Environmental-Economic Modelling of Novel Protein Foods: A General Equilibrium Approach

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Abstract

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Intensive animal production systems in Europe, particularly in the Netherlands, result in a series of environmental problems mainly due to manure surplus. This thesis aims to make contributions to identifying solutions to the problems related to protein production and consumption.

The first contribution concerns the theoretical modelling of environmental problems. This includes how to represent environmental impacts in economic models considering the interactions between the economic system and the environmental system, and how to deal with the relevant non-convexities. We represent the environmental impacts theoretically by including the biophysical processes of environmental changes and feedbacks to the economy in welfare optimisation and equilibrium models. This often brings non-convexities to the model, and thus has implications for policy recommendations, because a non-convex program usually has multiple local optima and has the difficulty of decentralisation. Particularly we illustrate how to solve a non-convex program using *parameterisation* for the interaction between pork and crop production and how to check decentralisability of the welfare optimum.

The second contribution is a systematic analysis of protein chains, which provides information on their environmental pressures. We use the environmental life cycle assessment (LCA) to compare the environmental pressures of a Dutch pork chain and a pea-based chain for Novel Protein Foods (NPFs). We concluded that NPFs are environmentally more friendly than pork based on per unit of protein consumption in terms of environmental pressure indicators.

The third contribution is the empirical application of Applied General Equilibrium (AGE) models to analyse the economic and environmental impacts of enhanced consumption of NPFs under different scenarios in a global context. Our model results show that an exogenous shift from animal protein foods to NPFs in the EU, which is represented by an increased expenditure share of NPFs in protein budget, will decrease the global NH_3 emissions. If EU consumers are willing to pay to improve air quality, the EU will reduce the pork production and increase pea production. If 'rich' consumers consume more NPFs through lifestyle change in meat consumption, the global emissions of NH_3, N_2O and CH_4 will be reduced.

PREFACE

When I came to the Netherlands at the end of 1997 for the reunion with my family, it was unclear what I would do. Having studied chemical engineering for some years I became curious about what economists did. With a strong motivation to study something different from engineering, I followed the ‘Agricultural Economics and Management’ MSc programme at Wageningen University, majoring in environmental economics. I realised immediately that this was something I would invest in. Since then I have got a better chance to learn in this fascinating field. When I started my MSc thesis under the supervision of Professor Ekko van Ierland in 1999, my next professional goal became to obtain PhD training in environmental economics. Fortunately when I finished the MSc thesis, I was appointed as a PhD researcher (AIO) at the Environmental Economics and Natural Resource Group from March 2000 onwards for four years. This thesis contains the main results of the work. I wish I could say that I am an economist now.

After more than four years of intensive study and hard work, it is now time to express my gratitude to the people who have been involved in my work or have influenced my work. During this period my debts to others are understandably too many to list comprehensively. To those with whom I have worked most closely I owe a special debt of thanks: Professor Ekko van Ierland who provided me this valuable chance to do my PhD project. He is a patient person who has experienced with me a lengthy process while I was waiting for several months to obtain a work permit. He not only supervised me on how to make progress in writing the thesis but also instructed me how to face the ups and downs during the process. In addition, he took the initiative to contact many experts assuring that I’d get the best supervision. For all this, my thanks are endless. In particular, my thanks go to Professor Michiel Keyzer from the Centre for World Food Studies, Vrije Universiteit Amsterdam (SOW-VU). He inspired me to work towards a more theoretical direction for a better understanding of economics and environmental problems. He also explained to me a lot of economic theory and inspired me to challenge myself. He seems to me an endless source of knowledge. With his great knowledge and patience, he influenced the dissertation a great deal although the usual disclaimer applies to the author.

I am indebted to various colleagues for the pleasant time, and useful discussions: the colleagues from the Environmental Economics and Natural Resource Group of Wageningen University and the PROFETAS colleagues. My special sincere thanks go to Hans-Peter Weikard who expressed his willingness to read part of my draft (Chapters 1 and 2) and provided useful comments and a lot of other help. My thanks also go to Heleen Bartelings for her generous help in many aspects. She has always been ready to answer my questions about general equilibrium theory and about life in the Netherlands. I would also like to mention my roommate Vincent Otto, with whom I had a pleasant work time by sharing frustrations and successes. Rob Dellink is appreciated for checking GAMS code and providing comments for Chapter 6. Justus Wessler, Rolf Groeneveld, Arjan Ruijs, Erik Ansink, Timo Kuosmanen, Juan-Carlos Altamirano-Cabrera, Ivo Mulder and all other colleagues at the group are very much appreciated for any help over the past years. Particularly, I would like to express my sincere thanks to our secretaries Wil den Hartog and Sjoukje Atema for their many practical supports. I also thank them for their incredible patience with my practising Dutch. *Ik heb veel geleerd van jullie*. *Hartelijke bedankt*! I also appreciate all the PROFETAS colleagues. Special thanks go to Martine Helm, David Niemeijer, Johan Vereijken, Jan Vos, Harry Aiking, Xinyou Yin, Dick Stegeman and many others in the PROFESTAS research team for all kinds of help.

In the last year I also spent a lot of time at SOW-VU, where I got a lot of help and inspiration. Lia van Wesenbeeck deserves a special word. She smoothly arranged a lot of things for my work there including having me as her roommate. We had a lot of useful discussion on general equilibrium theory. She also carefully checked my GAMS code for Chapter 3 and provided useful suggestions. She was always ready to answer any questions I had. I learned a lot from her.

I also would like to thank the Netherlands Organisation for Scientific Research (NWO) for the financial support for this four-year project, and special supports for conference visits in Monterey, USA, Durban, South Africa and Budapest, Hungary. My thanks also go to the LEB-fund of Wageningen University for the financial support for the conference visit in Ravello, Italy. I have also benefited a lot from the intensive PhD program provided by the Netherlands Network for General and Quantitative Economics (NAKE), which was very useful for my research.

I dedicate this dissertation to my families, who have given me strong support during these four years in many ways. My parents and two sisters in China provide me a lot of spiritual support by emailing and phoning; my second home in the Netherlands gives me all kinds of support. Jie, thanks for the full supports: the firm understanding for my absence in some weekends, patience for my endless chat about the thesis work and more... My lovely son Yiteng, you give me endless pleasure and compensate me a lot during my hard time. You really help me a lot in your own way: being considerate, independent, curious, warm-hearted, intelligent, musical, sporty and more… I am proud of you! I feel very privileged as your mother! You could even tell me that a too easy life is boring. I owed you a lot for my lack of care for you in the past years. I am glad that now I should have more time for both of you!

Wageningen, the Netherlands
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SUMMARY

INTRODUCTION

Intensive animal production systems in Europe, particularly in the Netherlands, result in a series of environmental problems, mainly due to manure surplus. A large proportion of minerals in manure affects the quality of soil, water and air. This thesis aims to make contributions to identifying solutions to the problems related to protein production and consumption.

The first contribution concerns the theoretical modelling of environmental problems. This includes how to represent the environmental impacts in economic models considering the interactions between the economic system and the environmental system, and how to deal with the relevant non-convexities in models. This is conducted in Chapters 1, 2 and 3. The second contribution is a systematic analysis of protein chains, which provides information on their environmental pressures. This is carried out in Chapter 4. The third contribution is the empirical application of Applied General Equilibrium (AGE) models to analyse the economic and environmental impacts of enhanced consumption of Novel Protein Foods (NPFs) in a global context. This can be found in Chapters 5, 6 and 7. Finally, Chapter 8 gives the main conclusions on the economic modelling of environmental impacts, the impacts of NPFs, and implications for policy recommendations.

ECONOMIC MODELLING OF ENVIRONMENTAL IMPACTS

There are interactions between the economic system and the environmental system. The main economic functions of the environment are to provide input for production and amenity services for consumption. Economic activities will influence the functions of the environment by changing the environmental states. The environmental changes are also due to the intrinsic environmental processes following biophysical laws. These environmental changes then give feedbacks on production and utility of the economic agents.

The causes of the environmental problems are economic activities (production and consumption), which use the environmental resource or emit pollutants to the environment, and the intrinsic environmental processes, which follows biophysical laws. Identifying solutions to environmental problems means that we want to achieve a balance between pollution and economic activities. Managing the environment does not simply mean that we

reduce the use of the environment but we understand how to use the environment efficiently. This can be analysed by welfare programs, which can represent economic and environmental policy objectives. In welfare programs, we represent the economic functions of the environment, the interactions between the economic system and the environmental system, and the relevant environmental processes.

Inclusion of the environmental process and feedbacks in a welfare program probably brings non-convexities, a property that departs from standard economic assumptions. In standard economic theory, a convexity of production sets and preference sets ensures that equilibrium exists and coincides with the welfare optimum. Therefore prices provide sufficient information to economic agents to realise their plans. A competitive market condition can achieve efficient allocation of the economy. That means decentralisation of the welfare optimum is possible. When non-convexities are involved in a welfare program, we will probably have multiple local optima. The problem is that only one can be chosen by the policymaker and this one might not be the same as the equilibrium. This means that each agent might choose a different level from the welfare optimum level. If the welfare optimum matches the equilibrium, then decentralisation is possible, otherwise we need policy intervention to achieve the welfare optimum. For a non-convex program we have to find the optimal solution and check its decentralisability.

If non-convexity is involved in a model, we can use a *graphical* method or a *parametric* method to find the optimal solution. A graphical method is easy but only works for one or two-dimensional non-convexities due to the limitation of graph making. We have shown the graphical method in an aquatic model in Chapter 2.

We can also solve non-convex programs by convexification. *Parameterisation* is one important technique of convexification for numerically solving non-convex programs. By setting the non-convex elements into parameters, the non-convexities become irrelevant. The practical way is to use GAMS software and scan the possible range of the non-convex elements to find all local optima. Then we compare all the local optima and spot the optimal solution with the highest welfare. Chapter 3 in particular illustrates how to solve the non-convex problems using *parameterisation* for the interaction between pork production and crop production through soil acidification. Pork production emits much NH_3, which has impacts on soil fertility, and crop production depends on both fertiliser input and soil fertility. Therefore, a soil acidification process model is included in the welfare program. Different cases for the setting of the economy containing non-convexities are specified and the optimal solution for each case is found.

After finding the welfare optimum we also check the decentralisability of the welfare optimum to each agent (consumer and producer). If each consumer receives his income and spends it on consumption of goods to maximise his utility, and if the producers obtain non-negative aggregate profit and maximise non-negative individual profits, then the welfare optimum is decentralisable. If it is decentralisable, then a competitive market condition will lead to the welfare optimum. Otherwise, we need policy intervention, such as quantity control, to achieve the welfare optimum.

ENVIRONMENTAL PRESSURES OF PROTEIN FOODS

This thesis (Chapter 4) has focused on comparing the environmental pressures of a Dutch pork chain and a pea-based chain for NPFs. We have chosen the environmental life cycle assessment (LCA) for the study. This includes the following steps. First, we describe the production and consumption chains of a prototype animal protein food (pork) and a novel plant-protein food (NPF) to understand the relationships between production, consumption and the environment. Second, we develop some environmental pressure indicators, including emission indicators and resource use indicators. Third, we subsequently assess and compare the environmental impacts of both chains using these indicators.

Our findings from the LCA study show that the pork chain contributes to acidification 61 times more, to global warming 6.4 times more, and to eutrophication 6 times more than the NPFs chain. Pork chain also needs 3.3 times more fertilisers, 1.6 times more pesticides, 3.3 times more water and 2.8 times more land than the NPFs chain. We thus conclude that NPFs are environmentally more friendly than pork, per unit of protein consumption.

MODEL APPLICATION

For the economy-wide impacts, we have to simplify the environmental processes in applied general equilibrium models due to their complexity and spatial differences. We have applied a model to different circumstances. In Chapter 5, we apply the model to a two-region (EU and ROW) economy, where EU stands for European Union and ROW the rest of the world. In this model, CO_2 emission influences the environmental quality, which has impacts on the utility. In Chapter 6, we apply the model to a three-region (EU, OOECD and ROW) economy, where OOECD stands for other OECD countries. In this model, we take NH_3 as the environmental substance as it is a major pollutant from animal protein production. In both Chapters 5 and 6, the environmental processes are simplified by assuming a linear relation between emission and environmental quality, which gives feedback on consumer utility. For the model in Chapter 5, we use predetermined production functions, utility functions and endowments to produce a benchmark. This presents a more methodological than empirical approach. Chapter 6 has a more empirical focus as we calibrate the model using the GTAP data source. The model in Chapter 6 is applied to two scenarios: exogenous shift from pork to NPFs and environmental concern (the consumer willingness to pay for the environmental quality). The exogenous shift from pork to NPFs in the model is represented by an increase of expenditure share of NPFs (from 2.5% to 25%) in protein consumption budget. The environmental concern is represented by a willingness to pay for air quality in the model. We assume that 1% of consumers' budget would be paid to improve air quality. We draw our main conclusions on the effects of a shift from animal protein to plant protein foods on the economy and the environment, based on Chapter 6.

If EU consumers increase their expenditure share of NPFs from 2.5% to 25%, pork consumption decreases by 23% in the EU. There are hardly impacts on the consumption of other goods and hardly impacts on consumption in other regions. Pork production in the EU decreases by about 8% accompanying an 11% decrease in animal feed production. For the emissions of NH_3 the EU will have a 3% decrease through less pork production. The other OECD countries will have a 2% decrease of NH_3 emission due to the import of pork from the EU, while ROW will have a 2% increase of NH_3 emission due to its increased feed production.

If EU consumers are willing to pay 1% of their income to improve air quality, the EU will reduce its pork production by 62% and feed production by 16%. It will increase pea production by 12%. Economically speaking, the major impacts are on the pork, NPFs and related sectors such as feed and peas. However, the EU will enjoy a much higher air quality if consumers are paying to improve it. Emissions in the EU will decrease by 90%, but there is a slight increase (about 1%) in other regions.

In Chapter 7 we use a more disaggregate model with four regions (EU, other high-income region, middle-income region and low-income region) and more detailed agricultural sectors, and we consider three emission substances (CH_4, N_2O and NH_3). The biophysical processes are not implemented in detail because information on environmental effects caused by emissions is lacking. We consider two types of scenarios to achieve lower emissions. The first scenario is related to consumers' lifestyle change in meat consumption by replacing meat with NPFs. The second scenario is to use environmental policy instruments (restriction of emissions) to achieve a similar emission reduction as lifestyle change.

If 'rich' consumers in the world consume 10kg/capita of NPFs per year to replace meat consumption, the global emission reduction for NH_3 will be 4%, for CH_4 0.2% and for N_2O 3.7%. However, this emission reduction does not necessarily happen in regions where more NPFs are consumed. Instead it happens in regions that switch to produce fewer ruminants concerning their comparative advantages in the regime of free international trade. For example, the agricultural emissions in the EU will be reduced by 2.9% for N_2O and increased by 6% for CH_4. There is almost no change in NH_3 emission in the EU. In this case, it is the other high-income region that reduces most of NH_3 emissions. A modest lifestyle change (i.e. 10kg NPFs per capita per year for rich consumers) is not sufficient to achieve an NH_3 emission target in the EU, as is the target set by the Gothenburg protocol.

Lifestyle change leads to the reduced emissions through reduction in production of meat sectors because less meat is demanded. Production in the NPFs sector will increase, which impacts the other related sectors such as feed and pulses. This change will make the production structure more extensive. Environmental policies reduce the emissions through either using a more extensive production system or by production reduction in high emission sectors, which increases the prices and therefore creates a loss in welfare for consumers.

POLICY RECOMMENDATION

Both an exogenous shift from pork to NPFs and a willingness to pay for good environmental quality contributes to an emission reduction. However, the latter contributes to more emission reduction than the former. This knowledge could be used in policy design. Stimulating the environmental concerns of consumers and providing them with information about the environmental performance of products is important for a sustainable consumption pattern. From a policy-making perspective it would be important to advocate environmental concerns of the consumers or introduce a payment system of environmental premiums for good environmental quality.

As the consumption of NPFs becomes higher, the emissions will become lower, thus promoting sustainable consumption patterns is important. Global emissions will be reduced if consumers change their lifestyle towards more NPFs. Considering the lower emission related to the replacement of meat by NPFs, the lifestyle change towards less meat and more NPFs should be promoted.

The reduction of environmental emissions in the EU, through lifestyle change, is very limited because more meat can still be produced in the EU to meet the increasing demand in other regions in a free international trade regime. Therefore we have to rely on local environmental policy in the EU to solve local environmental problems caused by NH_3 emission. From the policymaking perspective, we have to make policies which aim to reduce meat production (e.g. quantity control on pork production) in order to solve related environmental problems.

Introducing NPFs that have lower environmental pressures is only part of the measures for reducing environmental problems. It should, therefore, be a common responsibility of the government, society and industry to co-operate to promote new approaches for protein production and consumption, and to safeguard a sustainable future.

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CHAPTER 1 PROBLEM DEFINITION AND RESEARCH QUESTIONS

1.1 INTRODUCTION

This thesis deals with economic modelling of environmental problems, both theoretically and empirically. Theoretically, it discusses how to describe the environmental problems, how to include them in an economic model, and how to solve the model in a proper manner. Empirically, it focuses on the environmental and economic analysis of protein production and consumption chains. The study is conducted within the context of the PROFETAS[1] research program.

This chapter provides an introduction to the research background, problem definition, research questions and approaches to the questions. We first discuss the research background, which is closely related to the historical process of livestock production and the increasing demand for animal products. This is followed by a description of the PROFETAS research program. Next, we define the main problems related to the transition towards more sustainable protein production. Special attention is given to the relationship between protein chains and the environment, the interaction between the economic and the environmental system, and the economic modelling of environmental problems. After describing the aim of the thesis, the research questions and approaches to these questions are formulated. Finally, a concise overview of the structure of the thesis is provided.

1.2 A HISTORICAL BACKGROUND

Livestock production

Animals have always formed and will always form a central feature of the human world (Manning & Serpell, 1994). Development of human history is closely related to the rise of food production in the form of crop cultivation and animal husbandry. As early as about 8000 B. C., human beings domesticated big mammals like cows, sheep, goats, pigs and horses (Diamond, 1997). Table 1-1 shows the approximate dates of first evidence for domestication

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[1] PROFETAS stands for PROtein Foods, Environment, Technology And Society. It is financed by the Netherlands Organisation for Scientific Research (NWO), in order to investigate how global food production and consumption can be more sustainable. See www.profetas.nl for details.

of large mammal species. The domestic mammals were crucial to human societies, notably because they provided meat, milk products, fertiliser, leather, wool, land transportation, military assault vehicles and plough traction.

There is evidence that the rising density of the human population is associated with the rising food production. On the one hand, increased food production tends to lead to increased population densities because it allows for larger numbers of inhabitants per square kilometre. On the other hand, as population densities rise, food production becomes increasingly favoured because it provides the increased food outputs needed to feed the population. The rise of agriculture sustained higher *population densities* than the hunting-gatherer lifestyle.

Table 1-1 Approximate dates of domestication of large mammal species

Species	Date (B. C.)	Place
Sheep	8,000	Southwest Asia
Goat	8,000	Southwest Asia
Pig	8,000	China, Southwest Asia
Cow	6,000	Southwest Asia, India
Horse	4,000	Ukraine

Source: Diamond, 1997.

Urbanisation and human diseases

Historically, cultivation became possible after humans learned to fertilise crops by burning vegetation, applying manure and controlling flooding. Humans also learned to preserve food with pottery. As well, wheels emerged and transport became easier. Cities were formed and specialisation occurred. In that stage people might live in a concentrated way but no serious environmental problems occurred since manure was almost fully recycled in the system. Nowadays, livestock production is problematic because transportation of feed and animals has increased in importance. Transport generated problems since manure from animals and human manure in cities is often far from production of grains.

It is interesting to observe that high population density and intensive livestock systems have not only led to environmental problems but also to the incidence of severe diseases, both for humankind and animals. For instance, the major killers of humanity throughout our recent history – smallpox, flu, tuberculosis, malaria, plague, and cholera - are infectious diseases that evolved from diseases of animals. AIDS, first documented in humans around 1959, was derived from monkey viruses (Diamond, 1997). For other diseases, densities of population provided microbes with a short path from one person's body into another's drinking water: farmers were sedentary and lived amid their own sewage, while hunter-gatherers frequently shifted camp and left behind their own piles of faeces with accumulated microbes and worm larvae. Thus some diseases (e.g. smallpox, mumps and AIDS) evolved into *crowd diseases* as people lived in a more concentrated way (Diamond, 1997). In a similar way SARS, a recent disease in China is apparently related to a developed infection from viruses from cats.

Increased population and production and consumption of animal products

In the early years of livestock production, farms were family owned and operated. As the demand for livestock products increased rapidly, traditional livestock production was unable to meet the increased demand. The emergence of large-scale industrial livestock production systems with high capital inputs, support infrastructure, economies of scale and marketing network often resulted in the displacement of traditional land-based producers. Nowadays, the number of animals produced is increasing, while the number of farms is decreasing. Globally there is a rapid expansion of intensive livestock production. This expansion is fuelled by increasing demand for livestock products, driven by population growth (mostly in the urban areas), economic development and changing food preferences (Delgado *et al*., 1999; CAST, 1999).

Food production from animal and plant sources has increased steadily during the past century, keeping pace with population growth. Consumption of animal products (e.g. meat, milk and eggs) varies widely among countries, reflecting differences in food production resources, production systems, income and cultural factors. Per capita consumption of animal products is much higher in developed countries than in developing countries. It is estimated that in developed countries 70% of dietary protein is of animal origin (CAST, 1999). Per capita demand for animal food products has, however, expanded rapidly in a number of developing countries in the past 15 years (Delgado *et al*., 1999). The world population is currently increasing at a rate of 1.4% per year (CAST, 1999). Rising affluence, particularly in the developing countries, means that more people can afford the high-value protein that livestock products offer. Population growth and affluence has increased demand for proteins, especially for animal proteins. The demand for livestock products is much greater than for crop products (Pino and Martinez, 1981), and the consumption of livestock products is growing faster than the increase in world population. Figure 1-1 shows the trend of meat production over the period 1961-2002, indicating that world total meat production has increased tremendously over that period to meet the world-wide high demand.

Large increases in per capita demand for animal food products in the developing world are projected to continue in the next decades. The world population is projected to increase to 7.7 billion by the year 2020, equivalent to an average annual compound growth rate of approximately 1.2 % for the period 1995 to 2020, while the majority (95%) of this increase is forecasted to occur in developing countries. Thus, demand for foods of animal origin is expected to increase more rapidly than the total population (CAST, 1999). As a result, global meat demand is projected to grow from 209 million tons in 1997 to 327 million tons in 2020, and global milk consumption from 422 million tons to 648 million tons over the same period. In this period pork production is projected to increase from 40% to 50% (de Haan *et al*., 2001). The growing, increasingly urban and more affluent population in the developing world will most likely demand a richer, more diverse diet, with more meat and milk products. It is projected that there will be a ‘livestock revolution’ (or ‘livestock boom’) in the next two decades (Delgado *et al*., 1999).

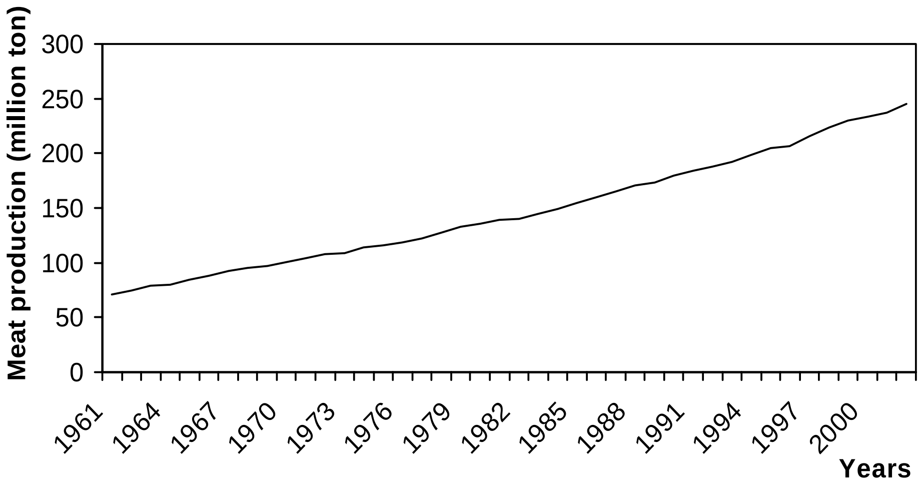


Figure 1-1 Trend of world meat production, 1961 to 2002

Source: FAO, 2003.

Intensive pork production in the Netherlands

Livestock can be classified into monogastrics (e.g. pig and poultry) and ruminants (e.g. cows, goats). In general, monogastrics are the main livestock that rely on concentrated feed (Delgado *et al*., 1999). Unlike ruminants, pigs are among the most efficient domestic animals in converting feedstuffs including domestic and agricultural by-products into edible meat (Delgado *et al*., 1999). Pork production has been intensified by the use of concentrated and better-balanced feed, and with the introduction of sophisticated housing, confinement systems and technology (Aumaitre, *et al*., 1982). Intensive livestock production including pigs and poultry is characterised by an increasing concentration into very large, capital-intensive, factory-like production units, largely divorced from agricultural land. Animal feed is purchased rather than grown, and the livestock remain inside buildings during their production (Bowler, 1985).

Intensive livestock production is not only due to the high demand for meat as a result of increasing income and population. There are also other factors, which contribute to the intensification of animal production in the Netherlands. These include the Common Agricultural Policy (CAP), the accessibility to the harbour of Rotterdam and farm conditions.

Firstly, the CAP has contributed to intensive pig production in the Netherlands. During the development of the European Union (EU), the CAP was created officially in 1962 (Ritson and Harvey, 1991). The basic feature of the CAP was to provide income support to European farmers, via increased prices, by protecting them from ‘low-priced’ imports. The basic principles of the CAP are: i) a common market, ii) free internal movement of agricultural products, iii) a uniform external tariff, iv) common prices within the market for the main products, v) community preference in agricultural trade and vi) sharing the financial burden of the CAP (Bowler, 1985). The CAP intended to give some support to certain agricultural products through common prices, import-levies and export-subsidies (Bowler, 1985). The

CAP has contributed to the expanding volume of cereal production by maintaining target and intervention prices above world prices. As a result, feed manufacturers and livestock farmers have sought substitutes for the relatively expensive cereals produced in the EU.

In the 1960's margarine was said to be healthier than butter and therefore the demand rose for the good. Importing soybeans and oilseeds for producing margarine seemed profitable for food producers like Unilever. In addition, exporters of soybeans and oilseeds such as the USA have protested that the markets would be restricted by import levies. Therefore the proposals to impose levies on imported soybeans and oilseeds have been resisted (Bowler, 1985). Soybeans and oilseeds were therefore imported for feed, because they were not subject to the EU import-tariffs.

Since a oilseed diet for livestock had to be supplemented with carbohydrates, a mixture of cassava and soybean became a substitute for corn or other feed grains (McCalla and Josling, 1985). Cassava (also called manioc, or tapioca), which is a woody, tuberous root crop grown in the tropics, is another important component of feed. It contains high volumes of carbohydrate (energy) per unit of output but it has very low protein content. The import duties (6%) on dried cassava chips and pellets are very low compared to a much higher import duties on cereals (van Amstel *et al.*, 1986). The mixture of cassava and soybean is based on complementarity. Therefore, as the demand for cassava increases, so does the demand for soybeans and soymeal.

Corn gluten is a joint product or by-product resulting from wet milling of corn production of high fructose corn syrup and grain alcohol. In the 1970's high fructose corn syrup became a substitute for sugar, and the demand for it rose, increasing the supply of corn gluten feed (McCalla and Josling, 1985). Other feed items (i.e. orange pulp, fish meal) emerged at the same time and those feed ingredients were not subject to the import-levies in the EU. Therefore, since the 1960's the feed composition has changed from more cereals to more oilseed cakes and other products (e.g. cassava) (Bowler, 1985).

To summarise, cereal substitutes (e.g. soymeal, cassava, corn gluten, and sweet potatoes) derived essentially from non-EU states, are unique in that they have penetrated the European market, mainly driven by the exception to pay levies or customs duties. The EU does not tax oilseed and protein crop imports from non-EU states (Charvet, 2001), therefore import-based feed is cheaper than European grain feed despite the cost of transport (Bolsius and Frouws, 1996). As a result, a high level of agricultural support in the EU, through CAP, has increased the use of feed imports and raised livestock densities (Brouwer *et al*., 1999).

Secondly, the level of accessibility to ports for the imports of relatively cheap animal feed appeared to be a major factor for stimulating pork production. Brittany (France), the Netherlands and Belgium have formed areas of increasing specialisation. The route from Rotterdam, up the Rhine and along the canal systems is the cheapest for bulk transport; there has been an increasing concentration of pig breeding along these routes (Duchêne *et al*., 1985).

Finally, land scarcity due to large families and low land quality in the sandy parts of the Netherlands in the 1950's and 1960's made pig and poultry production in stables more attractive than other agricultural activities. For all these reasons, intensification of livestock production has occurred in the Netherlands.

Table 1-2 shows the trend of the number of pigs in the Netherlands. It has increased substantially since the 1960's. In the 1990's, the number of pigs almost equalled the number of inhabitants of the Netherlands. With an area of about 37000 km^2, the Netherlands is densely populated, both with people and animals. Moreover, pigs are not distributed evenly over the country, but concentrated mainly in stables in southern and eastern regions, with little land devoted to pig farms.

Table 1-2 Number of pigs in the Netherlands (1000 head)

	1960	1970	1980	1990	1995	1996	1997	1998	1999	2000	2001	2002
Pigs	2,955	5,533	10,138	13,915	14,397	14,419	15,189	13,446	13,567	13,118	13,073	11,648

Source: CBS, 2003.

Pigs are fed with specially grown crops or by-products of crops. The concentrated feed is a mixture of energy-producing raw materials (i.e. tapioca, maize and wheat bran), and proteins (i.e. soybean or soybean cake, citrus fruits and fishmeals). As intensive livestock units multiply, so does the need for imported animal feed. The EU imports large amounts of soya and soya cakes from Brazil and Argentina. European imports of soya rose from 2.5 million tonnes in the middle of the 1960's to some 15 million tonnes in the middle of the 1990's. Imports of cereal feed substitutes (i.e. corn gluten feed, manioc, citrus pellets and molasses) increased from 5 million tonnes in 1975 to over 20 million tonnes by the end of the 1980's (Charvet, 2001).

In the Netherlands in 1996/97, feed consisted of 46.2% feed crops (20% tapioca, 17.3% wheat, 5.7% peas, and 3.2% barley) and 35% by-products (15% soy cakes, 7.6% sunflower seed cakes, 6.8% rapeseed cakes and 5.6% molasses) and 18.8% other ingredients (CBS & LEI, 1999). About 85% of the feed ingredients for Dutch pigs is imported from the rest of the world (de Haan et al., 1997). For example, soybeans are imported from the USA, Brazil and Mexico. Tapioca is imported from Thailand or Indonesia (see Table 1-3).

In summary, the Dutch pig production system is not only intensive but also import-dependent for feed. The intensification results in very serious environmental problems associated with pig production in the Netherlands. As well, it has also impacts on feed-crop producers elsewhere in the world, due to the international dimension.

Table 1-3 Main pig feed origins for the Netherlands

Ingredients	Tapioca[a)]	Cakes[b)]	Wheat[c)]	Peas[c)]	Barley[c)]
Origins	Thailand, Indonesia	USA, Brazil, Argentina, Mexico	EU	EU	EU

Sources: a) Bolsius and Frouws, 1996; b) Bolsius and Frouws, 1996; Brouwer *et al*., 1999; Charvet, 2001 and c) cf. Brouwer *et al*., 1999.

Problems of intensive pork production and consumption

Livestock transforms feed biomass into livestock products and manure. From ancient times manure was considered favourable for its fertilising value. The introduction of mineral fertilisers has led to the reduction in value of animal manure as a concentrated form of plant nutrient supply. Also, very intensive livestock systems have developed where manure production exceeds demand, resulting in 'manure surpluses.'

The large number of animals accounts for vast amounts of manure containing a high level of minerals e.g. nitrogen (N), phosphorous (P), potassium (K), and magnesium (Mg), and heavy metals e.g. copper (Cu), and zinc (Zn). The traditional solution of using manure as a natural fertiliser offers only a partial solution duo to the substantial manure surpluses. Let us now consider the main problems associated with pork production and consumption.

Firstly, the intensive production system results in a series of environmental problems related to manure surplus. The conversion process of nitrogen follows the following biophysical processes: intake of feed by pig, digestion of feed in pig's stomach, excretion, nitrogen (N) emissions from manure, part of N going to air, part of it going to soil, then leaching to ground water and surface water. Contaminated water has a negative impact on crop yields, animal health and human health. A large proportion of minerals in manure from the intensive production system affects the quality of the soil, water and air. Eutrophication of surface water, due to input of nutrients, will occur if manure gets into streams through discharge, run-off or overflow. Pollution of surface water threatens aquatic ecosystems and the quality of drinking water. Leaching of nitrate from manure to groundwater is also a threat to drinking water quality. Accumulation of nutrients and heavy metals in the soil can reduce soil fertility. The odour from intensive livestock farming can be a nuisance in populated areas. Volatilisation of ammonia (NH_3) to the air from manure causes N deposition in soil and soil acidification as well as eutrophication of sensitive ecosystems. Finally, methane (CH_4) from manure contributes to global warming.

Secondly, large-scale imports of feed make it so that the problems related to the Dutch pig production system are not only local but also global. For example, the increased production of raw materials for animal feed in Thailand, Brazil and Argentina has resulted in large-scale deforestation. The cultivation of soybeans in Brazil has led to serious nutrient depletion and soil pollution resulting from the use of pesticides. Feed production is quite land-intensive, imposing a great pressure on land in the developing world.

Thirdly, concentration of livestock might lead to an increase in the emergence of new disease patterns (e.g. swine fever, fowl pest and foot-mouth disease) and incidence of food-borne diseases. Intensive animal production systems, especially in areas close to population concentrations, result in increased risks of infection to livestock as well as human beings. Pathogens may occur in dirty water, farmyard manure and slurry, depending on the health of animals or the management of the livestock unit. If contaminated wastes enter water sources they can spread the disease to other livestock, wildlife and humans[2]. In summary, high-intensity animal production operations can increase the incidence of livestock diseases, and the emergence of new, often antibiotic-resistant diseases. It also contributes to pollution of groundwater and surface water pollution associated with animal wastes (Tilman *et al*., 2002).

Finally, intensive livestock production is likely to induce livestock rearing techniques that are unfriendly to animals, which reduces animal welfare, an issue that draws increasing attention in European society (de Haan *et al*., 2001).

Proposed solutions

What can be done about those problems? There are many suggestions, but all of them are questionable. Firstly, manure can, in principle, be processed into powder or granules and these are then fit for reuse. Unfortunately, these products cannot compete with artificial fertilisers in terms of price. Secondly, dumping of manure at sea has been suggested, but this is among the least environmentally friendly options. Thirdly, it has been suggested to export manure to developing countries to prevent nutrient depletion in soil. This would, however, be an extremely inefficient and expensive solution. Fourthly, some authors argued that from an environmental point of view it would be better to raise pigs in Thailand and transport meat to Europe. Agriculture in the Netherlands is, however, often the driving economic activity of a region and an important source of direct and indirect employment. If we would simply reduce the number of pigs in the Netherlands by 5 million, it would mean a loss of about 28,000 jobs (Bolsius & Frouws, 1996).

Environmentally speaking, more pig production could be located in areas with arable products where transport costs of feed stuffs would be relatively low, and few problems

[2] The recent spread of Bovine Spongiform Encephalopathy (BSE), commonly called “mad cow disease” which is thought to cause a new variant of Creutzfeldt-Jakob disease among humans, is an example of an inter-species disease transmission, though it is related to cows, not directly to pigs.

would arise regarding air, water and soil pollution. This would be a reversal of the present trend, which needs *political measures* in the form of subsidies and restrictions (Aumaitre *et al*., 1982). However, this incurs costs. The question of who benefits and who bears the costs of the problem (or its proposed solution) is often related to conflicts of interest between different interests for different people and organisations. Thus decision-makers need to make trade-offs between environmental policies aimed at solving the environmental problems associated with pig production and economic ambitions to improve income.

Concerning environmental problems and outbreaks of contagious diseases of intensive livestock production systems, the Dutch government policy in recent years has clearly been directed at reducing livestock numbers and has gradually tightened manure laws since the 1980's (Department of Agriculture, 2001). This is reflected in official manure directives and various government schemes to buy up livestock (CBS, 2003). Two types of policies can be observed:

1) Policy of restrictions on emissions, e.g. manure policy that is restricting emissions from manure.
2) Policy of changing the structure of the livestock production system.

The first policy includes manure and ammonia policies which intend to reach specific target for the deposition of acidifying compounds (SO_x, NO_y and NH_x) and nitrogen compounds (NO_y and NH_x) (Lekkerkerk, 1998). In addition to manure application techniques with low emissions, it also includes options to seal the storage facilities (Lekkerkerk, 1998) and isolate the livestock production.

The second policy aims to reduce the number of animals by restructuring the livestock production system. This can already be observed in Dutch society. From Table 1-2 we can observe a peak of the number of pigs in 1997. After 1997, however, the number shows a decreasing trend. The Dutch government has become more in favour of the second policy type for two reasons. One is that intensive livestock production cannot contain the outbreaks of animal diseases. The other is that the comparative advantage of meat production through tax benefits is decreasing since all other tariffs are also being abolished in reformed CAP. Introducing alternative protein foods to realise such a policy change becomes an option. For this purpose, a series of research programs have been launched to facilitate solutions to the problems associated with animal production system, one of them being the PROFETAS research programme.

1.3 The PROFETAS Program

The PROFETAS research program was launched in 1999 based on a previous research program on Sustainable Technology Development (DTO), where Novel Protein Foods (NPFs) were selected as an alternative option for meat ingredients in protein-containing diet.

NPFs are plant-protein-based food products, which are developed with modern technology, including biotechnology, and designed to possess desirable flavour and texture. Technically, NPFs can be made of peas, soybeans, other protein crops and even grass (Linnemann and Dijkstra, 2000).

The PROFETAS program was developed by a team commissioned to study options for making food production more sustainable. The central research question is to assess whether a partial transition from animal protein foods to plant protein foods is environmentally more sustainable, technologically feasible and socially desirable. More than a dozen researchers work for PROFETAS and provide multidisciplinary results for this central research question. Food technologists work for good texture and flavour of NPFs, while researchers who work on consumer behaviour translate consumer preferences into chemical or physical properties for food technologists. Environmental and ecological scientists try to find the environmental effects of pork and NPFs using environmental or ecological indicators. As well, political scientists work for defining the stakeholder network of protein issues, and economists look at the possible impacts of NPFs on the EU agricultural sector in a global context.

The PROFETAS program is devoted to the analysis of the practical implementation of an enhanced consumption of NPFs, which may have important implications for livestock production. The ultimate goal of PROFETAS is to provide a profound analysis, which will help to facilitate solving future problems related to food production and consumption. Therefore one of the initiatives of PROFETAS is to investigate the economic, social and environmental consequences of a partial transition from meat to NPFs.

1.4 PROBLEM DEFINITION

Protein chains and the environment

Systems of food production and consumption are supported by the natural resource base (i.e. water, air, or soil), which is used as both a source of inputs and for the disposal or recycling of wastes. The food consumption and production systems include the whole ‘chain’ of human-organised activities including agriculture, food processing, retailing and consumption by households where much of the activity of shopping, cooking and waste disposal is organised. Any economic system in pursuit of sustainability needs to consider this system as a whole with its interconnecting regional, national, and international dimensions. According to present estimates (Aiking, 2000), close to half the human impact on the environment is directly or indirectly related to food production and consumption. These estimates are based on analyses of the whole chain from primary production via processing to consumption, including multiple steps of storage, cooling, transport and waste generation.

