of CO_2, NO_x, eutrophying compounds (EC), biocide emissions to the air (quantified by the biocide-air-emission score (bcairsc)) and reduction of waste disposal (waste), illustrating the total costs of different combinations of options applied in the Dutch tomato sector and the resulting emission or waste reduction relative to the 1995 situation*

Cost curves

We carried out optimisation analyses for a range of costs, resulting in a number of cost curves for tomato cultivation in the Netherlands (Figure 5.9). Each dot in this figure represents the result of one optimisation run, and the curve is developed by connecting the dots. The curves show the costs of various emission reductions on a national level, relative to the 1995 reference situation. However, it cannot be used to analyse the costs of step wise emission reductions because each dot represents an application of different combinations of options over the total tomato sector. To achieve a higher reduction another combination of options may be selected including other options and excluding options that were selected at lower costs.

All cost curves start at net negative costs (Figure 5.9) indicating that in the 1995 reference situation emissions can be reduced without additional costs. Further, the curves show the maximum emission reduction for tomato cultivation in the Netherlands under the options considered. CO_2 emissions have the lowest maximum achievable emission reduction (50%). The CO_2 cost curve has a point of inflection at about 20% emission reduction, which is associated with rapidly increasing costs. For NO_x this point is at 40% emission reduction. The biocide-air-emission score can be greatly reduced (up to 90%); the cost slowly increases until a reduction of about 70% is achieved. For additional reductions the cost increases rapidly. This trend is also demonstrated in the case of eutrophying compounds (EC) emissions. However, for these emissions a 70% reduction can be achieved at costs lower than zero. The cost curve for waste reduction is flat, and indicates that the maximum reduction for the sector is about 70% relative to the defined 1995 situation.

Integrated analysis

The results of the integrated optimisation analysis are presented as cost curves using five multi-criteria methods (Figure 5.10). The maximum profit of combinations of options applied in the tomato sector is about NLG 20 million per year. At these (negative) costs the environmental impact can be reduced by at least 20%. From this point on the different multi-criteria methods result in different costs curves. For the Distance to target method the costs rapidly increase when reductions exceed 30%. The maximum reduction that can be achieved according to this method is about 45%. The maximum reduction for the MPS score is even lower (40%) because this method is based largely on activity levels (such as energy use) instead of emission levels (such as NO_x emission), which are mainly used in the other multi-criteria methods. The options considered in the analysis may reduce the activity levels and the emission levels. The MPS method does not take into account the decrease in the total environmental impact of those options that only reduce the emission level and do not affect any activity levels (such as the low-NO_x burner).

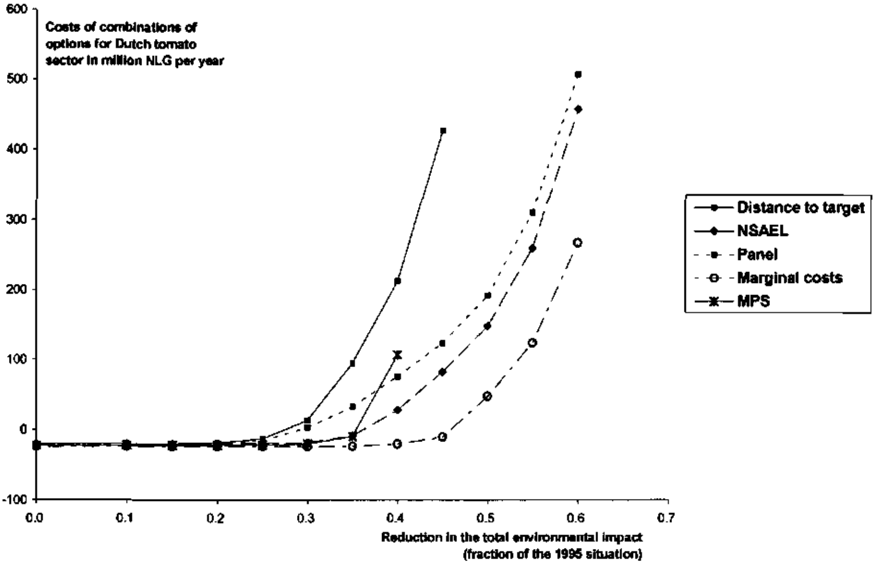

Figure 5.10 *Cost curve of the integrated environmental impact using 5 different multi-criteria methods: Distance to target, NSAEL, Panel, Marginal costs and the MPS. The curves illustrate the total costs of different combinations of options applied in the Dutch tomato sector and the resulting reduction of the overall environmental impact relative to the 1995 situation*

The Marginal costs method is the only method which considers the production of waste in the calculation of the integrated environmental impact. However, this is not the only reason why the Marginal cost method results in a higher maximum reduction (almost 60%) than the other methods. Another reason is the fact that the environmental problem which can be reduced most by the options analysed has a relatively high weight in the quantification of the overall environmental impact. An example is the use of biocide use as indicator in the Distance to target method, while in the NSAEL, Panel and Marginal costs method the biocide-air-emission score is used to quantify the environmental impact. As illustrated in Figure 5.8d and e, biocide use is more difficult to reduce than the biocide-air-emission score.

5.4.2.2 Optimisation type 2: Minimising costs for different environmental targets

Analyses per environmental problem

Figures 5.11a to 11e show the results of minimising the costs incurred in achieving the environmental targets listed in Table 5.1. The costs of achieving these targets are listed in Table 5.7. Table 5.8 presents the application rate of individual options as a percentage of total tomato cultivation area in the Netherlands selected in the cost-optimal solutions. The percentages also include the options that were already applied in the 1995 reference situation.

Our results indicate that the CO_2 emission target of 1.03 Gton can be achieved at net negative costs (Table 5.7). The highest investments are needed in the farm type Low-Costs. On about 26% of the area of this farm type a combination of options has to be applied which cost about NLG 8130 per hectare per year. The optimal solution includes the application of condensers (a combi- or a return condenser), fixed screens, heat buffers, temperature management options (no minimum pipe temperature or an Econaut) and strips around window panes on 100% of the area (Table 5.8). The CO_2 emission reduction also affects the emission of NO_x and to a less extent (related to the NO_x emissions) the emissions of eutrophying compounds (Figure 5.11a).

The two environmental targets (20% and 45% reduction) for emissions of eutrophying compounds (EC) (Table 5.6) can both be achieved at net negative costs. The difference in costs is only about NLG 500 000 per year for the whole area (Table 5.7). The additional reduction from 20% to 45% relative to the emission in 1995 can be achieved by increasing the area on which low-NO_x burners are applied from 20% to 80% of the total area and by the application of a connection to the sewage system on 24% of the area (all Innovators and part of the Low-Costs). These two options only affect the emission of eutrophying compounds (including the NO_x emissions) and not the CO_2 emissions. The options applied to achieve both targets largely correspond with the set of options applied to achieve the CO_2 emission reduction target. They only differ in the application of a screen (no screens are applied in the EC case), the use of an Econaut (in the EC case Econauts are applied on 100% of the area, while in the CO_2 case the no minimum pipe temperature is applied on 20% of the area) and the multi year use of rock wool combined with the V-cultivation system (which is applied on 20% of the area in the EC case).

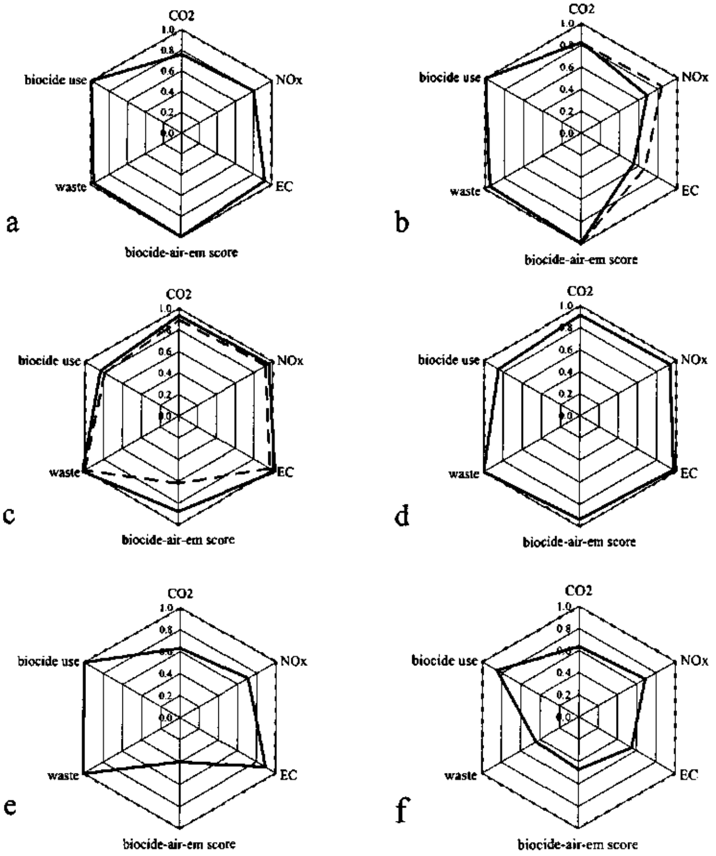

Figure 5.11 *Results of the optimisation of minimising the costs of achieving different environmental targets (see Table 5.1). For each optimisation the consequences for all environmental problems are presented as the remaining fraction (solid and dashed lines) of the emissions in the reference 1995 situation (dotted line). The costs are presented in Table 5.7. The targets are:*

a CO_2 *emissions reduction of 24%*

b Reduction of 20% of the emissions of eutrophying compounds (dashed line)
Reduction of 45% of the emissions of eutrophying compounds (solid line)

c Reduction of 15% of the biocide emission to the air (solid line)
Reduction of 38% of the biocide emission to the air (dashed line)

d Reduction of 15% of the biocide use

e 65% energy efficiency improvement relative to the 1980 situation

f Meeting environmental targets a to e simultaneously (CO_2 *emission reduction, EC emission reduction of 45%, biocide-air-emission score reduction of 38%, biocide use reduction of 15% and energy efficiency improvement of 65%)*

The 15% reduction target for biocide use and biocide-air-emission score can both be realised. The costs involved are negative for both targets, although the costs of reducing the biocide-air-emission score are higher than the costs of achieving the biocide use target. Low-Costs have to invest large sums on about 80% of their area to achieve the cost optimal solution at the national level, while on the rest of the tomato area combinations of options are applied with net negative costs (Table 5.7). The results of these two optimisations differ with respect to the application rate of netting, which is only selected to achieve the required biocide-air-emission score. Further, the electrostatic spraying technique is applied in both solutions, while for the biocide air emission target the application rate is higher. Strips around window panes are applied on 100% of the area in both optimal solutions (Table 5.8). The costs of achieving 15% emission reduction are higher than the costs of achieving 15% reduction in biocide use, because the emission of biocide into the atmosphere is not only related to the amount applied, but also depends on the vapour pressure of the biocides used. Additionally, we analysed the reduction for the biocide-air-emission score instead of the emission of biocides into the atmosphere. The difference between the emission into the atmosphere and the biocide-air-emission score is that the latter also includes the persistency and the toxicity of the biocides applied.

The cost optimal solution of achieving a 38% reduction of the biocide-air-emission score implies net positive costs for the tomato cultivation sector. Innovators, however, apply a combination of options at net negative costs. On about 20% of the In-Betweens area the options are applied at high costs (Table 5.7). The difference between the 15% reduction of the biocide-air-emission score and the 38% target is that for the 38% target a movable screen is used on 11% of the area, netting and strips in window panes (instead of only strips) on 68% of the area and the electrostatic spraying technique on 100% of the area (Table 5.8). The 38% reduction target for biocide use cannot be achieved by the (technical) reduction options included in the model.

The options for reducing the biocide use and biocide-air-emission score do not affect the emissions of other environmental pollutants to a large degree. Only the emission of CO_2 (and to a very small extent the emissions of NO_x) are affected by the options (Figure 5.11c and d), mainly due to the application of a moveable screen and strips in window panes.

To achieve a 65% improvement in energy efficiency relative to 1980, high investments are needed in all three farm types (Table 5.7). The highest investments are made on 76% of the area of In-Betweens. As in the solution to achieve the CO_2 emission target, the energy efficiency target requires the application of condensers (combi- or return type), heat buffers and change in temperature management (no minimum pipe temperature or an Econaut) on 100% of the tomato cultivation area. In addition, moveable screen, some kind of wall insulation option (double glass, foil or coated glass) are applied on 100% of the area and coated glass is used in the roof on 46% of the area. The options that are applied to achieve the energy efficiency target largely affect emissions, especially the emissions of CO_2, NO_x and biocides into the air (Figure 5.11e). This side effect is a consequence of the use of a moveable screen, which is applied on 100% of the area. The CO_2 and NO_x emission reduction are also affected by the use of coated glass in the roof.