Protein food production and consumption result in environmental impacts at all phases of the chain. For the focus and efficiency two reference production and consumption chains are highlighted in the PROFETAS Programme. For the animal protein chain pork is selected as the common reference meat chain since it makes a major contribution to the production of animal-based protein products. Also pig production is characterised by the absence of secondary products like milk or eggs. In addition, pigs are among the most efficient animals in converting feedstuffs and agricultural by-products into edible meat. For the plant protein chain, the PROFETAS program focuses on NPFs from green peas. Green peas were chosen as the main ingredient of NPFs because of their protein content, the ability to grow them in Europe and the availability of expertise on pea production.

The protein food chain is complicated, involving a variety of economic activities and environmental pollution. Each protein chain is composed primarily of two important parts: agriculture and industry. The first part of the chain is mainly crop or pig farming and the second concerns meat processing or NPF fabrication. The most relevant environmental impacts of the first part of the chain (covers primary production), include habitat loss and degradation through emissions of nutrients (e.g. N, P), herbicides, pesticides, and other pollutants such as NH_3, CH_4 and N_2O. The second part of the chain (secondary production and consumption) includes energy-use, waste and emissions of air pollutants (e.g. SO_2 and NO_x) and greenhouse gases (e.g. CO_2, CH_4 and N_2O).

Concerning the first part of the chain, there is a close, complex and dynamic relationship between agriculture and the environment. The extent of the environmental impacts depends on agricultural structures, and the amount of land and other resources used at the local, regional, national and international levels. Agriculture generates a wide range of effects on the environment. Examples of major environmental impacts associated with agriculture includes:

1) Soil quality (erodibility, nutrient supply, moisture balance, and salinity) and land conservation;
2) Water quality (nutrient pollution, water use efficiency, and irrigation) and flood prevention;
3) Air quality (ammonia emission, greenhouse gas emissions, and carbon sinks);
4) Biodiversity (animal and plant species, wildlife);
5) Wildlife habitats and landscape (OECD, 1998).

For the second part of the chain, regional air pollutants (e.g. SO_2 and NO_x) lead to acidification and eutrophication, while the greenhouse gases (e.g. CO_2, CH_4 and N_2O) lead to global warming.

The main cause of these environmental impacts of the protein chains is the related economic activities. One common problem of the environmental impacts is that they exhibits obvious 'external effects', which impacts other parts of society. Considering the complexity of the protein chains, a systematic analysis (including environmental assessment and economic analysis) is needed to diminish the environmental impacts. In past studies in the area of food and environmental impacts much attention has been paid to the environmental impacts in parts of the protein chain. For example, there are studies on the impacts of plant production on the environment through the use of pesticides (Oskam *et al.*, 1997), minerals (Dijk *et al.*, 1996), erosion (De Graaf, 1996), loss of landscape amenity values through monoculture, and loss of biodiversity (Heywood *et al.*, 1995). Some researchers have addressed the problem of ammonia emissions and resulting acidification from animal husbandry (e.g. Wijnands *et al.*, 1997; Brink, 2003), while others focused on the reduction of nitrogen use and leaching to groundwater and surface water (e.g. Fontein *et al.*, 1994; Dijk *et al.*, 1996; Oude Lansink *et al.*, 1997 and Groeneveld *et al.*, 1998). There is also extensive literature on the relationship between food consumption and environmental pressures (e.g. Carlsson-Kanyama, 1998; Mattsson, 1999 and Kramer, 2000). Despite these studies, a systematic analysis including environmental assessment and economic analysis of protein chains is still lacking. This analysis requires knowledge about the linkage between economic activities and the environmental system because these interactions are important for identifying sustainable solutions.

Interaction between the economic system and the environmental system

Systems are groups of interacting, interdependent parts linked together by exchanges of energy, matter and information (Costanza *et al.*, 1997). The economic system is an anthropogenic system, where production and consumption take place. The environmental system (or ecological system) is a natural system, where many biophysical processes, as well as economic activities, take place. The economic system and the environmental system influence each other in many ways. To produce and consume goods and services, we use the natural environment by taking natural resources from the environmental system, and convert them into goods and services by means of labour and capital. We also release emissions to the environment from production and consumption processes. The inputs of the natural environment to the economic system (production and consumption) and emissions from the economic system to the environmental system will change the stock of the resources, which in turn gives feedback to the economic system. In other words, the natural environment is both a source and a sink for the economic system, and there are feedback effects in both directions. Figure 1-2 shows some important interactions between the two systems, where the *processes* are indicated as *circles*, the *stocks* as *squares* and the *flows* as *arrows*. *Dashed lines* indicate the system *boundaries*. Figure 1-2 also depicts the spatial competition between the economic and ecological system. The more space needed for the economic system, the smaller the available area will be for the ecological system. The time dimension for both systems, which is not directly represented in the figure, is incorporated in the processes and the resulting flows and stocks.

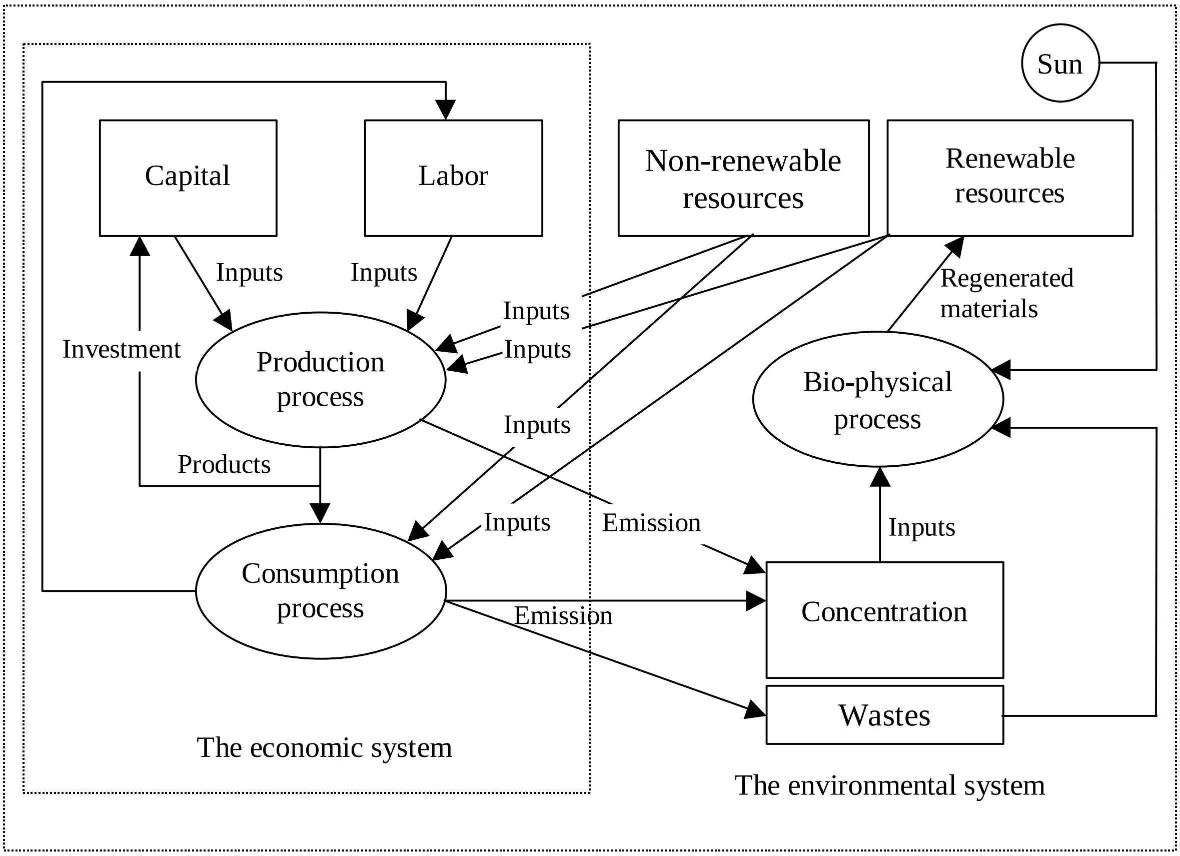


Figure 1-2 Interaction between the economic system and the environmental system

Source: Based on van Ierland (1993).

Considering these interactions, we must also address the economic aspects of food production in addition to environmental assessment. This requires a more elaborate economic framework because neo-classical economics often accounts for the natural environment exogenously or even omits it. The broadening of scope of the economic enquiry by including the interactions with the environmental system produces a better understanding of the mutual interaction between the economy and the environment.

The environment itself is permanently subject to a series of biophysical processes, even without human activities. An emphasis on the environmental (ecological) dimension and the *interaction* between the socio-economic system and the natural environment is an important perspective for environmental and ecological economists. A more detailed discussion on how to deal with these interactions in economic modelling follows in Chapter 2.

Incorporating biophysical principles into economic analyses was pioneered by Georgescu-Roegen (1971), who contributed to setting up a conceptual framework for *ecological economics* (Cleveland and Ruth, 1997)[3]. In the literature, the environment is dealt with in

[3] We do not distinguish between environmental economics and ecological economics in this thesis because both address the interface between economics and the life support system.

simplified ways because of the complexity of the environmental processes and for the specific focus of the analysis. There are different types of models that deal with different types of environmental processes. These models are simplified representations of the relationships between the economy and the environment, as indicated in Figure 1-2. Although many classifications are possible, we focus on four important types:

1) Resource use models (renewable and non-renewable) (e.g. Clark, 1976; Krautkraemer, 1985; Keyzer, 2000);
2) Models for economic growth and environmental quality (e.g. Smulders, 2000);
3) Climate change models (e.g. Nordhaus, 1993; Manne *et al.*, 1995; Nordhaus and Yang, 1996);
4) Other biophysical process models e.g. soil acidification (e.g. Schmieman, 2001) and water pollution (e.g. van Nes *et al.*, 1999).

These models play a very important role in dealing with specific questions on the economic and environmental aspects of human activities (see Appendix D of the thesis for the detailed description). It should be emphasised that some general assumptions in economic models (e.g. convexity of a constraint set, free disposal and continuity) may no longer hold when the environmental processes are incorporated, as environmental processes follow biophysical laws and mechanisms. These may be highly complex, containing non-linearities, irreversibilities, discontinuities or hysteresis (Stern *et al.*, 1992; Scheffer *et al.*, 2001; Mäler and Vincent, 2003). This problem needs careful theoretical attention as the consistency of results from economic models relies on assumptions of the mathematical properties of the functions used. Therefore, we should consider the interactions between the two systems and deal with the problem of modelling properly.

Economic modelling of environmental problems

Intensive livestock systems cause many environmental problems due to manure surplus. These environmental problems eventually lead to damages to the production and consumption system. Solving these problems needs proper study on the causes and effects, and once these have been established the best policy interventions can be designed.

The problem of defining an efficient policy is to derive an efficient industry structure by considering the environmental damages. Economic models are tools dealing with the issue of efficient allocation of resources. For this, it is necessary to represent the environmental problems in an appropriate manner. Therefore, a central question is how to represent the environmental problems in economic models, or more specifically: how to represent, in the model, the relevant interactions between the economic system and the environmental system, including the relevant biophysical processes, the damage functions and the impacts of environmental changes on welfare.

From a technical modelling perspective it is important to know if the inclusion of the process models and the damage functions causes mathematical complications (e.g. non-convexities, and multiple local optima) in solving the model. How environmental processes and the interactions between the economic system and the environmental system should be modelled is not yet fully elaborated in the literature. Particularly, how to find the optimal solution to problems with non-convexities and the policy implications of the optimum (e.g. decentralisability) are still not thoroughly addressed. Therefore we will also deal with the implications of the non-convexities in environmental-economic models.

1.5 OBJECTIVES OF THE THESIS

Environmental problems of protein production and consumption receive increasing attention in research and policy making due to their impacts and complexity. This thesis focuses on the analysis of the environmental and economic aspects of protein production and consumption chains. It analyses, in particular, the external effects at the various stages of protein production and consumption in Western Europe in a global context. The thesis aims to contribute both theoretically and empirically to analysing environmental problems of protein chains by modelling the environmental aspects consistently in economic models.

In order to do so, we first have to solve the theoretical problem of how to present the environmental issues properly in economic models. Therefore the first aim of the thesis is to make a theoretical contribution on how to describe the relevant environmental problems and represent them properly in an economic model. This theoretical contribution aims to represent the economic functions of the environment, environmental processes and environmental management (policies). This implies that the thesis elaborates on how to include the environmental processes in economic models, by analysing several existing models and discerning the mathematical problems that may arise. Next, we want to clarify what problems concerning the model results are associated with the violation of some standard assumptions (e.g. convexity). Finally, we will discuss how to deal with non-convexities of environmental process models, as non-convexities might cause multiple local optima. This theoretical study contributes to clarifying some fundamental problems in economic models that include environmental processes.

Concerning the empirical contribution, our task is to perform the comparative studies on environmental pressures of two different protein foods and to check the possible economic impacts of the enhanced consumption of NPFs. Specifically, we will provide information on the environmental pressures of the two alternative protein chains, namely the pork chain and the NPFs chain. Finally, we will assess the economic impacts of NPFs considering the possible trends of change of consumer attitudes towards protein foods and environmental quality, and the life style change in meat consumption. A scenario in which environmental policy instruments are used to reduce a similar quantity of emissions as a life style change will also be studied.

1.6 RESEARCH QUESTIONS AND APPROACHES

Research questions

Based on the aim of the thesis, the study focuses particularly on answering the following theoretical research questions:

(1) How can we theoretically model environmental issues in welfare optimisation and equilibrium models in order to identify solutions to the environmental problems? More specifically, how can we model the interactions between the economic system and the environmental system in a welfare program, which can represent policy objectives?
(2) Which complications do we face if we introduce a biophysical model into a mathematical program for a specific analysis, and how to deal with non-convexity?

The special empirical research questions are:

(3) What are the main environmental pressures of pork production and consumption compared with NPFs?
(4) What will be the expected effects of a shift from animal protein to plant protein foods (i.e. NPFs) on the economy and the environment?
(5) Which scenarios are relevant for and lead to a more sustainable food production and consumption?

The *first* research question concerns the incorporation of environmental problems into economic models, in particular the interactions between the economic system and the environmental system. In dealing with this question, we will consider the economic functions of the environment, such as providing inputs to the production process and amenity services to consumers, the environmental process and the feedback to the economic system.

The *second* research question tackles the theoretical consideration of economic modelling. The optimisation principle calls for some restrictive assumptions which are not consistent with characteristics of environmental problems. We want to deal with how standard economic assumptions, such as convexity, are violated, what problems this violation brings, and how to amend them.

The *third* research question will provide straightforward insights into the environmental pressures of different protein chains. The comparative quantitative study on environmental pressures of the two chains indicates the potential for the introduction of NPFs.

The *fourth* research question is on the economic impacts of a shift from animal protein foods to plant protein foods. The economic impacts of such a shift depend on many factors such as consumer preference, producer technology and market conditions in market economy. Therefore a proper economic model should be able to contain such aspects. The thesis will develop several versions of the model at different levels of details for studying the impacts.

The empirical application of this model will provide some information on the expected economic and environmental effects of the NPFs.

The *fifth* research question regards studying some scenarios on reducing environmental pressures in the future. There are alternative options for reducing environmental pressures, including introducing NPFs to replace meat consumption or implementing environmental policies to achieve lower emissions. We can expect that they have different impacts on the economy and the environment because of their different mechanisms. The comparison of the results for different scenarios will provide some insights into what leads to more sustainable food production and consumption.

The theoretical research questions aim to make some theoretical contributions to economic modelling for environmental problems in a proper manner. The empirical research questions aim at providing direct results for the PROFETAS research programme.

Approaches

For *the first research question,* a more elaborate economic framework is needed to consider the interaction between the economic system and the environmental system, explicitly focusing on their respective characteristics. More specifically, we want to represent, in a mathematical model, the most important aspects of the two systems and their interactions as shown in Figure 1-2.

Taking this into consideration, we need a framework, which can capture the environmental issues including the economic functions of the environment, economic damages and environmental management. We would like to represent the environmental problems in a *mathematical program* because the economic system and the environmental system are both formulated in terms of optimisation. Particularly, we have chosen the *welfare program* as specified in Ginsburgh and Keyzer (2002), because it provides a consistent tool for identifying efficient solutions.

The welfare program is based on the structure of applied general equilibrium (AGE) models. AGE models are considered economy-wide models in the sense that they cover all major economic transactions and every agent maximises his own objective. The reason for choosing the AGE framework is that AGE models have become a standard tool for the analysis of environmental issues and for the determination of optimal policies to reduce environmental pressures (Copeland and Taylor, 2003). Intuitively, the environment-economy interaction can be implemented in the AGE framework in four aspects. *Firstly,* the environment has amenity value for consumers so the environment should enter the utility function. This means that a consumer, as an agent of the economic system, has to finance the consumption of the non-rival environmental good. *Secondly,* the environment serves as input for economic activities. The production function should include environmental inputs in addition to the primary inputs (i.e. capital and labour services). Environmental emissions from the production process are in fact considered environmental inputs because the emissions reduce the availability of environmental goods like clean air or fresh water. When you view the environment in such a way, the systems perspective of the natural environment is more easily included in an economic model. *Thirdly*, the state of the environment is changing over time because a series of biophysical processes take place in the environmental system. The environment is a stock, which changes with net inflows. *Fourthly*, the economic activities influence the natural environment, which gives a feedback on consumer consumption and a producer's production plan. These steps are the principles for including the environmental issues in AGE models.

The detailed approach used for dealing with environmental issues in a welfare program is as follows. Firstly, we will describe the economic functions of the environment, the types of environmental problems and the environmental management. Then, we review some existing models containing environmental problems and discuss their limitations. Then our own ideas will be presented on how to represent environmental issues in economic models. Specifically we will demonstrate how to model the link between the economic system and the environmental system in a welfare program. We will show that an economic system needs environmental inputs such as water, air or soil fertility for crop production. Emissions from the economic system which change environmental conditions (i.e. soil fertility or concentrations of pollutants in water) are actually the use of clean environmental resources. There is a feedback of this change on the economic system (i.e. damages on crop production due to soil acidification). The specification of these interactions in a welfare program will enable us to analyse efficient allocation of resources, when the environmental damages are considered. These aspects are discussed in Chapters 2 and 3.

For *the second research question*, we will discuss the problem of non-convexity, since inclusion of an environmental process model, or the damages of environmental process on the economic system, often brings non-convexity. We will show if non-convexity arises when environmental damage is considered in a mathematical program and how to solve non-convex programs.

In micro-economic theory, physical processes are represented within the production activities of firms and are, in principle, supposed to satisfy the basic conditions of *divisibility* and *possibility of inaction* that guarantee *convexity* of the technology set. Divisibility implies that if a production plan is possible, then any production plan consisting of a reduction in its scale will also be feasible (Villar, 2000), which means that production can take place at any scale. *Possibility of inaction* gives each producer the freedom not to produce (Ginsburgh and Keyzer, 2002[4]). The convexity assumption has many implications, including existence and efficiency of equilibria, and the existence of a global maximum (Villar, 2000). Representation of production technology, considering the environmental input, is more problematic because of the characteristics of *non-convexity*, which is often caused by

[4] This reference will be intensively referred to in this thesis, thus hereafter referred to as GK, 2002.

indivisibility. Indivisibility is present in environmental problems due to a *lack of free disposal* and *no possibility of inaction* for environmental problems. The non-convexity[5] departs from the basic assumption of microeconomic theory (Keyzer, 2000) or leads to market failures as the lack of efficiency of market allocations (Villar, 2000). This problem is not well recognised in many environmental-economic models, though some problems of non-convex ecosystems are explored very recently in Dasgupta and Mäler (2004).

Therefore, there is a need to check the problems of existing models dealing with environmental problems in the environmental economic literature and to study the topic of non-convexity more extensively. We will discuss the non-convex problems in more detail in Chapter 2. For this purpose we will take a representative example from environmental-economic models that consider the environmental process. In order to show how non-convexities exist in the environmental modules of the model, we will analyse the DICE model (Nordhaus, 1993) because it is well-known, has a simple model structure and it incorporates an environmental process model (i.e. a climate change model). We will show why it is a non-convex problem and what implications the model results have in terms of analytical characteristics and its numerical solution. Next, we will elaborate on how to describe the environmental problems and how to include them in economic models, considering the interaction between the economic system and the environmental system. In Chapter 3, we give some numerical illustrations of modelling the environmental problems with pork production. By considering the non-convexities of the problems, we will show how to solve non-convex programs by parameterisation. In addition, we will also show how to check the decentralisability of the welfare optimum and the necessity for policy intervention.

For *the third research question*, we use an environmental life-cycle assessment (LCA) to compare the environmental impacts of two different protein chains, as LCA is a system analysis method for assessing environmental impacts of a material, product, or services throughout the entire life cycle. To do so, we need detailed information about protein chains. The analysis identifies the main environmental burdens in terms of global warming, acidification, eutrophication, water use, land use, and pesticide use. This analysis is specified in Chapter 4.

For *the fourth research question*, an empirical AGE model is applied. Concerning pork production, the problems are related to the increased demand for meat in developing countries and feed trade. As long as pork is highly demanded throughout the world and feed is imported from outside of the EU, the pork issue in the EU is an international one. The international dimension of the Dutch pork sector means that substantial changes have a direct impact on agricultural producers and traders elsewhere in the world. In the context of PROFETAS, we need a world-model to analyse this problem.

[5] See Chapter 2 for more discussion.

An AGE model can be chosen for this world-wide issue for the following reasons. Firstly, numerical, empirically based general equilibrium models can be used to evaluate concrete policy options by specifying production and demand parameters and incorporating data reflective of real economies. AGE models are tools for analysing policy issues or shock events. It provides an ideal framework for appraising the effects of policy changes on resource allocation and for assessing who gains and loses, policy impacts that are not well covered by empirical macro models (Shoven and Whalley, 1992). *Secondly,* the AGE models have been applied to a range of policy questions in a number of economic fields over the last twenty years. These include public finance and taxation issues, international trade policy questions, evaluations of alternative development strategies, and the implications of energy policies, regional questions and even issues in macroeconomic policy. It can thus provide a clear picture of how the economy will adjust after the reform takes place. In this sense no other models have such good properties. *Thirdly,* like all the other models, an AGE model is a simplification of the economic reality. It provides, however, an excellent approach because its framework is ideal for policy analysis and it makes it possible to integrate the natural environment into the economic analysis through the production functions and the utility functions. Therefore, the AGE framework is adopted and extended in the thesis.

AGE models can be written in different formats, such as the Computable General Equilibrium (CGE) format, the Negishi format, the full format and the open economy format. For the detailed representations of each format please refer to GK (2002). Different GE formats have their own strengths and weaknesses. In literature, most AGE models are written in the CGE format. In this thesis, however, we have chosen the Negishi format (Chapter 5 and 6) and the full format (Chapter 7) for model presentation because we deal with the *efficiency* of the introduction of NPFs and the *non-convexities* of the environmental problems. The reason for choosing these two formats is that they represent a welfare program, which can address efficiency directly, and are suitable for including environmental problems. When environmental aspects enter the model, the Negishi format provides an ideal framework for checking theoretical properties of the model (e.g. convexity). Another advantage of the Negishi format is that it is suitable for dealing with multi-consumers. In our study, this is important because we need a world model where more than one consumer, or region, is involved. The main difference between the CGE format and the Negishi format or full format is that the CGE format uses the dual approach and the Negishi format, or full format, takes the primal approach for representing producer and consumer behaviour. A dual approach means that one can use a profit function that is an explicit function of prices, and then obtain the net supply functions and input demand functions by Hotelling's lemma. The primal approach means that one can choose to maximise profits subject to a production set, or to a transformation function representing this set, (i.e. production functions are specified) in the model. The Negishi format and the full format are written as a welfare program, in which prices and welfare weights are exogenously calculated in the feedback program. Thus, prices and welfare weights are parameters for the central program. These parameters give agent-specific signals, which means that decentralisation is possible and efficiency can be achieved.

Since the Negishi format is formulated as a centralised welfare program, it is easier to deal with non-convexity in a mathematical program than in the decentralised CGE format.

For application of an AGE model to the empirical research questions we have to classify commodities and consumers and specify the production technology and consumer preferences. For the calibration of the model, data on current production and consumption are to be collected. The inputs and outputs for each production good, the consumer consumption structure and their willingness to pay for environmental amenities are relevant for the specification of the production function and utility function.

Theoretically, the interactions between the economic system and the environmental system call for the inclusion of environmental process models, however, in practice a simplification of the specification of the environmental processes is necessary due to lack of knowledge. We will illustrate in Chapters 5, 6, and 7 how to include the environmental aspects in an AGE model at different levels of simplification. In Chapter 5, we have an environmental quality indicator determined by total carbon dioxides (CO_2) emissions in the economic model. In Chapter 6 we have an environmental quality indicators determined by ammonia (NH_3) emissions. In Chapter 7, we take the emissions of nitrous oxide (N_2O), methane (CH_4) and ammonia (NH_3) as the relevant environmental aspects for assessment of the environmental effects of the protein chains.

For *the fifth research question*, we need to construct scenarios to illustrate the impacts of NPFs. If we want to have a closer look at the future, there are various approaches that can be taken: forecasting or scenario studies (Harmsen *et al.*, 2002). Regarding the question of the impacts of a shift from animal protein to plant protein consumption, we take the *scenario construction* approach, because so many uncertain factors play a role that forecasting is not feasible. Forecasting is tightly linked to predicting the development in previously identified quantifiable factors, in which a trend can be detected. Scenario construction involves identifying the factors that are expected to affect the issue concerned, separating certain from uncertain ones, and drawing the various scenarios by looking closely at variations in the uncertain factors logically (cf. Harmsen *et al.*, 2002). Scenario construction is therefore not the same as forecasting. The contribution of the scenarios is to shed light on possible future developments and thereby hopefully challenge conventional wisdom and stimulate visionary thinking both on economic and ecological developments.

To provide useful information to the policy makers, scenario construction and model simulation are needed for answering research question five. The scenarios should have the following criteria: *plausible*, i.e. the scenarios should be possible and credible*; internal consistent*, i.e. events in the scenario can not mutually exclusive; *challenging*, i.e. the scenarios should challenge people's mindset and stretch their perception of the future; *relevant*, i.e. scenarios should connect with the mental maps and concerns of the users and be relevant to the issue concerned; and *archetypal*, i.e. the scenarios should describe generically different futures rather than variations on a theme and highlight competing perspectives. In Chapters 5 and 6 we mainly simulate scenarios for different levels of willingness to pay for environmental quality. In Chapter 7, we compare the scenarios of lifestyle change and environmental policy for reducing emissions.

1.7 OUTLINE OF THE THESIS

In light of the research questions, the study is organised into eight chapters. Beginning with the general introduction of this chapter, the thesis then follows a research line from theory, followed by application and finally to conclusions. But we should emphasise that each chapter can be read independently of others as well.

Chapter 1 of the thesis is the introductory part that gives the general background to the problem definition, research questions and approaches.

Chapter 2 discusses how the environmental impacts can be integrated in economic models and how to solve these models. This includes an elaboration on the interaction between the economic system and the environmental system, the nature of the environmental problems and implications for environmental policies. It follows the discussion on the special features of the environmental problems including non-rivalry, non-excludability and non-convexity. Thereafter the representation of the environmental problems in welfare programs is formulated and methods to solve non-convex programs are briefly discussed. As an illustration, we also check the non-convexity of DICE model and its non-optimality of a numerical solution. For the graphical approach to solving a non-convex program, we show how to find the optimal solution in a simple aquatic model.

Chapter 3 illustrates the methodology of how to present environmental problems in economic models, particularly, how to model the environmental problems related to pork production. This includes a detailed discussion about the environmental problems caused by pork production, how to represent them in economic models (AGE model and welfare programs) considering the interaction between pork production and crop production, and a mathematical non-convexity check of the models. Following the discussion on the approach presented in Chapter 2, we illustrate the methodology of how to solve non-convex programs in numerical examples.

Before we apply the economic model in different settings, we first carry out the environmental assessment of two protein chains in Chapter 4. We describe the environmental impacts of protein production and consumption chains using a life cycle assessment. In order to assess the environmental impacts of pork and NPFs some environmental indicators are used for comparison. This chapter provides some background information of protein chains in terms of their environmental pressure indicators to justify NPFs as an option for reducing environmental pressures.

The choice of how to develop a model should depend on what problems are being analysed and for what specific purposes. For the PROFETAS project, we focus on an analysis that allows for a shift of consumer preferences, and on the allocation of capital, labour and land in different regions, as well as on the potential impacts of NPFs on emissions. For simplicity, we restrict ourselves, in the applied part, to comparative static analysis, although the dynamics are important for long-term environmental problems.

For the economic modelling we took a step-wise approach, considering different levels of simplification for environmental problems. Firstly, we prepare the ground for including the amenity value of environmental quality in a utility function and the international trade modelling in Chapter 5. We show the methodology of how to study the impacts of NPFs. We develop a model that is capable of dealing with international trade and environmental quality related to emissions (CO_2). As a simplification, the relationship between emissions and environmental quality is linear such that there is no problem of non-convexity. In the model, the environmental quality is part of the consumption bundles because of its amenity value. The utility function of the consumers depends not only on the consumption of rival goods but also on the non-rival environmental quality. Thus consumers have to finance the consumption of the environmental good expressed by environmental quality. On the other hand, the producers must also pay for the environmental input (e.g. emission permits) for the production process. With this mechanism, the environment gives a feedback on consumption and production.

Chapter 6 is the further empirical application of the AGE model, including the environmental concerns of consumers and considering the uncertainty about the values of the substitution elasticity between pork and NPFs, as well as utility elasticity with respect to the environment. In this chapter we focus on the theoretical representation of the model and give a more realistic representation of the economy. The environmental quality is now related to emissions of a more relevant pollutant (i.e. NH_3).

Chapter 7 is the application of a more dis-aggregated model with more detailed agricultural sectors, which combines an economic model with some important environmental emissions (i.e. CH_4, NH_3, N_2O). The model is a four-region, two-period model. In this chapter, environmental processes are not included and no utility impacts of emissions are considered due to lack of region-specific environmental process models. The model is applied to some scenarios concerning the lifestyle change of consumers and environmental policy instruments. This provides insights into how emissions of greenhouse gases and acidifying emissions are affected by a shift in consumer demand or by imposing restriction on emissions.

Finally, Chapter 8 gives the main conclusions of the study and highlights the main findings. The research questions raised in this chapter will be answered, and suggestions for further research and policy implications are discussed.

Chapter 2 Representing Environmental Issues in Welfare Optimisation and Equilibrium Models

2.1 Introduction

This chapter addresses the question 'how can we theoretically model environmental issues in welfare optimisation and equilibrium models in order to identify solutions to the environmental problems?' Although the environment is dealt with in several existing economic models in various ways, many questions remain on the consistency of the approaches used. The fundamental problems of many models in the literature are that the representation of biophysical processes is not fully included and/or the problem of the associated non-convexities is not discussed. Therefore, there is a need to discuss how environmental impacts can be integrated in economic models and how to solve these models properly.

The aim of this chapter is to provide a proper method to integrate environmental problems into economic models and to provide an economic tool for analysing environmental problems related to protein production and consumption for the following chapters. We follow the following story line for analysis in this chapter.

Firstly, we have to understand the interaction between the economic system and the environmental system for modelling environmental problems. The environment provides some functions to the economic system. Two feedbacks between the two systems are particularly relevant. The first feedback is that the use of the environmental resources in the economic system (i.e. extraction of the renewable and non-renewable resources, emissions of pollutants, dumping of wastes etc.) has impacts on the environmental system through an impact on ongoing biophysical processes in the environmental system. These impacts change the state of the environment. The second feedback is that the environmental changes provide feedback to the economic system, either by a reduction in the quantity or quality of the environmental goods and services provided to the economic system, or by a direct negative impact on the production or utility function. If the feedback of the environmental change to the economic system occurs in a negative way, then we have environmental problems. In this context, we need to consider the related environmental processes in order to identify the solutions to the environmental problems.

Secondly, we discuss special features of the environmental problems including non-rivalry, non-excludability and non-convexity. We identify their causes and implications.

Thirdly, we consider how those aspects can be integrated in economic models for efficient environmental management. For achieving efficient allocation of resources, including the environmental resources, we can represent the environmental problems in welfare programs. Specifically, we will discuss how to represent the economic functions of the environment, the environmental processes, and feedbacks between the economic system and the environmental system in welfare programs.

We will present two types of welfare programs which include the economic functions of the environment, environmental processes, and feedbacks. The first welfare program considers the amenity services of the environmental quality in utility functions. The second type of welfare program includes the impact of environmental quality on the production process. In both programs, the environmental quality is specified by a transformation function that represents an environmental process. Obtaining the optimal solution to the welfare programs depends on the properties (e.g. convexities of the constraint sets) of these functions. Therefore, we will briefly discuss how to check the convexity or non-convexity of the program and explain methods for solving the non-convex program. If non-convexity is not relevant, we can take the standard approach to solving the program. Otherwise we need special techniques such as a graphical approach or parametric approach, as will be detailed in Chapter 3.

Fourthly, checking the non-convexity of a model incorporated with environmental problems can be done by analysing the characteristics of the Hessian matrix. For illustrative purposes, we check the non-convexity of the DICE model (Nordhaus, 1993) and check if the current numerical solution to the DICE model is an optimum. Finally, we draw our main conclusions on how to treat the non-convexity in welfare optimisation and equilibrium models.

The chapter is organised as follows. Section 2.2 describes the relation between the economy and the environment, including the economic functions of the environment, the nature of the processes that damage the environment and the implications for environmental policies. Section 2.3 discusses the special features of environmental problems such as non-rivalry, non-excludability and non-convexity, their causes, and implications for the solutions. Section 2.4 explores how to represent the environmental problems in welfare programs by considering the environmental inputs to the economic system, the environmental processes of the environmental effects, and the feedback of the environmental effects on the economy. Section 2.5 illustrates how to check the convexity in the DICE model and optimality of its numerical solution. We also show how the optimal solution is found by graphical analysis in a simple aquatic model. Finally, in Section 2.6, we indicate how to simplify the environmental process models in their empirical applications in the remainder of the thesis.

2.2 ECONOMIC SYSTEM AND ENVIRONMENTAL SYSTEM

Interaction between two systems

As we discussed in Chapter 1, the economic system is part of the environmental system. The environment refers to the earth and its atmosphere and includes renewable and non-renewable resources. Air, water, solar energy, fish, forests and soil are examples of renewable environmental resources. Oil, coal and gas are considered non-renewable resources. The environmental resources and processes fulfil several functions and provide environmental goods and services to human beings.

Economic activities need environmental resources and the emissions and use of the resources influence the environmental system. The inputs of natural environment to the economic system (production and consumption) and emissions from economic system to the environmental system will change the stock of the environmental resources, which gives feedback to the economic system. In other words, the natural environment is both a source and a sink for the economic system, and feedback effects are in both directions. That is, the economic system and the environmental system interact.

Economic functions of the environment

The economic functions of the environment are the goods and services that the environment provides to the economic system. De Groot (1992) gives the following classifications of these functions.

1) *Regulating functions*: relates to the capacity of natural and semi-natural ecosystems to regulate essential ecological processes and life support system, which, in turn, contribute to the maintenance of a healthy environment by providing clean air, water and soil.
2) *Carrier functions*: natural and semi-natural systems provide space and a suitable medium for many human activities such as habitation, cultivation and recreation.
3) *Production functions*: nature provides many resources, ranging from food and raw materials for industrial use to energy resources and genetic material.
4) *Information functions*: natural ecosystems contribute to the maintenance of mental health by providing opportunities for reflection, spiritual enrichment, cognitive development and aesthetic experience.

Given different perspectives, the environmental functions can also be categorised into different classifications (see e.g. Turner, 1988, and Dixon and Sherman, 1990). For example, ecosystems provide a variety of benefits to people, including *regulating, provisioning*, *supporting* and *cultural* services (Jørgensen and Müller, 2000 and Millennium Ecosystem Assessment, 2003). They are consistent with the above classification in that *regulating* *services* are equivalent to *regulating functions*, *supporting services* to *carrier functions, provisioning services* to *the production function,* and *cultural functions* to *information functions.*

For the economic analysis of environmental problems, the following classifications based on Pearce and Turner (1990) and Ekins *et al*. (2003) are also useful because they consider the environmental contribution to economic activities. *First*, the environment provides *resources* for production, for instance, the raw materials that become food, fuels, metals or timber. *Second*, the environmental function is the absorption of wastes from production and consumption (e.g. *sink function*). *Third*, the environment provides the basic context and conditions within which production is possible and comprises basic *life-support functions*, such as climate and ecosystem stability and shielding of ultraviolet radiation by the ozone layer. *Fourth*, the environment contributes to human welfare through what may be called 'amenity services', such as the beauty of wilderness, and other natural areas (e.g. *amenity function*).

We can further summarise the functions of the environment for the purpose of economic modelling of environmental problems. The sink function of the environment can be considered the use of environmental goods and services for production and consumption. For example, the emissions from production go to the soil, and soil is polluted or soil fertility is reduced. Thus, we can view emissions to soil from production as the use of soil fertility for production. Similarly, compared with the four functions listed above, we can consider the regulation functions, carrier functions and production functions as the input function for production, and we may consider the information function as amenity services. Therefore the environmental functions can be summarised into two basic functions for economic purposes: input function and amenity function (service) in the economic system.

Nature of processes that damage the environment

Environmental problems are classified according to the environmental themes describing collections of closely interrelated environmental problems. According to EEA (1998), environmental problems are classified into the following items: climate change, stratospheric ozone depletion, acidification, tropospheric ozone, chemicals, wastes, biodiversity, inland waters, marine and coastal environment, soil degradation, urban environment, and technological and natural hazards. Moreover, the environmental problems are also classified according to the spatial effects: global, continental, regional, local or cross-sectional environmental issues (RIVM, 2001).

No matter how the environmental problems are classified, they are essentially the negative impacts or damages of the environmental process on the economic system. Use of the environmental resources in the economic system influences the environmental state due to the *ongoing biophysical processes* in the environmental system. The change of the environmental state gives feedback to the economic system, possibly in the form of damages that will play a role in the production function and utility function. The direct drivers of environmental problems are intrinsically physical, chemical and biological processes of the environmental system. The indirect drivers of environmental problems are demographic, economic, socio-political, scientific, technological, cultural and religious changes in human society.

Implications for environmental policies

Environmental impacts affect the quality of life of human beings. In order to reduce environmental problems, it is advocated that we manage the environment. The debate on environmental management on the global level was formally founded with the 1972 Conference on the Human Environment in Stockholm. In the past decades, environmental concern was recognised as an important part of the economic process, which is officially reflected in the principles of Agenda 21 from the remarkable 1992 UN Conference on Environment and Development (UNCED) in Rio de Janeiro, popularly known as the Earth Summit. Principle 1 of Agenda 21 states, "human beings are at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature." At the 2002 World Summit on Sustainable Development (WSSD) in Johannesburg, it was made clear again that sustainability, which captures the desire for persistent and equitable wellbeing in the long run, is a widely held social and political goal.

Solving environmental problems means that we want to use environmental resources efficiently. Economic modelling is a tool for the economic approach to environmental management. To achieve efficiency we should correctly represent the functions of the environment and environmental *processes* of the relevant environmental problems in economic models (e.g. welfare programs). This is because environmental problems are the result of biophysical processes, though the inputs to these processes are from human activities[1]. The properties of biophysical processes are part of the constraint set that bound economic activity (Turner, 1993). That is, feedback occurs. Thus for solving the environmental problems, we should consider the evolution of both economic and environmental systems. The co-evolutionary nature of ecology and economic systems is a key concept in ecological economics (Common and Perrings, 1992; Turner, 1993; Costanza *et al*., 1997 and Costanza *et al*., 2000).