Table 5.7 *Results of the optimisation type 2 of minimising costs for different environmental targets (see Table 5.1): the greenhouse area (hectare) to which reduction options are applied and the costs involved. Also shown are the results of the minimisation of costs without restrictions on the environmental impact (Lowest costs)*

Environmental target in the optimisation analysis	Farm type	Area (in ha)	Costs (in NLG per ha per year)	Total costs for tomato sector (in 10^6 NLG per year)
Global warming	Innovators	245	-14397.2	
CO$_2$ emissions	In-Betweens	730	-11433.9	
24% reduction	Low-Costs	65	10096.3	
		180	-800.5	
TOTAL		1220		-11.4
Eutrophication	Innovators	245	-16897.4	
EC[1] 20% reduction	In-Betweens	730	-16278.8	
	Low-Costs	245	-12582.2	
TOTAL		1220		-19.1
Eutrophication	Innovators	245	-16221.3	
EC[1] 45% reduction	In-Betweens	730	-15950.6	
	Low-Costs	198	-12582.2	
		47	-11060.9	
TOTAL		1220		-18.6
Biocide use	Innovators	245	-13166.9	
Biocide use 15% reduction	In-Betweens	300	-10113.1	
		430	-9214.1	
	Low-Costs	245	-9566.7	
TOTAL		1220		-12.6
Biocide-air-emission score	Innovators	245	-13166.9	
Bcairsc[2] 15% reduction	In-Betweens	730	-9214.1	
	Low-Costs	73	-7663.9	
		202	7928.1	
TOTAL		1220		-8.91
Biocide-air-emission score	Innovators	245	-13166.9	
Bcairsc[2] 38% reduction	In-Betweens	590	8345.7	
		140	28505.5	
	Low-Costs	245	9879.4	
TOTAL		1220		8.11
Energy efficiency improvement	Innovators	245	26506.7	
65% improvement relative to 1980	In-Betweens	174	2973.2	
		556	107339.4	
	Low-Costs	245	45354.5	
TOTAL		1220		82.5
All environmental targets simultaneously	Innovators	245	-17489.9	
	In-Betweens	335	205.9	
		395	6181.1	
	Low-Costs	207	-20551.9	
		33	-13301.2	
		5	-12911.5	
TOTAL		1220		-6.53
Lowest costs[3]	Innovators	245	-20137.4	
	In-Betweens	730	-19518.8	
	Low-Costs	245	-20551.9	
TOTAL		1220		-24.2

[1] EC = eutrophying compounds

[2] bcairsc = biocide-air-emission score

[3] resulting emissions reductions are 18% for CO$_2$ emissions, 16% for NO$_x$ emissions, 34% for eutrophying emissions. The biocide-air-emission score is reduced by 1% and waste by 57%.

Since some targets can be achieved at net negative costs we were interested in the maximum possible savings that can be achieved and the associated emission reduction. Therefore, we carried out an optimisation analysis in which we minimised the costs without any constraints on the emissions of compounds, use of biocides or production of waste. The maximum cost savings can be achieved in total tomato cultivation in the Netherlands with the options considered is calculated to be NLG 24.2 million per year (Table 5.7), which is almost 3% of the annual income. The associated emission reductions for CO_2, NO_x and eutrophying compounds are 18%, 16% and 34%, respectively. For biocide use an 8% reduction is achieved relative to the 1995 situation, while the biocide-air-emission score is reduced by 1%. The highest reduction is achieved in the production of waste (57%). In this situation the model selects for all farm types a type of condenser, a heat buffer, an Econaut, strips around window panes and composting at the regional level. Additionally, for Low-Costs, high-pressure cleaning and recirculation of drain water are selected (Table 5.8).

Integrated analysis (meeting all environmental targets simultaneously)

Minimising the costs of achieving all environmental targets simultaneously results in a saving of NLG 6.5 million per year for tomato cultivation in the Netherlands. These savings represent less than 1% of the average income of the firms (IKC, 1995). The relatively low costs of achieving all targets simultaneously can be explained by the approach we used in our analysis. When analysing, for example, the reduction of CO_2 emissions, we only included those options from the option groups that affect the CO_2 emission. In the integrated analysis we considered all options. In this way all the options which result in extra savings are applied and contribute to lower overall costs. The cost optimal way to achieve all targets simultaneously, therefore, results in a different application rate for some options (Table 5.8) than in the cost-optimal results of the single target analyses. In the integrated analysis coated double roofs, the no-window options and composting at the regional level are selected in the combinations of options, while in the individual analyses these options were never selected. . Double glass has the highest technical potential to reduce natural gas use of the options analysed, but results in a considerable reduction in production due to a decrease in radiation. Nevertheless, its cost-effectiveness in combination with other options (such as the no-window option) is higher than of other options when multiple targets are to be reached. The application of the no-windows options affects the use of energy (reduces the use of natural gas and increases the use of electricity), the emissions of biocides to the atmosphere and the tomato production (increase in production due to increase in radiation). Some options that were selected in the individual analyses were not selected in the integrated analyses. These include movable screens, coated glass, changing of minimum pipe temperature and netting in windows.

Table 5.8 *Percentage of the total area of tomato cultivation in which options are applied in the 1995 reference situation and in the results of the optimisation analysis. In the optimisation analysis the environmental targets are realised at minimum costs (type 2 Box 1) and the costs are minimised without restrictions on the environmental impact (Lowest costs). The environmental targets are described in Table 1 and include: the reduction of CO_2 emissions by 24% (CO_2), the reduction of eutrophying (PO_4-eq) emissions (EC) by 20% and 45%, the reduction of biocide use (in kg active ingredient) (Bc use) by 15%, the reduction of the biocide-air-emission score (m^3) (Bcair) by 15% and 38% and the energy efficiency improvement (E-eff) of 65% relative to the situation in 1980. The last column shows the results when all targets are met simultaneously*

Option group	Option	1995	Lowest costs	CO_2	EC 20%	EC 45%	Bc use	Bcair 15%	Bcair 38%	E-eff	All targets
Condensers	return condenser	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%
	combi-condenser	20%	40%	40%	40%	40%	20%	20%	20%	40%	40%
Screens	fixed screen	-	-	100%	-	-	-	-	-	-	56%
	moveable screen	-	-	-	-	-	-	-	11%	100%	-
Wall isulation	double glass	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
	foil	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%
	double glass coat	-	-	5%	-	-	-	-	-	20%	-
Roof isulation	coated glass	-	-	-	-	-	-	-	-	46%	-
	double glass	-	-	-	-	-	-	-	-	-	60%
CO_2 supply method	heat buffer	20%	100%	100%	100%	100%	20%	20%	20%	100%	100%
NO_x emission reduction	low-NO_x burner	20%	20%	20%	20%	80%	20%	20%	20%	20%	20%
Temperature	no min pipe temperature	-	-	20%	-	-	-	-	-	34%	-
management	Econaut	-	100%	80%	100%	100%	100%	100%	100%	66%	100%
Construction	strips around window panes	-	100%	100%	100%	100%	100%	83%	32%	100%	40%
change	no windows	-	-	-	-	-	-	-	-	-	60%
	netting and strips	-	-	-	-	-	-	17%	68%	-	-
Spraying technique	electrostatic spraying	-	-	-	-	-	55%	83%	100%	-	48%
Biocontrol	biocontrol and scouting	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Greenhouse hygiene	improved hygiene	80%	80%	80%	80%	80%	100%	100%	100%	80%	80%
High-pressure cleaner	high-pressure cleaner	80%	100%	80%	80%	80%	100%	100%	100%	80%	100%
Mechanical roof cleaner	own mechanical roof cleaner	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Recirculation	recirculation	80%	100%	80%	100%	100%	80%	80%	80%	80%	100%
Drain water disinfection	heating	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
Sewage	internal	-	-	-	-	24%	-	-	-	-	27%
Source of irrigation water	extra water basin1000 m^3	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Change of substrate	multi year rock wool use	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
use	multi year rock wool use and V-system	-	-	-	20%	20%	-	-	-	-	20%
Composting	at the regional level	-	100%	-	-	-	-	-	-	-	100%

In Chapter 4 we analysed the cost-efficiency of individual options and calculated the annual costs of each option relative to the zero case situation. Although we are dealing here with another reference situation (which may influence the annual costs), the costs of the options for the zero case situation can be used to illustrate which options contribute to extra savings in the integrated analysis. Composting at the regional level results in Chapter 4 in relatively high savings. The use of rock wool for more than one year combined with the V-cultivation system on 20% of the area results in a saving of about NLG 1.6 million per year for the total sector. Finally, the use of recirculation of drainwater in Low-Costs also saves costs (see also the results of the optimisation for 20% and 45% emission reduction of eutrophying compounds in Table 5.7 and 5.8).

The optimal solution of achieving all environmental targets simultaneously, of course, affects all the emissions of pollutants considered in the analyses. However, Figure 5.11f illustrates that for CO_2 emission and biocide emission the achieved emission levels are slightly lower than the prescribed targets, while the reduction of biocide use and emission of eutrophying compounds are exactly the same as defined in the target. In other words, biocide use and emissions of eutrophying compounds are binding constraints.

5.5 Discussion

Methodology

We performed our analysis using the model described in Chapter 3, and available data from the literature. As any modelling study has its shortcomings, we will discuss some important methodological choices that we made and their consequences. We also refer to Chapter 4 for a discussion of several aspects of our model approach.

We described heterogeneity in tomato cultivation in the Netherlands in 1995 by defining different farm types. The use of farm types enables us to describe a heterogeneous sector with respect to its environmental impact and the reduction options applied as a composition of a number of homogenous elements. For each homogenous element (i.e. for each farm type) we used our model to analyse the cost-effectiveness of combinations of reduction options. As illustrated in Figures 5.3 to 5.7 the farm types use different cost-effective combinations of options and different reduction possibilities. In other words, the definition of the three farm types and the assumption about the area they cover have a big influence on the results of the study. It also indicates that the heterogeneity of the tomato sector is an important aspect to consider while analysing the possibilities for reducing of the environmental impact of the sector. We notice that this method is just one way to describe heterogeneity. It is however a way to use our model, that is developed in such a way that either select an options or does not select one. In other words the model has a zero-one approach. By defining farm types and including the area as an extra variable we have formulated a discrete mathematical problem, allowing options to be applied to part of the total tomato area.

If an option was implemented in the reference situation, we did not allow application of other options from the same group. This assumption may affect the maximum possible reduction which could be achieved (Figures 5.3 to 5.7). The options which are applied in the reference situation and which, therefore, cannot be replaced by an option from the same group with higher reduction potentials, are the return condenser and the foil as wall insulation options for the In-Betweens, the extra water basin of 1000 m^3 (from the group source of irrigation water) for the Innovators and the multi-year substrate for both In-Betweens and Low-Costs. Changing this restriction will, therefore, affect the maximum possible emission of CO_2, NO_x and eutrophying compounds as well as the amount of waste disposed. It may be questioned, however, whether these options would be selected in the cost-optimal solution if we considered the additional costs of replacing techniques already in use.

One of the restrictions made in the optimisation analysis is that the areas of three different farm types are fixed. Hence, the analysis reveals an optimal solution relative to the 1995 situation and does not consider a possible shift from one farm type to another. In reality, however, these changes may occur. This could be a future extension of the model.

The environmental targets analysed are deduced from the environmental policy targets for Dutch greenhouse horticulture. We did not take into account some of the presently existing regulations on, for example, the recirculation of drain water and the purchase of low-NO_x burners. Not all options that are presently required by law are applied in the reference case. The reason that we did not force the model to select these options was that 1) in 1995 these laws were not yet in force, and 2) we wanted to be free to select all possible combination of options to analyse the most cost-effective strategies for achieving certain targets.

Some remarks on the interpretation of the results

Our optimisation analysis at the sectoral level indicates that present day environmental targets for the Dutch tomato sector can be achieved cost-effectively by applying combinations of reduction options with net negative costs in part of the area, while the other part of the area applies options with net positive costs. This result is directly related to our estimates for the areas of the three farm types. It shows that it is worthwhile looking at the differences in activity levels and application rates in tomato cultivation if we want to achieve a cost-optimal reduction of the environmental impact of the total tomato sector.

The maximum savings in costs that can be achieved in Dutch tomato cultivation are NLG 24.2 million per year (Table 5.7). The model results for individual environmental targets, however, indicate that environmental policies directed to single environmental problems may be associated with high costs. The highest investments are needed to achieve the energy efficiency target for 2010 (NLG 82.5 million per year). The difference between the maximum savings and the costs to achieve the energy efficiency target are NLG 106.7 million per year.

The integrated analysis in which we considered all the environmental problems simultaneously is carried out for two types of optimisation problems (Box 5.1). For the minimisation of the total environmental impact we applied five different multi-criteria methods to quantify the overall environmental impact of the tomato sector. As was discussed in Chapter 4 the choice of the multi-criteria method largely influences the outcome of the analysis. However, the results from the different multi-criteria methods showed that some options were always selected. These may be considered the robust options, and include a type of condenser, a heat buffer, the Econaut, the use of strips in window panes, the use of biological control and scouting, greenhouse hygiene and the use of rock wool for more years. Otherwise, the results strongly depend on the method used. The maximum achievable reduction depends on which indicators (e.g. kg biocide use or biocide-air-emission score, including or excluding the production of waste) are used to quantify the overall environmental impact.

Comparable studies

We compared our analysis with the studies by Balthussen et al. (1996) and Hietbrink et al. (1999) which are to some extent comparable with our study. These two studies focus on the environmental and economic consequences of the 'Greenhouse Horticulture and Environment' agreement (LNV, 1997) for the total greenhouse sector. Thus, these two studies include many more crops than tomato. They analyse the economic performance of the Dutch greenhouse sector in 2010 for different scenarios, whereas we focus on the possibilities for achieving 2010 targets relative to the 1995 situation independent of future economic trends. The reduction options analysed are similar to the options we included in our model. Balthussen et al. (1996) and Hietbrink et al. (1999) did not analyse cost-effective combinations of options, did not carry out an optimisation analysis and did not consider the analysis of options to reduce waste.

Balthussen et al. (1996) concluded that the sector needs to apply additional abatement measures relative to the present situation, to achieve the environmental targets for 2010. They also concluded that this will result in an increase in the percentage of farms that will have financial problems in 2010 compared with the situation without environmental restrictions. When excluding the most expensive options, the total costs per farm decreased considerably, without an effect on the realisation of the targets for energy efficiency and biocide use. There are two remarkable differences with our study: (1) our model calculations show that the energy efficiency target is expensive to achieve (Table 5.7), and (2) the highest reduction target for biocide use cannot be achieved by the options in our model (see section 5.4.2.2). The difference for energy efficiency may be explained by the fact that we analysed the 1995 situation while Balthussen et al. focussed on the situation in 2010 and included a production increase over the period 1995-2010, which increased the energy efficiency of the sector. In relation to biocide use, they consider large reductions in the area of soil cultivation resulting from the decrease in the use of soil disinfectant biocides. This does not apply to tomato cultivation, because tomato cultivation is almost entirely on substrate.

Hietbrink et al. (1999) also analysed a prognosis for 2010, and considered the economic and environmental effect of including and excluding the environmental targets of the agreement (LNV, 1997). A comparison of theirs and our results is difficult, because their study focused on the economic performance of greenhouse horticulture in the Netherlands as a whole, while we focused on the additional costs of technical options to reduce the environmental impact of only tomato cultivation. Another difference is that we analysed cost-optimal strategies to achieve single and multiple environmental targets including, an integrated approach. For future research it would be interesting to combine Hietbrink's analysis with our integrated approach in order to explore possible future developments by scenario analyses.

5.6 Conclusions

We investigated the possibilities for reducing the environmental impact caused by Dutch tomato cultivation in greenhouses. To this end, we choose the 1995 situation as a case and used the model that we developed to explore the most cost-effective strategies. We defined three farm types, Innovators, In-Betweens and Low-Costs, to characterise tomato cultivation in the Netherlands. In-Betweens produced the largest share of total emissions. The Low-Costs farms produced a relatively large share of total eutrophying emissions because in the reference situation for this farm type drainwater is not recirculated.

Our model includes technical options for reducing the environmental impact. The combinations of options selected by the model that are cost-effective or that result in maximum achievable emission reduction differ per farm type. Some options are, however, always considered cost-effective by the model, regardless of the farm type or optimisation target. These robust options include condensers, heat buffers, the Econaut, the use of strips around window panes, the use of biological control and scouting, greenhouse hygiene and the reuse of rock wool for a number of years. Our results show that an emission reduction strategy for one compound may also reduce the emissions of other pollutants. This is especially the case for the reduction of emissions of CO_2 and NO_x. In addition, a reduction in eutrophying emissions may affect emissions of CO_2 and biocides into the atmosphere, and vice versa.

At the national scale we analysed strategies for minimising the environmental impact of Dutch tomato cultivation for different cost constraints. These analyses resulted in a cost curve for each environmental problem analysed. The cost curves show the costs of different levels of emission reduction relative to the 1995 reference situation. All cost curves start at net negative costs for the sector as a whole. Furthermore, the cost curves illustrate the maximum reduction that can be achieved by the options considered relative to the 1995 reference situation. These maximum reductions are about 50% for CO_2 and NO_x emissions, 80% for the emissions of eutrophying compound, 90% for the biocide-air-emission score and 70% for waste.

For the integrated analysis, in which we minimised the overall environmental impact at some constraints on the costs, we used five different multi-criteria methods. These analyses resulted in one cost curve for each multi-criteria method applied. Although the results differ per multi-criteria method used, they also show some similarities. The results illustrate, for example, that the maximum profit from combinations of options applied in the tomato sector is about NLG 20 million per year for all five multi-criteria methods. At these (negative) costs the environmental impact can be reduced by about 20%.

We quantified the costs of achieving environmental targets by the Dutch tomato sector. Our model results suggest that the largest investments are needed to achieve the target of energy efficiency, followed by the targets of 38% reduction of biocide-air-emission score, while the costs of achieving the targets for CO_2, eutrophying compounds and biocide air emission reductions of 15% are negative. Moreover, our results indicate that the results of minimising the costs of achieving all environmental targets simultaneously are negative (NLG -6.5 million per year). This is caused by the fact that in the integrated analysis all options are considered and that some options have negative costs which compensate for the costs of more expensive options. The options with negative costs are the options composting at the regional level, the use of V-cultivation system and the recirculation of drain water in Low-Costs farms. The reduction of biocide use and emission of eutrophying compounds are binding constraints in the integrated analysis.

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6 Discussion

6.1 Introduction

This study assessed technical options for reducing the environmental impact of greenhouse horticulture in the Netherlands. The main objective was to identify technical options for reducing the environmental impact of greenhouse horticulture in the Netherlands and to evaluate the cost-effectiveness of these options. Environmental systems analysis was used. In addition, the study aimed to discuss the usefulness of environmental systems analysis as a method for evaluating cost-effective abatement strategies. The study was restricted to tomato cultivation in the Netherlands.

In the following section (6.2) the results of the analysis for tomato cultivation in the Netherlands are discussed, with respect to the first four subs-goals as described in Chapter 1. In section 6.3 I describe the possibilities to use the tomato case as a basis for an analysis of total greenhouse horticulture in the Netherlands. This would require at least an evaluation of the system boundaries and system components, the cost-effectiveness of reduction options for other cultivations and the possibilities to extrapolate the results of the tomato case to overall greenhouse horticulture. I will give guidance towards extending the tomato model to total greenhouse horticulture. This chapter closes with a discussion on the methodology and the usefulness of environmental systems analysis as method in this study (section 6.4).

6.2 Discussion of the results for the tomato case

System boundaries and system components

The first sub-goal was to identify the system boundaries and the input, output and processes that have to be taken into account when analysing the environmental impact of tomato cultivation. The definition of the systems boundaries and systems components is one of the first steps of systems analysis, and is related to the aim of the analysis. This thesis examines the environmental impact of tomato cultivation in the Netherlands and (on-farm) technical reduction options to reduce this impact. Related to this aim the model needed to include those processes and emissions that importantly contribute to the environmental impact. Furthermore, the model should cover options for reducing the environmental impact and consider the side effects of reduction options on environmental problems (as was discussed in Chapter 1).

We chose to carry out a thorough analysis of the environmental impact in order to find out which processes within the cultivation in greenhouses contribute to the total environmental impact of the sector. We based the definition of the system components on the relative contribution of the processes and related emission of polluting compounds to the total environmental impact of tomato cultivation. To identify the processes that should be included in the model system, a limited environmental life cycle analysis was carried out for tomato cultivation and global warming, acidification and eutrophication. We focused on these three environmental problems because of the interrelations between the underlying processes and the emissions. We quantified the emissions of greenhouse gases and acidifying and eutrophying compounds from agricultural activities (first-order processes) and the emissions from industrial activities (second-order processes), such as the production of electricity, fertilisers and biocides (Chapter 2). The results of the analysis indicate that for tomato cultivation some emissions from second-order processes (e.g. the production of electricity) can be relatively high compared with emissions from first-order processes (e.g. the combustion of natural gas). A study on the environmental impact of tomato cultivation in the Netherlands needs to consider: CO_2 emissions from gas use and electricity, NO_x emissions from the use of natural gas and fertilisers, and from the production of electricity and rock wool, and N and P emissions from fertiliser use. In addition, it is important to consider the emission of biocides in the environment and the production of waste (Chapter 3).

Alternatively, we could have decided to include only those processes and compounds for which environmental policies for greenhouse horticulture have been formulated (e.g. energy efficiency, emissions of eutrophying compounds, use and emissions of biocides). In that case, the analysis would have been limited to a smaller number of activities and emissions, and it would have been restricted to on-farm processes only. We included som off-farm processes because they have a considerable contribution to the environmental impact and because they are affected by the choices of the grower. The choice of system boundaries and components determines to a large extent what we can and cannot analyse with the model. For example, our model was not designed for macro-economic analysis. If we want to answer questions related to the consequences of Dutch environmental policy on competition with tomato production outside the Netherlands (e.g. Spain), other aspects would need to be included in the system description, including the environmental impact of production in Spain, transport and macro-economic consequences. Since this was not the aim of this study we did not include macro-economic aspects.

Model building

The second sub-goal was to develop a model which quantifies the environmental impact of tomato cultivation in the Netherlands and which can be used to evaluate the effect of combinations of options for reducing the environmental impact. The environmental problems considered in this study are global warming, acidification, eutrophication, the dispersion of toxic biocides and the production of waste. The calculated environmental impact does not reflect the actual effect on the environment but rather the potential effect, i.e. the environmental pressure (the emissions to the environment in most cases). The emissions are calculated as a function of the activity (e.g. the use of natural gas) and an emission factor (e.g. the amount of CO_2 emitted from the combustion of one m^3 natural gas).

The model was used to evaluate the effect of combinations of technical options on the environmental impact. The model rejects combinations of options that cannot be applied simultaneously (e.g. a fixed screen and a movable screen). The options are arranged in groups, each of which consists of options that are mutually exclusive. Combinations of options are obtained by selecting at most one option from each group. The computer application of the model generates all possible combinations of options and calculates the costs and the resulting environmental pressure. The number of possible combinations increases rapidly as the number of groups and the number of options within the groups increase, making the interpretation of the results difficult. For this reason a filter was developed that removes all those combinations of options that results in the same or lower reduction of the environmental pressure at higher costs than another combination of options.

A new aspect of this integrated model is that it can be used to analyse the cost-effectiveness of combinations of reduction options for different environmental problems simultaneously. The reduction options may affect activity levels or emission factors. The costs of the options are quantified as annual costs per hectare of tomato cultivation and are additional costs for a given reference situation. The environmental pressure is expressed through a number of environmental indicators, e.g. PO_4-equivalents for eutrophication and a biocide-air-emission score for the dispersion of biocides into the environment.

The options analysed were mainly technical options for reducing the environmental impact of greenhouse horticulture that can be applied at the farm level. We believe that the 57 options included in the analysis cover the most important on-farm possibilities for reducing the emissions. Greenhouse horticulture is an innovative sector for which constantly new (reduction) technologies and cultivation methods are being developed. An example of recent research is a study on tomato cultivars requiring lower temperatures (Heuvelink and Bakker, 2001). The model does not include off-farm reduction options that can be used for reducing the environmental impact by greenhouse horticulture, such as cogeneration of electricity and heat, and district heating (Bouwman et al., 1996; Bakker, 2000) and the use of renewable energy (Lange and Dril, 1997). Such strategies would require organisational changes at a higher level than changes in cultivation techniques. Similarly, a shift to organic production in which no chemical biocides, artificial fertilisers and substrates are used (see e.g. Kramer et al., 2000) was ignored. These could be interesting topics for further research, because they may offer new opportunities to reach more ambitious environmental targets.

The choice of the model approach affects the way the model can be used. The chosen modelling approach analysed the cost-effectiveness of all possibile combinations of options. Only the most cost-efficient combinations of options were used in the optimisation analysis. A disadvantage of this approach is the large number of possible combination of options. An alternative approach would have been to define cost-effective combinations of options on the basis of expert judgement, as is done in the RAINS model (Alcamo et al., 1990). This avoids the calculation of the effect of all possible combinations of options, but bears the risk that not all possible cost-effective combinations of options are considered. Despite the large number of options included in the analysis, the model is built in such a way that it can easily be expanded to include new and other farm level options. Including more options, however, increases the calculation time because there are more combinations of options to be evaluated for cost and environmental impact. Off-farm reduction options cannot easily be incorporated into the model.

Exploration of the model

The third sub-goal was to explore the model to get insight in the model. We explored the model performance for a hypothetical situation, where none of the reduction options are applied in tomtato cultivation (the so-called zero case). By analysing the effect of combinations of options for this zero case for tomato cultivation we gained insight into the most cost-effective combinations of options for different levels of investments. From these results, we concluded that the most profitable options are related to the reduction in gas use. Cost-effective combinations of options for reducing global warming, acidification and eutrophication always included a heat buffer and a combi-condenser, both leading to more efficient gas use. Furthermore, all types of screens and roof insulating options appear in the cost-effective combinations of options, as well as some wall insulating options and strips around window panes. For the reduction of biocide emissions other options are selected in the cost-effective combinations of options, including the movable screen. All types of changes in substrate use, composting at the regional level and all options for reducing foil waste are selected in the cost-effective combinations of options for the reduction of waste. The exploration also revealed that a considerable reduction in environmental impact compared with the zero case can be achieved by the options analysed.

The exploration of the model was important for analysing whether it could be used to answer our questions and whether the model results reflected reality. The model did indeed answer the question of which (combinations of) options were cost-effective in reducing the environmental pressure. With regard to the validity/reality of the model results there may be a problem when model validation is based on studies that were also used for the quantification of the model parameters and will, therefore, not be completely independent. In our analysis we tried to avoid the use of studies for both developing and validating the model. The results of model calculation were compared with the available information of the application of reduction options in greenhouse horticulture (see Chapter 4), information that had not been used in the model building step. When defining systems boundaries and systems components (Chapter 2) the information on the activity levels in tomato cultivation, the comparison of the results of the analysis with a complete LCA analysis, were based on the same study (from Nienhuis and Vreede (1994a)). The values of the emission factors were, however, obtained from other literature sources.

We carried out a sensitivity analysis of the model structure and some of the values of the parameters used in the model. We analysed, for example, the effect on the model results of an alternative method for calculating the total eutrophying impact. This revealed that the model results are sensitive to the inclusion or exclusion of NO_x as an eutrophying compound. The sensitivity analysis of the values of the parameters used in the model showed that the model results are sensitive to changes in the values of prices, of natural gas, and the atmopheric emission factors for biocides. Changes in the price of natural gas appeared to be crucial for the model results. At higher gas prices the savings in costs for each m^3 reduction in gas use are greater, and consequently more expensive reduction options are included in the model solution. The emission factors for biocides are an uncertain element in the model and have an important influence on the value of the indicator describing the environmental impact of biocides. More research is needed on the quantification of the emission of biocides from greenhouse horticulture. In section 6.4 I discuss the usefulness of sensitivity analysis as a tool in environmental systems analysis in our study.

If the overall effect of reduction strategies on various environmental problems are to be quantified simultaneously, it is necessary to quantify the relative importance of each environmental problem compared with other environmental problems. This can be done by multi-criteria analysis. We used five different multi-criteria methods to calculate the overall environmental impact of tomato cultivation in terms of one single environmental indicator. The results of the five different multi-criteria methods differ largely in the number of cost-effective combinations of options and in the options selected in these cost-effective combinations. On the other hand, the use of multi-criteria analysis in our study appeared to be a useful tool for tracing robust reduction options. These robust reduction options are options that were always selected in the cost-effective combinations of options, regardless of the multi-criteria method used, and include the combi-condenser, the heat-buffer, the high-pressure cleaner and composting at the regional scale.