The purpose of economic modelling is to understand the problems at stake, to determine the appropriate level of environmental resource use, and to provide good policy recommendations. Environmental problems are essentially based on the damages (i.e. environmental impacts) through certain environmental processes on production and consumption by decreasing the environmental functions as the input for production and the amenity services for consumption. Specifically, in order to solve environmental problems economically, we need to represent the environmental impacts by including them in economic models and by solving the integrated model correctly. Through proper economic

[1] We focus on economic activities such as production and consumption.

modelling it is possible to obtain insight into institutional changes, prices of environmental goods and other policies needed to protect the environment. Insights can be obtained from the results of well-designed models on implementing efficient environmental policies.

2.3 NON-RIVALRY, NON-EXCLUDABILITY AND NON-CONVEXITY: CAUSES AND IMPLICATIONS

Special features

Non-rivalry refers to a situation that a unit of a good can be consumed by one individual without detracting, in the slightest, from the consumption opportunities still available to others from that same unit. A good example of non-rivalry is a sunset, when views are unobstructed.

Non-excludability refers to the property that it is impossible to exclude people from consumption in a physical and/or legal sense (e.g. to build a fence). A good example is food safety regulations, because such regulations lead to high food quality, which no one can be excluded from. Air pollution is an example of both non-rivalry and non-excludability. One suffering from air pollution does not reduce the amount of suffering of anybody else. This is non-rivalry. Since one must breathe, they are not excluded from using the polluted air[2]. This is thus also non-excludability. A good that is both non-rival and non-excludable is a public good. Clean air is an example of a public good or, polluted air is a 'public bad'.

Some environmental problems have the characteristics of 'club goods.' Club goods are the goods that are non-rival but excludable. You can exclude people by charging a membership fee but for the members the consumption is non-rival because one person's consumption does not diminish that of others.

The non-rivalry and non-excludability of environmental problems, in the absence of environmental management, generates externalities (see Appendix B for the definition of externalities). If these two properties (non-rivalry and non-excludability) of the environmental problems do not generate non-convexities, the standard approach of internalising the externalities using Pigovian tax or Lindhal prices for non-rival goods can be used (Baumol and Oates, 1988; Helfand *et al.*, 2003). Then the environmental problems can be solved efficiently.

However, many environmental problems are also related to non-convexity, as will be illustrated in Chapter 3. Non-convexity requires special treatment because it causes market failures, that is, the competitive market condition can not achieve an efficient allocation. It

[2] Only if special helmets were used, would it technically be possible to exclude individuals from the free use of air; this, however, is not a realistic option.

may lead to multiple local maxima, and this might undermine efficient decentralisation. As well, we need special techniques to solve a non-convex problem in a mathematical sense. Therefore, it is worthwhile to elaborate about how non-convexities may arise.

Non-convexities and their implications

Non-convexities

Non-convexities related to environmental problems may develop from the characteristics of related environmental processes and the positive or negative environmental impacts on production and/or utility.

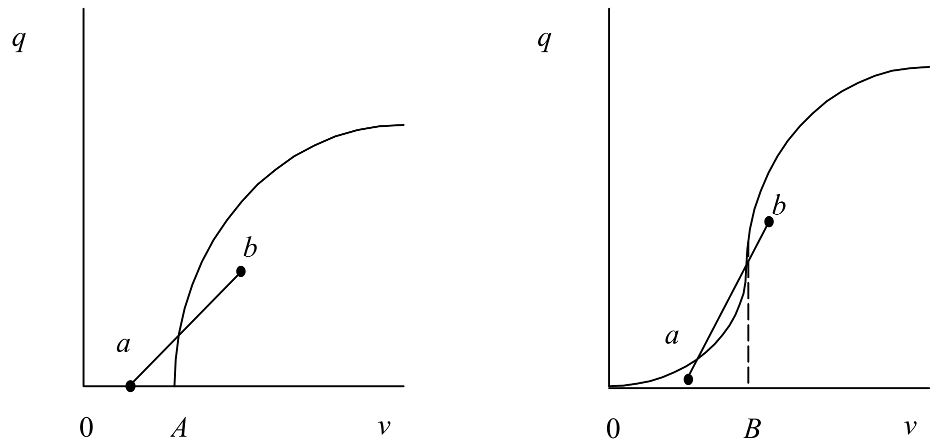
The production set of natural resources usually does not have the property of ‘convexity’ because a process generating natural resources follows biophysical laws, which usually do not fulfil convexity conditions (e.g. divisibility). An ecosystem tends to be indivisible because of the well-developed interdependence and positive feedbacks in human-nature interactions (Dasgupta and Mäler, 2004) and because of the interdependencies within ecosystems themselves. Production processes of many natural resources usually do not have the property of *constant returns to scale* because the natural resources are difficult to manage similarly to industrial production, and because the owners have few opportunities to influence (Crépin, 2002). Ecological systems, like shallow lakes, are usually non-linear and display discontinuities and hysteresis in their behaviour with multiple stable sates (Scheffer *et al.*, 2001), which yields non-convexity (Mäler, 2003).

Non-convexities may also be caused by the feedback of environmental changes to the economic system (i.e. the damages on production and consumption). This feedback may bring non-convexity of the production technology in the form of non-concave production functions. For example, the environmental impacts on production may lead to the non-convexity of the production sets because the combination, or multiplication of two functions does not necessarily generate a convex set.

Non-convexities may also exist in the economic system itself. In this system, non-convexity may occur at different levels. On the production side, there are two specific issues related to non-convexity at firm level: set-up costs and increasing-return to scale (GK, 2002). In Figure 2-1a, there are set-up costs requiring input $0A$ before production q can start, but the origin is part of the production set. This set is non-convex because a connected line (ab) between any point within $0A$ and any other point above v axis inside the set is not completely inside the set.

Increasing returns to scale means that production technologies are represented by single output production functions with increasing return to scale segments, but possibly also with constant- or decreasing return segments (Figure 2-1b). The production set is non-convex because line ab is not completely inside the set.

On the consumer side, the non-convexity may arise as a result of a non-concave utility function, or because the commodities are indivisible, or because consumers switch preferences (GK, 2002).



a: set up costs b: increasing return to scale

Figure 2-1 Non-convexity at firm level

Implications of a non-convex welfare program

When appropriate concavity-convexity assumptions are satisfied, the program is convex and everything works nicely in the competitive equilibrium case: 1) there will be a set of prices that determine optimal production and consumption levels. 2) at those prices, consumption and production plans are satisfied. 3) the value of total output at the optimal prices will be maximised. The maximisation of value of output coincides with maximisation of social welfare (i.e. Pareto optimality of the competitive equilibrium). When non-convexities are introduced, the above properties encounter complications that increase, at least in principle, the problem of formulating rules capable of leading the economy to an optimal solution (Baumol and Oates, 1988). With non-convexity, instead of a unique equilibrium society may have the difficult task of choosing among a set, and sometimes, a substantial set of discrete local maxima (Baumol and Oates, 1988; Crépin, 2002).

Non-convexity never causes non-existence of a welfare optimum and does not necessarily lead to non-existence of equilibrium. As long as the production possibilities of the economy are bounded and utility functions are continuous, non-convexities do not pose problems for the *existence* of a welfare optimum (GK, 2002). However, if more than one local maxima exists, a central planner has to choose the welfare optimum from a set of local maxima and implement policies that will lead to this optimum. This probably involves transfers among consumers, or forces the producers to produce at a certain level. Decentralisation of the optimal solution becomes difficult and the equilibrium may be inefficient. If equilibrium happens to exist, it may not be the welfare optimum, or social optimum.

Non-convexities can be introduced by representation of environmental impacts in economic models (e.g. by including an environmental process model). However, if we simply plug the non-convex environmental model in an economic model and solve it as if it were a convex problem, we may not obtain an optimal solution because of the possible existence of multiple local maxima. If we do not check the results, and simply interpret them and make policy recommendation in accordance, we may make serious mistakes, as it is not guaranteed that we have obtained the optimal solution. Therefore, we must deal with the environmental models in economic modelling very carefully, including testing the consistency of the results.

The problem of non-convexities is the impossibility of decentralisation of the optimal solution. For a non-convex program, the prices do not tell us whether we are at a welfare maximum or minimum, whether a maximum is local or global, or in which direction the economy should move to secure an increase in welfare. Even if the entire set of feasible output points is known, equilibrium prices in a non-convex mathematical program tell us nothing about Pareto optimality (see Figure 2-2). In Figure 2-2 there are four possible tangency points between production function and the profit lines with slope *c*/*p* (*c* is the price of input *v* and *p* is the price of output *q*). There are four possible equilibria with one set of prices. But only point *B* can be decentralised if the central planner chooses *B* (a social optimum) because *B* gives the highest profit to the firm. If the central planner wants to choose *D*, then a lower bound of output for firm (higher than *B*) should be imposed. This will create losses for the firm. If the planner wants to choose *A* or *C*, then the planner needs additional policy measures (e.g. transfers), because the firm has negative profits.

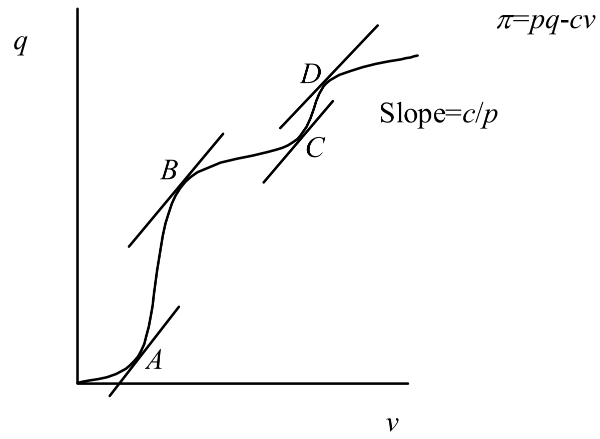


Figure 2-2 Price signal does not work when non-convexity occurs

In summary, non-convexity is an unwelcome property in economic models with many implications for the model results and related policy. Therefore, we must deal with non-convexities in economic models seriously, by checking the non-convexity, solving non-convex programs and finding the optimal solutions to the welfare programs.

2.4 REPRESENTATION IN WELFARE PROGRAMS: TOWARDS EFFICIENT ENVIRONMENTAL MANAGEMENT

A general competitive equilibrium and welfare program

Let us consider an economy with *r* commodities indexed by *k* =1, 2, … , *r*. The commodity space is an *r*-dimensional space, denoted by R^r. There are two types of agents who make decisions: producers (firms) and consumers. There are *n* producers, indexed by *j* =1, 2, …, *n*. Each producer *j* is endowed with a technology, represented by a set Y_j, which belongs to R^r. Let y_j be the production plan of producer *j*, and the outputs of production carry a positive sign and inputs a negative sign. The feasible production plan is expressed as: $y_j \in Y_j$. The producer chooses from the set of feasible production plans such that it maximises his profit, defined as py_j, where *p* is the price vector. The problem of the producers can be described as: $\Pi_j(p) = \max_{y_j}\{py_j \mid y_j \in Y_j\}$, where $\Pi_j(p)$ is the resulting maximal profit.

There are *m* consumers, indexed by *i* =1, 2, …, *m*. Every consumer is endowed with commodity endowments ω_i for sale and sets his or her consumption plan. The consumption of any commodity cannot be negative: $x \in R^r_+$. Each consumer is also faced with a budget constraint: $px_i \le h_i$, where h_i is the income of consumer *i*. The income consists of two parts: the proceeds $p\omega_i$ of selling the endowment ω_i and distributed profits, expressed as: $h_i = p\omega_i + \sum_j \theta_{ij}\Pi_j(p)$, where θ_{ij} is consumer *i*'s non-negative share in firm *j*. All profits are distributed so that $\sum_i \theta_{ij} = 1$ for producer *j*. Given price vector *p* and the income h_i, the consumer chooses his consumption plan x_i so as to maximise his utility $u_i(x_i)$. The problem of the consumers can be described as $\max_{x_i \ge 0}\{u_i(x_i) \mid px_i \le h_i\}$ (cf. GK, 2002).

A competitive equilibrium is a situation in which all agents are simultaneously realising their plans (i.e. producers maximising their profit and consumers maximising their utility), for a given vector of market prices. The formal definition is expressed below.

Definition of general competitive equilibrium: or;
The allocation y_j^*, all j, x_i^*, all *i*, supported by the price vector $p^* \ge 0$, $p^* \ne 0$ is a general competitive equilibrium if the following conditions are satisfied:

1) For every producer j, y_j^* solves $\max_{y_j}\{py_j \mid y_j \in Y_j\}$.
2) For every consumer *i*, x_i^* solves $\max_{x_i \ge 0}\{u_i(x_i) \mid px_i \le h_i\}$,
   where $h_i^* = p^*\omega_i + \sum_j \theta_{ij} p^* y_j^*$.
3) All markets are in equilibrium, $\sum_i x_i - \sum_j y_j - \sum_i \omega_i \le 0$.

There exists a general competitive equilibrium if the following assumptions hold:

1) Production sets: The production set Y_j of every producer j has possibility of inaction ($0 \in Y_j$). It is compact and convex. The convex production set can be seen from Figure 2-3, where *v* indicates input and *q* the output.
2) Utility function: The utility function $u_i : R_+^r \rightarrow R_+$, $u_i(x_i)$ is continuous, strictly concave, nonsatiated, and satisfies $u_i(0) = 0$ for all *i*; for *i* =1 it is increasing with respect to all commodities.
3) Endowments: $\omega_i \geq 0$, $\omega_i \neq 0$ for all *i*; for *i* =1, $\omega_i > 0$ [3].

The efficiency of a general competitive equilibrium is formally addressed in the theorem of efficiency of a competitive equilibrium: The competitive equilibrium allocation is Pareto-efficient (GK, 2002).

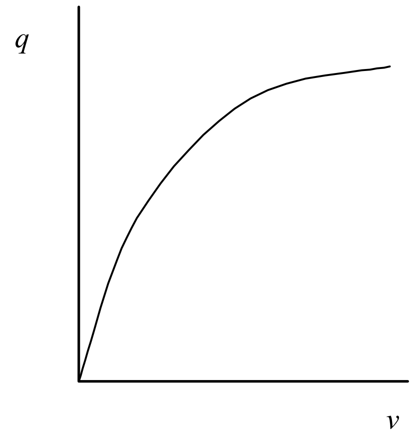


Figure 2-3 Convex production technology

Therefore in a competitive equilibrium, the equilibrium price vector *p** provides sufficient information for each agent to take optimal decisions with respect to production and consumption; the decisions of each agent can be decentralised. *Convexity* of a production set and a consumption set allows us to formulate conditions with regard to production technology and preferences that ensure the existence of a price system which sustains decentralised optimising production and consumption decisions. The fact that every competitive equilibrium is Pareto-efficient is also known as *the first welfare theorem*. An allocation that is an optimal solution to a welfare program is called a welfare optimum. A Pareto-efficient allocation is a welfare optimum with positive welfare weights (GK, 2002). Therefore, it follows that every competitive equilibrium can be represented as a welfare optimum, and a competitive equilibrium model can be represented by a welfare program.

A welfare program is a mathematical program that describes an allocation according to a specific welfare objective. A welfare program is defined as:

[3] Condition $\omega_i \geq 0$, $\omega_i \neq 0$ is different from $\omega_i > 0$ in that the former allows zero endowment for some *i*'s while the latter does not.

$$W(\alpha) = \max \sum_i \alpha_i u_i(x_i)$$
$$x_i \geq 0, \text{all } i, y_j, \text{all} j \quad , \qquad \text{(2-1)}$$

subject to

$$\sum_i x_i \leq \sum_j y_j + \sum_i \omega_i \ ,$$

$$y_j \in Y_j \ ,$$

for given $\alpha \in S^m = \{\alpha \big| \alpha_i \geq 0, \sum_i \alpha_i = 1\}$.

A welfare program can be thought of as a central plan that allocates goods over agents.

We need to present the economic functions of the environment, the environmental processes and the feedbacks in a welfare program. This can be done through: 1) input function of the environment in production function; 2) amenity services of the environment in utility function; 3) relevant environmental processes reflecting the feedbacks to the two systems (i.e. damages to the production and utility, and change of the environmental state).

Two welfare programs and methods of solving the programs

In this chapter we present two types of welfare programs that will be applied in the following chapters. Our first welfare program considers the input function of emission, or the use of environmental resources, and the amenity services of environmental quality. This environmental quality is a function of the total emissions, or the use of the resources. We will use this welfare program considering the impact of environmental quality on utility in Chapters 5 and 6. The second type of welfare program includes the impact of environmental quality on the production process. We will use this program in Chapter 3 for the case of interaction between pork production and crop production considering soil acidification. In both programs, the environmental quality is specified by transformation functions that represent an environmental process transforming the emissions into an environmental quality indicator.

i) Emissions, as production input, are a rival good for production but the environmental quality as a non-rival good has impacts on the utility (e.g. health effect):

$$\max \sum_i \alpha_i u_i(x_i, g_i) \qquad \text{(2-2)}$$

$$x_i \geq 0, g_i \geq 0 \text{all} \, i, y_{e\,j}^- \geq 0, y_j \text{ all } j, y_g^+ \geq 0 \ ,$$

subject to

$$\sum_i x_i - \sum_j y_j \leq \sum_i \omega_i \qquad (p) \ ,$$

$$\sum_j y_{e\,j}^- \leq \sum_i \omega_e \qquad (p_e) \ ,$$

$$g_i = y_g^+ \qquad (\phi_i) \ ,$$

$$F_j(y_j, -y^-_{e\,j}) \le 0\,,$$
$$F_g(y^+_g, -\sum_j y^-_{e\,j}) \le 0\,,$$

where x_i is the vector of consumption goods, g_i is the vector of non-rival consumption (environmental quality) for consumer i. y^+_g is environmental quality which is produced by an environmental process according to a transformation function $F_g(.)$, using total emission $\sum_j y^-_{e\,j}$. y_j is the vector of net output, positive one indicates the outputs and negative one indicates inputs. $y^-_{e\,j}$ is the vector of emission input for producer j. ω is the vector of initial endowments and ω_e is the vector of emission permits. Parameters in brackets give the shadow prices of the rival goods, emission permits and environmental quality. For notational convenience, we assume that vectors x_i, g_i, y_j, y^+_g and $y^-_{e\,j}$ refer to the same commodities space but they usually have different entries for the same k. α_i is the welfare weight of consumer i and is chosen such that,

$$px_i + \phi_i g_i = p\omega_i + \sum_i \theta_{ij}\Pi_j(p)\,,$$

if g_i is excludable.

If g_i is non-excludable, then it should not enter to the expenditure because the consumer will not pay for it. Then the budget constraint reads:

$$px_i = p\omega_i + \sum_i \theta_{ij}\Pi_j(p)\,.$$

ii) A non-rival environmental quality is produced as a by-product (e.g. emissions are joint output) of total production through an environmental process, which influences the production (e.g. damage on production):

$$\max \sum_i \alpha_i u_i(x_i) \qquad (2\text{-}3)$$
$$x_i \ge 0 \text{ all } i, y^+_g \ge 0, g_j \ge 0, y^+_j \ge 0, y^-_j \ge 0 \text{ all } j\,,$$

subject to

$$\sum_i x_i - \sum_j (y^+_j - y^-_j) \le \sum_i \omega_i \qquad (p)\,,$$
$$g_j = y^+_g \qquad (\psi_j)\,,$$
$$F_j(y^+_j - y^-_j, -g_j) \le 0\,,$$
$$F_g(y^+_g - \sum_j y^+_j) \le 0\,,$$

where y^+_j indicates the outputs, y^-_j the inputs.

With a welfare program that includes the environmental aspects, we still have to solve the program. The solution to the welfare programs depends on the properties of the specification of the functions. Therefore we must check the convexity or non-convexity of the program and discuss the methods for solving the non-convex programs.

This involves checking the convexity of the constraints of the model. Non-convexities can be checked by the Hessian matrix (the second order condition). The possible non-convexities are related to the non-convex production technologies $F_j(.)$ in the economic system and the environmental process $F_g(.)$ in the environmental system.

If all transformation functions $F_j(.)$ and $F_g(.)$ do not generate non-convexity, then the standard approach to solving a convex program can be taken (see Chapters 5, 6 and 7). If they generate non-convexity then we need special techniques to solve the program. These include graphical approach and parametric approach. We will show how to find the optimal solution to a non-convex welfare program in a simple aquatic model by graphical approach in Section 2.5. The parametric approach is illustrated in Chapter 3.

We would like to emphasise the importance of checking the non-convexities in integrated models and choosing proper method to solve non-convex programs. In the literature, however, non-convexity is not given sufficient attention and is not discussed in some models incorporated with environmental process models. Even in the famous models such as the DICE (Nordhaus, 1993) and MERGE (Manne *et al.*, 1995), checking the non-convexity is omitted and the standard approach to solving convex programs is used. This may have serious implications for the model results, which are used for proposing climate change polices. Therefore, in the next section we will check if the DICE model is convex and if its numerical solution is optimal by checking the Hessian matrix of the relevant variable.

2.5 TWO EXAMPLES: THE DICE MODEL AND A SIMPLE AQUATIC MODEL

In this section we discuss the convexity of the DICE model, which focuses on the impacts of climate change. We took the DICE model as an example, because it is a widely cited model with the novelty of including a climate change model (an environmental process model) in an applied growth model that basically has the characteristics of a general equilibrium framework. We also show how the optimal solution is obtained in a simple aquatic macrophytes model (van Nes *et al.*, 1999). The aquatic macrophytes model is chosen because the model has a fairly simple structure that allows a clear graphical analysis for optimality.

DICE model

Convexity in DICE

To check the convexity of a welfare program we should check the convexity of every constraint set. In the DICE model, a climate change model has been added to an economic model and the impact of climate change on production is simulated through a damage variable $\Omega(t)$, expressed as:

$$\Omega(t) = \frac{C_1}{1 + C_2 T(t)^2},$$

where T shows the temperature rise, C_1 and C_2 are parameters and t is the time subscript (see Appendix 2-A).

We mark the Cobb-Douglas production function $A(t)K(t)^{\gamma} L(t)^{1-\gamma}$ as $q(t)$. Then the production function (output $Q(t)$) with climate change impacts is expressed as:

$$Q(t) \leq \frac{C_1}{1 + C_2 T(t)^2} q(t).$$

We use the Hessian matrix (second order condition) to check the convexity of this constraint set. We rewrite the right hand side as:

$$f(T_t, q_t) = \frac{C_1}{1 + C_2 T_t^2} q_t.$$

If f is a concave function, then the constraint set is convex. By deriving the second-order derivatives of f, we have the Hessian matrix of f as:

$$|H| = \begin{bmatrix} f_{T_t T_t} & f_{T_t q_t} \\ f_{q_t T_t} & f_{q_t q_t} \end{bmatrix}.$$

For given parameters, we have

$$|H_1| \leq 0 \text{ if } |T|_t \leq 15 \text{ ; and } |H_1| > 0 \text{ if } |T|_t > 15 \,,$$

and

$|H_2| \leq 0$, for any T_t.

The Hessian determinants are not negative semidefinite, therefore function f is not a concave function. That means that the constraint set is non-convex. The mathematical program in this model is a non-convex program. For the detailed proof, please see Appendix 2-A.

<u>Characteristics of numerical solution of DICE</u>

The DICE model is mathematically a non-convex program. But non-convexity does not always lead to non-existence of equilibrium. For a non-convex program, you can calculate all the stationary points (i.e. local minima, maxima or saddle points) and compare them for optimal solutions. That is, analytically there is a possibility for the existence of multiple local optima in a non-convex program. Since finding numerical solutions does not need convexity, one can find a solution through software packages like GAMS[4], although optimality is not ensured. This is what was done in the DICE model.

[4] GAMS stands for General Algebraic Mathematical Systems, see Brooke *et al*. (1997) for details.

Since the DICE model is a non-convex program, we check its numerical solution to see whether it is an optimum. Since the non-convexity in the DICE model comes as a result of the climate change impacts (i.e. temperature rise) on the production function, we check the production function. A Cobb-Douglas production function q_t is built on the capital and labour domain with homogeneity of degree one, so we express the real production function as q_t and temperature rise T_t: $Q_t = F(T_t, q_t) = \frac{1}{1 + C_2 T_t^2} q_t$. Since T_t depends on the atmospheric concentrations of CO_2 in previous periods, thus also q_{t-1}, q_{t-2}, …, q_1, thus Q_t is, in fact, a function of q series: q_1,…, q_t. Then we need only to check the concavity of function Q with respect to the q series. We calculate the second derivatives of Q with respect to the path of q (that is, q_1, q_2,…, q_t). As an illustration, we only do three steps along the time path (Appendix 2-A gives a detailed mathematical formulation of the proof). We calculate the determinants of the Hessian matrix of the function f for each Q for the first three points of time path.

For first period t=1, we have $T_1(q_1)$ and $Q_1 = f(T_1(q_1), q_1)$,

$$D_1 = \frac{d^2 Q_1}{d q_1^2} < 0 .$$

Function Q_1 is a concave function of q_1.

For second period t=2, we have T_2 (q_1, q_2) and $Q_2 = f(T_2(q_1, q_2), q_2)$. The determinants of the Hessian matrix for f are as follows.

$$D_1 = \frac{\partial^2 Q_2}{\partial q_1^2} < 0$$

$$D_2 = \frac{\partial^2 Q_2}{\partial q_1^2} \frac{\partial^2 Q_2}{\partial q_2^2} - (\frac{\partial^2 Q_2}{\partial q_1 \partial q_2})^2 < 0$$

The Hessian matrix for f is thus not negative semidefinite.

For third period t=3, we have T_3 (q_1, q_2, q_3) and $Q_3 = f(T_3(q_1, q_2, q_3), q_3)$. We prove that the determinants of the Hessian matrix are as follows.

$D_1 < 0$,

$D_2 < 0$,

$D_3 > 0$.

The Hessian matrix for f is thus not negative semidefinite.

The second–order condition for a maximum requires *negative semidefinite* of the Hessian matrix. But for the second and third point of time period we found that the condition of negative (semi-) definiteness does not hold. This clearly shows that the current solution at the second and third time period is not a maximum. Therefore this solution of the DICE model is not an optimum.

<u>*Conclusions on DICE*</u>

The DICE model has included a climate change process model in economic modelling. It is a good illustration of how to include an environmental process model in an economic model. However our analytical check shows that the DICE model is a non-convex program. The further check on the numerical solution of the DICE shows that the DICE model did not obtain an optimal solution in the path of q_t. The major drawback of the DICE model is that the non-convexity of the climate change process model is not discussed.

This finding has major implications for policy analysis. First, non-convexity in the DICE model, shown by the analytical check, might create a theoretical difficulty to justify choice of policies. Second the numerical solution is not an optimum thus the policy implication from the model results is not reliable. Finally, identifying the solution to a non-convex program requires special techniques.

A simple aquatic macrophytes model

<u>*Finding an optimal solution in the aquatic macrophytes model*</u>

In an aquatic macrophytes model (van Nes *et al*., 1999), an overall welfare of the society is a weighted sum of welfare of different groups in society. The optimal strategy, from a rational social planner's point of view, is to aim at finding the biomass level where the total welfare function is optimal. In the model two groups of lake users are considered: nature conservationists and recreational users. Their welfare functions are expressed by a Hill function (i.e. a sigmoid function). The total welfare function is a weighted sum of these two welfare functions.

Mathematically, it can be presented as a welfare program, written in the following form:

$$W = \max_{B}[\alpha_1 w_1(B) + \alpha_2 w_2(B)], \tag{2-4}$$

subject to

$$w_1(B) \leq \frac{B^{p_1}}{H_1^{p_1} + B^{p_1}}, w_1 = 0 \text{ for } B = 0; w_1 = 1 \text{ for } B = \infty, \tag{2-5}$$

$$w_2(B) \leq \frac{H^{p_2}}{H_2^{p_2} + B^{p_2}}, w_2 = 1 \text{ for } B = 0; w_2 = 0 \text{ for } B = \infty, \tag{2-6}$$

where w_1 is the welfare function of group 1 (nature conservationist) and w_2 is the welfare function of group 2 (recreational users), B is the level of biomass in water. Welfare weights α_1 and α_2 are given 0.5. B is the level of biomass in water, and H_1 and H_2 is the half saturation, which is a specific B defined at w_1=0.5 and w_2=0.5 respectively; and p_1 and p_2 is the exponent which defines the steepness of the welfare functions of group 1 and 2 respectively.

Normally, for solving a maximisation problem we have to check if the objective function is differentiable and concave (i.e. a convex problem) or the constraint set is convex. For this simple model, it is easy to see that the objective function is concave. Since the constraint functions (right hand sides of (2-5) and (2-6) are sigmoid functions, they are non-concave. The sets generated by these constraints are non-convex[5]. But for this simple model, we can draw the individual welfare and total welfare with respect to the only choice variable *B* in a figure without checking the non-convexity. The optimal solution can be seen in the figure. In this case the non-convexity does not cause problems to find the optimal solution of the model because the total welfare, with respect to different levels of the choice variable, can be analysed graphically. From Figure 2-4 (a) and (b), one can simply observe the optimal solution of the model for two different cases.

Case 1: vegetation with a low growth form

The welfare function of group 1 is an increasing and non-concave function of *B* and the welfare function of group 2 is a decreasing non-concave function of *B*. The sum of an increasing non-concave function and a decreasing non-concave function is not necessarily a concave function. However, for given parameters, $p_1 = p_2$ and $H_2>H_1$, there exists one point at which the total welfare is maximised (see Figure 2-4(a)). It was concluded that under case 1, the optimum is at intermediate vegetation densities.

Case 2: canopy forming or floating vegetation

The welfare function of group 1 is an increasing function (non-concave) of *B* and the welfare function of group 2 is a decreasing function (non-concave) of *B* but with a slower rate with respect to *B* than case 1. From Figure 2-4(b) for given parameters $p_1 = p_2$ and $H_1>H_2$, there is one minimum point where total welfare is minimised at intermediate density of biomass, and the optima occurs at the two sides of *B* (*B*=0 and *B*=1). So the best policy is to provide two different lakes for different users.

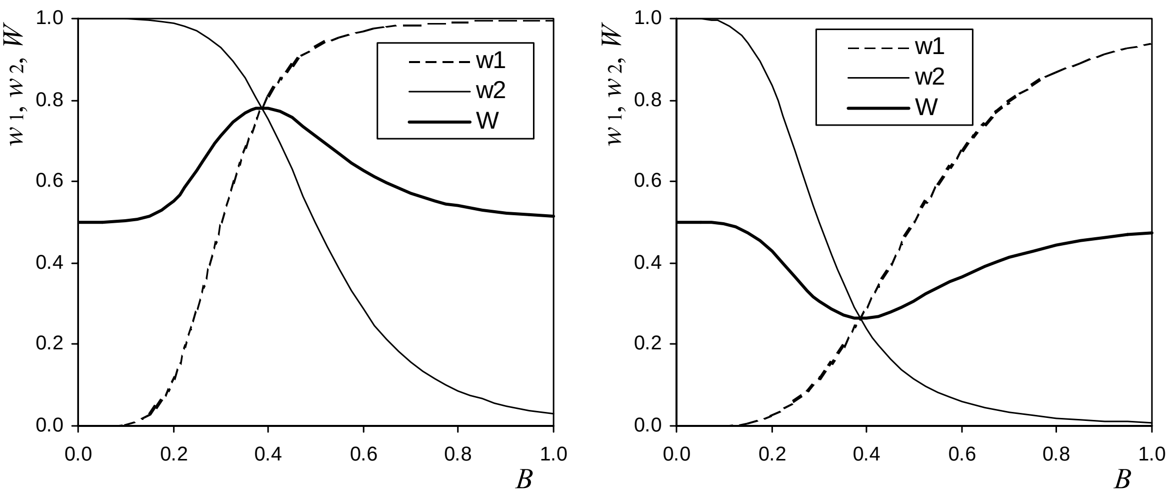
Conclusions on the aquatic macrophytes model

In the aquatic macrophytes model, we have an objective function with only one-dimensional choice variable (biomass density *B*), so it is easy to find the optimal solution although non-convexities are involved. For such a simple model with low dimension of non-convexities we do not necessarily follow a formal mathematical process to analyse the problem. We can draw a figure with the relation between choice variable and welfare with all possible stationary points and spot the optimal one for policy recommendation.

If more variables for a complicated issue are involved, it will be difficult to draw the graph that can show the optimal solution. Then a formal analytical study is called for. For the

[5] We can check the Hessian matrix to see if it is convex. But Figure 2-4 also shows that they are non-concave functions.

analytical study we need to check the mathematical properties of the model: its convexity and the optimality of its solutions.



(a) **(b)**

Figure 2-4 Welfare functions and total welfare

2.6 CONCLUDING REMARKS

Environmental problems are the negative impacts on the economic system, which are caused by the interactions between the economic and the environmental system. Solving the environmental problems needs proper economic modelling. This requires considering the economic functions of the environment, environmental processes, and feedbacks between the economic and the environmental system in economic modelling. Some special features of the environmental problems are non-rivalry and non-excludability. If they do not generate non-convexities, then standard Pigouvian tax (or Lindhal prices) can be used for solving the problem. If they generate non-convexities, then we need proper methods to solve the problem.

In welfare programs, we can represent the environmental problems through production functions, utility functions and an extra environmental process model. Non-convexities may have serious implications for the resulting policy recommendations. In welfare programs with environmental problems, non-convexities can arise from the production technologies in the economic system and the incorporated environmental processes. We should check the non-convexities of the model by analysing the characteristics of the Hessian matrix. Studying some existing models which claimed to have incorporated environmental processes, we find that the DICE model is a non-convex program and the numerical solution to the model is not an optimum because its second order condition for the optimal solution is not satisfied.

Finding optimal solutions to the welfare programs with non-convexities requires special techniques for different types of non-convexities. For simple models such as the aquatic model we can use a graphical method that represents the total welfare and choice variables in graph and spot the optimal solution. We will show in Chapter 3 how we deal with non-convex programs by *parameterisation* in numerical examples. We should be aware that for 'very serious' non-convex programs, such as those with both non-convex environmental process and economic constraints, we simply could not determine the optimal solutions.

For our applied models in the following chapters, we also consider simplification. Since we are investigating the possible impacts of NPFs on the whole economy considering the relevant environmental problems, we use an AGE model. This model, in principle, must include the whole economy. This, however, complicates the modelling since we want represent both the whole economy and the related environmental processes. Therefore, in the model application we need simplifications.

Simplification of the problems takes place in two aspects. One regards the representation of the economy, while the other regards the environmental processes. For the focus of our study, we have relatively detailed representations of agricultural sectors and for simplification on the economic side aggregated other sectors. For the representation of environmental processes in AGE models, we simplify the environmental aspects in different ways because of the complexity of the environmental processes and available data.

In Chapter 3 we show how to model the environmental problems related to protein issues in an illustrative way. This means we are not dealing with a full, empirical AGE model. Instead we will show how these mechanisms can be modelled if all data would be available. We will present welfare programs, which include the environment (e.g. soil fertility) used as input for production (i.e. crop), the environment (i.e. soil fertility) affected by production (i.e. pork) and the feedback (e.g. damage) of environmental effects on the economic system (in particular affecting crop production). Our concern, as such, is the interaction between pork production and crop production when soil acidification exists. For this specific focus, the welfare programs do not necessarily represent the whole economy, but rather a more restricted economic setting, such as a village economy.

In Chapters 5, 6, and 7 we will not always include the feedback of the environment on the economy fully. In Chapters 5 and 6, we will define an environmental quality indicator, which influences the amenity value of the environment to the consumers, based on the quantity of the total CO_2 emissions in Chapter 5 and NH_3 emissions in Chapter 6. We are interested in the impacts of a new product, such as NPFs, on the economy and the environment considering the preference changes of the consumers. Thus, we have an environmental amenity value in the utility function, and emission as input in the production function. We use a linear relationship between emissions and environmental quality and do not have the problems of non-convexity. This environmental quality indicator will influence the consumption decision and thus give impacts on production. We use the same theoretical model in Chapters 5 and 6 though Chapter 5 is more methodological with two regions and CO_2 as the relevant pollutant in application, while Chapter 6 is empirical with three regions and NH_3 as the relevant pollutant in application.

In Chapter 7, which is an empirical study on the impacts of NPFs with two time periods (present and 2020), we focus on the economic and environmental responses to changing life styles towards more NPFs as replacement of pork. The model is a multi-region, multi-product, two-period AGE model with accumulation of labour and capital, technological progress and alternative production systems. In this model we have more detailed agricultural sectors than in Chapters 5 and 6, and detailed livestock production systems, such as intensive production, grazing and mixed. However, we restrict ourselves to three important substances (NH_3, CH_4 and N_2O) from the production. Biophysical processes and their impacts on the economy are not studied because we intend to compare the impacts of life style change and environmental policy.

APPENDIX 2-A DETECTING A NON-CONVEXITY IN THE DICE MODEL AND THE NON-OPTIMALITY OF ITS NUMERICAL SOLUTION

Convexity of welfare program in DICE

Mathematically, the DICE model is presented as a welfare program, written in the following form:

$$\max_{c(t)} \sum_{t} (1+\rho)^{-t} P(t) \log[c(t)], \qquad \text{(2-A1)}$$

where ρ is the pure rate of social time preference, $P(t)$ is the level of population at time t, and $c(t)$ is the flow of consumption per capita at time t;
subject to

$$c(t) \leq C(t) / P(t), \qquad \text{(2-A2)}$$

where $C(t)$ is the total consumption;

$$C(t) \leq Q(t) - I(t), \qquad \text{(2-A3)}$$

where $Q(t)$ is the output and $I(t)$ is the investment;

$$Q(t) \leq \Omega(t) A(t) K(t)^{\gamma} L(t)^{1-\gamma}, \qquad \text{(2-A4)}$$

where $\Omega(t)$ is the feedback of climate impact on production through abatement and damage costs, $A(t)$ and γ are technological parameters, and K and L represent capital and labour;

$$K(t) \leq (1-\delta_k) K(t-1) + I(t), \qquad \text{(2-A5)}$$

where δ_K is the rate of depreciation of the capital stock.

In equation (2-A4), we have observed the symbol $\Omega(t)$ as the variable that expresses the impact of abatement and damage costs on total production. If this variable were a constant, then the program expressed by objective function (2-A1) and constrains (2-A2) to (2-A5) would be a standard convex program because the functions on the right hand side of the constraints are concave[6] and the constraints sets are convex[7].

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[6] If $f(x)$ is a linear function, then it is a concave function as well as a convex function (Theorem I, Chiang, 1984, p342). The right-hand side functions of constraints (2-A1), (2-A2), (2-A3) and (2-A5) are concave because (2-A1), (2-A2) and (2-A3) are linear functions and (2-A5) is a Cobb-Douglas production function if $\Omega(t)$ is constant.

[7] A concave function g(x) can generate an associated convex set, given some constant k. That convex set is $S \equiv \{x | k \leq g(x)\}$ [$g(x)$ concave] (c.f. Definition 11.28, Chiang, 1984, p351). Therefore the convex sets are generated by the concave functions on the right-hand sides of the constraints.