Three choices need to be made on how to perform a multi-criteria analysis: 1) the choice of normalisation method, 2) the choice of the method of multi-criteria analysis method and 3) the choice of the weighing factors. The calculated emissions of different types of pollutants can be normalised in various ways in order to relate them to a reference (e.g. the world, a country, a region or a person). The choice of the reference can influence the results (Lindeijer, 1996 and Chapter 4). In the five different methods for multi-criteria analysis that were applied in this study, three different references for normalisation were used: tomato cultivation, the Netherlands and Europe. The choice of multi-criteria analysis method depends on whether the criteria are expressed quantitatively (cardinal) or qualitatively (ordinal) (Janssen, 1984). In this quantitative study we applied the (cardinal) Summed-Weights method for reasons of data availability. We applied five different sets of weighing factors. The choice of the weighing factors used is subjective. Lindeijer (1996) described several requirements for the use of weighing factors including the transparency of the weighing method (understandable and reproducible), the practicability, the flexibility, the content (methodologically convincing) and goal consistency and goal acceptability.

In conclusion, there are many different methods for multi-criteria analysis. Although there are some requirements for the methods used, there are no clear reasons to choose for a specific multi-criteria analysis method. In most environmental studies, only one multi-criteria method is applied without a thorough discussion of other methods that could have been used. It may be recommended to use more than one method for multi-criteria analysis in environmental scientific research to gain insight in the effect of the use of multi-criteria analysis and to trace robust reduction options. When multi-criteria analysis is used in direct contact with the decision maker it is important to discuss different applicable multi-criteria analysis methods and their consequences, and to clarify the implications of the (subjective) choices that need to be made for the analysis.

One of the multi-criteria methods studied in this thesis, the MPS method from the Environmental Project for Floriculture (MPS; see Chapter 4), is used in the greenhouse horticulture sector in the Netherlands and developed in cooperation with the growers. The MPS method differs from the other methods in that it only focuses on the activity levels (e.g. use of energy, fertilisers, etc) and does not account for the emissions of pollutants. As a result, the MPS method will never select reduction (end-of-pipe) technologies that only reduce the emissions in the cost-effective combinations of options. An example of such an option is the low-NO_x burner. On the other hand, the MPS method is simpler and more transparent than the other methods analysed.

The model can be adapted for use by the grower to analyse reduction options at the farm level. However, the farm should be a homogeneous greenhouse and all input data should be farm specific. The model can be used to explore the possible cost-effective combinations of options while accounting for important environmental side effects of the options. More detailed information is probably needed to analyse the exact consequence of, for example, the use of natural gas, for which detailed energy models are available (e.g. Uffelen and Vermeulen, 1994; Zwart, 1996).

Model application

The fourth sub-goal was to analyse the cost-effectiveness of options to reduce the environmental impact of tomato cultivation in the Netherlands, with a special focus on strategies to meet the current environmental policy targets. We considered an actual situation (rather than the zero case of the previous analysis) for tomato cultivation in the Netherlands. We described the total tomato cultivation area in terms of three farm types (Innovators, In-Betweens and Low-Costs) which differ in the activity levels (e.g. the use of natural gas) and the application of reduction options. Up to this point in the analysis the model had been used for one reference hectare representing tomato cultivation in the Netherlands. The model could only select an option or not (a so-called 0-1 approach). In reality, however, options are applied on only part of the total cultivation area. By describing different farm types we could include some of this heterogeneity and the application of options in part of the area in the model. The options selected by the model differed per farm type. As a reference we used data in tomato cultivation for the year 1995.

We carried out an optimisation analysis using two types of objective functions. In the first type the objective was to minimise the environmental impact at given constraints on costs. We did this for each single environmental problem and for the overall environmental impact using the five above mentioned multi-criteria methods. The optimisation calculations of this first type resulted in cost curves for each individual environmental problem and in five cost curves for the total environmental impact using the five multi-criteria methods. The curves illustrate the costs of different levels of emission reduction for tomato cultivation at the national scale and show the maximum reduction in environmental impact that can be achieved by the options analysed relative to the 1995 situation. These cost curves illustrate that for the 1995 situation about 20% of the calculated environmental problem caused by tomato cultivation can be reduced at net zero costs.

In the second type of optimisation analysis we minimised the costs to achieve different environmental targets. We carried out the optimisation analysis for each single environmental target for greenhouse horticulture in Dutch policy plans and for several environmental targets simultaneously. The model calculations indicate that all policy targets can be achieved by the options considered in the analysis, except the target of the highest reduction in biocide use (i.e. 38% relative to the 1995 situation). Most individual environmental targets (for CO_2 emissions, eutrophying emissions, the lower targets for biocide use and biocide air emission reduction) can be achieved at net negative costs. The calculated costs for achieving the targets for the reduction in biocide emissions into the atmosphere and the energy-efficiency improvement target are relatively high. The application of options in the cost-optimal solutions additional to the 1995 situation include heat buffers, Econauts, strips around window panes, electrostatic spraying technique and composting at the regional level. When model results indicate that the costs of achieving a certain target are negative at the national level, this may not necessarily be the case for the individual firms. Model results indicate that at the national level the most cost-effective solutions are often achieved by applying relatively expensive options to part of the area and relatively cheap options to another part of the area. In these solutions, the investments are mainly made on farm types Low-Costs and In-Betweens. Implementation of these solutions in the real world may be achieved by regulations or subsidies that stimulate growers to invest in environmental friendly technologies that are relatively expensive, but effective in reducing the environmental pressure.

The model results indicate that in order to achieve all environmental targets simultaneously other combinations of reduction options are selected than for achieving the individual targets. Most noticeable in this respect are the selection of a fixed screen, double glass in the roof and the no-windows options in addition to the more generally applied options such as the combi-condenser, heat buffer, Econaut, strips around window panes and composting at the regional level. The fixed screen is also selected in the cost-optimal solution to achieve the CO_2 emission target. Double glass in the roof and the no-window options were not selected in any solution for achieving the individual environmental targets. Double glass has the highest technical potential to reduce natural gas use of the options analysed, but results in a considerable reduction in production due to a decrease in radiation. Nevertheless, its cost-effectiveness in combination with other options (such as the no-window option) is higher than of other options when multiple targets are to be reached. The application of the no-windows options affects the use of energy (reduces the use of natural gas and increases the use of electricity), the emissions of biocides to the atmosphere and the tomato production (increase in production due to increase in radiation).

The model was used for optimisation analysis, in which dynamic aspects were ignored. However, several model parameters may actually change over time. Examples of these variables are the prices of the inputs and the tomatoes, the production per hectare, the penetration rate of the reduction options and the cultivation area. It is not easy to account for all these time-dependant aspects in optimisation analysis. However, a scenario analysis based on WHAT IF type of questions (see Box 1.1 in Chapter 1) may provide insight into the effect of these time-dependent variables on the environmental impact of tomato cultivation as well on the costs of the application of reduction options. This may be an item for future research.

Summarising, we learned from the tomato case that to reduce the total environmental impact it is most cost-effective to focus on environmental problems simultaneously and account for the environmental interactions of reduction options. Furthermore, we learned that at the national level it can be more cost-effective to invest in a certain combination of options in part of the total greenhouse area than to invest in less expensive options in the total area. Besides, the use of different multi-criteria methods provides insight into which options are always cost-effective regardless of the multi-criteria method used (the robust options).

We recommend the following issues for further research on the tomato case. First, the correctness of the evaluation would increase if the uncertainties in some parameter values were reduced. For instance, figures for the emissions of biocides to the environment are relatively uncertain and the model turned out to be sensitive to these uncertainties. More research is needed on how and how much biocide is emitted, what the effect is of reduction options and how the environmental impact of the emission of biocides can best be quantified (thus the choice of environmental indicator). Other uncertain model parameters include the emission factors of NO_x, NO_3 and PO_4 from fertiliser use. The costs of options analysed in this study are relatively well known for the present situation, but they may change over time. In the optimisation analysis we assumed for practical reasons that the area of each farm type was constant. In future research it would be interesting to include the possibility of shifts from one farm type to another in order to analyse whether this would have an considerable effect on the emissions to the environment. Another point for further research is the expansion of the model with other options including the use of cogeneration, district heating, renewable energy and shift to organic production.

6.3 Implication of the study for greenhouse horticulture in the Netherlands in general

Extrapolation of the tomato case

In this thesis we identified cost-effective strategies to reduce the environmental impact of tomato cultivation for a certain reference year. To this end, we first calculated cost-effective combinations of reduction options per farm type and then identified the most cost-effective allocation of combinations of options over different farm types for reducing the environmental impact of tomato cultivation at a national scale. The question then is to what extent the model and model results can be used as a basis for an analysis of national greenhouse horticulture as a whole, including other crops. In this section I discuss the possible changes in system boundaries and system components, the comparison of the cost-effectiveness of reduction options for tomato cultivation with the cost-effectiveness for rose cultivation and on the implication of the results for the tomato case for total greenhouse horticulture.

System boundaries and system components

In Chapter 2 we analysed the differences in system boundaries and system components for tomato cultivation and for total greenhouse horticulture. The analysis shows that in both systems the same activities and emissions are important in the system descriptions. In other words, the system boundaries and the model components do not have to be changed when the model developed for tomato cultivation is used to analyse national greenhouse horticulture.

This similarity in system boundaries and model components suggets that it might be possibile to extrapolate the model of national tomato cultivation to national greenhouse horticulture by simply applying these results to the total greenhouse area in the Netherlands. To test this we compared the inputs (activity levels) and outputs (emissions) of both systems (the system total greenhouse horticulture derived from literature (see also Chapter 2) and the system total greenhouse horticulture derived from the upscaled tomato cultivation) for the year 1995 (Figure 6.1). The values for the upscaled tomato cultivation are calculated by multiplying the values of tomato cultivation by a factor of 8.3 (total greenhouse area divided by the area of tomato cultivation in the Netherlands). The activity levels for the use of natural gas, fertilisers and rock wool after upscaling are much higher than in reality (Figure 6.1a). The use of electricity is higher in reality than in the upscaled tomato system, due to the use of supplementary light in cut flower cultivation. Another difference is that rock wool is used as substrate in only part of the total greenhouse area. In 1995, 65% of total greenhouse area was cultivation in soil. The higher activity levels of the upscaled tomato system result in higher emission values. In particular the emissions of NO_x and the production of waste are higher (Figure 6.1b). These differences lead to the conclusion that the model results for the tomato case cannot be extrapolated as such to national greenhouse horticulture. The model can, however, be adapted and applied to other crops. In this case, the values of input parameters and, if necessary, emissions factors and parameter values of the options may have to be adapted.

Comparison with rose cultivation

Besides the activity levels and in some cases the associated emission factors, also the effect of the reduction options may differ for other crops. To illustrate this, we carried out a simple and quick analysis for rose cultivation. We compared the cost-effectiveness of single reduction options for rose cultivation (Frisco cultivar) with their cost-effectiveness for tomato cultivation as calculated in Chapter 3 (see Box 6.1). We used information about the effects of reduction options as described by Uffelen and Vermeulen (1994) and Project Office Greenhouse Horticulture and Environment (2000). Especially the options that reduce the use of natural gas and biocides have a different effect in rose cultivation than in tomato cultivation. The difference in costs and cost-effectiveness is caused by differences in activity levels, production value (NLG/ha) (the production value is higher for roses), sensitivity to a reduction in light (tomatoes are more sensitive than roses) and the different temperature regime for tomato and rose cultivation.

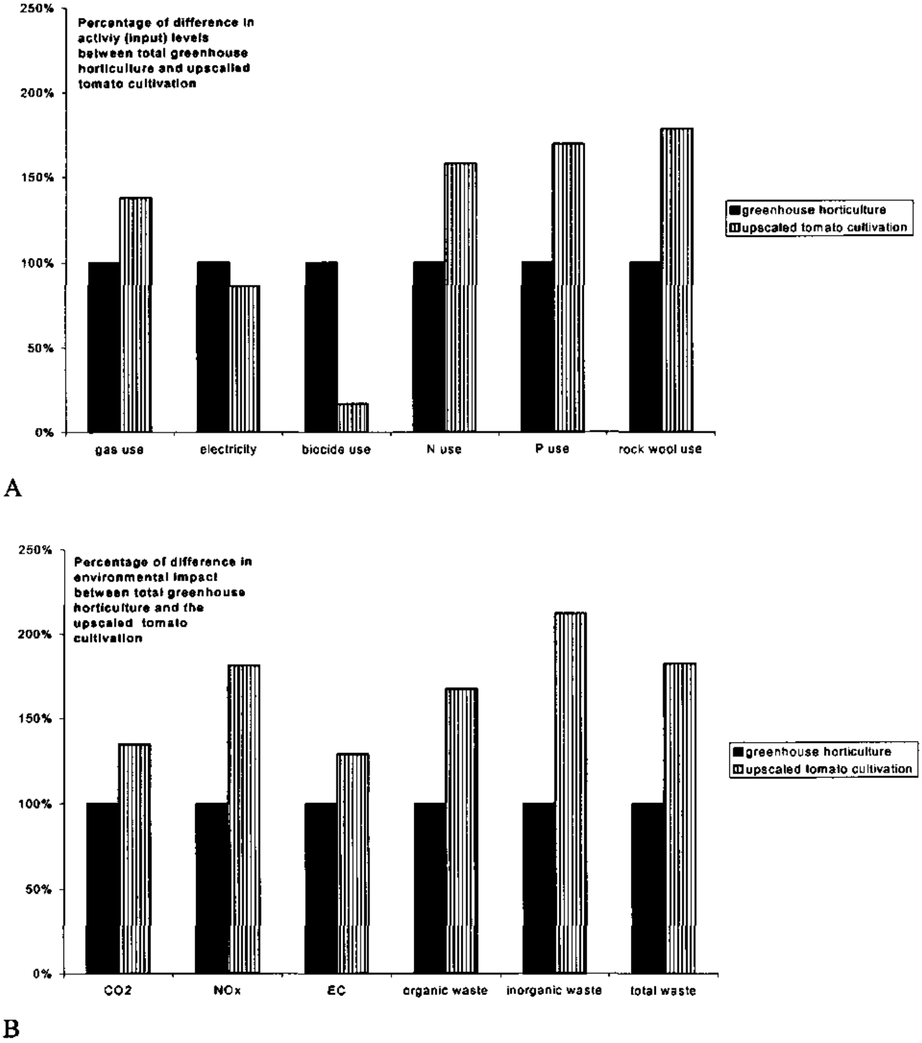

Figure 6.1 *Comparison between the activity levels (use of natural gas, electricity, biocide use, N and P use and rock wool) and emission values (CO_2, NO_x and eutrophying emissions (EC), production of organic, inorganic and total waste) of the upscaled tomato cultivation and total greenhouse horticulture. The values for total greenhouse horticulture are derived from Chapter 2. The values for the upscaled tomato cultivation are calculated by multiplying the values of tomato cultivation by a factor of 8.3*

Box 6.1 *Total annual costs and cost-effectiveness (CE) of options for reducing the environmental impact of tomato cultivation and rose cultivation*

In a 'quick scan' we analysed the cost-effectiveness of single reduction options for rose cultivation (see Chapter 3 for the method of calculation). We therefore adapted the input parameters (activity levels, yield and production value; see Chapter 3.3) of tomato cultivation to rose cultivation (based on Nienhuis and Vreede (1994b)). Furthermore, we adapted some reduction factors of the options based on Van Uffelen and Vermeulen (1994) and Project Office Greenhouse Horticulture and Environment (2000). No attention was paid to possible differences in emission factors, except for the emission of biocides, which are related to the biocides used (Leendertse et al., 1997 and CBS, 1997b). In the following four tables the total annual costs and the CE for different polluting compounds are presented for all options.

Table I *Options for reducing global warming*

Group	Options	Results for Rose cultivation		Result for Tomato cultivation	
		annual costs (NLG/ha/y)	CE CO$_2$ emission (NLG/kg CO$_2$ red.)	annual costs (NLG/ha/y)	CE CO$_2$ emission (NLG/kg CO$_2$ red.)
Condenser	return condenser	1637	0.02	-5550	-0.05
	single condenser	-1742	-0.04	-3086	-0.06
	combi-condenser	-2655	-0.03	-10217	-0.07
Screen	fixed screen	-1451	-0.01	240	0.00
	moveable screen	19982	0.15	29728	0.15
	double screen	30034	0.15	79294	0.26
Wall insulation	screen	11450	1.60	14620	1.70
	double glass	5645	0.11	15744	0.26
	foil	1845	0.38	16126	2.74
	dot foil	2099	0.19	35223	2.61
	coated double glass	-9878	-0.12	4848	0.05
Roof insulation	coated glass	162038	1.6	65825	0.27
	double glass	369467	2.13	220516	0.51
CO$_2$ supply method	heat buffer 80 m^3	-596	-0.01	-9948	-0.07
	heat buffer 100 m^3	1523	0.02	-7828	-0.06
	pure CO$_2$	24871	0.24	21817	0.18
Temperature management	T 1 degree lower	130210	1.85	57741	0.62
	T 2 degrees lower	289240	2.12	128347	0.65
	no minimum pipe T	7682	0.08	-7304	-0.06
	Econaut	-5885	-0.07	-8328	-0.08

Table II *Options for reducing acidification*

Option group	Option	Results for Rose cultivation		Result for Tomato cultivation	
		annual costs (NLG/ha/y)	CE NO$_x$ emission (NLG/kg NO$_x$ red.)	annual costs (NLG/ha/y)	CE NO$_x$ emission (NLG/kg NO$_x$ red.)
NO$_x$ emission	Low-NO$_x$ burner	657	2.00	657	1.67

(Box continued on next page)

Box 6.1 *(continued)*

Table III Options for reducing disperion of toxic compounds

Option group	Option	Results for Rose cultivation		Result for Tomato cultivation	
		annual costs (NLG/ha/y)	CE biocide-air-emission score (NLG/10^3 * m^3 red.)	annual costs (NLG/ha/y)	CE biocide-air-emission score (NLG/10^3 * m^3 red.)
Construction change	strips around window	-966	-0.24	-1424	-0.36
	panes	276608	0.76	311384	0.88
	no windows	8432	0.04	15994	0.08
	netting in window	6996	0.03	14101	0.07
	panes				
	netting and strips				
Spraying	electrostatic spraying	-835	-0.04	-2413	-0.12
technique	advanced technique	4075	0.20	2498	0.13
Resistant crop varieties	resistant crop varieties	-2618	-0.06	-1182	-0.06
Biological control and scouting	biocontrol and scouting	21124	0.35	22594	0.38
Greenhouse hygiene	greenhouse hygiene	-4720	-0.12	-136	-0.003
High-pressure cleaner	high-pressure cleaner	-14563	-690.00	-64202	-760.43
Mechanical roof	own roof cleaner	-2503	-126.50	-49039	-619.56
cleaner	by contract	11481	580	-350	-432

Table IV *Options for reducing eutrophication*

Option group	Option	Results for Rose cultivation		Result for Tomato cultivation	
		annual costs (NLG/ha/y)	CE PO_4-eq emission (NLG/kg PO_4–eq red.)	annual costs (NLG/ha/y)	CE PO_4-eq emission (NLG/kg PO_4–eq red)
Source of	extra basin of 1000 m^3	5100	1094	5100	518
irrigation water	extra basin of 4000 m^3	7990	257	7987	122
	unsalted tap water	17869	1080	17869	479
	reverse osmosis	13252	710	13253	336
	joint water basin	41152	1324	41152	627
	ground store	12724	409	12724	194
Sewage	internal sewage	1521	40	1521	19
treatment	connection	3355	90	3356	43
	external sewage connection				
Drain water	at the local level	33480	567	33480	268
cleaning	at the regional level	26784	453	26784	215

Extrapolation of the results

Keeping the differences between tomato cultivation and other cultivations in mind, we evaluate the conclusions for tomato cultivation with respect to greenhouse horticulture in general, focusing we focus on the possibilities for achieving the environmental targets for total greenhouse horticulture in 2010.

For the tomato case we concluded that achieving the current policy target for energy-efficiency (energy use per kg production) improvement is associated with high additional annual costs. For national greenhouse horticulture this conclusion may be different for several reasons. In the first place, the model calculations did not include the annual increase in physical production. This increase in production was 1.6% during the 1990s and may contribute significantly to achieving the energy-efficiency target (Bakker et al., 2000). Second, tomato production is relatively sensitive to reductions in light, as included in our model. Several energy saving options (e.g. a movable screen) cause a reduction in radiation and therefore also in production. The effect of a reduction in light on the average production in total greenhouse horticulture is lower than for tomato cultivation. On the other hand, tomato cultivation has a relatively high gas consumption and each percentage reduction in gas use saves more natural gas and thus more money than for many other crops. For this reason, options for reducing the use of gas may be more expensive for greenhouse horticulture in general. We did not analyse the use of cogeneration, district heating and renewable energy, which may also contribute to achieve the energy-efficiency target. For greenhouse horticulture we expect that the energy-efficiency target for 2010 (this is also 65% relative to 1980) can probably be achieved at lower costs than for tomatoes if the annual production increase is also taken into account.

For the tomato case, the model results show that the targets for 2000 and 2010 for the emission of eutrophying compounds can be achieved at net negative costs. It is questionable whether these targets can be achieved for total greenhouse horticulture. An important difference between the tomato sector and total greenhouse horticulture sector is cultivation in soil in part of the greenhouse area, whereas tomatoes are largely cultivated on substrate (rock wool). The emission of N and P can be reduced by recirculation of drainwater more easily in substrate than in soil. LNV (1997) indicates that the maximum reduction is 88% for substrate cultivation and 40% for cultivation in soil by 2010 if no new technical solutions become available. In our study not only are phosphate and nitrate considered eutrophying, but also a reduction in NO_x emissions can contribute to a reduction in the emission of eutrophying compounds. The model results for the tomato case show that many energy saving and rock wool reducing options contribute to achieving the policy target for the emissions of eutrophying compounds and to lower costs. Therefore, it may be difficult to achieve the policy target for the emissions of eutrophying compounds for total greenhouse horticulture. Including the reduction of NO_x emissions in the total emission reduction of eutrophying compounds may make it possible to achieve a higher maximum reduction at lower annual costs because of profitable savings in gas use.

Two policy targets are formulated with regard to the use of biocides in greenhouse horticulture. These are biocide use (in active ingredient) and the emissions of biocides (e.g. into the atmosphere). For the tomato case the model calculations show that the target for biocide use in 2000 can be achieved at net negative costs. The model not only selects biocide reducing options, but in some cases also energy-saving options in the cost-effective combinations of options. The energy-saving options have net negative costs, but may not reduce the biocide use. The policy target for biocide use for 2010 could not be achieved for the tomato case. Biological control is not applied at all greenhouse farms (as is the case in the tomato case (Table 8, Chapter 5)). This may indicate that higher reductions in biocide use are feasible in total greenhouse horticulture than in the tomato case. Indeed, Alleblas and Mulder (1997) calculated for two scenarios the use of biocide in 2010 and indicated that a maximum reduction of 35% is possible.

Model results for the tomato case showed that the target for the emissions of biocide to the atmosphere for 2010 could be achieved by the options analysed at net positive costs. However, we calculated the reduction in biocide-air-emission score and not the reduction in emissions to the atmosphere. From the tomato case we may assume that the targets for biocide emission to the atmosphere for total greenhouse horticulture can be achieved, but at a cost as in the tomato case. This assumption is based on the idea that the options applied to reduce the biocide emissions in the tomato case will probably have the same reduction effect for total greenhouse horticulture. However, as indicated in this thesis the emission of biocides is a relatively uncertain factor and for this reason we are unsure about the possibilities of achieving the policy target for the emissions of biocides. The options that might be of interest for achieving the target are movable screens, the use of strips around window panes (both reducing the emission of biocides) and the use of insect netting in window panes, electrostatic spraying technique and biological control (all reducing the use of biocides).

Summarising, we may argue that most of the environmental targets for 2010 can be achieved for total greenhouse horticulture, but that this may be associated with relatively high costs. The costs per hectare may be higher than those calculated for the tomato case due to lower savings in natural gas. The reduction in emissions of eutrophying compounds as formulated in the agreement (LNV, 1997) will probably difficult to achieve. It is uncertain whether the target for the emission of biocide to the atmosphere can be achieved. A more thorough analysis is needed to draw more definite conclusions on the reduction of the environmental impact of total greenhouse horticulture.

An approach to analysing total greenhouse horticulture

The adaptation of the model for rose cultivation (Box 6.1) shows that it is possible to adapt the model developed for tomato cultivation to other crops. In the following, guidance is given for extending the tomato model to total greenhouse horticulture.

As an example we describe a possible approach for upscaling the tomato model to analyse cost-effective strategies for reducing the environmental impact of greenhouse horticulture in the Netherlands at the national level. A model for analysing cost-effective strategies for total greenhouse horticulture in the Netherlands should reflect some of the heterogeneity of the sector. The description of all different cultivations of all crops in the greenhouse horticulture sector would require a mass of detailed information, including values for the activity levels, emission factors, reduction factors of the options and the costs of the options. It may be difficult to obtain all this information for cultivation of other crops. Furthermore, it will take too much time to use the model for each individual cultivation. Consequently, we recommend describing total greenhouse horticulture as a combination of different cultivation groups. The model can be aggregated from cultivation to cultivation group by adapting activity levels, emission factors, if necessary, and the values of the parameters of the reduction options.

A possibility is to adapt the five cultivation groups distinguished by Alleblas and Mulder (1997) for total greenhouse horticulture:

1. intensive fruit-vegetable cultivation: high gas use and cultivation in substrate: e.g. tomato
2. intensive cut flower cultivation: high gas use and use of assimilation lighting: e.g. rose
3. less intensive vegetable cultivation: lower gas use and cultivation in soil: e.g. lettuce
4. less intensive cut flower cultivation: no assimilation lighting: e.g. aster
5. pot plant cultivation for which a distinction can be made in cultivation on benches and cultivation on the ground.

For these groups, the general activity data, emission factors and information on reduction options need to be collected.

The description of biocide use per cultivation group may be difficult because the biocides used may be crop specific. For this reason, it might not be possible to use the biocide-air-emission score as an indicator for the impact of biocide emissions to the atmosphere. Instead, estimations can be made for the total use of biocide in kg active ingredients.

For each cultivation group different farm types can be defined in order to describe the heterogeneity within a cultivation group. These farm types preferably differ with respect to farm size, age of the greenhouse, activity levels, level of production and the reduction options (see also Chapter 5). The number of farm types that can be defined per cultivation group will depend, among others, on the degree of heterogeneity within the cultivation group. Within each cultivation group the reduction factors for the different options are the same, but the activity levels and the options applied may differ per farm type. The resulting model can be used to select per farm type the cost-effective combinations of options and an optimisation analysis can be carried out as in Chapter 5.

Extending the tomato model to the total greenhouse horticulture sector might lead to a reformulation of the model. Other processes may be relevant at a higher spatial scale. These are, for example, changes in the total cultivation area and the distribution of the area over cultivation groups and farm types. Changes in areal distribution of the different cultivation groups may affect the environmental impact of the greenhouse sector as a whole. Another change in the model structure might be the inclusion of economic consequences of the selected emission reduction options. In the tomato case we calculated the additional annual costs of the application of reduction options. We neglected the second-order effects of these increased costs. For a study of the total horticulture sector more macro-economic consequences need to be considered, such as the total production value of the sector, the export value and employment.