Climate change impact on production, as expressed as $\Omega(t)$, however, is determined by a series of biophysical processes due to CO_2 emissions, which are expressed by some extra equations in the DICE model. Since these equations construct some extra constraints for the welfare program, the convexity of the program should be checked. We check the convexity of these constraints one by one. We have the following extra constraints in DICE model:

$$\Omega(t) = \frac{C_1}{1 + C_2 T(t)^2}, \text{ with } C_1 = 1 - 0.0686\mu^{2.887} \text{ and } C_2 = 0.00144, \tag{2-A6}$$

where $T(t)$ is the temperature rise in time t with respect to a base time and μ is the fraction of emission reduction.

The temperature change $T(t)$ is related to the change in CO_2 concentration $M(t)$ and $T(t\text{-}1)$ by this relation:

$$T(t) = \eta \ln \frac{M(t)}{M_0} + CT(t-1) = \eta \ln[M(t)] + CT(t-1) - C', \tag{2-A7}$$

where M_0 is the concentration of CO_2 in base year.

The CO_2 concentration is related to CO_2 emission $E(t)$ and $M(t\text{-}1)$ by,

$$M(t) = 0.64E(t) + 0.9917M(t-1), \tag{2-A8}$$

Further, the CO_2 emission is proportional to the production $q(t)$:

$$E(t) = (1 - \mu(t))\sigma(t)q(t), \tag{2-A9}$$

where μ is the abatement ratio of emission, σ is the emission coefficient (emission-output ratio), and $q(t)$ is the output presented by a Cobb-Douglas function: $q(t) = A(t)K(t)^{\gamma} L(t)^{1-\gamma}$.

Equations (2-A7), (2-A8) and (2-A9) are concave functions (i.e. log function or linear functions) on right hand sides, so the set determined by these constraints is convex. We substitute equation (2-A6) into equation (2-A7) and we get a new equation for the production function of which we need checking the concavity. For simplification of notation, we use $q(t)$ for $A(t)K(t)^{\gamma} L(t)^{1-\gamma}$. Now we have:

$$q(t) \le A(t)K(t)^{\gamma} L(t)^{1-\gamma}, \tag{2-A10}$$

$$Q(t) \le \frac{C_1}{1 + C_2 T(t)^2} q(t). \tag{2-A11}$$

The set that is determined by constraint (2-A10) is convex because the function on the right hand side is a concave function. The constraint set of (2-A11) is not obviously convex because it is a product of two functions on the right hand side. We need the Hessian matrix to check the convexity of this constraint set. We use subscript t instead of (t) and note f as the function in right hand side of (2-A11):

$$f(T_t, q_t) = \frac{C_1}{1 + C_2 T_t^2} q_t \, .$$

If f is a concave function, then the constraint set (2-A11) is convex. By deriving the first-order derivatives and second-order derivatives of f we have the Hessian matrix of f as:

$$|H| = \begin{bmatrix} f_{T_t T_t} & f_{T_t q_t} \\ f_{q_t T_t} & f_{q_t q_t} \end{bmatrix} = \begin{bmatrix} -2C_1 C_2 q_t \dfrac{1 - 3C_2 T_t^2}{(1 + C_2 T_t^2)^3} & -\dfrac{2C_1 C_2 T_t}{(1 + C_2 T_t^2)^2} \\ -\dfrac{2C_1 C_2 T_t}{(1 + C_2 T_t^2)^2} & 0 \end{bmatrix} .$$

A function f is concave on S if and only if its Hessian matrix is *negative semidefinite* everywhere in S (Bazaraa *et al*., 1993).

Negative semidefinite requires (the necessary and sufficient condition of negative semidefinite is):

$$|H_1| \le 0 \, ,$$

$$|H_2| \ge 0 \, .$$

We have $|H_1| = -2C_1 C_2 q_t \dfrac{1 - 3C_2 T_t^2}{(1 + C_2 T_t^2)^3}$, which means:

If $|T|_t \le 15$, $|H_1| \le 0$; and if $|T|_t > 15$, $|H_1| > 0$, $|H_2| = -(\dfrac{2C_1 C_2 T_t}{(1 + C_2 T_t^2)^2})^2 \le 0$, for any T_t.

This violates the condition for *Negative semidefiniteness* of the Hessian matrix. Since the sufficient and necessary condition of the concavity of a function f is that its Hessian matrix is negative semidefinite in every point in S, therefore function f is not a concave function. That means constraint set (2-A11) is non-convex. That means if the climate change impact on production is included, the convexity of the welfare program no longer holds. The mathematical program in this model is then a non-convex program. This is the analytical proof of a non-convex program of DICE.

Characteristics of numerical solution of DICE

Now we will check if the numerical solution in the DICE model is an optimum to a non-convex program. We are interested in whether the DICE solutions over time are maxima over time, therefore we will check the signs of its Hessian determinants over the time path. We will check the second-order conditions of Q considering the climate change impacts in the first three steps of time path.

The DICE production function is:

$$Q_t = F(T_t, q_t) = \frac{C_1}{1 + C_2 T_t^2} q_t \,,$$

where $C_1 = 1 - 0.0686\mu^{2.887}$ and $C_2 = 0.00144$.

The climate change model is:

$$T_t = \eta \ln M_t + CT_{t-1} - C' \,,$$

$$M_t = 0.64 E_t + 0.9917 M_{t-1} \,,$$

$$E_t = (1 - \mu)\sigma_t q_t \,,$$

where μ is the fraction of emission reduction under abatement policy. Without any abatement policy, $\mu = 0$ and $C_1 = 1$. We also have the following parameters[8], $\eta = 3.0781$, and C=0.5819. Therefore, the real production function is:

$$Q_t = \frac{1}{1 + C_2 T_t^2} q_t = f(q_t, T_{t-1}, M_{t-1}) \,.$$

Since emission is linear to the Cobb-Douglas production quantity q_t, the climate change model is written as:

$$M_t = 0.64 E_t + 0.9917 M_{t-1} = 0.64(1 - \mu)\sigma_t q_t + 0.9917 M_{t-1} \,,$$

$$T_t = \eta \ln M_t + CT_{t-1} - C' = \eta \ln[0.64(1 - \mu)\sigma_t q_t + 0.9917 M_{t-1}] + CT_{t-1} - C' \,,$$

$$\frac{\partial M_t}{\partial E_t} = 0.64 \,,$$

$$\frac{\partial E_t}{\partial q_t} = (1 - \mu)\sigma_t \,,$$

$$\frac{\partial M_t}{\partial M_{t-1}} = 0.9917 \,,$$

$$\frac{\partial M_t}{\partial q_t} = 0.64(1 - \mu)\sigma_t \,,$$

$$\frac{\partial T_t}{\partial q_t} = \frac{\partial T_t}{\partial M_t} \frac{\partial M_t}{\partial E_t} \frac{\partial E_t}{\partial q_t} = \frac{\eta}{M_t} 0.64(1 - \mu)\sigma_t \,,$$

$$\frac{\partial^2 T_t}{\partial q_t^2} = \frac{\partial}{\partial q_t}\left(\frac{\eta}{M_t} 0.64(1 - \mu)\sigma_t\right) = \eta 0.64(1 - \mu)\sigma_t \left(-\frac{1}{M_t^2}\right) \frac{\partial M_t}{\partial q_t} = -\frac{\eta[0.64(1 - \mu)\sigma_t]^2}{M_t^2} \,.$$

Under $\mu = 0$,

$$\frac{\partial T_t}{\partial q_t} = \frac{\eta}{M_t} 0.64\sigma_t \,,$$

[8] η is calculated as 4.1/log2×0.226 and *C* as 1 + 0.226 (-1.41-0.44) (see Nordhaus, 1994).

$$\frac{\partial^2 T_t}{\partial q_t^{\,2}} = -\frac{\eta[0.64\sigma_t]^2}{M_t^{\,2}}.$$

In order to simplify notation, we denote

$$B_t = 0.64\sigma_t,$$

$$M_0' = 0.9917M_0,$$

$$T_0' = CT_0.$$

Then,

$$M_t = B_t q_t + 0.9917M_{t-1},$$

$$T_t = \eta\ln(B_t q_t + 0.9917M_{t-1}) + CT_{t-1} - C',$$

$$\frac{\partial T_t}{\partial q_t} = \frac{\eta}{M_t}B_t,$$

$$\frac{\partial^2 T_t}{\partial q_t^{\,2}} = -\frac{\eta B_t^{\,2}}{M_t^{\,2}}.$$

Since the real production function depends on the Cobb-Douglas production function q_t and temperature rise and concentration in previous periods (T_{t-1} and M_{t-1}), the latter can be expressed by the Cobb-Douglas production function as well. Thus Q over time t is, in fact, a function of q series: q_1, …, q_t. Then we need only check the concavity of function Q with respect to q series.

We use the *chain rule* to obtain the first and second derivatives of the function f with respect to q,

$$Q_t = F(T_t, q_t) = \frac{1}{1 + C_2 T_t^2} q_t.$$

We have the following partial derivatives with respect to T and q:

$$\frac{\partial F}{\partial T_t} = -\frac{2C_1 C_2 T_t}{(1 + C_2 T_t^2)^2} q_t,$$

$$\frac{\partial F}{\partial q_t} = \frac{C_1}{(1 + C_2 T_t^2)},$$

$$\frac{\partial^2 F}{\partial T_t^2} = -2C_1 C_2 q_t \frac{1 - 3C_2 T_t^2}{(1 + C_2 T_t^2)^3},$$

$$\frac{\partial^2 F}{\partial q_t^{\,2}} = 0,$$

$$\frac{\partial^2 F}{\partial T_t \partial q_t} = -\frac{2C_1 C_2 T_t}{(1 + C_2 T_t^2)^2}.$$

Now, we check the second derivatives of Q with respect to the path of q in order to check whether the DICE solution is a maximum.

At the first period, t=1:

$$Q_1 = \frac{1}{1+C_2 T_1^2} q_1 = F(T_1(q_1), q_1),$$

$$M_1 = B_1 q_1 + M_0',$$

$$T_1 = \eta \ln(B_1 q_1 + M_0') + T_0' - C',$$

$$\frac{dT_1}{dq_1} = \frac{\eta B_1}{M_1},$$

$$\frac{d^2 T_1}{dq_1^2} = -\frac{\eta B_1^2}{M_1^2}.$$

For $Q_1 = \frac{1}{1+C_2 T_1^2} q_1 = F(T_1(q_1), q_1)$, we have:

$$\frac{dQ_1}{dq_1} = \frac{\partial F}{\partial T_1}\frac{dT_1}{dq_1} + \frac{\partial F}{\partial q_1},$$

$$\frac{d^2 Q_1}{dq_1^2} = \frac{\partial F}{\partial T_1}\frac{d^2 T_1}{dq_1^2} + (\frac{dT_1}{dq_1})^2 \frac{\partial^2 F}{\partial T_1^2} + \frac{\partial^2 F}{\partial q_1^2} + \frac{\partial^2 F}{\partial T_1 \partial q_1}\frac{dT_1}{dq_1}.$$

Since

$$\frac{\partial F}{\partial T_1} = -\frac{2C_2 T_1}{(1+C_2 T_1^2)^2} q_1,$$

$$\frac{\partial F}{\partial q_1} = \frac{1}{(1+C_2 T_1^2)},$$

$$\frac{\partial^2 F}{\partial T_1^2} = -2C_2 q_1 \frac{1-3C_2 T_1^2}{(1+C_2 T_1^2)^3},$$

$$\frac{\partial^2 F}{\partial q_1^2} = 0,$$

therefore we have the following first and second derivatives:

$$\frac{dQ_1}{dq_1} = -\frac{2C_2 T_1}{(1+C_2 T_1^2)^2}\frac{\eta B_1}{(B_1 q_1 + M_0')} q_1 + \frac{1}{1+C_2 T_1^2},$$

$$\frac{d^2 Q_1}{dq_1^2} = \frac{2C_2 \eta}{(1+C_2 T_1^2)^2}\{(\frac{B_1}{M_1})^2 [T_1 - \eta \frac{1-3C_2 T_1^2}{(1+C_2 T_1^2)}] q_1 - \frac{\eta B_1}{M_1} T_1\}.$$

For the second period t=2:

$$Q_2 = \frac{C_1}{1+C_2 T_2^2} q_2,$$

$$M_1 = B_1 q_1 + M_0',$$

$$M_2 = B_2 q_2 + 0.9917 M_1,$$

$$T_1 = \eta \ln(B_1 q_1 + M_0{}') + T_0{}' - C',$$
$$T_2 = \eta \ln(B_2 q_2 + 0.9917 M_1) + C T_1 - C',$$
$$T_2 = \eta \ln[B_2 q_2 + 0.9917(B_1 q_1 + M_0{}')] + C[\eta \ln(B_1 q_1 + M_0{}') + T_0{}' - C'] - C',$$
$$\frac{\partial T_2}{\partial q_1} = \frac{\eta \times 0.9917 B_1}{M_2} + \frac{C\eta B_1}{M_1},$$
$$\frac{\partial T_2}{\partial q_2} = \frac{\eta B_2}{M_2},$$
$$\frac{\partial^2 T_2}{\partial q_1 \partial q_2} = -\frac{0.9917 \eta B_1 B_2}{M_2{}^2},$$
$$\frac{\partial^2 T_2}{\partial q_1{}^2} = -\eta B_1{}^2 (\frac{0.9917^2}{M_2{}^2} + \frac{C}{M_1{}^2}),$$
$$\frac{\partial^2 T_2}{\partial q_2{}^2} = -\frac{\eta B_2{}^2}{M_2{}^2}.$$

For $Q_2 = \frac{1}{1 + C_2 T_2{}^2} q_2 = F(T_2(q_1, q_2), q_2)$, the derivatives of Q_2 with respect to q_1 and q_2 are as follows:

$$\frac{\partial Q_2}{\partial q_1} = \frac{\partial F}{\partial T_2}\frac{\partial T_2}{\partial q_1},$$
$$\frac{\partial Q_2}{\partial q_2} = \frac{\partial F}{\partial T_2}\frac{\partial T_2}{\partial q_2} + \frac{\partial F}{\partial q_2},$$
$$\frac{\partial^2 Q_2}{\partial q_1{}^2} = \frac{\partial F}{\partial T_2}\frac{\partial^2 T_2}{\partial q_1{}^2} + \frac{\partial^2 F}{\partial T_2{}^2}(\frac{\partial T_2}{\partial q_1})^2,$$
$$\frac{\partial^2 Q_2}{\partial q_2{}^2} = \frac{\partial F}{\partial T_2}\frac{\partial^2 T_2}{\partial q_2{}^2} + (\frac{\partial T_2}{\partial q_2})^2 \frac{\partial^2 F}{\partial T_2{}^2} + \frac{\partial^2 F}{\partial T_2 \partial q_2}\frac{\partial T_2}{\partial q_2} + \frac{\partial^2 F}{\partial q_2{}^2},$$
$$\frac{\partial^2 Q_2}{\partial q_1 \partial q_2} = \frac{\partial F}{\partial T_2}\frac{\partial^2 T_2}{\partial q_1 \partial q_2} + \frac{\partial^2 F}{\partial T_2{}^2}\frac{\partial T_2}{\partial q_2}\frac{\partial T_2}{\partial q_1} + \frac{\partial^2 F}{\partial q_2 \partial T_2}\frac{\partial T_2}{\partial q_1}.$$

Since

$$\frac{\partial F}{\partial T_2} = -\frac{2 C_2 T_2}{(1 + C_2 T_2{}^2)^2} q_2,$$
$$\frac{\partial F}{\partial q_2} = \frac{1}{(1 + C_2 T_2{}^2)},$$
$$\frac{\partial^2 F}{\partial T_2{}^2} = -2 C_2 q_2 \frac{1 - 3 C_2 T_2{}^2}{(1 + C_2 T_2{}^2)^3},$$
$$\frac{\partial^2 F}{\partial q_2{}^2} = 0,$$

therefore,

$$\frac{\partial^2 F}{\partial T_2 \partial q_2} = -\frac{2C_2T_2}{(1+C_2T_2^{\ 2})^2},$$

$$\frac{\partial^2 Q_2}{\partial q_1^{\ 2}} = \frac{2C_2\eta B_1^{\ 2}}{(1+C_2T_2^{\ 2})^2} q_2T_2(\frac{0.9917^2}{M_2^{\ 2}} + \frac{C}{M_1^{\ 2}}) - \frac{2C_2\eta^2 B_1^{\ 2}(1-3C_2T_2^{\ 2})}{(1+C_2T_2^{\ 2})^3} q_2(\frac{0.9917}{M_2} + \frac{C}{M_1})^2,$$

$$\frac{\partial^2 Q_2}{\partial q_2^{\ 2}} = \frac{2C_2}{(1+C_2T_2^{\ 2})^2}\frac{\eta B_2}{M_2}\{\frac{B_2}{M_2} q_2[T_2 - \eta\frac{(1-3C_2T_2^{\ 2})}{(1+C_2T_2^{\ 2})}] - T_1\},$$

$$\frac{\partial^2 Q_2}{\partial q_1 \partial q_2} = \frac{2C_2\eta B_2}{(1+C_2T_2^{\ 2})^2}\{q_2[\frac{0.9917B_1}{M_2^{\ 2}}T_2 - \frac{(1-3C_2T_2^{\ 2})\eta B_1}{(1+C_2T_2^{\ 2})M_2}(\frac{0.9917}{M_2} + \frac{C}{M_1})] - (\frac{0.9917}{M_2} + \frac{C}{M_1})T_2\}.$$

For the third period t=3,

$$Q_3 = \frac{C_1}{1+C_2T_3^{\ 2}} q_3,$$

$$M_1 = B_1q_1 + M_0^{\ \prime},$$

$$M_2 = B_2q_2 + 0.9917M_1,$$

$$M_3 = B_3q_3 + 0.9917M_2,$$

$$T_1 = \eta\ln(B_1q_1 + M_0^{\ \prime}] + T_0^{\prime} - C',$$

$$T_2 = \eta\ln(B_2q_2 + 0.9917M_1] + CT_1 - C',$$

$$T_2 = \eta\ln[B_2q_2 + 0.9917(B_1q_1 + M_0^{\ \prime})] + C(\eta\ln(B_1q_1 + M_0^{\ \prime}] + T_0^{\prime} - C') - C',$$

$$T_3 = \eta\ln M_3 + C\eta\ln M_2 + C^2\eta\ln M_1 + C^2T_0^{\prime} - C^2C' - CC' - C',$$

$$\frac{\partial T_3}{\partial q_1} = \frac{0.9917^2\eta B_1}{M_3} + \frac{0.9917C\eta B_1}{M_2} + \frac{C^2\eta B_1}{M_1},$$

$$\frac{\partial T_3}{\partial q_2} = \frac{0.9917\eta B_2}{M_3} + \frac{C\eta B_2}{M_2},$$

$$\frac{\partial T_3}{\partial q_3} = \frac{\eta B_3}{M_3},$$

$$\frac{\partial^2 T_3}{\partial q_1^{\ 2}} = -\frac{0.9917^3\eta B_1^{\ 2}}{M_3^{\ 2}} - \frac{0.9917^2 C\eta B_1^{\ 2}}{M_2^{\ 2}} - \frac{C^2\eta B_1^{\ 2}}{M_1^{\ 2}},$$

$$\frac{\partial^2 T_3}{\partial q_2^{\ 2}} = -\frac{0.9917^2\eta B_2^{\ 2}}{M_3^{\ 2}} - \frac{C\eta B_2^{\ 2}}{M_2^{\ 2}},$$

$$\frac{\partial^2 T_3}{\partial q_3^{\ 2}} = -\frac{\eta B_3^{\ 2}}{M_3^{\ 2}},$$

$$\frac{\partial^2 T_3}{\partial q_2 \partial q_1} = -\frac{0.9917^3\eta B_1B_2}{M_3^{\ 2}} - \frac{0.9917C\eta B_1B_2}{M_2},$$

$$\frac{\partial^2 T_3}{\partial q_1 \partial q_3} = -\frac{0.9917^2\eta B_1B_3}{M_3^{\ 2}},$$

$$\frac{\partial^2 T_3}{\partial q_2 \partial q_3} = -\frac{0.9917\eta B_2 B_3}{M_3^{\ 2}}.$$

For $Q_3 = \frac{1}{1+C_2T_3^{\ 2}} q_3 = F(T_3(q_1, q_2, q_3), q_3)$, the derivatives of Q_3 with respect to q_1, q_2 and q_3 are as follows:

$$\frac{\partial Q_3}{\partial q_1} = \frac{\partial F}{\partial T_3}\frac{\partial T_3}{\partial q_1},$$

$$\frac{\partial Q_3}{\partial q_2} = \frac{\partial F}{\partial T_3}\frac{\partial T_3}{\partial q_2},$$

$$\frac{\partial Q_3}{\partial q_3} = \frac{\partial F}{\partial T_3}\frac{\partial T_3}{\partial q_2} + \frac{\partial F}{\partial q_3},$$

$$\frac{\partial^2 Q_3}{\partial q_1^{\ 2}} = \frac{\partial F}{\partial T_3}\frac{\partial^2 T_3}{\partial q_1^{\ 2}} + \frac{\partial^2 F}{\partial T_3^{\ 2}}\left(\frac{\partial T_3}{\partial q_1}\right)^2,$$

$$\frac{\partial^2 Q_3}{\partial q_2^{\ 2}} = \frac{\partial F}{\partial T_3}\frac{\partial^2 T_3}{\partial q_2^{\ 2}} + \frac{\partial^2 F}{\partial T_3^{\ 2}}\left(\frac{\partial T_3}{\partial q_2}\right)^2,$$

$$\frac{\partial^2 Q_3}{\partial q_1 \partial q_2} = \frac{\partial F}{\partial T_3}\frac{\partial^2 T_3}{\partial q_2 \partial q_1} + \frac{\partial^2 F}{\partial T_3^{\ 2}}\frac{\partial T_3}{\partial q_1}\frac{\partial T_3}{\partial q_2},$$

$$\frac{\partial^2 Q_3}{\partial q_3^{\ 2}} = \frac{\partial F}{\partial T_3}\frac{\partial^2 T_3}{\partial q_3^{\ 2}} + \left(\frac{\partial T_3}{\partial q_3}\right)^2\frac{\partial^2 F}{\partial T_3^{\ 2}} + \frac{\partial^2 F}{\partial T_3 \partial q_3}\frac{\partial T_3}{\partial q_3} + \frac{\partial^2 F}{\partial q_3^{\ 2}},$$

$$\frac{\partial^2 Q_3}{\partial q_1 \partial q_3} = \frac{\partial F}{\partial T_3}\frac{\partial^2 T_3}{\partial q_1 \partial q_3} + \frac{\partial^2 F}{\partial T_3^{\ 2}}\frac{\partial T_3}{\partial q_3}\frac{\partial T_3}{\partial q_1} + \frac{\partial^2 F}{\partial q_3 \partial T_3}\frac{\partial T_3}{\partial q_1},$$

$$\frac{\partial^2 Q_3}{\partial q_2 \partial q_3} = \frac{\partial F}{\partial T_3}\frac{\partial^2 T_3}{\partial q_2 \partial q_3} + \frac{\partial^2 F}{\partial T_3^{\ 2}}\frac{\partial T_3}{\partial q_3}\frac{\partial T_3}{\partial q_2} + \frac{\partial^2 F}{\partial q_3 \partial T_3}\frac{\partial T_3}{\partial q_2}.$$

Since

$$\frac{\partial F}{\partial T_3} = -\frac{2C_2T_3}{(1+C_2T_3^{\ 2})^2} q_3,$$

$$\frac{\partial F}{\partial q_3} = \frac{1}{(1+C_2T_3^{\ 2})},$$

$$\frac{\partial^2 F}{\partial T_3^{\ 2}} = -2C_2 q_3 \frac{1-3C_2T_3^{\ 2}}{(1+C_2T_3^{\ 2})^3},$$

$$\frac{\partial^2 F}{\partial q_3^{\ 2}} = 0,$$

$$\frac{\partial^2 F}{\partial T_3 \partial q_3} = -\frac{2C_2T_3}{(1+C_2T_3^{\ 2})^2},$$

therefore,

$$\frac{\partial^2 Q_3}{\partial q_1^{\ 2}} = \frac{2C_2\eta B_1^{\ 2}}{(1+C_2T_3^{\ 2})^2} q_3\{(\frac{0.9917^3}{M_3^{\ 2}} + \frac{0.9917^2 C}{M_2^{\ 2}} + \frac{C^2}{M_1^{\ 2}})T_3 - \frac{(1-3C_2T_3^{\ 2})\eta}{(1+C_2T_3^{\ 2})}(\frac{0.9917^2}{M_3} + \frac{0.9917C}{M_2} + \frac{C^2}{M_1})^2\},$$

$$\frac{\partial^2 Q_3}{\partial q_2^{\ 2}} = \frac{2C_2\eta B_2^{\ 2}}{(1+C_2T_3^{\ 2})^2} q_3\{(\frac{0.9917^2}{M_3^{\ 2}} + \frac{C}{M_2^{\ 2}})T_3 - \frac{(1-3C_2T_3^{\ 2})\eta}{(1+C_2T_3^{\ 2})}(\frac{0.9917}{M_3} + \frac{C}{M_2})^2\},$$

$$\frac{\partial^2 Q_3}{\partial q_1 \partial q_2} = \frac{2C_2\eta B_1 B_2}{(1+C_2T_3^{\ 2})^2} q_3\{(\frac{0.9917^3}{M_3^{\ 2}} + \frac{0.9917^2 C}{M_2^{\ 2}})T_3 - \frac{(1-3C_2T_3^{\ 2})\eta}{(1+C_2T_3^{\ 2})}(\frac{0.9917^2}{M_3} + \frac{0.9917C}{M_2} + \frac{C^2}{M_1})(\frac{0.9917}{M_3} + \frac{C}{M_2})\},$$

$$\frac{\partial^2 Q_3}{\partial q_3^{\ 2}} = \frac{2C_2\eta B_3}{(1+C_2T_3^{\ 2})^2} q_3\{T_3\frac{B_3}{M_3^{\ 2}} - \frac{1-3C_2T_3^{\ 2}}{(1+C_2T_3^{\ 2})}(\frac{\eta B_3}{M_3^{\ 2}}) - T_3\},$$

$$\frac{\partial^2 Q_3}{\partial q_1 \partial q_3} = \frac{2C_2\eta B_1}{(1+C_2T_3^{\ 2})^2}\{\frac{0.9917^2 B_3}{M_3^{\ 2}}T_3 - \frac{(1-3C_2T_3^{\ 2})\eta B_3}{(1+C_2T_3^{\ 2})}(\frac{0.9917^2}{M_3} + \frac{0.9917C}{M_2} + \frac{C^2}{M_1})(\frac{1}{M_3}) - (\frac{0.9917^2}{M_3} + \frac{0.9917C}{M_2} + \frac{C^2}{M_1})\}$$

$$\frac{\partial^2 Q_3}{\partial q_2 \partial q_3} = \frac{2C_2\eta B_2}{(1+C_2T_3^{\ 2})^2}\{\frac{0.9917 B_3}{M_3^{\ 2}}T_3 - \frac{(1-3C_2T_3^{\ 2})\eta B_3}{(1+C_2T_3^{\ 2})}(\frac{0.9917}{M_3} + \frac{C}{M_2})(\frac{1}{M_3}) - (\frac{0.9917}{M_3} + \frac{C}{M_2})T_3\}.$$

We use the given values of parameters in the DICE model to calculate the determinants of the Hessian matrix for the first three points.

For t=1, $D_1 = \frac{d^2 Q_1}{dq_1^{\ 2}} = -0.00001 < 0$.

For t=2, $H = \begin{bmatrix} \frac{\partial^2 Q_2}{\partial q_1^{\ 2}} & \frac{\partial^2 Q_2}{\partial q_1 \partial q_2} \\ \frac{\partial^2 Q_2}{\partial q_2 \partial q_1} & \frac{\partial^2 Q_2}{\partial q_2^{\ 2}} \end{bmatrix}$.

The determinants of the Hessian matrix are as follows,

$$D_1 = \frac{\partial^2 Q_2}{\partial q_1^{\ 2}} = -1.82\times 10^{-5} < 0,$$

$$D_2 = \frac{\partial^2 Q_2}{\partial q_1^{\ 2}} \frac{\partial^2 Q_2}{\partial q_2^{\ 2}} - (\frac{\partial^2 Q_2}{\partial q_1 \partial q_2})^2 = -9.92 \times 10^{-10} < 0 .$$

The Hessian matrix is not negative semidefinite.

For t=3, we have:

$$H = \begin{bmatrix} \frac{\partial^2 Q_3}{\partial q_1^{\ 2}} & \frac{\partial^2 Q_3}{\partial q_1 \partial q_2} & \frac{\partial^2 Q_3}{\partial q_1 \partial q_3} \\ \frac{\partial^2 Q_3}{\partial q_2 \partial q_1} & \frac{\partial^2 Q_3}{\partial q_2^{\ 2}} & \frac{\partial^2 Q_3}{\partial q_2 \partial q_3} \\ \frac{\partial^2 Q_3}{\partial q_3 \partial q_1} & \frac{\partial^2 Q_3}{\partial q_3 \partial q_2} & \frac{\partial^2 Q_3}{\partial q_3^{\ 2}} \end{bmatrix} .$$

The determinants of the Hessian matrix are:

$$D_1 = -1.75 \times 10^{-4} < 0 ,$$
$$D_2 = -1.06 \times 10^{-6} < 0 ,$$
$$D_3 = 1.44 \times 10^{-5} > 0 .$$

The Hessian matrix is not negative semidefinite.

For the maximum of a function, we need *negative semidefinite* of its Hessian matrix. But for the second and third point, we found that the condition of negative (semi-) definiteness does not hold. This clearly shows that the DICE solution at the second and third time period is not a maximum.

CHAPTER 3 TOWARDS INTEGRATED ASSESSMENT: INCLUDING THE NON-CONVEXITIES OF ENVIRONMENTAL IMPACTS IN A WELFARE MODEL

3.1 INTRODUCTION

As we have discussed in Chapters 1 and 2, the environmental system and the economic system interact, and the environment provides many functions or services to human society. The two basic functions or services that the environment provides to the economic system are inputs for production, and amenity services for people (i.e. consumers). If environmental changes, or environmental effects occur, then the capacity of the environment to provide the basic functions or services to the economic system is affected, which will have impacts on the economic system. As mentioned previously, the impact of the environmental changes on the economic system is called a ‘feedback’. The feedback of the environmental effects on the economic system may influence the economic activities by lowering agricultural productivity due to soil pollution, or by reducing the amenity services due to air or water pollution. In this sense, these environmental problems are due to the feedback of the environmental impacts on human society.

How to model environmental issues and to what extent the environmental processes are included in economic models depend on the specific environmental problems under study. In the context of the PROFETAS research programme, it is important to look at the environmental processes related to pork production and their impacts on other parts of the economic system.

In order to understand the environmental problems of pork production, we need to understand emissions from the production, environmental effects of the emissions, and their feedback on production and consumption. We use human or human-made inputs such as feed, capital and labour, and natural inputs such as clean water and soil for pork production. Pigs transform feed biomass into meat products and manure. Manure generates emissions of gaseous substances (mainly NH_3, CH_4 and N_2O), minerals (e.g. N and P), and compounds (e.g. NO_3), which have effects on the environment. These emitted substances enter the environment (i.e. air, soil and water), where many biophysical processes take place. These processes transform these emissions into different substances, which can change environmental states and lead to effects such as global warming, acidification and eutrophication. These effects, in turn, give feedbacks to the economic system, for example acidification leads to reduced crop and timber production.

This chapter aims to show, in a systematically designed set of numerical examples, how to model environmental problems related to pork production. This includes a detailed discussion about these problems, how to represent them in economic models (i.e. AGE models and welfare programs) considering the interaction between pork production and crop production, and finally a mathematical non-convexity check of the models. Following the discussion of the modelling approach presented in Chapter 2, we illustrate the methodology of how to solve non-convex programs in numerical examples by parameterisation, that is, finding the optimum by scanning a choice variable over a certain range.

In environmental economics literature, there exist a variety of so-called integrated assessment models (IAMs) such as DICE (Nordhaus, 1993), MERGE (Manne *et al*., 1995) and RICE (Nordhaus and Yang, 1996). However, the integration is not as far as we have expected. As indicated in Chapter 2, the DICE model is a non-convex program and the solution is not a real optimum. Considering such insufficient attention to non-convexities of the environmental processes, this chapter also aims to make some new contributions to integrated assessment of environmental impacts. Besides showing the method of finding the optimal solution to a non-convex model, we also illustrate how to check the decentralisability of the welfare optimum and its potential policy implications.

This chapter is organised as follows. We first discuss the general effects of manure on the environment and the impacts of environmental effects (e.g. water eutrophication and soil acidification) on the economic system (e.g. fish and crop production) in Section 3.2. Next, in Section 3.3 we specify the environmental problems of acidification caused by pork production and the impacts on crop production in a welfare program. We discuss the convexity of the welfare program with interaction between pork and crop production, and show how to solve the non-convex program numerically in a general equilibrium model setting. In Section 3.4, we design more cases where manure has impacts on the crop production, since manure influences soil fertility negatively (i.e. if acidification occurs) or positively (i.e. if manure is used as organic fertiliser for crop production). These cases portray different economies of reality with non-convexities caused by the lack of free disposal of manure or by a non-convex locally decreasing response of crop production to manure output. We demonstrate how to represent these cases in welfare programs and how to solve them in numerical examples (in a simpler model setting than will be used in Section 3.3). Finally, we draw conclusions.

3.2 ENVIRONMENTAL PROBLEMS WITH PORK PRODUCTION

Effects of manure on the environment: emission flows and environmental resource flows

Manure contains considerable amounts of nutrients, such as *N*, *P, K* and *M*, and heavy metals, such as *Zn* and *Cu*. These nutrients will enter the environment through manure storage and land application, which affects the quality of soil, water and air (Brandjes *et al*., 1996; Menzi, 2003).

Emissions from manure enter the environment in three main flows. The first flow is the flow of minerals (i.e. *N*, *P*, *K*) and heavy metals (i.e. *Zn*, *Cu*) *to soil*. If high doses of manure are applied to land, the accumulation of these nutrients and heavy metals in soil will threaten soil fertility. This phenomenon is called *soil eutrophication*.

The second flow is the flow of nutrients (e.g. *N, P, K*), and organic and other compounds (e.g. NO_3, formed during nitrification of NH_3) *to water* through direct manure storage contact with soil and leaching. The liquid from manure can seep into the soil and groundwater. The leaching of these substances to groundwater causes a *problem of groundwater quality*. High NO_3 concentrations in the groundwater makes it unsuitable for drinking water. Contaminated water can flow into surface water (*runoff*). High NO_3 concentrations in surface water can lead to eutrophication. Nutrients (e.g. NO_3, *P*) can also enter streams through discharge, runoff or overflow. Finally, runoff of nutrients into surface water causes *water eutrophication*.

The third flow is the flow of gaseous substances, such as NH_3, CH_4 and N_2O emissions, *to air* due to volatilisation. NH_3 will be first transported in the atmosphere and then deposited somewhere in soil, which increases soil acidity. This is called *soil acidification*. If deposition is on lakes, then it is called *lake acidification*.

For the focus of our study, we discuss the effects of water eutrophication and soil acidification and omit other impacts such as global warming. We do not discuss the impacts of climate change in our study because climate change is more relevant to energy use and the contribution from manure to climate change is relatively small.

In the analysis we would like to clearly distinguish between the concepts of *emission flows* and *environmental resource flows*. Considering the input functions and amenity services of the environment to the economic system, we can see the emission flow as the use of clean resources. Figure 3-1 shows the physical emission flows or streams (solid lines) connecting the variables (in circles) and processes (in squares) in one direction and the environmental resource flow (dashed lines) in the opposite direction.

The first physical flow considers the emissions of *N*, *P* and NO_3 to the water system, resulting in water *eutrophication*. If *N*, *P* and NO_3 concentrations are high in surface water, they will lead to excessive growth of algae, causing oxygen depletion, which consequently influences fish production. Since fish production depends on the availability of clean water, the reduction of fish production due to the water pollution can be considered as the reduction of the availability of clean water. In this case, the pork producer uses the clean water. When the emission flow from pork production goes to the water system, the clean water flow goes in opposite direction of the emission flow back to the pork producer. This is a typical illustration of how the environmental resources move in opposite direction of the physical flows of emissions. As such, there exists an interaction between pork production and fish production. As well, for the consumer who enjoys water amenity services, the pollution from pork production reduces these services.

The second physical flow of NH_3 deposits in soil and leads to *soil acidification*. This acidified soil mobilises aluminium in soil and disturbs the absorption of nutrients by crops. This process can be thought of as the use of soil fertility (which indicates the nutrients available for crop growth), therefore reducing crop yields. When the NH_3 emission flow is released from the pork producer to the soil, the soil fertility flow is moving from soil against the NH_3 flow to the pork producer. In this case, the pork producer actually uses the environmental flow of soil fertility, which influences the crop producer. This means that there exists interaction between pork production and crop production.

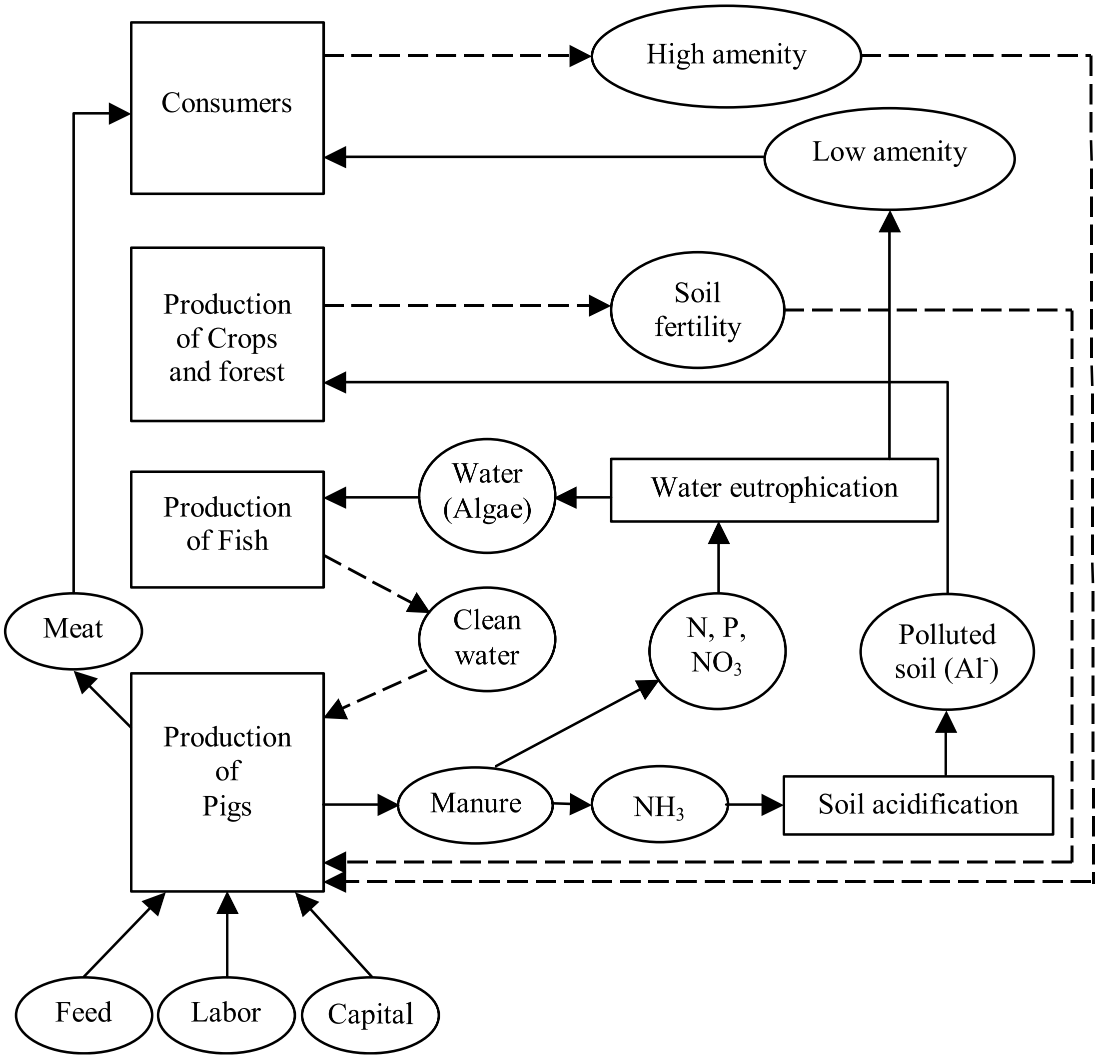

Figure 3-1 Environmental processes (□), flows of inputs and outputs of production and emissions (⟶) and environmental inputs (- - -▶) related to pork production

Impacts of environmental effects (water eutrophication and soil acidification) on production and consumption

Eutrophication has impacts on lakes and groundwater, while acidification affects lakes, groundwater, agricultural crops and forests (Schmieman, 2001). Eutrophication is not only detrimental to water supply, but also to instream uses such as recreational activities, commercial fishing and aquaculture (Kitabatake, 1982). As such, water eutrophication inflicts either an aesthetic distress or economic burden on the utilisation of water resources. Impacts of *surface water eutrophication* on fish production are due to the following processes: the growth of algae and loss of oxygen which causes death of fish (Hanley, 1990; Menzi, 2003). For example, the damage on carp, or cod production is mostly caused by periodic reduction of oxygen levels in eutrophic lakes (Kitabatake, 1982) or in the Baltic Sea (Turner *et al*., 1999).