In this study we focused on greenhouse horticulture in the Netherlands. If only the Netherlands tightens up its environmental legislation production may move to other countries. To analyse the net effect of this on the environment would require an adaptation of the model. The Netherlands faces competition from among others southern European countries, Kenya and Colombia. The conditions for cultivation in these countries differ from those in the Netherlands, for example the climate and labour costs, and these differences may lead to different environmental problems related to (greenhouse) cultivation in each country (see e.g. Heuvelink and Costa (2000) for the situation in Spain). Furthermore, the transport of the products should also be considered in the environmental evaluation.

The results of the tomato case may give an indication of the possibilities for reducing the environmental impact of greenhouse horticulture in the Netherlands as a whole. The tomato model can, however, not be used directly to analyse total greenhouse horticulture because of the many crop-specific characteristics of the model. We identified a possible approach to expand our model to other crops or total greenhouse horticulture.

6.4 Discussion on the methodology of environmental systems analysis

Environmental systems analysis is a methodology that is used to analyse complex environmental problems and to find solutions. It has been used for many environmental problems. We described the methodology of environmental systems analysis in six steps (based on Checkland, 1979 and Wilson, 1984): (1) problem definition and description of the system components and system boundaries, (2) description of the objectives, (3) model building, (4) analysis of the model system, where the model was explored for a hypothetical situation, (5) use of the model for optimisation analysis and (6) description and presentation of the analysis and conclusions.

Depending on the specific goals of the study, each environmental systems analysis follows its own approach. In the following, we discuss some of our experiences in the use of environmental systems analysis as an analytical method. One aspect that has already been discussed in this chapter (section 6.2) is the definition of the system boundaries. We carried out a detailed analysis on the system boundaries, which is uncommon for this stage in a systems analysis. However, we found this to be a very useful step in the whole analysis which provided insight into the causes of the environmental impact of tomato cultivation and greenhouse horticulture. In this section we pay special attention to the iterative nature of the systems analysis method and the tools used in our analysis.

Iterative procedure

In Chapter 1 we described the procedure of systems analysis in six steps based on Checkland (1979) and Wilson (1984). Typically, the first step of our research is not reported in this thesis. We carried out a preliminary systems analysis to explore the procedure and possible approaches to the problem. This analysis was restricted to the use of natural gas and the emissions of CO_2 in tomato cultivation in the Netherlands (Pluimers, 1998) and thus did not include the complex interactions of different environmental problems. In this preliminary analysis we developed the general model set-up and the approach to dealing with mutually exclusive options. Based on this analysis, we designed the research set-up for the thesis as it stands.

This thesis followed the different steps of the procedure described in Chapter 1 (see Figure 6.2). In Chapter 2 we described the system boundaries and system components (step 1). Chapter 3 described the model (step 3), while in Chapter 4 we described the model performance for a zero case situation (step 4). In Chapter 5 we described the model application at the national scale and the results of the optimisation analysis (step 5). In this chapter we discuss the main results and draw conclusions (step 6). It has been our experience that these steps are performed interactively rather than strictly linear.

As an example of iteration within systems analysis, we will describe four relevant iteration loops in the analysis (see also Figure 6.2):

1. from systems analysis (step 4) back to the objectives (step 2)
2. from systems analysis (step 4) back to model building (step 3)
3. from optimisation analysis (step 5) back to model building (step 3)
4. from optimisation analysis (step 5) back to objectives (step 2).

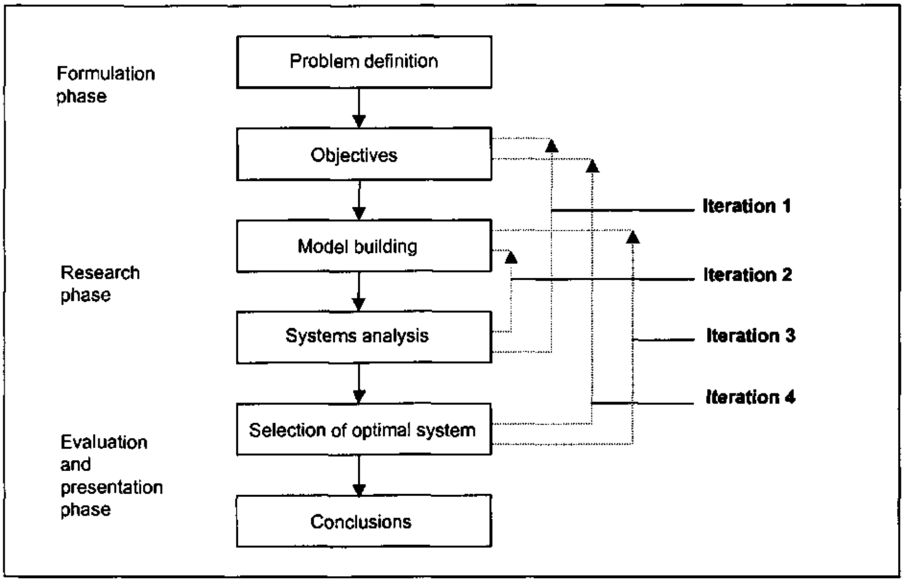

Figure 6.2 *The six steps of the environmental systems analysis procedure as followed in this thesis and iteration loops (see text)*

Iteration 1

This iteration loop was from the *systems analysis* back to the *objectives*. In the systems analysis step we analysed the model performance and checked whether the model could be used to answer our questions. The iteration was not meant to adapt the objectives, but in fact we were able to refine the objective of the analysis and we gained insight under what assumptions we could answer our questions.

Iteration 2

This iteration loop was from the *systems analysis* step back to the *model building*. When analysing the model behaviour we realised that the model needed refinement. For example, we concluded that the indicator for the environmental impact of biocides emitted to the atmosphere is sensitive to changes in the emissions factors for biocides to the atmosphere, which have a large uncertainty range. For this reason we adapted the model and included the use of biocides (in active ingredients) in the model output.

Iteration 3

This iteration loop was from the *optimisation* (model application) back to the *model building*. In the optimisation step we used the model to analyse tomato cultivation for the year 1995. At first, the model approach did not permit application of options on part of the area (zero-one approach). At the sectoral level, however, this is generally the case. This unrealistic model approach was solved by describing farm types. The zero-one approach is used per farm type but at the national scale options can be applied on part of the area.

Iteration 4

This iteration loop was from the model *optimisation* back to the formulation of the *objectives*. The optimisation analysis required refinements of the objectives. In fact, for optimisation one needs strictly defined objectives (object functions). In the first phase of the study it was difficult to formulate the objectives and constraints for the optimisation in detail because we needed experience with the model before fully developing ideas on how best to use it. Furthermore, during model calculations we became interested in additional constraints after analysing the consequences of the initial constraints. Definite objective functions were defined during the optimisation step.

Iteration and feedback are used when refining a complex system, especially since assumptions have to be made in an early step of the analysis. We illustrated how these iterations may contribute to refining the objectives, making model improvements and adapting the constraints.

Tools

There are many different tools available that can be used in an environmental systems analysis. In Chapter 1 we gave an overview of some of these tools. Depending on the aim and type of the analysis, a combination of tools has to be defined. Here we illustrate how we applied different tools in the analysis.

Environmental life cycle analysis

In Chapter 2 we described environmental life cycle analysis (LCA). This tool is used for assessing the environmental impact of a product with a certain function during the whole product life 'from cradle to grave'. LCA was a useful tool for defining the boundaries and components of the system studied. We carried out a 'partial' LCA and distinguished a primary production system (the production in greenhouses) and an industrial system comprising the production of production factors (e.g. the production of fertilisers). We quantified all emissions in these two systems and determined which processes and compounds significantly contribute to the environmental impact of greenhouse horticulture. These were included in the model system developed later. The advantage of LCA is that it potentially considers all environmental problems and processes during the whole production 'life'. Most analyses of the environmental impact of greenhouse horticulture focus on on-farm processes and do not include, for example, the production of production factors (fertilisers, electricity, etc.), which may make a considerable contribution to the overall environmental impact (see Chapter 2). Furthermore, the LCA approach (as described by Heijungs et al (1992)) includes useful environmental indicators. The disadvantage of LCA in our analysis was that far more information is needed to carry out a full, or more complete, LCA.

Environmental indicators

Environmental indicators are parameters or values derived from parameters that provide information about the environment (Bakkes et al., 1994). Aspects we considered for the use of environmental indicators in our study were (mainly based on Opschoor and Reijnders, 1991):

- the indicator should be simple to calculate as well simple to explain
- the indicator should be able to quantify the environmental impact
- the indicator should be useful at the aggregation level of the study
- the indicator should be comparable with policy targets described for greenhouse horticulture to be able to analyse possibilities for achieving certain policy targets, and
- the data needed to use the indicator should be available.

The indicators we used in our analysis are environmental pressure indicators and do not quantify the environmental impact explicitly, but may reflect the potential impact of human activities on the environment. The indicators indicating the environmental pressure for global warming, acidification and eutrophication used in this thesis are similar to the indicators typically used in LCA studies. The advantage of LCA indicators for our study was that they meet the above mentioned requirements and that they do not account for local conditions making them easily applicable at higher aggregation levels. For biocides two indicators were used because no indicator could be defined that reflects the overall environmental impact or pressure, and because policy has been formulated for both the use and emissions of biocides. The production of waste may contribute to different environmental problems depending on the way it is treated. To reduce the complexity of the analysis (and thus exclude waste treatment) we considered the amount of waste as an environmental pressure indicator.

Cost-effectivity analysis and optimisation analysis

Cost-effectivity reflects the relation between the costs and the amount of environmental improvement. In our study this is the reduction in the environmental pressure. We first calculated the cost-effectiveness (CE) of single options (NLG per kg emission reduction) by dividing the costs by the reduction in the environmental pressure (e.g. reduction in emission). The CE of single options did not give sufficient information about which options are applied in cost-effective solutions for the sector. The CE does not indicate how much reduction is achieved. For this reason we quantified for each possible combination of options the reduction in environmental impact and the associated costs. Then we filtered out the cost-effective combinations of options, which reduce the environmental pressure most at minimum costs.

The cost-effectivity analysis was a useful tool for ranking the alternatives (combinations of options) with respect to their costs and the reduction of the environmental pressure for individual environmental problems. This tool only considers the financial consequences and ignores all costs other than money, such as costs of environmental damage, whereas cost-benefit analysis considers the costs of environmental pollution (Quade and Miser, 1995). A cost-benefit analysis as part of the analysis of the environmental impact of greenhouse horticulture would be a study on its own and also take macro-economic consequences into consideration.

Optimisation analysis is related to cost-effectivity analysis and can be used to find the least expensive way to achieve certain objectives. We used two types of object functions, one minimising the costs and one minimising the environmental impact, both under defined constraints. The result of an optimisation analysis, the optimal solution, depends on the assumptions made and constraints set and therefore is not the one and only solution. There may be hidden constraints, that can influence the decision that were not included in the analysis, such as the availability of options or the grower's knowledge about their availability. Nevertheless, the optimisation analyses provided insight into the options frequently selected by the model and what the cost-optimal allocation of combinations of options over the different farm types. Furthermore, the analysis showed that the integrated optimisation (including all environmental targets simultaneously) resulted in other options than the analysis per single environmental problem.

Multi-criteria analysis

To select cost-effective combinations of options for more than one environmental problem we used multi-criteria analysis. Multi-criteria analysis is a tool for evaluating alternatives (reduction options in our study) based on different criteria (environmental problems). Or, in other words, it is a tool to evaluate the overall or integrated environmental pressure. We used five different multi-criteria methods (see Chapter 4) and concluded that the results differed per method used. The choice of the method to be used in the analysis is a subjective one. If a systems analysis team is in contact with the decision maker(s) the choice for the multi-criteria method could be based on the priority of the decision makers. It may be worthwhile to compare the results of several multi-criteria methods (different priorities) in order to gain insight into the effect of the multi-criteria method on the model results.

In our study multi-criteria analysis appeared to be a useful tool to get insight in the robustness of reduction options. Some options were always selected in the cost-effective combination of options independent of the multi-criteria method used. We considered these robust options. The analysis also showed that the results differed per multi-criteria method used.

Sensitivity analysis

Sensitivity analysis is a systematic inventory of the changes in model results as a consequence of changing the values of parameters or input variables used in the model.

The results of the analysis may indicate whether model results are sensitive to uncertainty in parameter values or estimations in modelling approach. We carried out a partial sensitivity analysis for selected parameters or modelling approaches. For the selected parameter values we varied the values to their estimated minimum and maximum, based on the ranges found in the literature, calculated the emissions, costs and cost-effectivity and compared them with the original model results. Changes in individual parameters were explored one factor at a time, except for the values of the emission factors for biocide emission to the air (which are biocide specific), which were changed together.

Sensitivity analysis proved to be an important tool for understanding which parameters have an important influence on the model results. We carried out a partial sensitivity analysis. Ideally, a more complete systematic analysis sould be performed in which all parameter values are included. This was not practical in this study because of the large number of model parameters, a reason why Integrated assessment models are seldom subject to a complete sensitivity analysis. We learned that a partial sensitivity analysis in which few parameter values are considered may provide a valuable insight into the sensitivity of the model results to changes in parameter values.

In complex modelling applications, sensitivity analysis can be a useful tool for identifying the most influential model parameters and their effect on the model results. The more complex a system is, the more attention needs to be paid to uncertainty and sensitivity analysis. We did not carry out an uncertainty analysis. Uncertainty analysis is used to determine the overall uncertainty in the model outcome due to parameter uncertainty, for which information on the uncertainty of the model parameters is required. An uncertainty analysis can help to determine the value of information from the model and can help to indicate the most uncertain aspects of the model.

6.5 Epilogue

In this environmental systems analysis we analysed the complex problem of reducing the environmental impact of tomato cultivation in the Netherlands taking into account the costs of emission control. The study shows that considerable reductions of emissions from tomato cultivation may be achieved by using combinations of on-farm technological reduction options. Several of these reduction options are increaslingly being used in the Dutch greenhouse sector. On the other hand, the analysis illustrated that some environmental targets may be impossible to achieve or only at very high costs if only on-farm technological options are used. Therefore probably other solutions are needed.

The extensive use of natural gas in the Dutch greenhouse sector is an important reason of the environmental problems caused by the sector and contributes to global warming, acidification and eutrophication and leads to the depletion of fossil fuels. The application of energy saving options may until now have reduced the energy use per kg of product but not the total energy use of this sector since production levels have been increasing. I think a lot of effort is needed to reduce the actual use of energy instead of only focusing on the energy efficiency (per kg production). Large reductions in the use of energy may be achieved by technical options, new types of greenhouses, the use of district heating, long-term heat storage, etc.

The current environmental policy plans for greenhouse horticulture sector will be revised in the future. To achieve the environmental targets of greenhouse horticulture in the Netherlands now and in the future without losing competitiveness with production outside the Netherlands, changes may be needed. In the Netherlands, the greening of the horticulture sector has already started by applying on-farm technical options. The sector has proved to be innovative and successful in developing and applying the newest technologies. The question may arise whether technology alone may bring about the solutions for the environmental problems. The sector might have a tendency to continue to pursue this technological path. However, there are also other approaches that may lead to a more sustainable production in greenhouse horticulture, for example biological production and intensive cooperation between different firms in (new) greenhouse areas with regard to the production and use of energy, water storage and waste management. It may be a challenge for the greenhouse sector to combine the technological innovations with aspects of biological production and more organisational changes.

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Summary

Objective of the thesis

The greenhouse horticulture sector in the Netherlands covers about 10,000 hectares and produces vegetables, cut flowers and pot plants. This agricultural sector is of social and economic importance because of its annual production value, export earnings and the employment it provides. Cultivation in greenhouses, however, is characterised by high inputs of energy, fertilisers and chemical biocides, which contribute to several environmental problems. Through technical options, these environmental problems can be reduced.

The general objective of this thesis is to identify technical options to reduce the environmental impact of greenhouse horticulture in the Netherlands and to evaluate their cost-effectiveness. The study focuses on tomato cultivation and on the environmental problems of global warming, acidification, eutrophication, dispersion of toxic biocides and the production of waste. The method of environmental systems analysis is used as a tool for the assessment of technical options for reducing the impact of the sector on multiple environmental problems. A side-objective is to discuss the usefulness of environmental systems analysis in such analyses.

System boundaries and model components

The first step of the analysis is the definition of the system boundaries and the determination of the system components. To this end we carried out a limited environmental life cycle analysis (LCA) for tomato cultivation under glass and its contribution to global warming, acidification and eutrophication. We focused on these three environmental problems because of the interrelations between the underlying processes and the emissions. We quantified the emissions of first-order processes (these are activities such as the use of natural gas and fertilisers) and second-order processes (these are industrial activities such as the production of electricity and fertilisers). Results indicated that, in general, the emissions of first-order processes exceed the emissions of second-order processes. However, in some cases the off-farm emissions were relatively high. For example, the production of electricity and rock wool contribute almost 25% to total acidifying emissions. We concluded that a study of the environmental impact of tomato cultivation in the Netherlands needs to consider CO_2

emissions from the use of natural gas and the production of electricity, NO_x emissions from the use of natural gas and fertilisers, and from the production of electricity and rock wool, and losses of nitrogen and phosphorus from the use of fertilisers. In addition, we considered biocide use and biocide emissions to the environment and the production of waste. We argue that a profound study of the definition of system boundaries is worthwhile and provides a better understanding of the system.

Model building

A model was developed that can be used to quantify the environmental impact of tomato cultivation in the Netherlands and that can be used to evaluate the cost-effectiveness of technical options for reducing the environmental impact. The model calculates the environmental impact as a function of the activities, emission factors and reduction options applied. The impact is quantified by using environmental pressure indicators mainly. The activities include the use of natural gas, fertilisers, biocides and rock wool, as well as the production of electricity and rock wool. The model calculates the environmental impacts through global warming (emission of carbon dioxide in kg CO_2), acidification (emission of nitrogen oxides in kg NO_x), eutrophication (emission of eutrophying compound in kg phosphate (PO_4)-equivalents), dispersion of toxic compounds (indicated by the use of biocide in kg active ingredients and the emission of biocides quantified by the biocide-air-emission score) and the production of waste (kg waste). The model includes 22 groups of technical options that reduce the activity levels (e.g. the use of gas) and/or the emission factors (e.g. NO_x emissions from gas use). The model accounts for important side effects of the reduction options on the tomato production and on the levels of the activities and other emissions. The reduction costs are calculated as annual costs per hectare and include the annualised investment costs, operational costs and variable costs of the technical options applied (e.g. saving in gas use and effects on the production level). The model selects the most cost-effective combinations from all possible combinations of options.

Exploration of the model

We explored the model for a hypothetical reference situation in which none of the technical reduction options were applied. The model calculations, for instance, showed that most of the profitable options are related to a reduction in the use of gas. The combi-condenser and heat buffer were selected by the model in all cost-effective combinations of options. The cost curves for the hypothetical reference situation illustrate the costs of combinations of options for different reductions in emissions. The cost curves indicated that considerable reduction of the environmental impact could be achieved at net zero costs, but that increasing reduction of the environmental impact resulted in rapidly increasing costs.

The model calculations show that reducing the emissions for one compound may also affect the emissions of other pollutants (the above-mentioned side effects). This is especially the case for the reduction of emissions of CO_2 and NO_x. Furthermore, the options for reducing emissions of eutrophying compounds may affect the emissions of CO_2 and biocides into the atmosphere and vice versa.

To further explore the model we carried out a sensitivity analysis. The model results were found to be sensitive to changes in the values of the emissions factors for biocides into the atmosphere. These emission factors are relatively uncertain. We point out that more research is needed on the quantification of the emission of biocides from greenhouse horticulture. The model results are also sensitive to the inclusion or exclusion of NO_x as an eutrophying compound, and to changes in prices, in particular to changes in the price of natural gas. The higher the gas price the higher the savings in costs for each m^3 reduction in gas use; consequently, the more expensive reduction options are selected by the model in cost-effective combinations of options.

We applied five different methods for multi-criteria analysis (MCA) in order to evaluate the cost-effectiveness of the reduction options in reducing several environmental problems simultaneously. The results of these MCA methods differed considerably. They resulted in different numbers of cost-effective combinations of options and in different options selected in the cost-effective combinations. On the other hand, the use of multi-criteria analysis appeared to be useful for tracing robust reduction options. These robust reduction options are options that were always selected in the cost-effective combinations of options, independent of the multi-criteria method used. Robust reduction options for tomato cultivation include the combi-condenser, heat buffer (both improving energy efficiency), high pressure cleaner (reducing the biocide use) and regional schemes for composting organic waste (reducing the amount of waste disposed). Many different MCA methods are available and the choice of the methodology is subjective. For this reason, and because of the observed differences in the results of the five MCA methods, it may be recommended to use more than one method for MCA in (environmental) research to gain insight into the effect of the choice of MCA method used and to trace robust reduction options.

Model application and optimisation analysis

We analysed cost-optimal strategies to meet national environmental targets for tomato cultivation in the Netherlands. We accounted for some of the heterogeneity of Dutch tomato cultivation (1220 hectare) by defining three farm types: Innovators (245 hectare), In-Betweens (730 hectare) and Low-Costs (245 hectare). The main differences between these farm types are the size of the greenhouse, the production volume, the intensity of the production (and therefore the activity levels) and the application of emission reduction options. Innovators produce tomatoes in relatively large new greenhouses and apply several technical reduction options. Low-Costs farmers produce tomatoes in relatively small old greenhouses and apply few options. The In-Betweens occupy the middle ground between the two other farm types. Data were based on the 1995 situation.

Two types of optimisation analysis were performed. The first type aimed at minimising the costs to achieve selected environmental targets for the tomato cultivation sector as a whole. The environmental targets for tomato cultivation are based on current policy for Dutch greenhouse horticulture. In the second type of optimisation analysis we analysed the extent to which the environmental impact could be reduced under different cost constraints. In both types of optimisation analysis we calculated the areas on which cost-effective combinations of options are applied on the different farm types to achieve the optimal situation.

The results of the optimisation analysis indicate that current policy targets for the tomato sector for global warming (24% reduction in CO_2 emission) and eutrophication (45% reduction in the emissions of eutrophying compounds) can be achieved at net negative costs. The targets for biocide emissions to the atmosphere (a reduction of 38% from 1995 levels) and energy efficiency improvement (65% over 1980 levels) can be achieved at relatively high costs. The target for the reduction in biocide use in 2010 cannot be achieved by the technical reduction options analysed. When model results indicate that the costs of achieving a certain target are negative at the national level, this may not be necessarily the case for all individual firms. Model results indicate that the most cost-effective solutions are often achieved at the national levels by applying relatively expensive options to part of the tomato cultivation area and relatively cheap options to other parts of the area. In these solutions, the costs fall mainly on the farm types Low-Costs and In-Betweens.

We also calculated cost-optimal ways to achieve the above mentioned policy targets for tomato cultivation sector simultaneously. The model results indicate that the net costs of achieving all targets simultaneously are negative. We observed that the model selects other combinations of reduction options in the multiple target optimisation than for the optimisation of the individual targets. Most noticeable in this respect are the selection of a fixed screen and double glass in the roof in combination with the no-windows options, in addition to the more generally applied options such as the combi-condenser, heat buffer, Econaut, strips around window panes and regional composting.

The results of the second type of the optimisation analysis were used to develop cost curves. These curves illustrate the costs of different levels of national emission reduction for tomato cultivation and were developed for all individual environmental problems analysed as well as for the integrated environmental impact using the five multi-criteria methods. The cost curves illustrate that, for the 1995 situation, for each environmental problem considered about 20% of the impact from tomato cultivation in the Netherlands can be reduced at net zero costs.

Extrapolating the results to total greenhouse horticulture

Extrapolating the results of the tomato case to the whole greenhouse sector is not easy because of crop specific characteristics. Most importantly, tomato cultivation uses relatively more natural gas, fertilisers and rock wool than the greenhouse horticulture sector as a whole, but less electricity. Furthermore, tomatoes are relatively sensitive to a reduction in radiation (light) that may result from the application of some reduction options, such as screens. These differences may have an important effect on the cost-effectiveness of the options. Despite these differences we discussed the possibilities of achieving the environmental targets for greenhouse horticulture in 2010, based on the tomato case. We argue that most of the environmental targets probably can be achieved, but that targets for the emission of eutrophying compounds and biocides to the atmosphere will probably be difficult to achieve. A more thorough analysis is needed to draw more definite conclusions on the reduction of the environmental impact of greenhouse horticulture as a whole.

Environmental systems analysis

This thesis shows that environmental systems analysis can be useful for analysing complex problems concerning economic and environmental aspects. The environmental systems analysis procedure involves six steps: 1. definition of the system boundaries and the system components, 2. description of the objectives, 3. model building, 4. systems analysis, 5. selection of the optimal system, and 6. conclusions and documentation. It is our experience that these steps are performed interactively rather than in a strict sequence. Iteration and feedback occur to help refine the objectives, improve the model and adapt the constraints. In the analysis we applied a combination of tools, including environmental life cycle analysis, environmental indicators, cost-effectivety analysis and optimisation analysis, multi-criteria analysis and sensitivity analysis.

Samenvatting

Doel van het proefschrift

De Nederlandse glastuinbouw beslaat ongeveer 10.000 hectare kassen, waarin groenten, snijbloemen en potplanten worden geteeld. Deze sector is van sociaal en economisch belang voor Nederland vanwege de jaarlijkse productie, de export en de werkgelegenheid. De productie in kassen gaat echter gepaard met een hoog gebruik van energie, kunstmest en chemische bestrijdingsmiddelen waardoor de sector bijdraagt aan verschillende milieuproblemen.

Het doel van dit proefschrift is om technische opties te identificeren voor het reduceren van de milieuproblemen die door de glastuinbouw veroorzaakt worden en deze opties te evalueren op basis van hun kosteneffectiviteit. De studie richt zich op de Nederlandse tomatenteelt en op de volgende milieuproblemen: klimaatverandering, verzuring, vermesting, verspreiding van toxische bestrijdingsmiddelen en de productie van afval. De methode van de milieusysteemanalyse wordt gebruikt voor de evaluatie van reductie-opties voor verschillende milieuproblemen. Een nevendoel is het bediscussiëren van de bruikbaarheid van milieusysteemanalyse in dergelijke studies.

Systeemgrenzen en modelelementen

De eerste stap van de analyse behelst de vaststelling van de systeemgrenzen en de bepaling van systeemelementen. Hiervoor is een beperkte milieukundige levenscyclus analyse (LCA) uitgevoerd voor de teelt van tomaten in kassen in Nederland en de bijdrage hiervan aan klimaatverandering, verzuring en vermesting. We richtten ons op deze drie milieuproblemen vanwege de relaties tussen de onderliggende processen en emissies. De emissies van eerste-orde processen (dit zijn activiteiten op het bedrijf, zoals de verbranding van aardgas en het gebruik van kunstmest) en tweede-orde processen (dit zijn industriële activiteiten die buiten het bedrijf plaatsvinden, zoals de productie van elektriciteit en kunstmest) zijn gekwantificeerd. De resultaten tonen aan dat in het algemeen de emissies van eerste-orde processen die van tweede-orde processen overschrijden. In bepaalde gevallen zijn de tweede-orde emissies echter relatief hoog. De productie van elektriciteit en steenwol dragen bijvoorbeeld voor 25% bij aan de totale (eerste en tweede-orde) emissies van verzurende stoffen. We concluderen dat een studie naar de milieuproblemen van de Nederlandse tomatenteelt de volgende processen en emissies zou moeten omvatten: CO_2 emissies ten gevolge van het door het gebruik van aardgas en de productie van elektriciteit, NO_x emissies ten gevolge van het gebruik van aardgas en kunstmest, en de productie van elektriciteit en steenwol, en de emissies van stikstof en fosfor ten gevolge van het gebruik van kunstmest. In de algehele studie hebben we daarnaast ook het gebruik en de emissie van bestrijdingsmiddelen en de productie van afval in beschouwing genomen. Een grondige studie van de systeemgrenzen bleek van belang voor onze analyse en geeft inzicht in het te bestuderen systeem.