Impact of *soil acidification* on forests or plants is due to acid deposition which increases the acidity of soils, leach out nutrients from soil and convert aluminium (*Al*) in the soil from an insoluble to soluble form. Root hairs absorb and are damaged by this soluble aluminium and this impairs a plant's water and nutrient uptake. Acid deposition also causes direct foliar damage. Acid deposition erodes the waxy, protective layer on the outside of leaves, leaches out nutrients, and increases vulnerability to pests and disease (Alcamo *et al*., 1990). As such, the main mechanism of acidification impacts on plants is that the reduction of water and nutrient uptake reduces plant growth.

For example, soil acidification has impacts on the pasture (Cregan, 1998). Acid soils have a pH of less than 5.6. Figure 3-2 shows the *Al* concentration and yields for different values of pH. It shows that yields are *a sigmoid function* of pH value. The low pH is associated with a number of soil chemical and biological characteristics that manifest themselves as the components of the acid soil syndrome. These components may adversely affect plant growth but differ from region to region. Van der Eerden *et al*. (1997) reported the effects of ammonia deposition on forests in the Netherlands. Except for highly polluted regions, the impacts of ammonia on forests are generally not on production but on the decrease of the number of tree species.

In summary, water eutrophication has impacts on both consumers who use water as a recreational means and on producers who use water for fish production, that is, decrease of water quality due to eutrophication influences amenity services of the water system and fish production. The impacts of soil acidification can be both on crop and forest production and biodiversity. The impact on productivity of plants is due to the decrease of soil fertility.

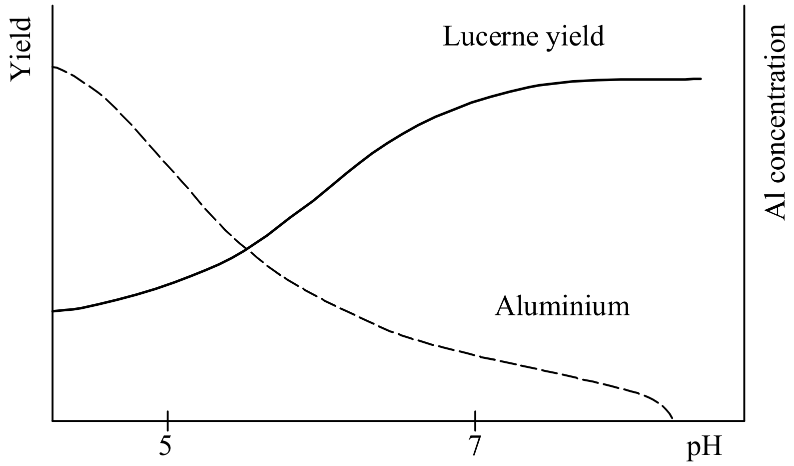

Figure 3-2 Effects of soil pH on aluminium ion activity in soil solution (---) and on Lucerne growth (—) (source: Cregan, 1998)

3.3 Specification of the environmental problems with pork production in a welfare program

Welfare program

Environmental problems can be represented in a welfare program (see e.g. Gerlagh and Keyzer, 2003 and 2004). Here we want to show how to specify the environmental issues that are relevant for our study in an example. In this example we consider the damages of soil acidification on production of plants for illustration. We use the welfare program (2-3) for solving our problem. For convenience, we rewrite the welfare program here:

$$\max \sum_i \alpha_i u_i(x_i) \qquad (3\text{-}1)$$

$$x_i \geq 0 \,\text{all}\, i, y_g^+ \geq 0, g_j \geq 0, y_j^+ \geq 0, y_j^- \geq 0 \,\text{all}\, j,$$

subject to

$$\sum_i x_i - \sum_j (y_j^+ - y_j^-) \leq \sum_i \omega_i \qquad (p),$$

$$g_j = y_g^+ \qquad (\psi_j),$$

$$F_j(y_j^+ - y_j^-, -g_j) \leq 0,$$

$$F_g(y_g^+ - \sum_j y_j^+) \leq 0,$$

where $y_g{}^+$ is the non-rival output produced as by-products of total production $\sum_j y_j^+$ via a transformation function $F_g(.)$, g_j is the non-rival input to the production of good j. If F_j is strictly quasi-convex but F_g is not, the program is still non-convex.

In the context of this welfare program, we have to specify producers, consumers and environmental processes, and we need to check its convexity. As a methodological demonstration, we consider a very simple model setting. There are four types of producers: pork producer, plant producer, other-goods producer, and fertiliser producer. There is one consumer who will consume three consumption goods: pork, food and other-goods. There are three production factors: capital, labour and land. The pork producer uses capital and labour as factor input and feed as intermediate input to produce pork. The plant producer uses labour, capital and land as production factors and nutrients (provided by soil and fertiliser application) for producing crop, which is used as food for consumers and feed for the pork producer. The fertiliser producer uses capital and labour to provide fertiliser to the plant producer. The other-goods sector is included in the welfare program for competing use of all resources in the economy.

In this economic model we would like to consider the soil acidification process caused by ammonia (NH_3) emissions from pork production. This process has impacts on crop production by changing the soil fertility, which is input for plant growth. This requires us to deal specifically with agricultural production, because agricultural production is different from industrial production. Agriculture uses more natural inputs such as soil and water in its production process. Its output has specific properties such as *yield per hectare*, or *liveweight per pig*. Therefore, we have to specify the production technologies for pork and crop differently from those for fertiliser and other-goods. We also have to specify a soil acidification process, which has impacts on crop production. As such, we want to show how to model the agricultural production of pork and crop, and how to model the acidification process and the impacts of acidification on crop production in mathematical terms.

The detailed production technology can be presented by an associated transformation function F_j and by soil fertility transformation F_g due to the acidification process. Since we deal with F_j and F_g in a welfare program, which is a mathematical program, we have to consider its convexity. Thus we check the convexity of the associated transformation functions F_j for production goods and the transformation function F_g for soil fertility.

Transformation functions F_j for production goods

Pork production

Many kinds of feed components can be used in pork production and they can be combined in many ways. A number of carbohydrate feeds such as corn, barley, or wheat can be substituted for each other and used in combination. Animal proteins and vegetable proteins such as soybean oilmeals, linseed oilmeals, and cottonseed oilmeals can also be substituted for each other or used in combination (Heady and Dillon, 1961). In Heady and Dillon (1961) a Cobb-Douglas or a quadratic function is recommended for liveweight per pig.

Since the best combination of carbohydrates and proteins for liveweight has become clear over time, we have now a relatively fixed feed composition (compound feed or concentrated feed) in pork production. We will not discuss the substitution between feed components, but rather focus on the relation between liveweight and feed input. The liveweight per pig is an exponential function of corn input when protein input is fixed[1]. In our example, we have one plant producer who provides crop (i.e. feed) to the pork producer; we also follow this relation in representation of pork production technology. Pork production needs labour and capital as factor inputs. We describe them in a Constant Elasticity of Substitution (CES) functional form. Since there is no substitution between feed input and factor input for pork production, (simply because pigs must eat), we use a Leontief functional form to describe the technology. The total output of pork depends on the production input per pig and the number of pigs. We have the following production function:

$$q_1 = a_1 f_D^{\ 0.696},$$

$$Q_1 = n \min\{q_1, [a_{11} k_1^{-\rho_1} + a_{12} l_{B1}^{-\rho_1}]^{-\frac{1}{\rho_1}}\},$$

where q_1 is the liveweight (kg per pig), f_D is the feed input (kg). Q_1 is the total output of pork sector, and n is the number of pigs; a_1, a_{11}, a_{12} and ρ_1 are parameters. k_1 and l_{B1} indicate respectively capital and labour use per pig production. The transformation function is then:

$$F_1(Q_1, -n, -f_D, -k_1, -l_{B1}) = Q_1 - n \min\{q_1(f_D), [a_{11} k_1^{-\rho_1} + a_{12} l_{B1}^{-\rho_1}]^{-\frac{1}{\rho_1}}\}.$$

It is strictly quasi-convex because q_1 is an exponential function of f_D, and the composite of other inputs is a CES function. Then the term $n \min\{q_1, [a_{11} k_1^{-\rho_1} + a_{12} l_{B1}^{-\rho_1}]^{-\frac{1}{\rho_1}}\}$ is an extended concave function of a Leontief function[2] (cf. GK, 2002, Appendix, Theorem 1.5).

Crop production

Crops cannot simply be produced in a 'factory,' because agriculture uses the so-called environmentally interactive technologies (Weaver, 1998). Different yields can be attained with different combinations of nutrients such as *N*, P_2O_5 and K_2O. In the chemical processes of the plant one element of nutrients may not be substituted for another (Heady and Dillon, 1961). Many model applications on nutrient availability and plant growth concern agriculture species, and apply only to single nutrients (Mohren and Ilvesniemi, 1995). So far the nutrients considered are mostly *nitrogen* (N), with some attention to magnesium and potassium. Because nitrogen is a bulk element stored in soil organic matter, it is often the most limiting element and easily lost via leaching or denitrification. With fertilisers as nutrient inputs, plant scientists have obtained yield response functions with respect to nutrients.

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[1] For classical literature see e.g. Heady, 1952 and for more recent literature, see e.g. Gardebroek, 2001.

[2] Exponential function, CES function and Leontief function are concave functions, therefore the set of the dependent variables of these functions are convex.

The yield response to the quantity of nutrients can be expressed as a Spillman equation which is an exponential equation, see Heady & Dillon, 1961:

$$Y = M - AR^x,$$

where M is the maximum total yield by increasing the nutrient input x, A is a constant defining the maximum response attainable from use of x, and R is the coefficient defining the ratio by which marginal productivity of x declines. Figure 3-3 shows an empirical example of the potato yield response with respect to nitrogen uptake. It represents an exponential equation:

$$Y = 1942 - 1900 * 0.95^X,$$

where X is the N uptake (g m^{-2}) and Y is the dry matter (DM) production (g m^{-2}). N uptake of crop depends on the availability of nitrogen in soil, which is a sum of natural N in soil f_s and N supply (artificial fertilisers added to the soil) f_f. For simplicity, the N uptake (X), can be expressed as a percentage[3] of available nitrogen ($f_s + f_f$). Soil fertility and fertiliser input are perfect substitutes in this case. Therefore the potato yield function can be expressed as: $q_2 = 1942 - 1900 * 0.95^{E(f_s + f_f)}$, where E is the efficiency rate. Figure 3-4 is another example showing the yield response of oats to the nitrogen availability.

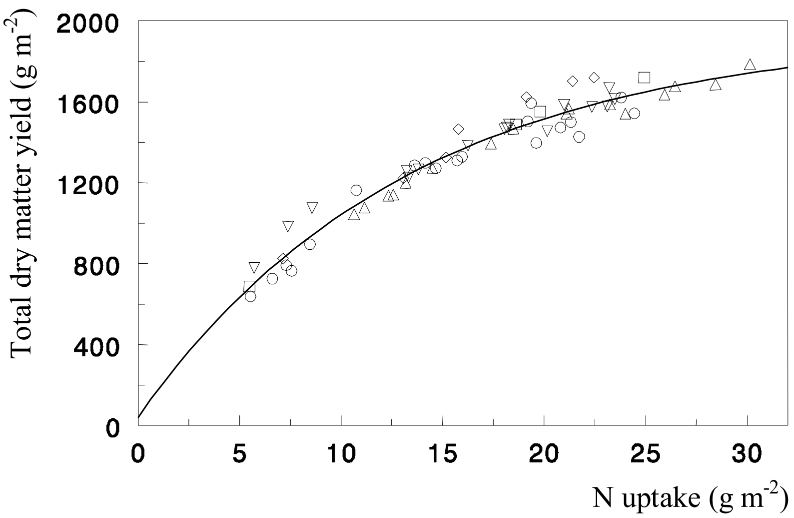

Figure 3-3 Total dry matter production of potato at crop maturity as a function of the total uptake of N (Source: Vos, 1997).

Plant production also needs other inputs (i.e. capital and labour), and fixed capital and labour inputs can be specified per hectare of land. The production function for crop is thus a Leontief function between yield (depending on soil fertility and fertiliser input) and other inputs because of the fixed proportions.

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[3] Strictly speaking, the maximum uptake rate of available nitrogen is only 70%. The uptake rate is also dependent on the level of nitrogen. The higher the level of nitrogen, the lower the uptake rates. We use a 60% uptake rate of available nitrogen in our numerical example.

The production function of crop production is written as:

$$Q_2 = L_{D2} \min(q_2, z_2),$$

where Q_2 is the total output of crop, L_{D2} is the land used for crop production (hectare), z is a composite of capital k_2 and labour l_{B2} per ha, which can be specified as

$$z_2 = [a_{21} k_2^{-\rho} + a_{22} l_{B2}^{-\rho}]^{-\frac{1}{\rho}}.$$

The transformation function of F_2 $(Q_2,\ -q_2,\ -z_2) = Q_2 - L_{D2} \min(q_2, z_2)$ is *strictly quasi-convex* because the Leontief function is concave and $L_{D2} \min(q_2, z_2)$ is an extended concave function (see Appendix of GK, 2002,). At lower levels of q_2 and z_2, they are concave functions because of exponential function q_2 and CES function z_2.

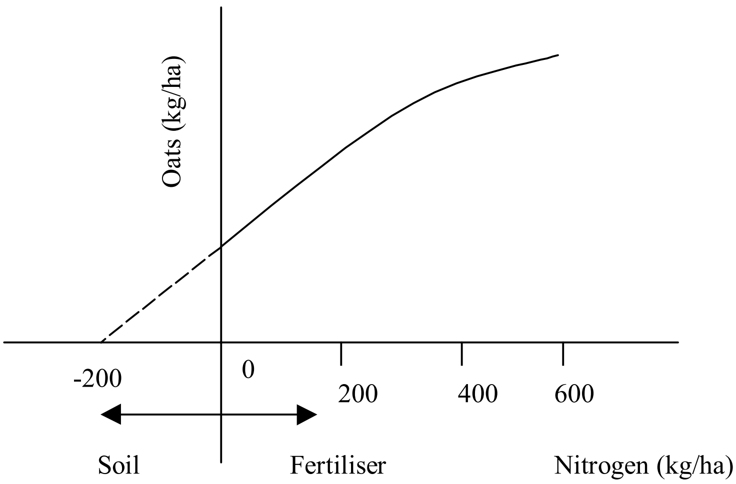

Figure 3-4 Nitrogen response curve of oats with respect to nitrogen (Source: de Wit, 1992)

<u>Fertiliser and other-goods production</u>

The production functions of other-goods and fertiliser have the standard Cobb-Douglas functional form. The transformation functions are:

$$F_3(Q_3, -K_3, -L_{B3}, -L_{D3}) = Q_3 - A_3 K_3^{\alpha_3} L_{B3}^{\beta_3} L_{D3}^{1-\alpha_3-\beta_3},$$

$$F_4(Q_4, -K_4, -L_{B4}) = Q_4 - A_4 K_4^{\alpha_4} L_{B4}^{1-\alpha_4}.$$

Similarly Q indicates total output, K capital use, L_B labour use and L_D land use; subscript 3 indicates other-goods and 4 indicates fertiliser. They are convex transformation functions. That is, F_3 and F_4 are strictly quasi-convex.

Transformation function F_g for soil fertility

The processes involved in soil acidification include various buffering mechanisms such as weathering of carbonates, silicates and aluminium hydroxides, and base cation exchange.

Depletion of these buffers leads to a decrease in soil pH, a decrease in base cation availability, and an increase in aluminium concentrations in the soil solution. Decreased root uptake of base cation in this situation may be caused by a decreased availability in the soil, or by restricted root uptake capacity in the presence of high aluminium concentrations, or by both (Mohren and Ilvesniemi, 1995).

The transformation function of soil fertility is a function of emissions from pork production. For the focus of the model approach, rather than a comprehensive soil model we use the steady state of soil dynamics[4] for analysis. Soil base saturation (*B*) is defined as the *fraction* of exchangeable base cations in the solid phase of a soil. *B* is a chemical soil parameter that can be considered as a soil quality indicator for acidification. It indicates the availability of nutrients in the soil and this availability of nutrients influences growth of forests and other vegetation (Schmieman, 2001). Although pH of a soil, or *Al* concentration in a soil, could be other indicators for soil acidification, we use the base saturation ($0 < B \leq 1$) because it directly indicates the availability of nutrients in soil, and thus impacts on the growth of crops. Then, the relationship between base saturation (*B*) and deposition of acidity (*D*) is specified as, $B = e^{-\frac{\gamma D}{\beta}}$.

In this simplified soil acidification model, we consider that the deposition of acidity comes from the ammonia emissions from pork production *H*. Although higher *B* indicates higher availability of nutrients, uptake efficiency is lower with higher level of nutrients (Vos, 2004). Since *B* indicates the soil nutrients available in a relative term, we need another indicator for the nutrients that can be absorbed by crops. For this, we define an indicator called 'soil fertility' (kg/ha), which indicates the nutrient uptake by crops. We simplify the series of acidification processes to a direct effect of soil acidification on soil fertility. We express soil fertility as a function of *B*, just like that yield is a convex-concave function[5] of pH in Figure 3-2. The simplified model then looks like:

$$
\begin{aligned}
&H = cQ_1 \\
&D = H / A \\
&B = e^{-\frac{\gamma D}{\beta}} \\
&f_s = y_g^+ = a_0 \frac{B^2}{1+B^2}
\end{aligned}
\qquad (3\text{-}2)
$$

[4] The state equation for soil base saturation can be described by: $\dot{B}(t) = -\beta B(t) \ln B(t) - \gamma D(t) B(t)$, where *D* is the deposition of acidity (acidity kg/ha), γ and β are soil acidification parameters depending on the soil property. For the steady state, $\dot{B}(t) = 0$. Therefore, dropping the subscript of *t*, we have $B = e^{-\frac{\gamma D}{\beta}}$.

[5] We adapt the functional form of a convex-concave function from Dasgupta and Mäler, 2004.

where A is the area in which ammonia emission deposits[6], and y_g^+ or f_s is the soil fertility[7] influenced by acidification. Parameter c is the emission coefficient, a_0 is soil parameter indicating the soil contents of nutrients such as N, P and K. Without acidification, B = 1 and $f_s = f_0 = \frac{1}{2}a_0$; if serious acidification occurs, B is close to zero and f_s is close to zero. Figure 3-5 gives the graphical representation of the function.

In this soil acidification model, f_s is actually a function of pork production Q_1 (or emission from pork H) following the relevant biophysical laws: $f_s = f_g(Q_1)$. So far we have obtained all the equations needed for the transformation function of $F_g\ (f_s,\ -Q_1)$. We now check the convexity of f_s with respect to Q_1 before checking the convexity of $F_g(f_s,\ -Q_1) = f_s - f_g(Q_1)$. By using second order conditions, we can prove that $F_g(f_s,\ -Q_1) = f_s - f_g(Q_1)$ is non-convex because $\frac{\partial^2 f_s}{\partial {Q_1}^2} \geq 0$ (See Appendix 3-A for the proof). That is, F_g is not strictly quasi-convex.

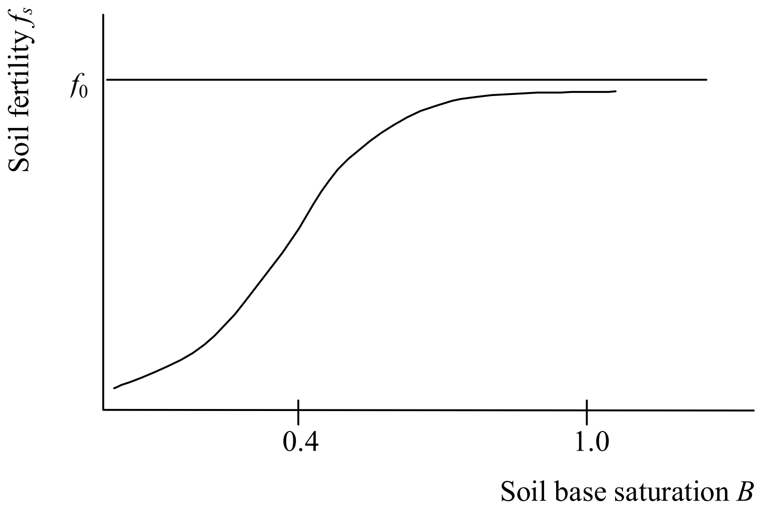

Figure 3-5 Relationship between soil base saturation (B) and soil fertility (f_s)

For welfare program (3-1), we have strictly quasi-convex transformation functions of F_j (.) (j = 1, 2, 3 and 4) but non-convex transformation $F_g(f_s, -Q_1)$. Therefore the welfare program is a non-convex welfare program.

We specify the welfare program as follows. For the consistency of notation, three consumption goods (pork, food and other-goods) are denoted as scalar C_1, C_2 and C_3; four

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6 If NH_3 deposits in all the land $\overline{A}$, we can reduce the model to: $f_s = a_0 \frac{(e^{-\frac{\gamma a Q_1}{\beta}})^2}{1+(e^{-\frac{\gamma a Q_1}{\beta}})^2}$, where $a = \frac{c}{\overline{A}}$.

7 The original notation in welfare program (3-1) is y_g^+ but in this specification we use f_s for a clear explanation.

production goods (pork, crop, other-goods and fertiliser) are denoted as Q_1, Q_2, Q_3 and Q_4. We also denote soil fertility as Q_g in its production technology presentation (output by soil acidification process), f_s as the input of soil fertility, f_f as the fertiliser input for crop production, and f_d as the input of feed in pork production. Production factors include capital K, labour L_B and land L_D. For production of pork, the function q_1 is not homogenous of degree one. In order to derive farm accounts, we proceed as in Keyzer (2000) and Albersen et al. (2003), and introduce a fixed factor n_q in q_1 for homogeneity. We assign a unit quantity for this fixed factor and retrieve its shadow price π_q, which indicates the payment to the fixed factor. The variables with a bar above are the exogenous variables.

The model reads:

$$\max \sum_i \alpha_i u_i(x_i), \tag{3-3}$$

$$x_i \geq 0 \,\text{all}\, i, y_g^+ \geq 0, f_s \geq 0, y_j^+ \geq 0, y_j^- \geq 0 \,\text{all}\, j,$$

subject to

$$\sum_i x_i - \sum_j y_j \leq \sum_i \omega_i \qquad (p),$$

$$f_s = y_g^+ \qquad (\psi),$$

$$F_j(y_j, -f_s) \leq 0, j = \text{crop},$$

$$F_j(y_j) \leq 0, j \neq \text{crop}, j = \text{pork, other goods, fetiliser},$$

$$F_g(y_g^+, \sum_j y_j^+) \leq 0, j = \text{pork},$$

where the vectors indicating:

$$x = \begin{Bmatrix} C_1 \\ C_2 \\ C_3 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}, \; y = \begin{Bmatrix} Q_1 \\ Q_2 - f_d \\ Q_3 \\ Q_4 - f_f \\ y_g^{+} - f_s \\ -(K_1 + K_2 + K_3 + K_4) \\ -(L_{B1} + L_{B2} + L_{B3} + L_{B4}) \\ -(L_{D2} + L_{D3}) \end{Bmatrix} \text{ and } \omega = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \bar{K} \\ \bar{L}_B \\ \bar{A} \end{Bmatrix}.$$

To use the scalar as the notation, we have the specified model:

$$\max C_1^{\mu_1} C_2^{\mu_2} C_3^{(1-\mu_1-\mu_2)}$$

$$C_1, C_2, C_3 \geq 0, Q_1, Q_2, Q_3, Q_4 \geq 0, f_s > 0, Q_g > 0, \tag{3-4}$$

subject to

$$C_1 - Q_1 \le 0 \qquad (p_1),$$

$$C_2 + f_D - Q_2 \le 0 \qquad (p_2),$$

$$C_3 - Q_3 \le 0 \qquad (p_3),$$

$$f_f - Q_4 \le 0 \qquad (p_4),$$

$$K_1 + K_2 + K_3 + K_4 \le \overline{K} \qquad (r_K),$$

$$L_{B1} + L_{B2} + L_{B3} + L_{B4} \le \overline{L}_B \qquad (r_L),$$

$$L_{D2} + L_{D3} \le \overline{A} \qquad (r_D),$$

$$f_s = Q_g \qquad (\psi),$$

$$H = cQ_1 \qquad (\mu),$$

$$n_q = 1 \qquad (\pi_q),$$

$$Q_1 - n\min\{2.12 f_D^{\ 0.7} n_q^{\ 0.3}, A_1[a_{11}k_1^{\ -\rho_1} + a_{12}l_{B1}^{\ -\rho_1}]^{-\frac{1}{\rho_1}}\} \le 0,$$

$$Q_2 - L_{D2}\min\{[19420 - 19000 * 0.95^{(f_s+f_f)/10}], A_2[a_{21}k_2^{\ -\rho_2} + a_{22}l_{B2}^{\ -\rho_2}]^{-\frac{1}{\rho_2}}\} \le 0,$$

$$Q_3 - A_3 K_3^{\alpha_3} L_{B3}^{\beta_3} L_{D3}^{1-\alpha_3-\beta_3} \le 0,$$

$$Q_4 - A_4 K_4^{\alpha_4} L_{B4}^{1-\alpha_4} \le 0,$$

$$Q_g = a_0 \frac{(e^{-\frac{\gamma}{\beta}\frac{cQ_1}{\overline{A}}})^2}{1 + (e^{-\frac{\gamma}{\beta}\frac{cQ_1}{\overline{A}}})^2},$$

$$K_1 = nk_1,$$

$$L_{B1} = nl_{B1},$$

$$K_2 = L_{D2}k_2,$$

$$L_{B2} = L_{D2}l_{B2}.$$

We have checked that this welfare program is non-convex by the second order conditions. This kind of non-convexity is called above-firm level non-convexity, since non-convexity arises from the by-product of activities in other sectors (i.e. manure in the pork sector). Different levels of non-convexity in welfare programs have different implications. Some non-convex problems (e.g. if both F_j and F_g are non-convex) cannot be solved because the non-convexities can by no means be excluded. Some others (e.g. only F_g is non-convex), however, might be solvable because then a numerical method can be applied. For our problem we have convex F_j but non-convex F_g, and the problem is thus solvable (GK, 2002). We discuss how to solve this type of non-convexity in what follows.

A numerical solution to the welfare program in a general equilibrium model setting

In the welfare program (3.1), if F_j is strictly quasi-convex but F_g is not, the program is still non-convex. Non-convexities enter the program through variables of y_g^+ and $\sum_j y_j^+$. For this non-convex program one may consider it as the convex program with y_g^+ and $\sum_j y_j^+$ entering as parameters rather than choice variables so that the non-convexity becomes irrelevant and decentralisation can be achieved. This treatment is called *convexification* via parameterisation. Since variables which bring non-convexity into the program are now given, they do not create discontinuity and thus equilibrium exists. The assumption for the existence of this equilibrium is that producers agree to pay the associated contributions for the use of non-rival goods y_g^+ by prices ψ_j (GK, 2002).

In our specified non-convex welfare program (3-4), the by-product $\sum_j y_j^+$ is the emission from pork production: $\sum_j y_j^+ = H = cQ_1$. For the use of non-rival good g: $g_j = y_g^+$, it is $f_s = Q_g$ in our model. In such a welfare program with a combination of non-rivalry of f_s and non-convexity of F_g, f_s has to be set centrally. This makes H (or Q_1) determined. Then we have program with f_s and thus Q_1 entering as a parameter rather than a choice variable. This program can be decentralised because the non-convexities enter the program through variables (f_s and Q_1) which are now given. They do not create discontinuity and then equilibrium exists. For given levels of emissions from pork production, Q_1 and f_s are given. Then the non-convexity becomes irrelevant. By solving the welfare programs for different levels of emission (H) or soil fertility (f_s), one can obtain a series of equilibria and find the optimal level of production and consumption over the range of parameterised emission levels.

The requirement for the feasible equilibrium in a welfare program with non-rivalry constraint is that producers, who use non-rival inputs, agree to pay the associated contributions for non-rival goods y_g^+ by prices ψ_j. That is, no free-riding occurs for the use of non-rival goods. In our welfare program, we attribute the property right of soil fertility to the consumer for the sake of the functioning of the market mechanism. The crop producer uses soil fertility as a direct input for his production, therefore payment from the crop producer for the utilisation of the non-rival soil fertility (combined with land) is made to the owner of soil fertility[8]. The

[8] In the model the consumers not only own the usual endowments such as capital and labour but also the natural endowments.

pork producer emits ammonia for his production, which decreases the soil fertility. This actually means that the pork producer also uses soil fertility for his production. Therefore the pork producer should also pay for the indirect use of soil fertility. This payment is made in the form of compensation to the crop producer. By pricing the soil fertility, the compensation can be made. In such a setting, the welfare program has an optimal solution.

Given the exogenous level of capital, labour and land, and given utility functions and production functions with existing parameters, we can find the optimal solution to the welfare program analytically or numerically. For the analytical solution we can use first-order conditions and for the numerical solution we can use the software GAMS for this non-convex program. Since there are already many variables involved in this small example, it will be difficult to solve it analytically. Instead we employ GAMS for the numerical solution. As we are now solving a non-convex program, we will not simply put the welfare program in its current state in GAMS. We have discussed that some non-convex elements have to be set centrally, thus we will fix these non-convex elements in the program. After comparing the different levels of welfare with respect to different levels of the centrally determined elements (i.e. the fixed elements), we can obtain the optimal solution. This is the 'parametric approach,' or scenario analysis. Since the non-convex elements are now parameters, the welfare program is convex and will adapt to the variations of the parameters to reach a unique equilibrium for each set of values of parameters. We call it scenario analysis because the values of parameters are discretely given at a certain range and each combination of the values is a 'scenario.'

For the numerical example, we set some exogenous variables and parameters (Table 3-1) for the program (3-4). We scan the optimal solution over the range of 0 to 200 kg/ha of soil fertility. For given levels of the non-convex element (i.e. soil fertility), we depict a graph with the relation between levels of soil fertility and welfare. This drawing shows a local optimum (see Figure 3-6). We only depict the feasible solutions over the range for their relevance. When the emission level is very high, we have a lot of pork production but then soil fertility is very low. This will result in very low crop production. This is infeasible because consumers have a utility function, which demands both pork and crop. Similarly, if the emission level is very low, pork production will be very low. Then soil fertility is high and a lot of crop can be produced. The utility function requires both crop and pork and therefore, a low emission level is not feasible.

Table 3-1 Exogenous parameters used in the model

Economic parameters	Soil process parameters
μ_1=0.15, μ_2=0.25;	c=200 kg NH_3/ton pork
$\bar{K}$=25000 k €, $\bar{L}_B$=40000 k hours, $\bar{A}$=1000 hectares;	a_0=400 kg/ha
ρ_1=ρ_2= -0.25 (or σ_1=σ_2=0.8);	γ=0.0001;
A_1=1.0, A_2=2.0, A_3=1.0, A_4=4.0;	β=0.015.
a_{11}=0.5, a_{12}=0.5, a_{21}=0.5, a_{22}=0.5; α_3=0.3, β_3=0.3, α_4=0.4.	

The solution shows that at the soil fertility f_s=123.5 kg/ha, the welfare program gives the highest total welfare. This is the optimal level of the soil fertility in the range of $0 < f_s \leq 200$ kg/ha (or $0 < B \leq 1$). Corresponding to this level of soil fertility, the emission level from pork production in our example is 60.448 ton; and the soil base saturation is 0.668. The commodity account in quantities and their prices are shown in Table 3-2, which shows how much is used as input for production and for consumption, and how much is supplied for each commodity. For example, the supply of crop is 4891 ton, whereas 743 ton is used as feed for pork production and 4148 ton is used for consumption.

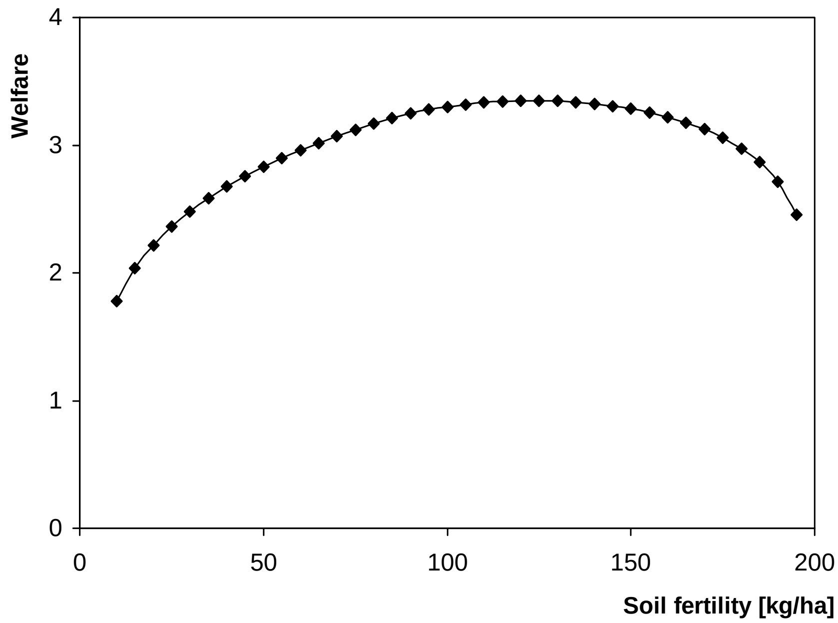


Figure 3-6 Relation between soil fertility and welfare

Table 3-2 Commodity account in quantities and their prices

	Input				Consumption	Supply	Price
	Pork	Crop	Other-goods	Fertiliser			
Pork (ton)					302	302	101.065
Crop (ton)	743				4148	4891	12.274
Manure (ton)						60	342.000
Other-goods (ton)					5588	5588	21.867
Fertiliser (ton)		9				9	0.653
Capital (k €)	251	2029	22718	2		25000	1.613
Labour (k hrs)	368	2975	36655	2		40000	1.000
Land (ha)		524	476			1000	102.655

In this economy, the consumer maximises utility and the two farms maximise profits if decentralisation is possible. The consumer solves:

$$\max C_1^{\mu_1} C_2^{\mu_2} C_3^{(1-\mu_1-\mu_2)},$$

subject to,

$$p_1 C_1 + p_2 C_2 + p_3 C_3 \leq r_K \bar{K} + r_L \bar{L}_B + r_D \bar{A}.$$

Our interest is on the interaction between pork and crop farms. Therefore, we specify the maximisation problems of pork and crop farms. The pork farm solves:

$$\Pi_1(p_1, p_2, r_L, r_K, \mu) = \max_{Q_1, f_D, L_{B1,} K_1, H} (p_1 Q_1 - p_2 f_D - r_L L_{B1} - r_K K_1 - \mu H),$$

while the crop farm solves:

$$\Pi_2(p_2, \mu) = \max_{Q_2, f_f, f_s, L_{B2}, L_{D2}, K, H} (p_2 Q_2 + \mu H - p_4 f_f - r_D L_{D2} - r_L L_{B2} - r_K K_2).$$

We report the accounts for the pork farm, crop farm and consumer in Tables 3-3a, b and c. In the tables, the left columns show the revenues and the right columns the expenditures of the farms.

Table 3-3a Revenue and expenditure Pork farm

Revenue		Expenditure	
Pork sales	30546	Feed expenditure	9126
		Compensation to crop farmers	16736
		Factor payment: labour	368
		Factor payment: equipment	405
		Fixed factor payment n_q	3911
Total	30546		30546

Table 3-3b Revenue and expenditure Crop farm

Revenue		Expenditure	
Crop sales	60036	Fertiliser expenditure	6
Compensation from pork farms	16736	Factor payment: land including soil	70517
		Factor payment: labour	2975
		Factor payment: equipment	3274
Total	76772		76772

Table 3-3c Income and expenditure Consumer

Income		Expenditure	
Labour	40000	Pork	30522
Capital	40325	Crop	50912
Land	119361	Other-goods	122193
Fixed factor return	3911		
Total	203627		203627

In the pork farm, the revenue (30546) comes from the sale of pork and expenditures are due to feed purchase (9126), payment to labour (368), to equipment (405), and to fixed factor (3911). In addition, the pork farm decreases soil fertility via emissions, and therefore the crop farm must be paid for the negative impacts on crop production. This payment from the pork farm to the crop farm is 16736. After such payment, the pork farm has non-negativity of profit because the pork farm has the possibility of inaction. In the crop farm, the revenues (76772) are from the sales of crop (60036) and from the compensation received from the pork farm (16736). The expenditures are from fertiliser purchase (6), payment to labour (2975), equipment (3274) and land (70517).

On the consumer side, the consumer will spend 30522 on pork consumption, 50912 on crop consumption and 122193 on consumption of other-goods using his total income of 203627. This model shows an economic situation where pork production is intensive and has negative impact on soil fertility, and thus on plant production. In this economy, manure is not used as a direct organic fertiliser, rather manure has negative impacts on soil fertility due to acidification. The crop producer uses both chemical fertilisers and soil fertility as input for his production. Though we have taken potato as the example for a plant, the model can be extended to other plants as well, or to a forest. A central planner could aim to obtain an optimal production structure to achieve the highest welfare when the interaction between animal and plant production is considered.

Thus far we have shown how to deal with above-firm non-convexity, which is caused by the production technology of soil fertility y_g^+, by parameterisation in a general equilibrium model. Non-convexities are caused by ‘no free disposal’ of manure. Manure is excreted by pigs and the related NH_3 emissions deposit in soil and change soil acidity. This change in soil acidity influences the soil nutrients available for crop production and reduce crop yield. Manure cannot be disposed of freely because crops have a locally decreasing growth response due to soil acidification. Non-convexities of soil acidification probably have different impacts on the economy depending on the economic and soil conditions. In the following section we will show how different cases (reflecting different economies) with non-convexities have different implications for the outcomes of the welfare models. Although the model in this section could be classified into one of the cases in the next section, we keep it separate because it shows a more general model setting (i.e. a general equilibrium model setting).

3.4 Dealing with non-convexities in different cases

In Section 3.3 we have shown how to solve a non-convex model, which represents an economy with one consumer, three production factors, four production goods and three consumption goods. In this section we further show how to deal with the non-convexities caused by the lack of free disposal of manure in different circumstances, which reflects *different types of economies*. For the focus of this discussion in order to show the mechanism of dealing with non-convexities, we use a simpler model setting than that in Section 3.3. The economy, which can be thought of as a village, consists of two producers (the pork producer and crop producer) and one consumer. The consumer consumes two goods produced by two producers, pork and crop. The production technology of the pork producer is to use feed as input to produce pork and also to generate manure emission. The crop producer uses land and soil fertility to produce crop. Manure emissions have impacts on the crop production as manure negatively influences soil fertility if acidification occurs, or positively if used as organic fertiliser for crop production. As such, there are interactions between pork and crop production. The interaction between pork production and crop production depends on the circumstance, for example, how pork is produced, what crop is produced and what the soil condition is. Therefore, we wish to show a set of cases which reflect different situations that can be relevant in reality.

In different cases we have similar economic agents (i.e. a consumer, pork farmer and crop farmer) and production factors (e.g. land), but we may change the endowment or use different yield functions to illustrate different impacts of soil acidification, and to create different settings for the non-convexities. Case 1 considers an economy in which all land has to be cultivated, and acidification occurs on all land. We also distinguish if feed is purchased externally (Case 1-1) or from the crop producer (Case 1-2). In Case 1-3 we reduce the land size and use different crop yield functions to show crops that response to soil acidification differently. Case 2 considers situations in which only cultivated land is affected by manure and manure has negative or positive impacts on crops but fallow for crop production is allowed. In Case 2-1, manure-caused acidification only occurs on the cultivated land. In Case 2-2, manure is scarce and used as an organic fertiliser for crops on cultivated land in a developing economy. Case 3 considers a setting in which all land is affected by acidification but fallow is possible. Case 4 considers a case in which manure can be disposed of at a cost by using machinery, or other technology to reduce the acidification impact on crop production. Detailed distinctions between the cases are listed in Table 3-4. Since non-convexities are caused by the lack of free disposal of manure, we can scan the optimal solution over a certain range of manure emissions (e.g. parameterisation of emission levels).

Case 1 Acidification and cultivation occurs on all land

In this simplified economy, the pork producer produces pork and at the same time generates manure. The manure emits NH_3 (denoted as *H*) which contributes to soil acidification in the area (all the land $\overline{A}$) where the emissions deposit. Crops are cultivated in this land and have a positive yield function *y*(*h*), where $h = H / \overline{A}$. The consumer maximises his utility by choosing the consumption quantity of pork and crop under the given prices. We study the following subcases one by one.

Table 3-4 Technical parameters and settings used in different cases[9]

Cases	Technical parameters
Case 1-1	$\bar{A}$=1000 hectares; Crop cultivation and acidification occurs on all land ($A=\bar{A}$); Feed (composite product) is purchased at given price (0.1); Crop yield function: y=(19420-19000$\times 0.95^{f_s}$).
Case 1-2	Similar to Case 1-1 but crop is used as feed of pig.
Case 1-3a	Similar to Case 1-1 but $\bar{A}$=250 ha, and crop yield function is: $y=20000-19000\times 0.992^{f_s}$
Case 1-3b	Similar to Case 1-3 a but crop yield function is: $y=20000-19000\times 0.995^{f_s}$
Case 2-1	Similar to Case 1-1 but cultivation and acidification does not necessarily occur on all land ($A\le\bar{A}$)
Case 2-2 a	Similar to Case 1-1 but Manure is an organic fertiliser on cultivated land ($A\le\bar{A}$), Crop yield function: $y=19435-19450\times 0.99^{f}$.
Case 2-2 b	Similar to Case 2-2 a but with calorie constraints: $\delta_{pork}C_{pork}+\delta_{crop}C_{crop}\ge Tcal$.
Case 3	Combined Case 1-1 and Case 2-1. Acidification occurs on all land $\bar{A}$ but cultivation does not necessarily occur on all land ($A\le\bar{A}$).
Case 4-1	Similar to Case 1-1 but purification is possible at price (0.015)
Case 4-2	Similar to Case 4-1 but purification is possible at price (1.0)

Case1-1 Feed is purchased at a given price

In this economy, consider a utility function: $U(X_q,X_y)=X_q^{0.3}X_y^{0.7}$, where X_q is the consumption of pork and X_y is the consumption of crop. The consumer's problem is to maximise utility, which can be expressed by:

$$\max_{X_q,X_y\ge 0} X_q^{0.3}X_y^{0.7},$$

subject to

$$p_qX_q+p_yX_y\le I,$$

where p_q is the price of pork, p_y is the price of crops and I is his income, which comes from the sales of endowments and distributed profits in firms (see Chapter 2).

[9] The model in Section 3.3 is different from any of the following cases. It is similar to Case 1-2 in the sense that crop is used for feed as well. It is different from Case 1-2 because cultivation is not necessarily on all land. It is similar to Case 3 in the sense that acidification occurs on all land but cultivation does not necessarily occur on all land. It is different from Case 3 in the sense that crop is also used as feed.

The producer's problem is to maximise profit of producing pigs and crops and it can be expressed as a profit function:

$$\Pi(p_q, p_y, p_f) = \max_{F\geq 0} p_q Q(F) + p_y y(H(F)/\overline{A})\overline{A} - p_f F \ ,$$

subject to production technology. We express the production technology with production functions of pork including emissions and crop yield as follows:

$$Q = 3F^{0.9} \ ,$$

$$H = 1.5F^{0.7} \ ,$$

$$y = (19420\text{-}19000 \times 0.95^{f_s}) \ .$$

The yield function of crop depends on the soil fertility, which is determined by the soil biophysical process. This process is influenced by the NH_3 emissions from the manure of pork production. The following relations are relevant:

$$h = D = H / \overline{A} \ ,$$

$$B = e^{-\frac{\gamma D}{\beta}} \ ,$$

$$f_s = a_0 \frac{B^2}{1+B^2} \ ,$$

where D is the deposition per hectare, B is the soil base saturation indicating soil nutrients availability in fraction influenced by acidification, f_s (kg/ha) is the nutrients per unit of area that can be taken up by crops (i.e. soil fertility), and a_0 is the soil parameter indicating the soil contents of *N*, *P* and *K*.

Q is strictly concave increasing and *H* is as well (in this numerical example, *H* is also strictly concave increasing), but $y(h)$ is possibly not concave everywhere because of soil acidification. The non-concavity of *y* in this model may bring non-convexity to the program. Depending on the extent of the non-concavity of *y* and the concavity of *Q*, the combination of these two may or may not pose a problem for a unique optimal solution. Since *F* is a choice variable, the optimal solution to this model can be obtained by scanning over *F*. The scanning over *F* in a certain range avoids the non-convexity because scanning over *F* is just equivalent to setting it as a parameter. If *F* is set as a parameter, then the emission also becomes a parameter and thus the soil fertility (nutrients uptake) *fs* in yield function becomes a parameter. Then the non-convexity caused by soil acidification in yield function $\tilde{y}(h) = y(f_s(h))$ is eliminated.

Alternatively, for the operational purpose we can also treat emissions *H* (from manure) as the key variable because a direct relation between *H* and *F* exists. Then the producer's problem reads:

$$\Pi(p_q, p_y, p_f) = \max_{H\geq 0} p_q \tilde{Q}(H) + p_y y(H/\overline{A})\overline{A} - p_f F(H). \tag{3-5}$$

Then we can scan over H to find the optimal solution.

Now we present the consumer's problem and the producers' problem in a welfare program. To derive the farm accounts, we again proceed as in Keyzer (2000) and Albersen *et al.* (2003), and explicate the fixed factors in the functions that are not homogenous of degree one. We assign a unit value to each fixed factor, denoted by the scale variable n_q or n_f.

Since feed is purchased from outside, or feed is an external good, the objective of the economy is to maximise consumer utility and to minimise the cost of purchasing the external good. Therefore the objective of this economy can be presented by:

$$\max_{H,\tilde{H},X_q,X_y,A,F,D,B,f_s\geq 0}\left[X_q^{\ 0.3}X_y^{\ 0.7}-p_fF\right], \tag{3-6}$$

subject to

$$X_q = Q \qquad (p_q),$$

$$X_y = yA \qquad (p_y),$$

$$Q = 3F^{0.9}n_q^{\ 0.1},$$

$$H = 1.5F^{0.7}n_f^{\ 0.3},$$

$$y\text{=(19420-19000}\times 0.95^{f_s}),$$

$$D = H/A,$$

$$B = e^{-\frac{\gamma D}{\beta}},$$

$$f_s = a_0\frac{B^2}{1+B^2},$$

$$A = \bar{A} \qquad (\pi_a),$$

$$n_q = 1 \qquad (\pi_q),$$

$$n_f = 1 \qquad (\pi_f),$$

$$H = \tilde{H} \qquad (\mu).$$

For the pork farm we use the Euler's rule to obtain the value exhaustion for the homogeneity of production function: $p_qQ=\pi_q+\pi_f+p_fF+\mu\tilde{H}$, where μ is the Pigovian price of manure and $\mu\tilde{H}$ is the compensation that the pork farm makes to the crop producer when acidification occurs. For the crop farm, the value exhaustion is: $p_yyA+\mu\tilde{H}=\pi_a\bar{A}$. Since the production function of pork Q is concave and increasing, π_q is positive factor payment. We consider the decreasing return to scale for the emissions because of the possibility of absorption by some fixed equipment, and as such a non-linear relation between emissions and feed. Emission production function H is dependent on feed input F and fixed factor n_f, the payment π_f on n_f can be negative, indicating the absorption of emission by the fixed factor. A negative factor payment is called a handicap, which means that the owner gets a 'subsidy' for possessing the fixed factor.

The consumer maximises his utility, which is a function of two internal consumption goods (i.e. crop and pork). In deriving his accounts, we have to consider the trade balance of the feed import (external good), which is balanced by exporting pork. That is, pork is sold to the consumer (internally) and to the outside of the economy (externally).

For the welfare optimum, we have to check if it is decentralisable to each agent, that is, consumer and producer. The 'decentralisability' of the welfare program to the consumer can be checked by the budget constraint. If each consumer spends his income on consumption at the optimum, then it is decentralisable to the consumer. In this case, we check $p_q X_q + p_y X_y = I$, where $I = \pi_q + \pi_f + \pi_a \overline{A}$.

The 'decentralisability' of the welfare optimum to the producer is determined by the non-negativity of aggregate profit and individual profits of the two farms. First, the aggregate profit in this model is $\Pi = p_q X_q + p_y X_y - p_f F$. Decentralisability requires $\Pi \geq 0$. Second, we should check if the crop farmer chooses the same level of H as the pork producer. The pork farm then solves:

$$\Pi_q(p_q, p_f, \mu) = \max_{\breve{F}, H_q, n_f, n_q, Q \geq 0} p_q Q - p_f \breve{F} - \mu H_q$$

subject to

$$Q = 3F^{0.9} n_q^{\ 0.1},$$

$$H_q = 1.5 F^{0.7} n_f^{\ 0.3},$$

$$n_f = 1 \qquad (\pi_f),$$

$$n_q = 1 \qquad (\pi_q),$$

while the crop farm solves:

$$\Pi_y(p_y, \mu) = \max_{H_y, A, Y \geq 0} p_y Y + \mu H_y,$$

subject to

$$Y = (19420 - 19000 \times 0.95^{f_S(H_y/A)})A,$$

$$A = \overline{A} \qquad (\pi_a).$$

If $H_q = H_y$, then Pigovian pricing of manure disposal can be decentralised. Since the pork farm has a concave program the prices p_q and μ support its optimum. Profit Π_q will be non-negative because the pork farm has possibility of inaction. For the crop farm, there is non-concavity in the yield function. The crop farmer might choose a different level of output than the optimal one at the prices of p_y and μ. That is, he might not be willing to absorb exactly the quantity of manure delivered by the pork farm. If this is the case, then decentralisation by Pigovian pricing is not feasible, and policy intervention such as quantity controls, is needed. The second check for decentralisability is to check if the given prices provide the crop farm the highest profit Π_y.

We use the given parameters in Table 3-4 for solving the model (3-6) in GAMS. We scan over a range of 5 to 250 ton for emission *H* to find a series of equilibrium solutions corresponding to each *H*. The relation between *H* and welfare is drawn in Figure 3-7. The optimum allocation of commodities in quantities and their prices are shown in Table 3-5. We report accounts in value terms for the pork farm, crop farm and consumer in Table 3-6.

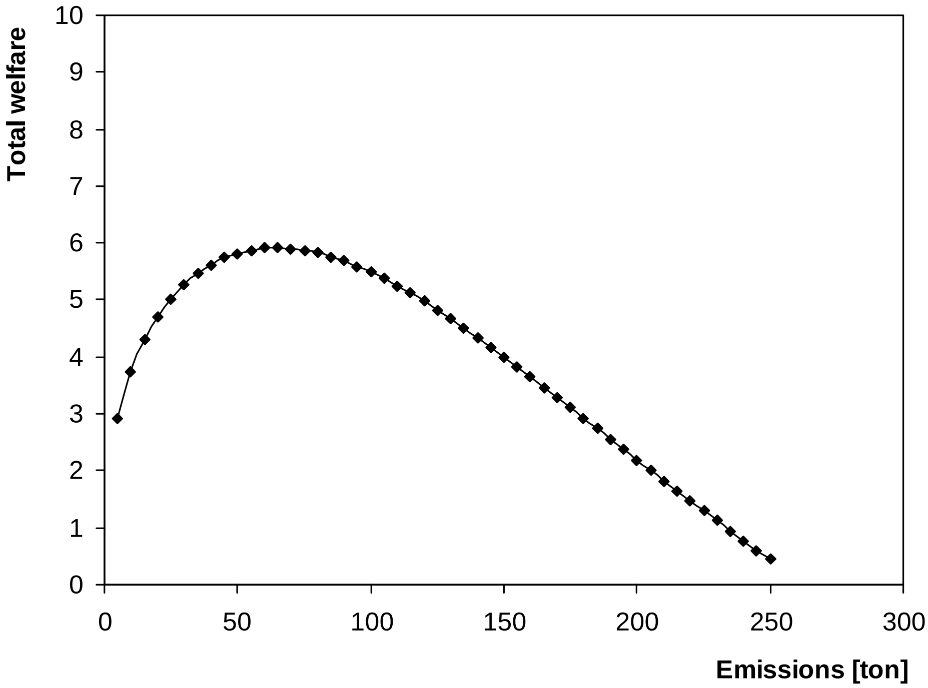


Figure 3-7 Relation between emission and total welfare for Case 1-1

Table 3-5 Commodity account in quantities and their prices for Case 1-1

	Input		Consumption	Supply	Price
	Pork	Crop			
Pork (ton)			2746	2746	0.692
Manure (ton)				65	28.355
Crop (ton)			9067	9067	0.489
Feed	4208			4208	0.1
Land (ha)		1000		1000	4.435

Table 3-6a Income and expenditure of consumer in Case 1-1

Income		Expenditure	
Land	6279	Pork	1480
Fixed factor n_q return	190	Crop	4436
Fixed factor n_f subsidy	-553		
Total	5916	Total	5916

Table 3-6b Revenue and expenditure Pork farm for Case 1-1

Revenue		Expenditure	
Pork sales	1901	Feed expenditure	421
		Payment on fixed factor n_q	190
		Payment on fixed factor n_f (handicap)	-553
		Compensation to crop farms	1843
Total	1901	Total	1901

Table 3-6c Revenue and expenditure Crop farm for Case 1-1

Revenue		Expenditure	
Crop sales	4436	Factor payment: land	6279
Compensation from pork farms	1843		
Total	6279	Total	6279

The result shows that the optimal solution is at the total emission level of 65 ton or at per hectare level of 65 kg/ha. This emission level gives the soil fertility level of 118 kg/ha. This also shows the optimal production structure and livestock intensity. The total pork production should be 2746 ton and crop production 9067 ton.

Table 3-6a shows the income and expenditure of consumer. The consumer earns income from his endowment of production factors (i.e. land, and fixed factors n_q and n_f), which is 6279, 190 and –553, respectively. In this case, the total pork sale is 1901, of which 421 is sold externally in order to obtain the same value of feed, while the remainder (1480) is internally sold to the consumer. The consumer will thus spend 1480 on pork consumption and 4436 on crop consumption from his income (5916) to maximise utility under the given prices.

Table 3-6b shows that the revenue of the pork farm is 1901 from sales of pork. The pork farm pays 421 for feed and 190 for fixed payment on pork production and saves 553 due to the absorption of emissions. For the negative impacts on the crop farm, compensation of 1843 is paid to the crop farm at Pigovian price ($\psi = 28.355$) for 65 ton of manure. Then the net profit of the pork farm is zero.

The revenue of the crop farm (Table 3-6c) is from selling crops (4436) and receiving compensation from the pork farm (1843). The expenditures of the crop producer, including paying for the land use and maintaining soil fertility for production (because it was polluted by the pork farm) are totally 6279 (Table 3-6b). Then its profit is zero.

Now we check the decentralisability of this solution. On the consumer side, expenditure (5916) is equal to his income (5916). On the producer side, our model result shows that aggregate profit is positive (5916>0). The crop farmer has the highest revenue (6285) when H=60 ton, which is similar to the welfare optimum (6279 for H=65 ton). Therefore, by Pigovian pricing of manure, the solution is decentralisable and thus efficient. We do not need additional policies to achieve a welfare optimum in a competitive market.

For a range of emission from 10 to 250 ton, the soil fertility is decreasing from about 187 to 14 kg/ha. It is interesting to look at the price development over this range for a better understanding of the mechanism. Table 3-7 shows the prices of pork, crop and emission as the emission changes over the range. As emission level is increasing, soil fertility is decreasing and thus the price of soil fertility increases. This means that the crop producer has to invest on the land for a reasonable soil condition to produce crops. As emission increases, the crop producer gets a lower yield and output due to lower soil fertility. As such the crop price becomes higher. Higher emissions also mean higher pork production. Therefore, the price of pork is decreasing with the increase of emission level. The Pigovian price of manure is changing from high to low (from positive to negative) if emission restrictions are increased. To allow a high emission level, the price of emission is negative, which means emission can be compensated. Restricting the emission to a low level leads to a high and positive emission price, which means the emission surplus should be taxed. As for the price of land, it is low at low emission levels (< 70 ton), because then acidification effects on land are not serious. But after a certain emission level, acidification gets stronger and land quality is lower, and as such, land becomes cheaper with the increase of emission. Around the optimum, the price of land is the highest.

Table 3-7 Price development over a range of emission from 5 to 250 ton for Case 1-1

Emission (ton)	Soil fertility (kg/ha)	Soil fertility	Pork	Crop	Manure	Land
250	14	123.058	0.064	1.355	-11.345	2.326
220	20	103.929	0.088	1.183	-8.806	2.710
190	29	85.714	0.124	1.023	-5.504	3.152
160	42	68.749	0.177	0.877	-1.134	3.621
155	45	66.000	0.190	0.850	0.000	3.850
130	60	53.301	0.260	0.744	4.772	4.062
100	83	39.594	0.393	0.623	13.041	4.385
70	113	27.766	0.633	0.508	25.561	4.460
65	118	25.977	0.692	0.489	28.355	4.436
40	148	17.706	1.189	0.388	48.720	4.082
10	187	8.147	4.574	0.218	141.392	2.641

If manure does not reduce the soil fertility, but is beneficial to crop production, then manure should be paid for. This is mostly the case in developing countries where manure is scarce and is beneficial to the growth of crops. In Western Europe, however, manure is a problem, because there is simply too much. The soil fertility is reduced due to acidification, and the pork producer should pay the crop producer for his pollution. This mechanism should work because it is then possible to reduce the problem of pork production. Otherwise, the problem of manure pollution will not be solved.

<u>*Case 1-2 Crop is used as feed as well*</u>

If the crop is also used as feed, then the welfare program (3-6) becomes:

$$\max_{H,\tilde{H},X_q,X_y,A,F,D,B,f_s\geq 0} X_q^{0.3} X_y^{0.7} \tag{3-7}$$

subject to

$$X_q = Q \qquad (p_q),$$

$$X_y + F = yA \qquad (p_y),$$

$$Q = 3F^{0.9} n_q^{0.1},$$

$$H = 1.5F^{0.7} n_f^{0.3},$$

$$y = (19420 - 19000 \times 0.95^{f_s}),$$

$$D = H / A,$$

$$B = e^{-\frac{\gamma D}{\beta}},$$

$$f_s = a_0 \frac{B^2}{1+B^2},$$

$$A = \bar{A} \qquad (\pi_a),$$

$$n_q = 1 \qquad (\pi_q),$$

$$n_f = 1 \qquad (\pi_f),$$

$$H = \tilde{H} \qquad (\mu).$$

The emission level of 35 ton is the optimal solution, shown in Figure 3-8. When the emission level is higher than 95 ton, the problem is infeasible. In this case, crop is also used as feed. High emissions mean high pork production, which needs a high feed input. Therefore high emissions need high crop production. But this is impossible, since soil fertility is very low in conjunction with high emission level. This can be seen from the balance equation for crop:

$C_{crop} + FD \leq Q_{crop}$. We cannot get sufficiently high Q_{crop} under high emissions, therefore, feed cannot be high either. As such, feasible production requires restricting the pork production which leads to a relatively low emission level. In Figure 3-8 we did not represent the points after 95 ton because they are infeasible.

Tables 3-8 shows the optimal allocation of input, consumption and supply of commodities (in quantities) and their prices. The accounts (in value terms) for the consumer, the pork farm and the crop farm are given in Tables 3-9a, b and c, respectively.

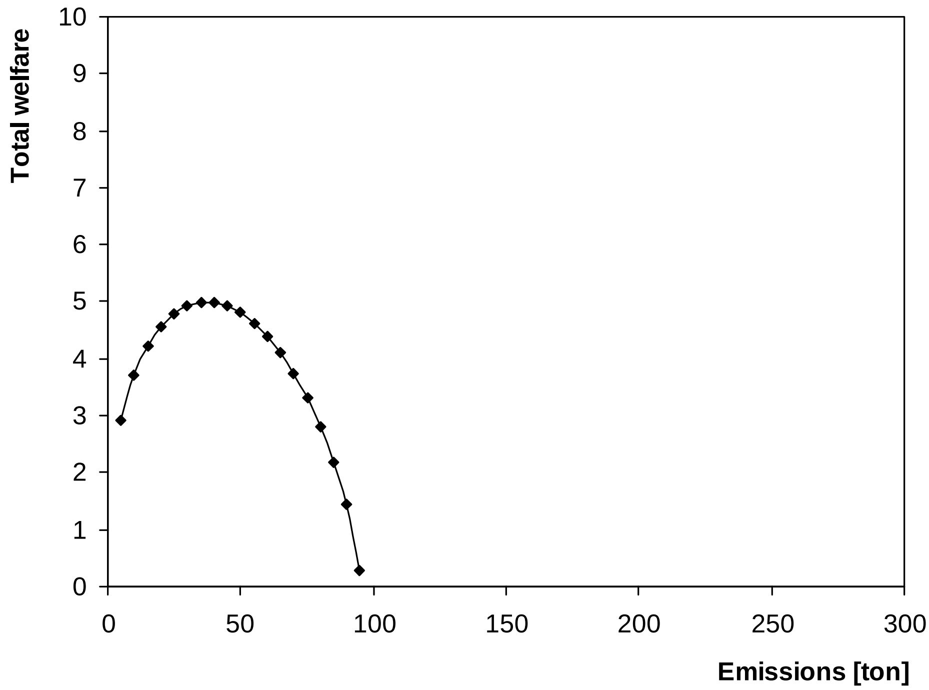


Figure 3-8 Relation between emission and total welfare for Case 1-2

In this case the optimal pork production is 1239 ton, corresponding to an emission level of 35 ton and soil fertility level of 154 kg/ha. Comparing this case with Case 1-1 (Table 3-5), Table 3-8 shows that more crops are needed when crop is also used as feed than if feed is purchased (Case 1-1). Therefore, better soil fertility is required which implies less emissions are allowed and thus less pork production. Therefore, the relative price of pork to crop is increased (1.208/0.385 versus 0.692/0.489). Since feed becomes expensive (0.385 versus 0.1), total welfare is lower than in the previous case (4.99 versus 5.916). Compared with Case 1-1, there is an income decrease because of the change of relative prices. Pork becomes more expensive because the feed becomes expensive; crop (for consumption) becomes cheaper because there is more production. The production quantity of crop increases from 9067 to 10803 ton, while the quantity of pork decreases from 2746 to 1239 ton. The consumption quantity of pork decreases from 2746 to 1239 ton, while the consumption quantity of crop does not change (9066 ton). Because of the higher marginal utility from crop than pork (in utility function), crop demand does not decrease while pork demand does. We also observe a decrease of compensation (1843 to 968) from the pork farm to the crop farm. This is because there is less pork production, and thus fewer negative impacts on crop production. The comparison of this case with Case 1-1 implies that more compensation from pork production should be made to the crop producer if feed (composite) is purchased at a low price (such as in western Europe), than if more expensive crop is directly used for feed (such as in eastern Europe).

Table 3-8 Commodity account in quantities and their prices for Case 1-2

	Input		Consumption	Supply	Price
	Pork	Crop			
Pork (ton)			1239	1239	1.208
Manure (ton)				35	27.665
Crop (ton)	1737		9066	10803	0.385
Land (ha)		1000		1000	4.163

Table 3-9a Income and expenditure Consumer Case 1-2

Income		Expenditure	
Land	5131	Pork	1497
Fixed factor return	150	Crop	3494
Fixed factor subsidy	-290		
Total	4991	Total	4991

Table 3-9b Revenue and expenditure Pork farm Case 1-2

Revenue		Expenditure	
Pork sales	1497	Feed (crop) expenditure	669
		Compensation to crop farmers	968
		Payment fixed factor n_q	150
		Payment fixed factor n_f (handicap)	-290
Total	1497	Total	1497

Table 3-9c Revenue and expenditure Crop farm Case 1-2

Revenue		Expenditure	
Crop sales	4163	Factor payment: land including soil	5131
Compensation from pork farms	968		
Total	5131	Total	5131

Table 3-9a shows that the consumer will spend 1497 on pork consumption and 3494 on crop consumption, using his income of 4991, in order to maximise his utility under the given prices. Tables 3-9b and c show the revenue and expenditures of two farms. The producers maximise profit under the given prices. In the pork farm, the revenue is from the sale of pork (1497) and the expenditures are from crop-feed purchase (669), payment for fixed factor (150), saving or subsidy (-290, a handicap of fixed factor for emission absorption) and compensation to crop producer (968). In this case, the crop producer receives compensation of 968 from the pork producer, and 4163 from crop sales. The expenditure of the crop farm is on land (5131).

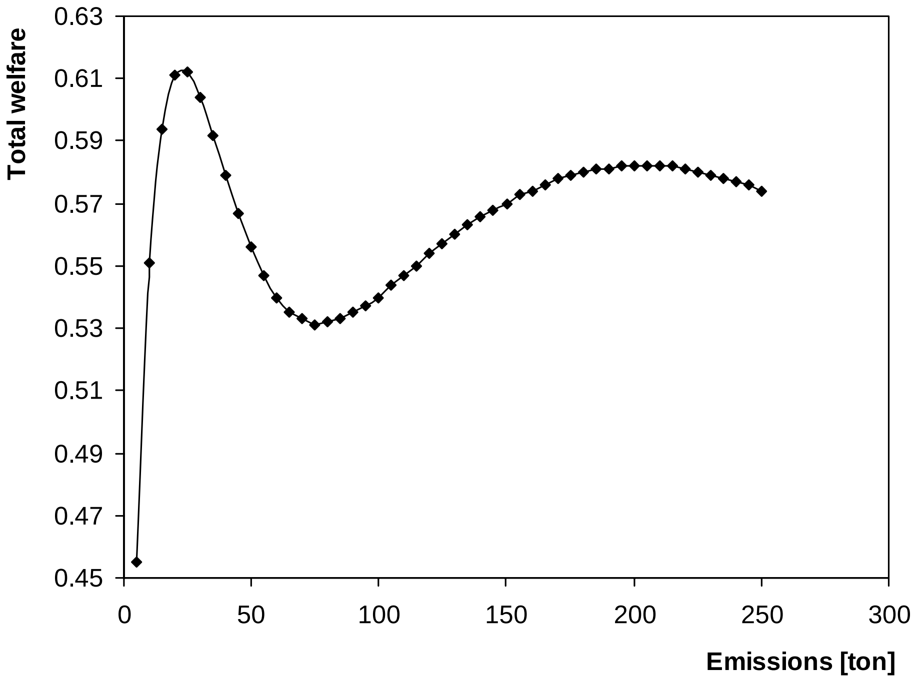
We must then check the decentralisability of this solution. In this case the aggregate profit of the welfare optimisation is positive ($\Pi = p_q X_q + p_y X_y > 0$) and the highest profit of the crop farm is at H=15 ton, which is different from the welfare optimum (H=35 ton). Therefore the optimal solution cannot be decentralised by Pigovian pricing of manure. Then we need policies to give a quantity control to the pork farm to emit no more than 35 ton, or to produce no more than 1239 ton of pork.

This model reflects an economy where crop is produced both for human consumption and for feed. It fits the current situation such as in eastern European countries. These endogenous policies on compensation and quantity control of pork production can achieve efficiency there.

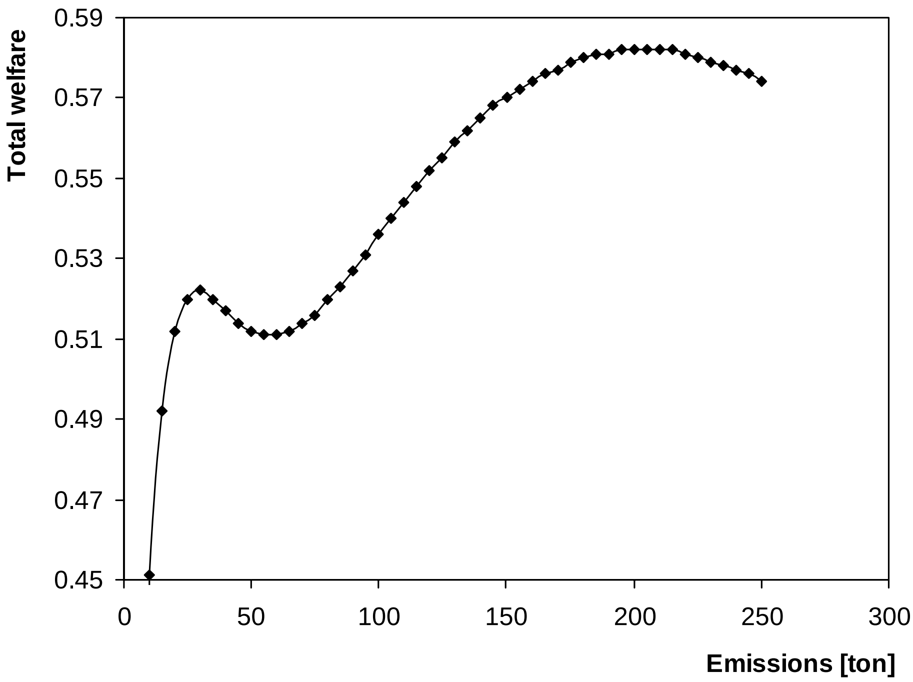
<u>*Case 1-3 Multiple local optima*</u>

Under some specific conditions (i.e. very limited land is available for crop production and crop production function has different parameters of soil fertility response in contrast to Case 1-1), multiple local optima might exist. In this example, total land is 250 ha instead of 1000 ha in order to have high emission levels per hectare and crops that respond to the soil acidification. We model the following production functions for two crops in order to have different responses of crops to acidification under two subcases. In Case 1-3a, we have the following yield function for crop *a*: $y = 20000 - 19000 \times 0.992^{f_s}$. In Case 1-3b, crop *b* has the yield function: $y = 20000 - 19000 \times 0.995^{f_s}$. Using the same model as in Case 1-1, we solve the model for crop *a* and *b* respectively. Figure 3-9 shows the existence of multiple local optima when these two crops are produced. It also shows that crop *a* is more productive than crop *b* at any level of emission because the total welfare is higher for crop *a* than crop *b*.

However, the optimal solution occurs at different emission levels for different agricultural economies, which produce different crops. This happens because the responses of two crops to soil fertility are different. For crop *a*, higher soil fertility will increase the yield more than crop *b*. As such, lower emission or higher soil fertility will be more beneficial for producing crop *a*; the optimal level is for the lower level of emissions. In such cases, we can observe two local maxima and one local minimum, at which a competitive market equilibrium might arrive in the absence of controls. In Figure 3-9a, only the left peak (emission level at 25 ton) is the optimum and not the right peak. For Case 1-3a, the left peak value shows that lower emissions or lower pig intensity is required for crop *a*, because crop *a* is sensitive to soil fertility. In Figure 3-9b, the right peak (emission level at 205 ton) is the optimum. For Case 1-3b, the right peak shows that higher emissions or higher pig intensity can be allowed because crop *b* is less sensitive to soil fertility and thus has less demand for the soil fertility level.



a. Local optima with low emission for Case 1-3a



b. Local optima with high emission for Case 1-3b

Figure 3-9 Two local optima

There are multiple optima in these subcases. Therefore a bound is required for manure production or livestock intensity to ensure that the real optimum is achieved. This implies that policy intervention in quantity bounds of manure disposal or pork production intensity is required. This can be done by the following welfare program:

$$\max_{H,\tilde{H},X_q,X_y\geq 0} U(X_q, X_y) - p_f F(\tilde{H}), \quad (3\text{-}8)$$

$$\begin{aligned} X_q &= \tilde{Q}(\tilde{H}) && (p_q), \\ X_y &= y(H/\overline{A})\overline{A} && (p_y), \\ \tilde{H} &= H && (\phi), \\ \underline{h} &\leq H/\overline{A} \leq \overline{h}. \end{aligned}$$

The optimal solution of commodity accounts in quantities and their prices with respect to different crops (crop *a* and *b*) are shown in Tables 3-10 and 3-12 respectively. The commodity accounts in value terms for the consumer, the pork farm and the crop farm when pork farm interacts with crop *a* are shown in Table 3-11. The results when the pork farm interacts with crop *b* are shown in Table 3-13.

Comparing Table 3-11 with Table 3-13, we find that the compensation (224) between the producer of crop *a* and the pork farm is larger than the compensation (23) between the producer of crop *b* and pork farm. This is due to different responses to soil fertility of different crops. Crop *a* is more sensitive to soil fertility and thus needs higher compensation. As we have discussed, there are two possible local optima for both subcases studied. We can also check the decentralisability of these two cases by assessing aggregate profit and revenue of the crop farms. The optimal solutions by Pigovian prices of manure disposal are not decentralisable for the two producers of both crops, thus, we need to give different quantity control of pork production by implementing policies. If crop *a* is produced we should limit pork production to no more than 804 ton or emissions to no more than 25 ton. If crop *b* is produced, pork production should be no more than 12025 ton or emission around 205 ton.

Table 3-10 Commodity account in quantities and their prices (crop *a*) for Case 1-3a

	Input		Consumption	Supply	Price
	Pork	Crop			
Pork (ton)			804	804	0.232
Manure (ton)				25	9.000
Crop (ton)			558	558	0.781
Feed (ton)	1075			1075	0.1
Soil fertility (kg/ha)		83		83	2.787
Land (ha)		250		250	1.743

Table 3-11a Income and expenditure of consumer Case 1-3a

Income		Expenditure	
Land	660	Pork	176
Fixed factor return	19	Crop	436
Fixed factor subsidy	-67		
Total	612	Total	612

Table 3-11b Revenue and expenditure Pork farm (crop a) from Case 1-3 a

Revenue		Expenditure	
Pork sales	187	Feed (crop) expenditure	11
		Compensation to crop farmers	224
		Payment fixed factor n_q	19
		Payment fixed factor n_f (handicap)	-67
Total	187	Total	187

Table 3-11c Revenue and expenditure Crop farm (crop a) for Case 1-3a

Revenue		Expenditure	
Crop sales	436	Factor payment: land including soil	660
Compensation from pork farms	224		
Total	660	Total	660

Table 3- 12 Commodity account in quantities and their prices (crop b) for Case 1-3b

	Input		Consumption	Supply	Price
	Pork	Crop			
Pork (ton)			12025	12025	0.020
Manure (ton)				205	0.000
Crop (ton)			250	250	2.237
Feed (ton)	21710			21710	0.100
Soil fertility (kg/ha)		0.007		0.007	5.237
Land (ha)		250		250	2.238

Table 3-13a Income and expenditure of consumer for Case 1-3b

Income		Expenditure	
Land	559	Pork	23
Fixed factor return	23	Crop	559
Total	582	Total	582

Table 3-13b Revenue and expenditure Pork farm for Case 1-3 b

Revenue		Expenditure	
Pork sales	240	Feed expenditure	217
		Compensation to crop farmers	0
		Payment fixed factor nq	23
		Payment fixed factor nf	0
Total	240	Total	240

Table 3-13c Revenue and expenditure Crop farm (crop b) for Case 1-3 b

Revenue		Expenditure	
Crop sales	559	Factor payment: land	559
Compensation from pork farms	0		
Total	559	Total	559

The non-convexity of crop production for these two crops is obvious because both graphs show two local optima. Two different local optima imply that we should give different quantity control to emissions or pork intensity when different crops are produced, because different crops have different responses to the acidification. The model can also help policy makers choose suitable crops for cultivation when acidification occurs due to pork production. In any case, crop *a* gives an equal or higher total welfare than crop *b*. If the two crops are perfect substitutes for consumers, then crop *a* should always be chosen for production.

Case 2 Manure has impacts on crops on cultivated land with possible fallow

Case 2-1 Acidification occurs on cultivated land with possible fallow

In the above cases, all the land is used for the production of crop, which is explicitly specified in the model by using $A = \bar{A}$. But it is not always necessary that all the land be used. In this case, we allow for fallow. That means that land usage can be decided by the optimisation, rather than by imposing any restrictions on land usage. We assume that the emissions of NH_3 from manure are dispersed across the cultivated land A. Then the optimisation problem becomes,

$$\Pi(p_q, p_y, p_f) = \max_{A,H\geq 0, A\leq \bar{A}} p_q\tilde{Q}(H) + p_y y(H/A)A - p_f F(H). \tag{3-9}$$

Or, it can be expressed as a function with respect to *H* instead of *A*,

$$\Pi(p_q, p_y, p_f) = \max_{A,H\geq 0, A\leq \bar{A}} p_q\tilde{Q}(H) + p_y \tilde{y}(A/H)H - p_f F(H). \tag{3-10}$$

We use the welfare program to solve the model. The welfare program reads,

$$\max_{H,X_q,X_y\geq 0} U(X_q, X_y) - p_f F(H), \tag{3-11}$$

subject to

$$X_q = \tilde{Q}(H),$$

$$X_y = y(H/A)A,$$

$$A \leq \bar{A}.$$

We use the same numerical example as in Case 1-1 but let $A \leq \bar{A}$ instead of $A = \bar{A}$ and solve the welfare program. The result indicates that $A = \bar{A}$. This happens because manure has negative impacts on soil fertility, and thus more land use can produce more crop outputs. As such, using all the land for crop production gives the highest crop production and thus the highest welfare. We then get the same result as in Case 1-1 (see Table 3-5 and 3-6). Again this model can be used for efficient allocation between crop and animal production in the countries or big farms where acidification occurs, but not to a serious extent. The following case shows a situation where manure is scarce and land is probably not completely used in order to have a high level of manure content in soil for the land where manure is applied.