Modelbouw

Een model is ontwikkeld dat de milieuproblemen veroorzaakt door de tomatenteelt in Nederland kwantificeert en dat gebruikt kan worden om de kosteneffectiviteit van technische opties ter reductie van deze milieuproblemen te evalueren. Het model berekent de bijdrage aan milieuproblemen als een functie van 'activiteiten' in de sector, emissiefactoren en de reductie-opties voor zover deze zijn toegepast. De milieuproblemen worden gekwantificeerd met behulp van indicatoren voor de belasting (druk) op het milieu (milieudruk-indicatoren). De activiteiten omvatten het gebruik van aardgas, kunstmest, bestrijdingsmiddelen en steenwol als ook de productie van elektriciteit en steenwol. Het model berekent de bijdrage van de tomatenteelt aan klimaatverandering (de emissie van kooldioxide in kg CO_2), verzuring (de emissie van stikstofoxide in kg NO_x), vermesting (de emissie van vermestende stoffen in kg fosfaat (PO_4)-equivalenten), verspreiding van toxische stoffen (op basis van het gebruik van bestrijdingsmiddelen in kg actieve stoffen en op basis van een milieuscore die een indicatie is voor de effecten van emissie van bestrijdingsmiddelen naar de lucht), en de productie van afval (in kg afval). Het model bevat 22 groepen van technische reductie-opties die de activiteiten (bijvoorbeeld het gebruik van aardgas) reduceren en/of de emissiefactoren (bijvoorbeeld de emissie van NO_x door aardgasgebruik) beïnvloeden. Het model houdt rekening met belangrijke neveneffecten van de reductie-opties op de omvang van de tomatenproductie, de bovengenoemde activiteiten en op emissies van andere stoffen dan die waar de optie voor is bedoeld. De kosten van de opties worden berekend als jaarlijkse kosten per hectare en omvatten de jaarlijkse investeringskosten, operationele kosten en variabele kosten (onder meer de besparing in aardgasgebruik en de effecten op de productieomvang). Het model selecteert uit alle mogelijk combinaties van opties de meest kosteneffectieve combinaties van opties.

Verkenning van het model

Het model is verkend voor een hypothetische referentie situatie voor de Nederlandse tomatenteelt waarbij verondersteld werd dat geen van de bovengenoemde reductie-opties was toegepast. De modelberekeningen tonen onder meer aan dat de opties die het aardgasgebruik reduceren het meest winstgevend zijn. De combi-condensor en de warmtebuffer worden door het model geselecteerd in alle kosteneffectieve combinaties van maatregelen. De kostencurven voor deze hypothetische situatie geven de kosten weer van combinaties van opties voor verschillende niveaus van emissiereductie. Deze curven laten zien dat aanzienlijke emissiereducties mogelijk zijn tegen geringe of nul netto kosten, maar dat bij toenemende reducties de kosten snel stijgen.

De reductie van één stof kan de emissie van een andere stof beïnvloeden (hiervoor genoemd als neveneffecten). Dit treedt met name op bij de reductie van de emissies van CO_2 en NO_x. Bovendien kunnen opties ter vermindering van de emissie van vermestende stoffen de emissie van CO_2 and bestrijdingsmiddelen naar de lucht beïnvloeden en andersom.

Om het model nader te verkennen is een gevoeligheidsanalyse uitgevoerd. De modelresultaten bleken gevoelig voor veranderingen in de waarden van de emissiefactoren voor de verliezen van bestrijdingsmiddelen naar de lucht. Deze emissiefactoren zijn relatief onzeker. We benadrukken dat meer onderzoek nodig is naar de kwantificering van de emissie van bestrijdingsmiddelen uit de glastuinbouw. De modelresultaten bleken ook gevoelig voor het wel of niet meenemen van NO_x als een vermestende stof, en verandering in prijzen, met name de prijs van aardgas. Hoe hoger de aardgasprijs des te hoger de besparing in kosten voor elke m^3 reductie in aardgasgebruik, en hoe duurder de maatregelen worden die door het model worden geselecteerd in de kosteneffectieve combinaties van opties.

Er zijn vijf verschillende methodes voor multi-criteria analyse (MCA) toegepast om de kosteneffectiviteit van reductiemaatregelen te evalueren waarbij verschillende milieuproblemen tegelijk werden beschouwd. De resultaten voor de verschillende MCA benaderingen lopen sterk uiteen. De resultaten verschillen in het aantal kosteneffectieve combinaties en ook in de opties die in deze combinaties worden geselecteerd. Aan de andere kant blijkt het gebruik van verschillende MCA methodes een goede manier te zijn om robuuste opties te selecteren. Robuuste opties worden door het model in alle kosteneffectieve combinaties geselecteerd onafhankelijk van de MCA methode die werd gebruikt. Robuuste reductie opties voor de tomatenteelt zijn de combi-condensor, de warmtebuffer (beide verhogen de energie efficiëntie), de hoge-druk reiniger (ter reductie van het bestrijdingsmiddelengebruik) en het op regionale schaal composteren van organisch afval (ter reductie van de productie van afval). Er zijn vele verschillende MCA methodes beschiknaar en de keuze voor een bepaalde methode is subjectief. Om deze reden en omdat de verschillende MCA methodes verschillende resultaten opleveren, raden wij aan om in een (milieukundige) analyse meer dan één methode voor MCA te gebruiken, om inzicht te krijgen in het effect van de keuze voor bepaalde MCA methodes én om robuuste maatregelen op te sporen.

Modeltoepassing en optimalisatie analyse

Het model is gebruikt voor het bepalen van de kostenoptimale inzet van reductie-opties voor het realiseren van nationale milieudoelstellingen voor de tomatenteelt. Daarbij is rekening gehouden met de heterogeniteit van de Nederlandse tomatensector (1220 hectare) door drie bedrijfstypen te beschrijven; 'Innovators' (245 ha), 'In-Betweens' (730 ha) en 'Low-Costs' (245 ha). De belangrijkste verschillen tussen deze bedrijfstypen zijn de grootte van de bedrijven (in hectare kas), de omvang van de tomatenproductie en de omvang van de daarbij behorende activiteiten, en de toepassing van reductie-opties. De 'Innovators' produceren tomaten in relatief grote en nieuwe kassen en passen verschillende opties toe. De 'Low-Costs' produceren tomaten in relatief kleine en oudere kassen en passen veel minder opties toe. De 'In-Betweens' omvatten de groep tussen de twee andere bedrijfstypen in. De beschrijving van de drie bedrijfstypen is gebaseerd op de situatie in 1995.

Er zijn twee typen optimalisatieberekeningen uitgevoerd. Het eerste type behelst een kosten-minimalisatie onder de voorwaarde dat bepaalde milieudoelen werden bereikt. De milieudoelen voor de tomatenteelt werden daarbij gebaseerd op beleidsdoelen zoals geformuleerd voor de Nederlandse glastuinbouw. In het tweede type optimalisatieberekeningen betreft een minimalisatie van de milieueffecten (emissies) onder verschillende voorwaarden voor de kosten daarvan. In beide type berekeningen was de beslissingsvariabele het aantal hectares waarop kosteneffectieve combinaties van opties op de drie bedrijfstypen werden toegepast. De resultaten van deze optimalisatieberekeningen gaven aan dat de milieubeleidsdoelen voor de tomatensector voor klimaatverandering (24% reductie van de CO_2 emissie) en vermesting (45% reductie van de emissie van vermestende stoffen) kunnen worden gerealiseerd tegen negatieve netto kosten. De beleidsdoelen voor de emissie van bestrijdingsmiddelen naar de lucht (een reductie van 38% ten opzichte van 1995) en de verbetering van de energie-efficiënte (65% ten opzichte van 1980) kunnen worden bereikt tegen relatief hoge netto kosten. Het doel voor de reductie van het bestrijdingsmiddelengebruik in 2010 kon niet worden gerealiseerd met de reductie-opties die in deze studie zijn opgenomen. Wanneer optimalisatieberekeningen aangeven dat bepaalde doelen tegen negatieve kosten gerealiseerd kunnen worden, hoeft dat niet noodzakelijkerwijs te gelden voor alle individuele bedrijven. De resultaten tonen aan dat de meest kosteneffectieve wijze om een bepaald milieudoel te bereiken op nationaal niveau doorgaans bestaat uit de toepassing van relatief dure maatregelen op een deel van het tomatenareaal en relatief goedkope maatregelen op een ander deel van het areaal. In de resultaten van de optimalisatieberekeningen worden de kosten met name gemaakt op de bedrijfstypen 'Low-Costs' en 'In-Betweens'.

Tevens is een optimalisatieberekening uitgevoerd waarbij alle bovengenoemde milieudoelen voor de tomatensector tegelijk gerealiseerd zouden moeten worden. De netto berekende kosten om alle milieudoelen tegelijk te bereiken zijn negatief. Het model selecteerde in deze oplossing andere combinaties van reductie-opties dan bij de optimalisatie van de individuele milieudoelen. Een opvallend verschil is dat het model vaste schermen en dubbelglas in het kasdek selecteert, in combinatie met het verwijderen van ramen uit kassen (de 'no-windows' optie). Daarnaast worden algemener toegepaste opties geselecteerd, als de combi-condensor, de warmtebuffer, de Econaut, isolatiestrippen rond de kasramen en het composteren op regionale schaal.

De resultaten van het tweede type optimalisatieberekeningen zijn gebruikt om kostencurven te maken voor de tomatensector. Deze curven illustreren de kosten van verschillende emissiereductie-niveaus en zijn gemaakt voor alle individuele milieuproblemen als ook voor het totale (geïntegreerde) milieueffect op basis van de vijf MCA methoden. Deze kostencurven betreffen de situatie in 1995, en laten zien dat elk milieuprobleem met ongeveer 20% gereduceerd kan worden zonder netto kosten.

Implicaties van de resultaten voor de totale glastuinbouw

Extrapolatie van de resultaten van de tomaten-studie naar de totale glastuinbouw is niet eenvoudig vanwege de verschillen tussen de geteelde gewassen. Een belangrijk verschil wordt veroorzaakt door het relatief hoge gebruik van aardgas, kunstmest en steenwol, terwijl het gebruik van elektriciteit relatief laag is vergeleken met de gehele glastuinbouwsector. Tomaten zijn bovendien relatief gevoelig voor een reductie in licht, die kan worden veroorzaakt door de toepassing van reductie-opties (bijvoorbeeld een isolatie-scherm). Deze verschillen tussen de tomatenteelt en de gehele glastuinbouw hebben een belangrijk effect op de kosteneffectiviteit van de reductie-opties. Ondanks deze verschillen hebben wij de mogelijkheden bediscussieerd voor het realiseren van de milieudoelen die voor de glastuinbouwsector zijn geformuleerd voor 2010, op basis van de resultaten voor de tomaten-studie. We beargumenteren waarom de meeste milieubeleidsdoelen redelijkerwijs haalbaar moeten worden geacht, maar dat de doelen voor de emissie van vermestende stoffen en de emissie van bestrijdingsmiddelen naar de lucht waarschijnlijk niet of moeilijk zijn te realiseren. Een grondigere studie is nodig om meer feitelijke conclusie te trekken over de mogelijkheden voor en de kosten van reductie van de milieubelasting door de Nederlandse glastuinbouw.

Milieusysteemanalyse

Dit proefschrift laat zien dat milieusysteemanalyse nuttig is voor de analyse van complexe problemen waarin zowel economische als milieukundige aspecten een rol spelen. De procedure van de milieusysteemanalyse zoals toegepast in dit proefschrift behelst zes stappen: 1) definitie van de systeemgrenzen en systeemelementen, 2) beschrijving van de doelen, 3) modelbouw, 4) systeemanalyse, 5) selectie van het optimale systeem, en 6) conclusies en documentatie. Onze ervaring is dat deze stappen eerder iteratief worden doorlopen dan strikt opeenvolgend. Iteratie en terugkoppeling hielpen onder meer om de doelen aan te scherpen en het model te verbeteren. In deze studie hebben we een combinatie van systeemanalytische methoden en technieken toegepast. Dit waren onder meer milieukundige levenscyclusanalyse, milieu-indicatoren, kosteneffectiviteitsanalyse en optimalisatie analyse, multi-criteria analyse en gevoeligheidsanalyse.

Curriculum vitae

Jacomijn Catherine Pluimers was born on August 26th, 1971 in Buenos Aires, Argentina. In 1989 she completed secondary school (VWO) at "Rijnlands Lyceum" in Wassenaar and started to study Biology in Leiden. After one year she switched studies and started her study Environmental Science at Wageningen Agricultural University (WAU), with specialisation in the relation between agriculture and the environment, soil science and nature conservation. During her study she spent five months in Guápiles (Costa Rica) at the research station of the WAU (Atlantic Zone Programme), and three months at the 'Universidad Nacional' in Heredia (Costa Rica).

In May 1996 she started her PhD research 'Environmental systems analysis of greenhouse horticulture in the Netherlands' at the Environmental Systems Analysis group and the former department of Horticulture (now Horticultural Production Chain group).