Case 2-2 Manure (without acidification) is used as organic fertiliser for crop production

Case 2-2a Without calorie constraint

Suppose now manure is scarce and manure can be directly used as a fertiliser for crop production. This is mostly the case in developing countries. We have a slightly different crop yield function. In this case, fallow is possible because we want to have reasonably high manure content in soil for crop growth. There is no acidification thus manure is used as an organic fertiliser from crop production. The crop yield function has the following form: $y = 19435 - 19450 \times 0.99^{f}$, where f is the manure input per hectare. The model in (3-6) is then specified as follows.

$$\max_{H,\tilde{H},X_q,X_y,A,F,D,f\geq 0} \left[X_q^{\ 0.3} X_y^{\ 0.7} - p_f F \right], \tag{3-12}$$

subject to

$$X_q = Q \qquad (p_q),$$

$$X_y = yA \qquad (p_y),$$

$$Q = 3F^{0.9} n_q^{\ 0.1},$$

$$H = 1.5F^{0.7} n_f^{\ 0.3},$$

$$y = 19435 - 19450 \times 0.99^{f},$$

$$D = H / A,$$

$$f = D,$$

$$A \leq \bar{A} \qquad (\pi_a),$$

$$n_q = 1 \qquad (\pi_q),$$

$$n_f = 1 \qquad (\pi_f),$$

$$H = \tilde{H} \qquad (\mu).$$

Figure 3-10 shows the results for this case (Case 2-2a). The results show that in order to have a high nutrient content in the soil, not all the land is used for crop production when manure production level is low. Figure 3-10 also shows that if more emission is produced, more land can come into use to maximise crop production, as long as above a certain fertility level. There is a trade-off between more land use with lower fertility per ha and higher fertility per ha with less land use. As emissions increase to a level of 230 ton, all the land should be used for high crop production because the fertility level becomes sufficiently high. Then it is better to allocate all land for crop production. Of course, the highest welfare occurs at the point of the highest manure emission and the highest crop production (where all land is used). Only when land can be used for other purposes, can the highest welfare be achieved under the condition where land is not completely used for crop production.

For an optimal solution, we report the commodity accounts in quantities and their prices in Table 3-14, and accounts in value terms for the consumer, the pork and crop farms in Table 3-15. The optimal solution is decentralisable.

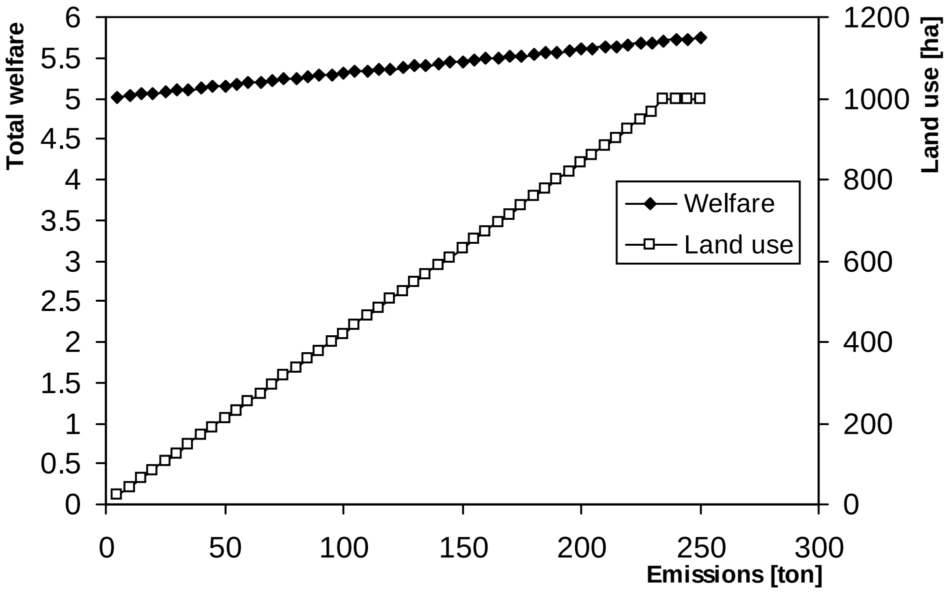


Figure 3-10 Total welfare and land use with respect to emission levels for Case 2-2a

Table 3-14 Commodity account in quantities and their prices for Case 2-2a

	Input		Consumption	Supply	Price
	Pork	Crop			
Pork (ton)			1869	1869	0.163
Manure(ton)		250		250	0.000
Crop (ton)			783	783	0.909
Feed (ton)	2744			2744	0.100
Land (ha)		1000		1000	0.001

Table 3-15a Income and expenditure Consumer for Case 2-2a

Income		Expenditure	
Land	711	Pork	31
Fixed factor return	31	Crop	711
Total	742	Total	742

Table 3-15b Revenue and expenditure Pork farm for Case 2-2a

Revenue		Expenditure	
Pork sales	305	Feed expenditure	274
From manure	0	Payment to fixed factor n_q	31
		Payment to fixed factor n_f	0
Total	305	Total	305

Table 3-15c Revenue and expenditure Crop farm for Case 2-2a

Revenue		Expenditure	
Crop sales	711	Factor payment: land	2
		Payment for spreading manure	709
Total	711	Total	711

This case reflects an economy where manure is scarce and thus beneficial for crop production, such as an isolated African village. There, manure is the only input for crop production, as farmers do not have access to chemical fertilisers. They rely on their own produced pork and crop for survival. This actually hearkens back to the historical days of food production. In this case, manure has a positive effect on crop production and is freely disposable. The price of manure is zero.

Case 2-2 b With calorie requirement

Suppose now the consumption of crop and pork is controlled by a nutritional requirement (Case 2-2b). For survival, people have to eat crop and pork for a minimum calorie requirement. We assume that crop has a higher calorie content (2000 MJ/ton) and pork has lower calorie content (1000MJ/ton). In this case, farmers in the village will make tradeoffs between crop production and pork production to meet both the utility maximisation and calorie requirement. This can be modelled by adding a calorie constraint to (3-12). In the model, we use the yearly calorie requirement per person and the number of people in the village to calculate the total calorie requirement for a year. This can be done by introducing:

$$\delta_{pork} C_{pork} + \delta_{crop} C_{crop} \geq Tcal ,$$

where δ indicates the calorie contents from pork and crop, and *Tcal* indicates the total calorie requirement for the whole village.

In this case a very low level of emissions (below 50 ton), which means low pork production, is infeasible, because even all land is used for calorie requirement but the soil fertility is not sufficiently high to achieve the required crop production. Until a higher level of emission (50 ton) is achieved, the problem becomes feasible. In the range of 50 to 140 ton of emissions, if pork production is low, more land for crop production should used in order to meet the calorie requirement. This range is the 'subsistence range' giving the lowest total calorie. As the emission increases in this 'subsistence range', more pork and less crop will be produced, because pork gives higher utility than crop as long as the calorie requirement is met. In order to have a certain content of manure in soil, the land is not fully used. Until the emission level reaches a level of 140 ton, more land use and pork production will bring a higher utility. This is because the manure content in the soil is sufficiently high for the calorie requirement to be easily met. Figure 3-11 shows how much land will be used for different levels of emissions in order to meet both the calorie requirement and utility maximisation. The optimal solution is at the highest emission level of 250 ton. In this case, manure is favoured and all land is used for the highest utility. This is the same as Case 2-2a (see Table 3-14 and 3-15). Similarly, the welfare optimum is decentralisable.

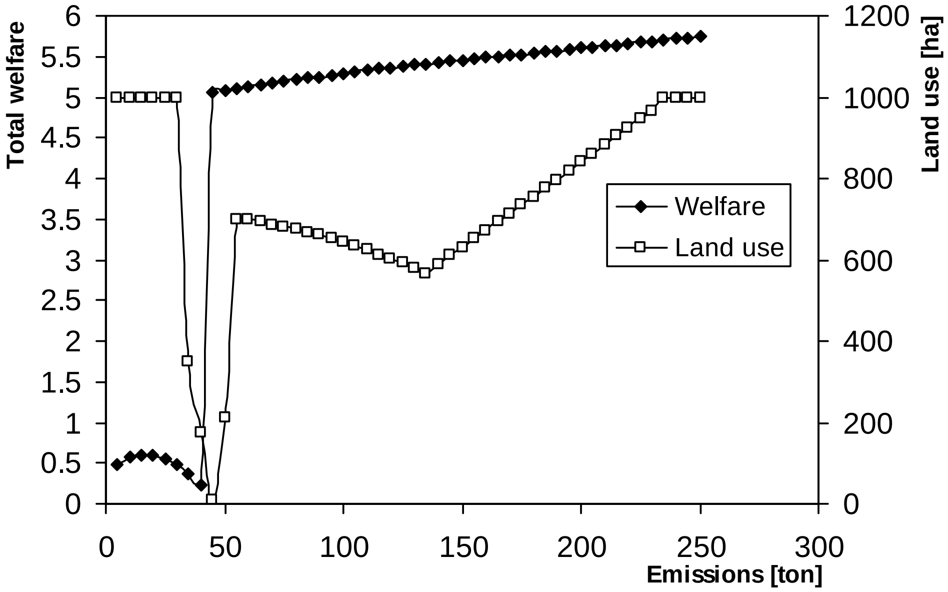


Figure 3-11 Total welfare and land use with respect to emission levels for Case 2-2b

Case 3 Mixed case (Acidification occurs on all land but fallow is possible for cultivation)

Another interesting case is that manure emission has impacts on all the land but cultivation is not necessary. The model reads:

$$\Pi(p_q, p_y, p_f) = \max_{A,H\geq 0, A\leq \bar{A}} p_q\tilde{Q}(H) + p_y y(H/\bar{A})A - p_f F(H) \quad (3\text{-}13)$$

Then the welfare program can be written as:

$$\max_{H,X_q,X_y \geq 0} U(X_q, X_y) - p_f F(H), \tag{3-14}$$

subject to

$$X_q = \tilde{Q}(H),$$

$$X_y = y(H / \overline{A})A,$$

$$A \leq \overline{A},$$

For this case, we use the same parameters as in the numerical example of Case 1-1 and solve this welfare program. The result is not surprising; $A = \overline{A}$, the same as in Case 1-1 (see Table 3-5 and 3-6). In this case, acidification occurs on all land, and more land use will produce higher crop output and thus higher welfare. Therefore all the land will come into use.

In Section 3.3 we have discussed the non-convexities in a general equilibrium model, where manure affects all land $\overline{A}$, though $\overline{A}$ is not necessarily for cultivation but can also be used for other production purposes such as the production of other-goods. The difference of this case from that presented in Section 3.3 is that there crop is used as feed, while here feed is a purchased composite. In Section 3.3, we have A= 524 ha ($A = 52\%\overline{A}$), or 52% of land can be used for crop production (see Table 3-2). This implies that the optimal land allocation to crop production is 52% and to other-goods is 48%.

Case 4 Reduce waste disposal on land by machinery

Now we consider the possibility of using purification appliances, e.g. applying lime to reduce the negative impacts of soil acidification. Whether we apply this method depends on its cost. This can be examined by solving the profit maximisation problem. The profit maximisation problem is to maximise the following profit function with increased yield at a cost of the rent price of the purification appliance. The model reads:

$$\Pi(p_q, p_y, p_f, p_n) = \max_{A,H,N \geq 0, A \leq \overline{A}} p_q \tilde{Q}(H) + p_y y(\frac{H-N}{A})A - p_f F(H) - p_n N. \tag{3-15}$$

The corresponding welfare program can be written as,

$$\max_{H,X_q,X_y \geq 0} U(X_q, X_y) - p_f F(H) - p_n N, \tag{3-16}$$

subject to

$$X_q = \tilde{Q}(H),$$

$$X_y = y(\frac{H-N}{A})A,$$

$$A \leq \overline{A}.$$

If p_n were very small, then it would be worthwhile to use purification appliances, but if p_n were large then it would not be. We solve this welfare program in GAMS again by scanning over H. In the first example we have low rent for purification appliances: p_n=0.015. The relation between total welfare and emission level with cheaper purification appliance is shown in Figure 3-12. Table 3-16 gives the optimal levels of production, consumption and input in quantities and their prices. Table 3-17 shows the consumer and producer accounts in value terms for this case.

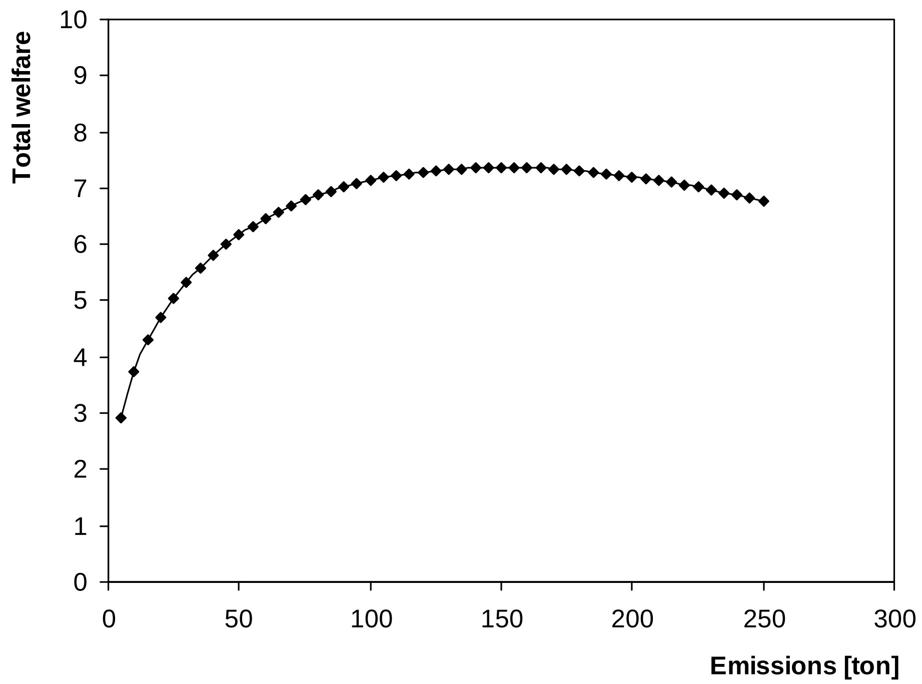


Figure 3-12 Low rent for purification appliance for Case 4-1

Table 3-16 Commodity account in quantities and their prices for Case 4-1

	Input		Consumption	Supply	Price
	Pork	Crop			
Pork (ton)			8069	8069	0.409
Manure(ton)		150		150	0.015
Crop (ton)			12574	12574	0.613
Feed (ton)	13895			13895	0.100
Land (ha)		1000		1000	7.716

In this case, the purification is profitable due to the low rent and thus it will be used. The optimal solution will be at the emission level of 150 ton, though 149 ton will be purified (i.e. N = 149). As well, the soil is hardly affected and crop production is very high. Although purification is cheap, the compensation from the pork producer is still needed. The pork producer earns revenue from sales of pork (3302). The expenditure of the pork farm is on feed (1390), on fixed factor (330), on the handicap fixed factor (–676, which is actually a saving) and compensation to the crop producer (2255). The crop farm earns revenue from crop sale (7705) and receives compensation from pork farm (2255). It pays 7716 for land and 2244 for purification. It is now decentralisable under the Pigovian price of manure because the aggregate profit is positive and the crop farm obtains non-negative profit under the optimal solution. Again, to achieve the optimal solution, we do not need to use policy but rather a competitive market by which the pork farm and the crop farm will negotiate the compensation according to the Pigovian price of manure such that the optimum is achieved.

Table 3-17a Income and expenditure Consumer for Case 4-1

Income		Expenditure	
Land	7716	Pork	1909
Sale from purification apparatus	2244	Crop	7705
Fixed factor return	330		
Fixed factor subsidy	-676		
Total	9614	Total	9614

Table 3-17b Revenue and expenditure Pork farm for Case 4-1

Revenue		Expenditure	
Pork sales	3302	Feed expenditure	1393
		Compensation to crop farmer	2255
		Payment fixed factor n_q	330
		Payment fixed factor n_f (handicap)	-676
Total	3302	Total	3302

Table 3-17c Revenue and expenditure Crop farm for Case 4-1

Revenue		Expenditure	
Crop sales	7705	Factor payment: land	7716
Compensation from pork farm	2255	Payment: purification	2244
Total	9960	Total	9960

If we increase the rent for the purification appliance to p_n=1.0, then the relation between total welfare and emission level is shown in Figure 3-13. This is exactly the same as in Figure 3-7. In the case of high rent, purification will not be used (N=0) and the optimal solution is at the emission level of 65 ton. This is the same as in Case 1-1. The corresponding optimal solution for other variables is shown in Tables 3-5 and 3-6. Again, the decentralisability of Pigovian pricing of manure is possible.

Comparing Figure 3-12 with Figure 3-13, we find that the optimal solution gives a higher emission level in Case 4-1 because purification is cheaper than in Case 4-2. The total welfare is also higher in Case 4-1 than in Case 4-2. We can conclude that cheap purification technology is always beneficial to welfare.

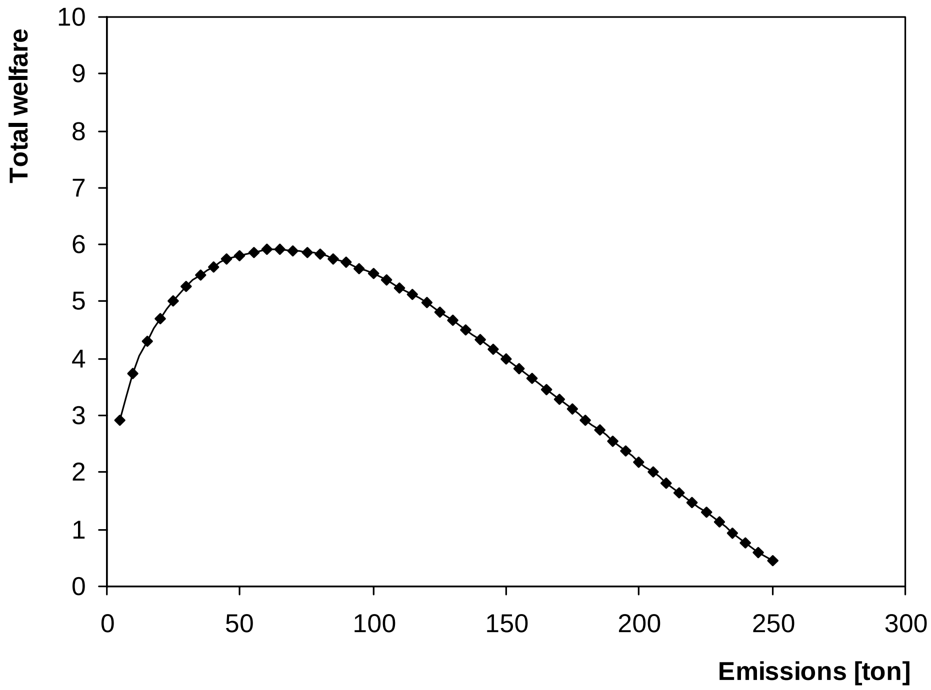


Figure 3-13 High rent for purification appliance for Case 4-2

3.5 CONCLUDING REMARKS

For economic modelling of environmental problems we need to consider the functions of the environment and the feedbacks between economic activities and environmental processes. The two basic functions of environmental resources are the input function for production and amenity services for consumption. Therefore, emissions from economic activities can be treated as the use of the environmental resources. The feedback of environmental changes on the economic system can be contained in the input function of the environment in production function, utility function, and the related biophysical processes.

The environmental impacts associated with pork production are water eutrophication and soil acidification. The feedback of water eutrophication to the economic system is on the production of fish and the amenity services of water system through depletion of oxygen in the water from an increase in algae growth. The feedback of soil acidification is on the production of crop through changing the soil fertility. For economic modelling of pork production and related environmental problems, we should represent such impacts.

We have illustrated in different cases how to represent the impacts of soil acidification on crop production considering the interaction between pork production and crop production in numerical examples. Such representation in welfare programs often brings non-convexities due to the biophysical process model of acidification and the locally decreasing response function of crop yields to soil fertility. We have illustrated how to solve models with non-convexities. Here are the main conclusions.

Firstly, we have considered the soil acidification process in a relatively wide model setting, namely, an AGE model setting. In this model, pork production also generates emissions, which affect soil fertility by an acidification process. We include a crop yield function with soil fertility and a fertiliser as input in the model. We also include other-goods for the competing use of all resources to represent an economy. The economy maximises the objective function (e.g. the total welfare) subject to the specified production technology, consumer's preference and biophysical process of soil acidification. The result from such a model gives proper policy intervention information about setting standards for emissions or pig intensity. Nevertheless, such a model is not mathematically well-behaved. We have shown that the model has the characteristics of above-firm level non-convexity, due to the soil acidification process, influenced by the emission from the pork sector. Therefore, solving a non-convex model becomes an issue. We use the parametric approach which makes the non-convexities irrelevant by setting the non-convex element (i.e. soil fertility) as a parameter. Solving this model over a range of the values of soil fertility, we obtain a range of total welfare. Scanning the total welfare, with respect to the values of the parameter, one can spot the optimal solution with the highest total welfare corresponding to a certain level of soil fertility. In such a way, a non-convex problem can be solved. Looking back at the non-convexity of the DICE model discussed in Chapter 2, we think that this model can also be solved by parameterisation; i.e. scanning the global welfare over a range of emission levels for each time period, and finding the real optimal solution, though we may expect many combinations of the emission paths over the time path.

Secondly, we have shown how to solve models with non-convexities in different settings of the economy considering the interaction between pork and crop production. For simplicity we use a welfare program with a simpler setting: only pork and crop production are considered in the welfare programs. Several cases were considered including the interaction between crop and pork without fallow, with fallow, and with the possibility of purification of emissions, which reflect specific economic situations. Solving these non-convex problems requires a similar method used to solve the first model. Now we consider that emission is a choice variable. We solve the models by scanning the emissions over a certain range. For each value of this choice variable, there exists an equilibrium point. By plotting the relation between the emission level and the total welfare level, one can see the optimum.

Thirdly, we have discussed the decentralisability of a welfare optimum for different cases. When non-convexity is present in the model, the welfare optimum might be different from an individual's (e.g. crop farm) optimisation. Thus, there is a need to check the decentralisability of the optimal solution. This check includes two steps; checking the non-negativity of the aggregate profit, and verifying the coherence of the optimal point of the each agent and the welfare optimum. If the decentralisation of the Pigovian price of manure is not possible, then we need a policy intervention, such as quantity control, to achieve the optimum. We found that in Cases 1-1, 2-1 and 3, where acidification occurs on all land and feed is purchased externally, the Pigovian pricing of manure is decentralisable. This means that to achieve the optimal solution, we do not need to use policy but rather ensure a competitive market. The pork farm and the crop farm can negotiate the compensation such that the optimum is achieved. If manure is used as an organic fertiliser for the crop farm (Case 2-2), it is also decentralisable. In Case 4, where purification is possible, decentralisation is feasible. However, it is not decentralisable if crop is also used as feed (Case 1-2) or if two local optima exist (Case1-3), because the welfare optimum is far from the profit maximisation of the crop farm. Then we need to give a quantity control (bounds on manure production or livestock intensity) to the pork farm and make the crop farm produce near the welfare optimum.

The exercises in this chapter clearly show a method for modelling environmental problems with non-convexities in welfare programs. This method contributes to illustrating integrated assessment of environmental impacts containing non-convexities. Welfare programs are powerful tools for modelling different levels of economy. A welfare program can represent a world model with detailed economic agents as in Section 3.3. It can also represent a village economy, isolated from the rest of the world, as in Case 2-2 of Section 3.4. As long as the objective for different levels of economy and the constraints to the objective are well-represented, optimal management can be achieved for different settings of the economy.

In environmental-economics literature, some IAMs such as DICE, RICE and MERGE do not explicitly consider the non-convexities, although an environmental process model (e.g. a climate change process model) is included. Therefore the solutions to these models are not guaranteed to be a welfare optimum. The detailed and proper representation of the environmental impacts in an economic model and solving them seems a good start in integrated assessment modelling. Our approach considers both the environmental process of soil acidification and the subsequent non-convexities. By solving a non-convex model with a specific method, we found the welfare optimum. This approach makes a step further towards integrated assessment of the environmental problems and the results are more reliable for policy recommendations. However, solving non-convex integrated assessment models is a difficult task in integrated assessment modelling. Once this has been done for a specific environmental problem, insights from the model results can be obtained for optimal environmental management.

In this chapter we have shown how to deal with non-convexities, due to the soil acidification process and the non-concavity of a crop yield function. Dealing with non-convexities is an interesting topic. Further efforts should be given to this topic because non-convex models cannot directly provide proper policy information. Solving high dimensional non-convexities is a challenge for further research, since the implications of non-convexities of models to policy making is great.

APPENDIX 3-A NON-CONVEXITY OF SOIL ACIDIFICATION MODEL

The soil acidification caused by emissions from pork production is presented as:

$$D = aQ_1 \tag{3-A1}$$

$$B = e^{-\frac{\gamma D}{\beta}} \tag{3-A2}$$

$$f_s = a_0 \frac{(B)^2}{1+(B)^2} \tag{3-A3}$$

where $a = c / A$, the emission coefficient per hectare. We use the chain rule to obtain the first and second derivatives:

$$\frac{\partial f_s}{\partial Q_1} = \frac{\partial f_s}{\partial B} \frac{\partial B}{\partial Q_1} \tag{3-A4}$$

$$\frac{\partial^2 f_s}{\partial {Q_1}^2} = \frac{\partial^2 f_s}{\partial B^2} \frac{\partial B}{\partial Q_1} + \frac{\partial^2 B}{\partial {Q_1}^2} \frac{\partial f_s}{\partial B}. \tag{3-A5}$$

From equation (3-A1) to (3-A3) we have,

$$\frac{\partial B}{\partial Q_1} = (-\frac{\gamma a}{\beta}) e^{-\frac{\gamma}{\beta} D} \tag{3-A6}$$

$$\frac{\partial^2 B}{\partial {Q_1}^2} = (\frac{\gamma a}{\beta})^2 e^{-\frac{\gamma}{\beta} D}. \tag{3-A7}$$

From equation (3-A3) we have,

$$\frac{\partial f_s}{\partial B} = \frac{2a_0 B}{(1+B^2)^2} \tag{3-A8}$$

$$\frac{\partial^2 f_s}{\partial B^2} = \frac{2a_0(1-3B^2)}{(1+B^2)^3}. \tag{3-A9}$$

Substituting (3-A6)-(3-A9) to (3-A5), we have,

$$\frac{\partial^2 f_s}{\partial Q_1{}^2} = \frac{2a_0(1-3B^2)}{(1+B^2)^3}(-\frac{\gamma a}{\beta})B + 4aa_0(\frac{\gamma a}{\beta})^2 \frac{B^2}{(1+B^2)^2}$$

$$= \frac{2a_0}{(1+B^2)^2}\frac{\gamma aB}{\beta}\frac{[3B^2 + 2a^2\frac{\gamma}{\beta}B(1+B^2) - 1]}{(1+B^2)}.$$

If $\frac{\partial^2 f_s}{\partial Q_1{}^2} \geq 0$, then we have f_s as a convex function of Q_1. As soil base saturation is defined as B>0, with the given values of other parameters a, β and γ, we have $\frac{\partial^2 f_s}{\partial Q_1{}^2} \geq 0$, if B is not very close to zero. Function f_s is a convex-concave function of Q_1. For the present level of NH_3 emission from pork production in the Netherlands, the emission level per ha (parameter a) is very high due to intensive production system. Therefore $F_g(f_s, Q_1) = f_s - f_g(Q_1)$ is not convex everywhere, or we simply treat it as a non-convex transformation function.

CHAPTER 4 PROTEIN CHAINS AND ENVIRONMENTAL PRESSURES: A COMPARISON OF PORK AND NOVEL PROTEIN FOODS[1]

Abstract

The production and consumption chains of pork and Novel Protein Foods (NPFs) and their environmental pressures have been compared using life cycle assessment (LCA) in terms of environmental pressure indicators. We define two types of environmental pressure indicators: emission indicators and resource use indicators. We focus on five emission indicators: CO_2 equivalents for global warming, NH_3 equivalents for acidification, N equivalents for eutrophication, pesticide use and fertiliser use for toxicity, and two resource use indicators: water use and land use.

The results of LCA show that the pork chain contributes to acidification 61 times more than, to global warming 6.4 times more than, and to eutrophication 6 times more than the NPFs chain. It also needs 3.3 times more fertilisers, 1.6 times more pesticides, 3.3 times more water and 2.8 times more land than the NPFs chain. According to these environmental indicators, the NPFs chain is more environmentally friendly than the pork chain. Replacing animal protein by plant protein shows promise for reducing environmental pressures, in particular acidification.

Keywords: protein chains, life cycle assessment, environmental indicators, Novel Protein Foods, pork.

4.1 INTRODUCTION

The current way of producing and consuming food has a considerable impact on the environment (Goodland, 1997; CAST, 1999). This impact is expected to increase in the future as global population grows and the consumption of animal products increases. Growing populations of both humans and livestock require an increased production of food and feed, and a competitive use of available cropland (CAST, 1999; Delgado *et al*., 1999). In addition, the conversion of plant protein to animal protein is rather inefficient compared to *direct* human consumption of plant proteins (Goodland, 1997; CAST, 1999; Delgado *et al*., 1999). Enhancing plant protein consumption in society is suggested as one of the options for reducing the environmental pressures of food production and consumption (Baggerman and

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[1] This chapter is mainly based on: Zhu, X. and E.C. van Ierland, 2004. Protein chains and environmental pressures: a comparison of pork and Novel Protein Foods, *Environmental Sciences* Vol.1, No.3: pp.254-276. The short version of this chapter has been published in a brochure 'De maatschappelijke impact van Ketenkennis' by Agro Keten Kennis as an essay for an encouragement prize 2003.

Hamstra, 1995; Goodland, 1997; Carlsson-Kanyama, 1998). Novel Protein Foods (NPFs) are modern plant-protein based food products, designed to have a desirable flavour and texture. Technically, Novel Protein Foods can be made of peas, soybeans and other protein crops.

The research programme PROFETAS[2] studies the current meat-based protein chain and the prospect of replacing meat in the western diet with plant protein products. The programme focuses on two reference production and consumption chains, namely, the pork and NPF chains. The pork chain is selected for the animal protein chain, mainly because pork is one of the most efficient meat products and has the highest share of meat consumption (EC, 2002), although its production is causing large environmental impacts both in developing and developed countries (Bolsius and Frouws, 1996). For the production of NPFs, the dry pea was chosen as the protein source because it is considered to be a suitable protein source and because of the possibility to grow peas in Western Europe.

Protein-food production and consumption impose considerable pressures on the environment, which leads to environmental impacts in all phases of the chain. In the literature, however, the environmental impact analysis of food has mainly focused on only a few stages of the chain, particularly the agricultural stage (e.g. Pimentel, 1997; Nell, 1998), or on specific environmental impacts, such as the greenhouse effect (cf. Carlsson-Kanyama, 1998; Kramer, 2000). Further study is needed to understand the environmental impacts of an entire protein chain, i.e. from the primary production via processing and distribution to consumption.

This chapter first describes the production and consumption chains of a prototype animal protein food (pork) and a novel plant-protein food (NPF) to understand the relationships between production, consumption and the environment, and subsequently assess the environmental impacts for both chains. We focus on a systematic description of the protein chains, environmental life cycle assessment (LCA) of the chains, and developing environmental indicators.

The aim of the chain representation is to develop a consistent framework for a quantitative analysis of the chain. The aim of LCA is to get a complete picture of the most relevant inputs and outputs along the chains. To understand the environmental impacts of the protein chains, a number of quantitative environmental pressure indicators are used to compare the chains.

The chapter is organised as follows. Firstly we present the pork chain and the NPFs chain according to the present situation in the Netherlands. Secondly we briefly describe the concepts and methods of LCA. Thirdly the environmental issues for agriculture are discussed as a preparation for the application of LCA. Fourthly inputs and outputs in each stage as well as their relevant environmental effects are presented and discussed. Fifthly we convert the emissions into environmental indicators and compare the environmental pressures of the two

[2] Please see www.profetas.nl for details.

protein chains. Sensitivity analysis for the energy use for transportation is also carried out to show the implications of uncertainty in data. Finally, we draw our main conclusions and discuss briefly how to implement chain management in order to improve the environmental performance.

4.2 CHAIN PRESENTATION OF PROTEIN FOODS

The term 'chain' is often used to describe the stages of production and distribution that a product goes through before reaching the final consumer (Bijman, 2002). Processes in a chain are interconnected through physical flows. The two representative chains are shown in Figure 4-1.

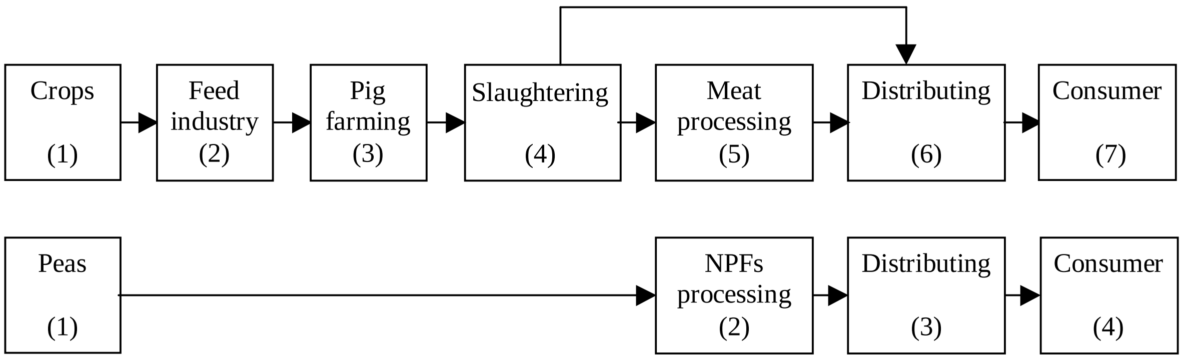

Figure 4-1. Production and consumption chains of pork and Novel Protein Foods

Along the pork chain (upper chain in Fig. 4-1), crops are grown (Stage 1), processed into feed (Stage 2), which is fed to pigs (Stage 3). Pigs are slaughtered (Stage 4), parts of the carcass are processed into meat products and transported to the retailers for distribution (Stage 5 and 6), parts of the carcass as fresh pork are transported to the retailers for distribution (Stage 6). Finally the consumers will prepare and consume the meat products (Stage 7). Similarly a production and consumption chain of Novel Protein Foods (lower chain in Fig. 4-1) includes agricultural production of peas, NPFs processing (including protein extraction, texturisation and flavour addition), distribution and consumption. Compared with the pork chain, the NPFs chain has fewer stages.

4.3 ENVIRONMENTAL LIFE CYCLE ASSESSMENT (LCA)

Environmental life-cycle assessment (LCA) is a system analysis method for assessing the environmental impacts of a material, product, process or service throughout its entire life-cycle. It is an increasingly important tool for supporting choices at both the policy and industry levels (Guineé, 1995; Mattson, 1999). LCA is intended for comparative use, i.e. the results of LCA studies have a comparative significance rather than providing absolute values on the environmental impact related to the product. LCA is usually carried out in four phases.

These phases are goal and scope definitions; inventory of environmental inputs and outputs; impact assessment and lastly interpretation (ISO, 1995).

4.4 ENVIRONMENTAL PROBLEMS IN THE AGRICULTURAL SYSTEM

The agricultural component stands at the basis of both chains. Interaction between agriculture and the environment are complex and variable. We first review the major environmental problems to facilitate an emission typology.

Agriculture is the managed exploitation of selected plants and animals to produce products of value to humans, and it generates a wide range of effects on the environment (OECD, 1998). Like any natural system, agricultural enterprises are systems receiving external inputs and exporting energy and matter outputs. Inputs are provided by nature (e.g. soil, solar radiation or precipitation) or by man-made capital (e.g. agro-chemicals and seeds). The latter inputs include seeds, livestock, fertilisers, pesticides, feeds and fuel energy. The main environmental problems related to agriculture are summarised in Figure 4-2.

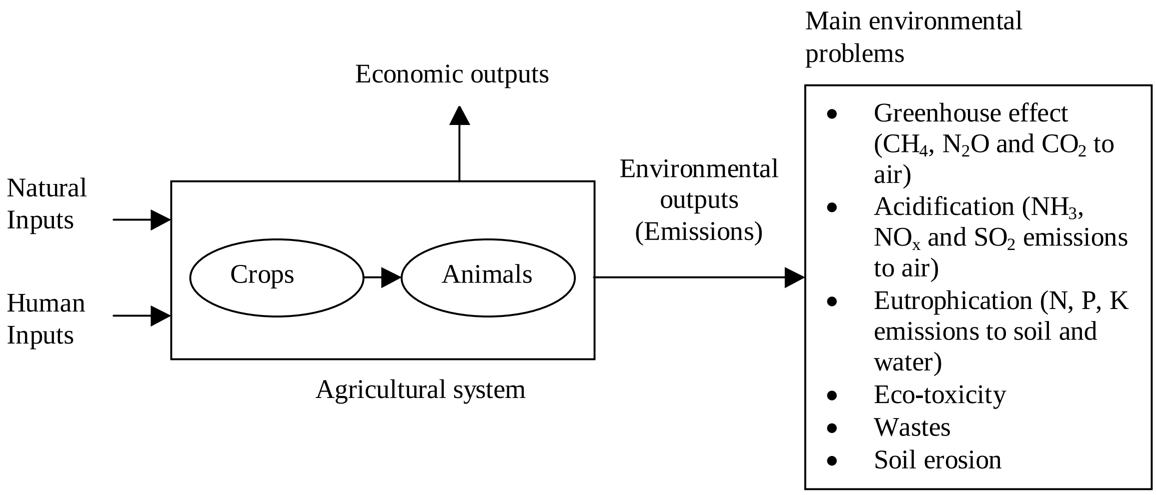

Figure 4-2. Environmental problems in the agricultural system

4.5 INVENTORY OF INPUTS AND OUTPUTS OF THE PROTEIN CHAINS

The *inventory analysis* of an LCA provides detailed information on the chains, including inputs and outputs at each stage. We elaborate our findings based on one *functional unit*. A functional unit is chosen to provide comparability between the chains. The functional unit should be determined by the specified main function of the product system under study. All data is related to the functional unit. When various food products are to be compared, it seems relevant to consider their roles or functions in the diet, for example, the content of proteins for meat (Mattsson, 1999). For our two protein chains, we take the protein content for consumption as the functional unit for the study because the aim of PROFETAS is to find alternative non-meat protein products (or meat substitutes) for meat by developing consumer-oriented *Novel Protein Foods*. Current plant protein products are not attractive because they do not meet the tastes and sensory expectation of consumers. Although meat consumption is determined by a large variety of soicio-economic variables, we use NPFs as a protein alternative for meat because the two protein products intend to have comparable nutritional value and sensory expectations. In addition, other aspects of meat consumption like social aspects are difficult to quantify for a LCA study. Furthermore, the social aspect such as that rich people eat more meat is probably more relevant in a developing world than in a developed world. Nowadays there is a tendency in the western countries that more consumers of Western-style diet are changing their attitude towards meat consumption, and the demand for meat substitutes is increasing because of their health and environmental consideration (MAF, 1997; Miele, 2001; Jin and Koo, 2003). All these considerations lead us to use protein consumption as a functional unit for comparison of environmental impacts of the two protein products. We choose *1000-kg protein content for consumption* as a functional unit for both chains. A categorisation of inputs and outputs of the chains is shown in Figures 4-3 and 4-4.

Main quantities of products per functional unit

Pigs are slaughtered at an average weight of 112.2 kg and a carcass weight of 87 kg (Praktijkonderzoek veehouderij, 2001) with about 53 kg of pork (PVE, 2001). Product quantity per functional unit can be calculated via the protein contents of pork and NPFs. The protein content of pork[3] is 180g protein/kg pork (Carlsson-Kanyama, 1998). Then for pork one functional unit is equivalent to 5555 kg of pork. One functional unit of pork is therefore equal to 105 head of pigs. The average meat pig consumes 290 kg of feed over its lifetime (Bedrijfsvergelijking Siva-software B.V., 2001). Thus the feed quantity for one functional unit of pork is 30450 kg.

For NPFs as a theoretical product, the intended products have a protein content of 25%. One functional unit of NPFs thus corresponds to 4000 kg products of NPFs. Production of 1000kg NPFs requires 2500 kg of harvested dry peas (van der Steen, 2002; van Boekel, 2003). One functional unit of NPFs is equal to 4000 kg of NPFs, which needs 10,000 kg of peas as input. The quantities for one functional unit of pork and NPFs are shown in Table 4-1.

Table 4-1 Product quantities related to one functional unit of pork or NPFs

	Protein content (kg/kg product)	Product quantity (kg)	Pig numbers	Feed quantity (kg)	Pea quantity (kg)
Pork	0.18	5555	105	30450	
NPFs	0.25	4000			10000

Source: Carlsson-Kanyama, 1998; PVE, 2001; Bedrijfsvergelijking Siva-software B.V., 2001; van der Steen, 2002.

[3] The protein content based on carcass is 11.4% (CAST, 1999). This is equivalent to 18% based on pork.

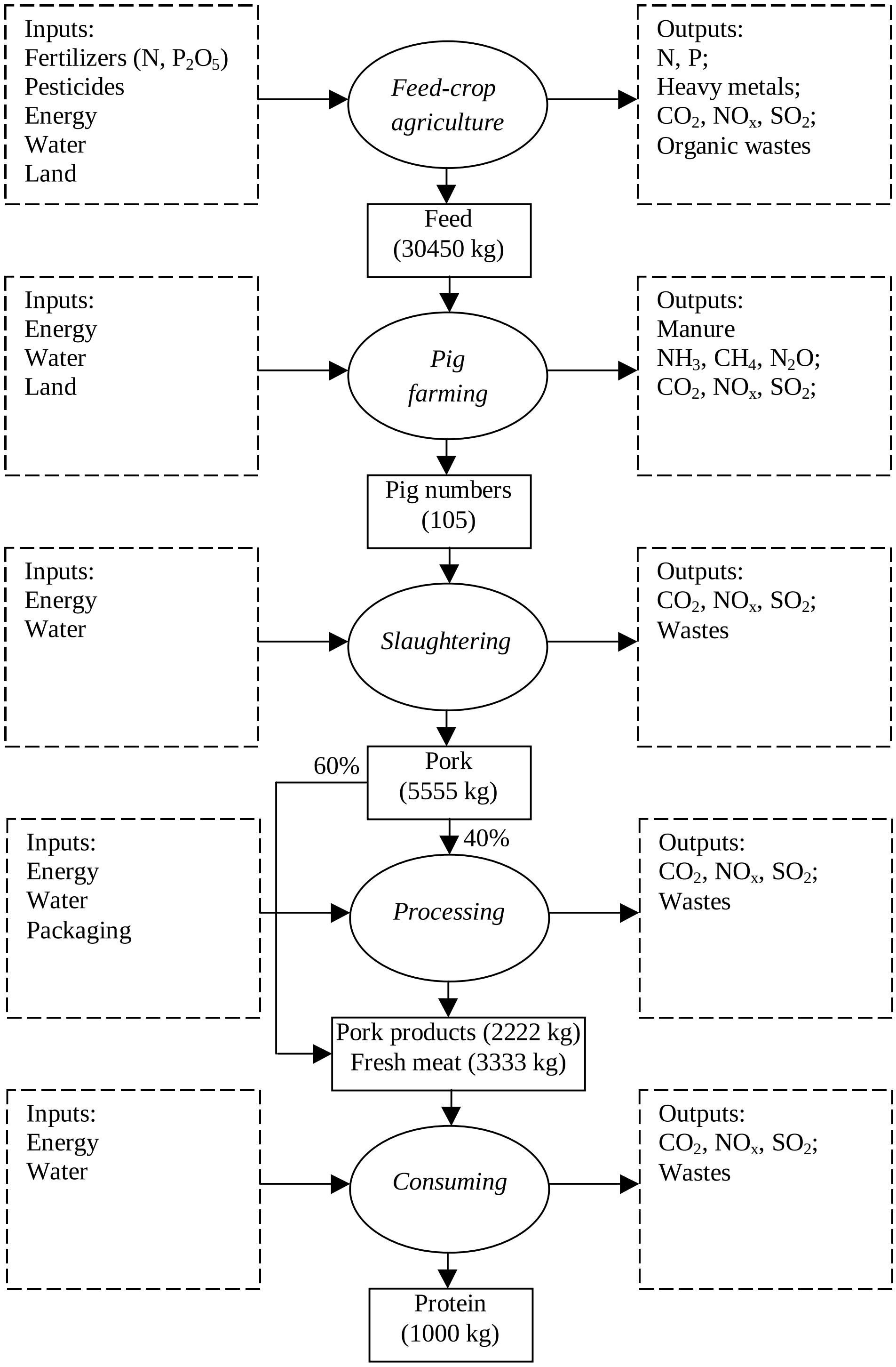

Figure 4-3. Categories of inputs and outputs of the pork chain producing one functional unit of pork

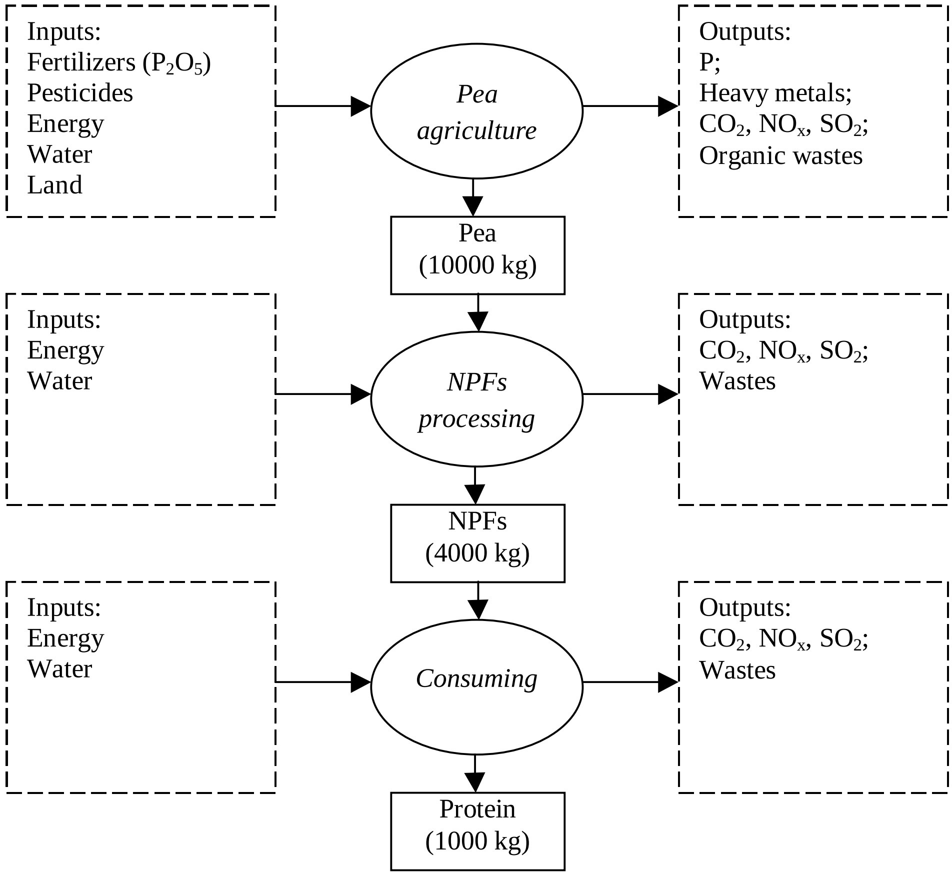

Figure 4-4. Categories of inputs and outputs of the NPFs chain producing one functional unit of NPFs

Allocation of environmental burdens

By ignoring the environmental costs that by-products in feed may have, some studies (e.g. van den Berg, 1995) might underestimate the environmental burdens of pork production. In fact, these by-products are joint products with potential economic value to producers. Indeed by-products (e.g. soycakes) from food industry are not free wastes but are sold to the livestock feed industry. It is more accurate to use the term ‘rest streams’ (Nonhebel, 2004) or ‘crop residues’ (Smil, 1999), because they are not worthless but can be used for different purposes. For example, except for being used as feed, they can also be used as potential renewable energy resources (Smil, 1999; Nonhebel, 2004). Now that they have other ways of use, they should be treated similarly to the main products of food industry and be accounted for their shares in the environmental burdens. For instance, for soy cakes we need to allocate the environmental burdens (e.g. land use, water use and fertiliser use etc.) between joint-products (oil and soy cakes). We attribute environmental burdens to soy cakes and oil respectively according to their relative economic values in oil industry using soybeans. That is, the resource use attributed to the by-products is a proportion of the total resource use in terms of their relative economic values. An overview of relative values of joint products in the food industry is shown in Table 4-2.

Table 4-2. Relative weights and values of joint products

	Soybeans[a]		Sunflower seeds [b),c)]		Rape seeds[b),c)]		Sugar beets[d)]		Peas[e)]	
	oil	cakes	Oil	cakes	oil	cakes	sugar	molasses	protein	meals
Weight (%)	20	80	50	50	40	60	16	84	15	85
Values (%)	30	70	84	16	77	23	91	9	93	7

Source: a) USDA, 2001; b) FAO, 2003; c) LEI, 2002; d) van der Linde *et al*., 2000 and e) Aurelia, 2002.

Main input

Feed is the main input for pig production, which uses land, water, energy, fertilisers and pesticides. Physical capital, although an input too, is ignored. In LCA calculations, the industrial production of capital goods, such as machinery and buildings is normally left out because one can argue that capital goods often have a long lifetime and the environmental burdens of their production allocated to food production would be negligible (Mattsson, 1999). Another important feature for the two chains is that they use similar physical capital for processing and packaging. Therefore for the environmental impact assessment, we will consider the inputs of feed in pork chain and peas in NPFs chain, whose production involves land, water, energy, fertilisers, and pesticides, and energy use for other parts of the whole chains.

Feed input

In the Netherlands in 1996/97, feed consisted of 46.2% feed crops (20% tapioca, 17.3% wheat, 5.7% peas, and 3.2% barley) and 35% by-products, or more precisely, ‘rest streams’ (15% soy cakes, 7.6% sunflower seed cakes, 6.8% rape seed cakes and 5.6% molasses) and 18.8% other ingredients (CBS and LEI, 1999). The following calculation of inputs (resource uses) and outputs (environmental emissions) for the pork chain is based on these major components (81.8%, consisting of feed crops and by-products). We should, however, also consider the possible pressures of the category of other ingredients (18.8%) in feed. For simplicity, we assume that the pressures from this category are proportional to those of the major part because the other ingredients also mainly consist of crops (e.g. oats, maize, rye) and by-products (e.g. milling products), which are produced in similar manner as the major part. Besides, the individual shares in category of other ingredients are very small (less than 1%). Therefore, for brevity of calculation we use the proportion of the major part for the resource use and relevant emissions as a proxy for the category of other ingredients.

According to the feed composition and feed requirement for one functional unit of pork, we can get the component amount of crops and by-products in feed. The use of feed components is summarised in Table 4-3.

Land use

Land is needed for producing feed components in the pork chain and for producing peas in the NPFs chain. Land use for crops is calculated by dividing the crop quantities by the crop yields (FAO, 2003). Tapioca chips or pellets used in feed are dried cassava, which require 2.5

kg of cassava for production of 1 kg tapioca feed products (Nonhebel, 2004). We consider this conversion factor in calculating land use for tapioca when using the yields of cassava. Since some components (soy cakes, sunflower seed cakes, rapeseed cakes and molasses) in feed are *by-products* from food industry, we cannot use the land use for primary crops as the land use for by-products. We calculate the land use for the primary crops that produce the by-products and multiply the land use by the value share of by-products in the food industry to obtain the land use for by-products. The land use for one functional unit of pork is 5.5 ha, shown in Table 4-3. The land use for NPFs chain is the land use for peas (quantity of peas divided by yield) multiplied by the relative value of the protein (Table 4-2), which gives 1.95 ha (Table 4-5).

Table 4-3 Feed-component quantities and land use for a functional unit of pork

Feed components	(kg)	Primary crops for feed	(kg)	Land use from primary crops (ha)	Land use for feed components (ha)
Tapioca	6090	Cassava	15225	1.075	1.075
Wheat	5268	Wheat	5268	0.739	0.739
Peas	1736	Peas	1736	0.363	0.363
Barley	974	Barley	974	0.147	0.147
Soy cake	4568	Soybeans	5710	2.257	1.580
Sunflower cake	2314	Sunflower seeds	4628	2.066	0.331
Rape seed cake	2070	Rape seeds	3450	0.990	0.228
Molasses	1705	Sugar beets	2006	0.037	0.003
Subtotal	24725				4.466
Other ingredients	5725				1.034
Total	30450				5.500

Source: calculation based on feed composition (CBS and LEI, 1999), crop yields (FAO, 2003) and relative weights and values (Table 4-2).

Water use

Water is used for crop production, animal production and processing. The water use for the pork chain includes the water required for the production of feed crops and the direct water use by pigs. According to Pimentel (1997), production of one kg of crops needs about 1 m^3 of water, direct water consumption by pigs is about 1.3% of total water use for pig production. The water use for the by-products in feed is calculated as for land use, considering the relative value share in food industry. Water use for NPF chain includes water use for pea production and water addition in NPF processing. The water use for two chains is shown in Table 4-5.

Energy use

Energy is a crucial input in every stage of the chain. For pork, energy is used for growing all the feed crops, for feed manufacturing, transport, pig farming, slaughtering, processing, distribution, and consumption. The energy use for growing feed crops, manufacturing feed, and pig farming is 2650MJ/pig (Pimentel, 1992). The energy use for processing fresh pork (slaughtering) is 3.76 MJ/kg and for processing meat products (including slaughtering and processing) is 6.30 MJ/kg. The pork chain in the Netherlands includes 60% fresh pork and 40% processed meat products (Vlieger *et al*., 1995).

The energy used in distribution and consumption is for refrigeration and cooking. For refrigeration, 0.0272 MJ/kg per day is used and for freezing 0.0404 MJ/kg per day. Energy use for household consumption of processed pork is 3.45 MJ/kg and 6.9 MJ/kg for fresh pork (Sainze, 2002). In addition, energy use for transportation between each stage depends on the means of transport, the distance. The mode of transport and distances used in baseline as well as energy requirement for each means of transport are shown in Table 4-4.

Table 4-4 Transportation means, distances and energy requirement in both chains

	Items	Distance (km)	Transport means	Energy requirement* ($MJ \cdot t^{-1} \cdot km^{-1}$)
Pork	Tapioca & soy cakes	10,000	100% waterway	Waterway: 0.33
	Other feed & pork	500	50% rail, 50% truck	Rail: 0.50
NPFs	Peas & NPFs	500	50% rail, 50% truck	Truck: 3.47

*Source: Pimentel, 1992.

For the NPFs chain, energy use for growing peas, processing NPFs, distribution and consumption as well as transportation is accounted. The information for the processing of NPF (stage 3) is most difficult to obtain since NPFs are not available at industrial level. The processing of NPFs includes extracting protein from peas, extruding the isolated protein and adding some water and other ingredients for flavour and texture. The processing is thus involved in the energy use for operating equipment. We have to rely on the laboratory data for energy use in this part of the chain (van der Steen, 2002; van Boekel, 2003). The energy use and the energy types used for both chains are shown in Table 4-5.

<u>*Fertiliser use*</u>

For crop production, mineral fertilisers and pesticides are used to enhance yields or control pests. The fertiliser use rates depends on crops and vary from region to region. In this study we use the country- and crop-specific data for fertiliser use rates in crop production (IFA, IFDC and FAO, 1999) considering the origin of the crops in feed and the land use for each chain for the calculation of fertiliser use (see Table 4-5).

<u>*Pesticide use*</u>

We consider per hectare use of pesticides in terms of *active ingredients* per crop (Oskam, 1997) and land use for each feed component to calculate the pesticide use (see Table 4-5). Since the pork chain uses more land but at lower pesticide use rate, and the NPFs chain uses less land but at higher pesticide use rate, one functional unit of two chains needs similar quantities of pesticides.

Table 4-5 Inputs per functional unit

Types of inputs	Pork chain	NPFs chain
Land (ha)	5.5	1.95
Water [a)] (m^3)	36152	10912
Energy[b)] (MJ)		
Electricity	239638	50348
Natural gases	15332	22356
Fuels	132282	55718
Total	397252	128422
Fertilisers[c)] (kg)		
N	342	39
P_2O_5	143	105
Pesticides[d)] (kg)	18	11.1

Source: calculation based on a) Pimentel, 1997; b) Pimentel, 1980; Pimentel, 1992; Sainze, 2002, and van der Steen, 2002; c) IFA, IFDC and FAO, 1999 and d) Oskam, 1997.

Main outputs and emissions

Due to the inputs (fertiliser use, pesticides use in crop production and energy use in each stage of the chains) and outputs (manure of the pork chain, and packaging wastes from two chains), many kinds of emissions enter the environment.

On the input side, we consider energy use, which lead to the emissions of greenhouse gases (CO_2, NO_x and SO_2), and fertiliser use, which leads to the emissions of N and P. We consider the direct pesticide use and fertiliser use for their emission impacts. We do not focus on solid wastes because both chains generate similar packaging wastes in distribution. On the output side, we consider manure and fertilisers, which contributes to the N_2O, CH_4 and NH_3 emissions to air and to nitrogen (N) and phosphate (P) emissions to soil and eventually to water.

Ammonia (NH_3)

NH_3 emissions are mainly related to manure production by animals. The NH_3 emissions include emissions from animal houses, manure storage and surface spreading. In 1997, the emissions from agricultural sectors are 177 million kg and there are 14,419,000 pigs in the Netherlands (CBS, 1999). The emission of NH_3 from pig sectors occupies about 29% of the whole NH_3 emissions from agriculture (Brink *et al.*, 2001), amounting to approximately 51.33 million kg. Since the lifetime of pigs is 7 months, the NH_3 emission per pig was 6.1 kg in 1997. One functional unit of pork contributed 640 kg NH_3 emission in 1997.

Methane (CH_4)

CH_4 emissions related to the pork chain are mainly related to enteric fermentation (digestive processes) of animals and manure management systems. A pig emits 1.5 kg CH_4 from its enteric fermentation (IPCC, 1997). The amount of CH_4 released from animal manure has been estimated to be 4.3 kg/pig (Kramer, 2000). So, the total CH_4 emission is 5.8 kg/pig, and 609 kg per functional unit of pork.

Nitrous oxide (N_2O)
According to IPCC (1997) the N_2O emissions include three parts: N_2O emissions from manure management, direct N_2O emissions from agricultural soils (mainly fertilisers) and indirect N_2O emissions.

The N_2O emissions from manure management depend on the N-excretion from animals and manure management systems. Although Dutch pig production is more intensive than average, the emissions from manure depend on manure management system. Intensity of Dutch system increases the total emissions but not emissions per animal produced. Liquid manure or slurry storage system is the system of manure storage where faces and urine are stored together. This is the main system in intensive livestock systems in OECD countries. The pig waste management in the EU includes 77% of liquid system and 23 % solid storage and drylot. Thus we can use the EU emission factors for calculation. The nitrogen excretion from pigs are 20 kg-N/animal/year. The emission factors are 0.001 kg N_2O-N/ kg N excreted for liquid system, and 0.02 kg N_2O-N/kg N excreted for solid storage and drylot. The N_2O emission from manure management for the pig chain is 11.3 kg.

The direct N_2O emissions depend on the fertiliser use for crops. The emission factor is 0.0125 kg N_2O-N/kg N- fertiliser. It is 4.275 kg N_2O-N for pork chain and 0.5 kg for NPFs chain.

The indirect N_2O emissions come from the pathways for synthetic fertiliser and manure input due to the volatilisation and subsequent atmospheric deposition of NH_3 and NO_x, nitrogen leaching, and runoff. The emission factors for deposition is 0.01 kg N_2O-N/kg NH_3-N and NO_x-N emitted, for leaching and runoff is 0.025 kg N_2O-N/kg N leaching/runoff. As for the NO_x volatilisation, it is 0.1 kg nitrogen/kg synthetic fertiliser and 0.2 kg nitrogen/kg of nitrogen excreted by livestock. The leaching of nitrogen world-wide is 0.3 kg/kg of fertiliser or manure-N. The indirect N_2O emissions for the pork chain are 22.86 kg and 0.33 kg for the NPFs chain.

To summarise, the total N_2O emissions are 38.44 kg for the pork chain and 0.88 kg for the NPFs chain.

Carbon dioxide (CO_2)
CO_2 emissions are mainly due to the energy use. We calculate the CO_2 emissions according to the energy use and emission factors of energy types. The CO_2 emission from electricity according to the Dutch electricity production is 0.755 kg/kWh (Kramer, 2000), which is 0.21kg/MJ. The CO_2 emission from natural gas is 0.0137 kg/MJ, and from fuels 0.0199 kg/MJ (Manne *et al.*, 1995). Multiplying the energy use by the emission coefficients gives the

CO_2 emissions. The CO_2 emissions are 53178 kg for the pork chain and 11,988 kg for the NPFs chain.

Nitrogen oxides (NO_x)

NO_x emission mainly comes from energy use, and also denitrification in the soil because of the manure and fertiliser use (Charles and Gosse, 2002). NO_x emission along the chain is only related to the energy use and agriculture, and the contribution of agriculture is generally very small (2% from the agriculture, CBS, 1999). We therefore only consider the emission related to energy use. In 1995 the total NO_x emissions are 484 million kg, the total energy use is 2947×10^6 GJ (CBS, 2002). Thus, the NO_x emission coefficient is 0.164 kg/GJ. We multiply the energy use for protein chains by the emission coefficient to obtain the NO_x emissions. For one functional unit of pork, the energy use is 397.252 GJ and the NO_x emission is 65 kg. For NPFs chain, the energy use is 128.422 GJ and the NO_x emission equals 21 kg.

Sulphur dioxide (SO_2)

SO_2 is considered in the chain because of energy use. In 1995 the total SO_2 emissions are 141 million kg (CBS, 1999) and thus the SO_2 emission coefficient is 0.0478 kg/GJ. Therefore the SO_2 emission is 15 kg for the pork chain and 6 kg for the NPFs chain.

Nitrogen (N)

Because of manure and fertiliser use, nitrates (NO_3-N) are emitted to soil and leached to water. The nitrogen production per pig in 1997 is 6.4 kg (CBS & LEI, 1999). For 105 pigs, it is 672 kg N emission from manure. Nitrogen fertiliser use is already discussed, which amounts to 342 kg for pork chain. Except for the take-up by the plant, the remaining nitrogen from the fertilisers is cycled in soil, water and air. The uptake rate of nitrogen by plant depends on the soil properties. The average rate of N-uptake is 30% (De Vries *et al*., 2002). The remaining nitrogen is emitted to soil and water systems. Then the total nitrogen emissions from the pork chain are 911 kg. For the NPFs chain, the nitrogen emissions only come from fertiliser use and amount to 27.3 kg.

Phosphorous (P)

Phosphorous (P) emission is also related to manure and fertiliser use. The phosphorus (P) production is 1.0kg/pig (CBS & LEI, 1999). For 105 pigs, the P emission from manure is then 105 kg. The take-up rate of P_2O_5 by plant is 15 % (UNEP, 2000). For 143 kg of P_2O_5 fertiliser use for the pork chain, the remaining part (P_2O_5 emission) is then 121.5 kg, which is 53 kg P emission since 1 kg P_2O_5 emission is equal to 0.4366 kg P emission. The total P emission for one functional unit of pork is 158 kg. For 105 kg of P_2O_5 fertiliser use for NPFs chain, the P_2O_5 emission is 89 kg, which is 39 kg of P emission.

4.6 ENVIRONMENTAL PRESSURE ASSESSMENT OF PROTEIN CHAINS

We have summarised the emissions in Table 4-6. Environmental indicators can provide valuable information on complex issues in a relatively accessible way as they have the ability to isolate key aspects from an otherwise overwhelming amount of information (Niemeijer, 2002). In terms of the environmental problems caused by the inputs and outputs along the chains, we develop two types of *environmental pressure indicators*: *emission* indicators and *resource use* indicators.

Considering the diversity of the emissions and their environmental impacts, we define emission indicators based on the 'environmental themes' because many environmental emissions have the same effect on the environment. The emissions contributing to the same environmental impact can be aggregated into one indicator. The emissions of CH_4, CO_2 and N_2O lead to global warming and thus can be converted into CO_2 equivalents. Similarly, the emissions of NH_3, NO_x and SO_2 can be defined as the acidification indicator by using NH_3 equivalents. Nitrogen (N) and phosphate (P) emissions to soil and water systems cause eutrophication and can be defined as the eutrophication indicator by using N equivalents. Emissions from pesticides and fertilisers have effects of ecotoxicity and human toxicity. Since direct measurement of ecotoxicity and human toxicity of pesticide use and fertiliser use is difficult, we use the direct pesticide use and fertiliser use as emission indicators for toxicity. Therefore, for the protein chains, we define five emission indicators: *CO_2 equivalents for global warming*, *NH_3 equivalents for acidification*, *N equivalents for eutrophication*, *pesticide use* and *fertiliser use*. Using the conversion factors of emissions (1 kg CH_4 = 21 kg CO_2, 1 kg N_2O = 310 kg CO_2; 1 kg NO_x = 0.38 kg NH_3, 1 kg SO_2=0.53 kg NH_3 and 1 kg P=10 kg N)(CBS, 1999), we obtained the CO_2 equivalents, NH_3 equivalents and N equivalents in Table 4-6.

Table 4-6 Emissions of GHGs and other pollutants (kg) for one functional unit of pork and NPFs and their totals in CO_2 equivalents, NH_3 equivalents and N equivalents

Types of emissions		Pork chain	NPFs chain
Greenhouse gases	CO_2	53178	11988
	CH_4	609	0
	N_2O	38.44	0.88
(Total	CO_2 equivalents	77883	12260)
Acidifying gases	NH_3	640	0
	NO_x	65	21
	SO_2	19	6.2
(Total	NH_3 equivalents	675	11)
Eutrophication	N	911	27.3
substances	P	158	39
(Total	N equivalents	2491	417.3)

On the other hand we define the resource use indicator because agriculture requires land and water as inputs. The consideration about land use in this chapter focuses on the environmental resource use because available cropland use is competitive (de Haan *et al*., 1997; CAST, 1999). It is true that land use has other functions such as providing landscape, amenity, biodiversity and so on, but land use for a certain purpose reduces the opportunity of being used as another purpose. 'Saving land for nature' is advocated and intensive land use imposes a big pressure on the land quality because most of the best quality farmland is already used for agriculture, which means future land expansion would occur on marginal land that is vulnerable to degradation (Tilman et al., 2002). Therefore land use can be viewed as an environmental pressure indicator. Water use also imposes direct pressure on the environmental resources. Therefore we define two resource use indicators: *land use* and *water use*.

The environmental indicators are shown in Table 4-7. Our estimates suggest that the pork chain contributes to acidification 61 times more, to global warming 6.4 times more, and to eutrophication 6.0 times more than the NPFs chain. The pork chain also needs 3.3 times more fertilisers, 1.6 times more pesticides, 3.3 times more water and 2.8 times more land than the NPFs chain.

Table 4-7 Emission and resource use indicators per functional unit of pork and NPFs

	Pork	NPFs	Ratio (pork/NPFs)
Acidification (NH_3 equivalent, kg)	675	11	61
Global warming (CO_2 equivalent, kg)	77883	12236	6.4
Eutrophication (N equivalent, kg)	2491	417	6.0
Pesticide use (active ingredient, kg)	18	11	1.6
Fertiliser use ($N+P_2O_5$, kg)	485	144	3.4
Water use (m^3)	36152	10912	3.3
Land use (hectares)	5.5	1.95	2.8

4.7 SENSITIVITY ANALYSIS

The above study is based on a few assumptions, for example, the transportation distance and transport means. Except tapioca and soycakes, which are, transported over 10,000 km from Thailand and USA, we consider in the sensitivity analysis a scenario of increasing the transportation distance of other parts in the chain to be 1500 km instead of the previous 500 km considering the trade in the EU. The modes of transportation remain the same as the baseline: 50% truck and 50% rail. The energy use for transportation will change and consequently the CO_2 emission, NO_x emission and SO_2 emissions from the energy use will also change. The CO_2 equivalents for the pork chain increase by 1.5% from 77883 kg to 79011 kg, and for NPFs chain by 5% from 12236 to 12930 kg. The NH_3 equivalents for the pork chain increase by 0.6% from 675 to 679 kg and for the NPFs chain by 21% from 11 to 14 kg. The relative ratio for the global warming indicator of pork to NPFs decreases from 6.4 to 6.0, the relative ratio for acidification indicator decreases from 61 to 48. See Table 4-8 for the results.

Table 4-8 Acidification and global warming indicators for sensitivity analysis

	Pork	NPFs	Ratio (pork/NPFs)
Acidification (NH_3 equivalent, kg)	679	14	48
Global warming (CO_2 equivalent, kg)	79011	12930	6.1

For illustration purpose, we only carry out the sensitivity analysis for the parameter change in transportation distance. The impact of other changes in parameter values such as the diet composition can also be analysed in additional sensitivity analyses.

4.8 Conclusions and Discussion

Using the reported environmental indicators, this study indicates that the NPFs chain is more environmentally friendly than the pork chain. This is a very interesting result because producing plant proteins using crops only is less damaging to the environment than via an additional step from crops to animals. Replacing animal protein by plant protein is promising in reducing environmental pressures, especially acidification. Since NPFs need less land, introducing NPFs can reduce the pressure on land for the production of food and feed. Thus from an economic perspective it gives the opportunity to grow other crops on the available land.

In this study we have used environmental pressure indicators for environmental impact assessment. This is a straightforward way of assessing the environmental impacts, which avoids the difficulties of collecting data on the environmental effects. We should, however, be aware that actual environmental impacts have spatial dimension. Although in this study we have considered the locations of specific products (e.g. for fertiliser use for feed crops), we could not give specific indication for the pressure indicators about where this pressure is imposed. This gives a direction for a further study on the assessment of spatial environmental impacts.

Moreover, from sensitivity analysis of energy use for transportation we find that the environmental impacts from each chain depend on the choices of the practices along the chain. Having long transportation distance increases the absolute emissions of CO_2, NO_x and SO_2 for both chains, but reduces the relative ratio of emission indicators of the pork chain to the NPFs chain. This is because the emissions from NPF chain is mainly due to the energy use and pork chain is due to the manure. This implies that long distance transportation reduces the relative advantage of the NPFs with respect to pork.

As illustrated in the sensitivity analysis, changing some parameters in the chains will change the relative advantages of the different chains. It implies that modifying the protein production and consumption chain offers possibilities to enhance sustainability by reducing inefficiency and its environmental impacts. It will be interesting to show in future study how changing some inputs in chains will result in less environmental pressures. This is an important challenge for chain management policies, which can improve the economic and environmental efficiency of the chain. It will lead to the identification of possibilities of environmental impact reduction and system optimisation. For example, changing the animal diets (feed strategy) may improve the environmental quality because some components of the feed are less polluting than others. As CAST (1999) pointed out, the potential to reduce pollution through modifying animal diets is a field in the early stages of development, but one that offers substantial promise of future environmental benefits. According to Carrouee *et al.* (2002), grain legume protein can substitute for soybean in animal diets. Due to high lysine content, the use of legume seeds in animal diets complements cereals (which are poor in this essential amino acid), and may promote a more efficient use of the protein N, reduce the N surplus excreted in the animal urine, and therefore reduce the environmental problems associated with animal production. Therefore redesigning the chain can achieve lower environmental pressures and impacts. Through chain management, economic and environmental efficiency of the chain can be improved.

Chapter 5 Introducing Novel Protein Foods in the European Union: economic and environmental impacts[1]

5.1 Introduction

In Chapter 2, we have discussed how to represent the environmental impacts in economic models considering the economic functions of the environment. We have therefore developed two welfare programs (2-2 and 2-3) for representing environmental problems in the PROFETAS context. In Chapter 3, we have intensively applied the welfare program (2-3), which focuses on the biophysical process of acidification, in numerical examples. In that model we consider the input function of the environment, and the non-convexities are a major concern in solving the model. In this chapter we will apply welfare program (2-2), which focuses on the representation of the amenity value of environmental quality in the utility function. The differences between this chapter and Chapter 3 are as follows. The first difference is that in this chapter we consider the amenity function of the environment in the utility function and the emission input in the production function, whereas in Chapter 3 only the input function of the environment in the production function was included. Second, we considered the non-convexity of the environmental process model in Chapter 3 and illustrated how to solve non-convex models in numerical examples. In this chapter, however, we avoid the non-convexity by using a linear relation between environmental quality and emissions. Third, the model in this chapter is closer to a real economy with more detailed classification of goods and economic regions. But we have to acknowledge that the model in this chapter is still more methodological than empirical, because we use predetermined production functions and utility functions. The base run is produced using the real exogenous variables such as total labour, capital and emissions. In this manner, this chapter prepares the ground for further empirical application of the model containing the amenity value of the environmental quality in the utility function in Chapter 6.

The purpose of this chapter is to study, from a primarily methodological perspective, some of the potential economic and environmental consequences of a shift from animal protein foods to NPFs in the European Union (the EU). In order to investigate the consequences of a shift from animal protein foods to NPFs, we apply the AGE framework and include the

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[1] This chapter is mainly based on Zhu, X., E. C. van Ierland and J. Wesseler. 2004. Introducing Novel Protein Foods in the EU: Economic and Environmental Impacts. In: R. E. Evenson and V. Santaniello (eds.), Consumer Acceptance of Genetically Modified Food. CAB International, Oxfordshire: 189-208.

environmental aspects in the utility function of consumers and the use of the environment as input in the production function of the producers. The contribution of this chapter is to show how to apply an environmental AGE model that can capture environmental concerns of the consumers for examining the impacts of the enhanced introduction of NPFs.

The environmental concern of the consumers is embodied in the utility function of our AGE model. The consumer's utility depends not only on the consumption of the rival goods but also on the environmental quality, as a non-rival public good. The introduction of NFPs to society is simulated in the model by an exogenous shift in consumer demand, i.e. by increasing the expenditure share of NPFs in the protein budget (δ) to partially replace the consumption of pork. We use an increasing expenditure share of NPFs because we simulate a voluntary shift to NPFs, which is the central hypothesis in the research program. This shift might be considered to be the result of consumer's orientation to the 'green products' and to the safety of the plant protein products. The substitution between pork and NPFs is represented by the substitution elasticity (σ) in the utility function. In the application of the model, the expenditure share of NPFs in the total protein budget of the consumers (δ) is increased from 0% in the base run to 30% after the enhanced introduction of NPFs in the simulation run. The substitution *elasticity* between pork and NPFs (σ) is chosen to be 0.8, considering the consumers' concerns with health and the tendency to the new products on one hand, and the present diet habits on the other hand. For the environment, we temporarily only consider the atmospheric emissions of CO_2 as an environmental indicator for several pollutants and environmental effects related to the use of energy in the model application. The nitrogen and phosphate emissions from the manure of pork production could also be included, but they are not yet considered in the application because of data problems. The consumers' concern for the environmental quality is represented by the willingness to pay for the environment. To be specific, it is represented by the utility elasticity for environmental quality (ε) in the utility functions. Since the value for ε is difficult to obtain, we analyse the impacts of NPFs by means of sensitivity analysis for ε over a relatively wide range of values (0.05 to 0.20). The new runs for the different values of ε construct different scenarios. The comparison between the results of the base run and those of the scenarios provides insights in the potential economic impacts of a shift towards the consumption of NPFs, considering consumers' concern for the environment.

The chapter is organised as follows: Section 5.2 gives the specification of the AGE model considering environmental pollution, where emission is viewed as an input of the production and the consumers have to pay for their consumption of the environmental quality. Section 5.3 includes the model application and the sensitivity analysis of the utility elasticity for environmental quality. In this section, some simulation results are presented and a brief interpretation of the results of the model application is also given. Finally, Section 5.4 gives the preliminary conclusions of the impacts of NPFs based on the application of the model, and some discussions of the model.

5.2 THE SPECIFICATION OF THE AGE MODEL

Based on the theoretical structure of the AGE model with environmental concerns presented in Chapter 2 (welfare program 2-2) and discussed in Appendix5-A, we have specified the model for this study. In this section we describe the characteristics of the applied model, and specify the functional forms of the model.

The characteristics of the model

In the AGE model applied in this paper, the world is divided into two regions: the EU and the ROW. Thus we have two representative consumers, i= EU and ROW. The flow of the commodities in these two regions is shown in Figure 5-1.

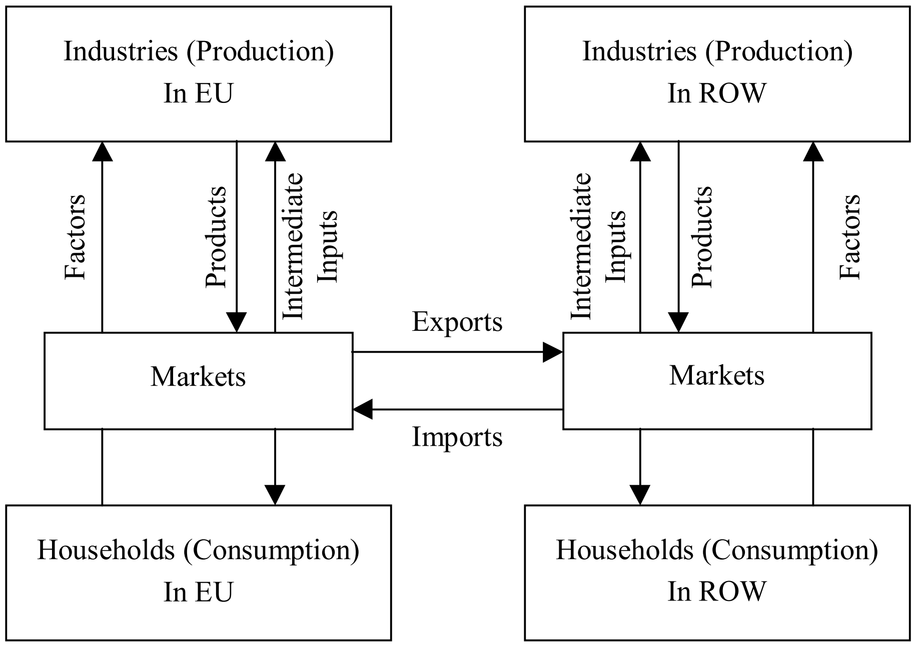

Figure 5-1 The flows of the two-region AGE model

Six products are distinguished: pork, other food, non-food, NPFs, peas and feed. The former four goods ─ pork, other food, non-food, and NPFs ─ are the consumption goods of the consumers. Peas are both direct consumption goods and intermediate goods for production of NPFs. Feed is intermediate input of pork production. For the production of pork, the factor inputs (labour, capital and land) and intermediate input (feed) are used, while for the production of other food and feed, only the factor inputs are used. NPFs are produced by capital, labour and an intermediate good of peas. The non-food product only uses the factors: capital and labour. Feed and peas are both produced as intermediate goods in agriculture by the factor inputs: labour, capital and land. The environment is specified in two ways. Firstly, the use of environmental services is included as input for production. Secondly, the utility of each consumer is related to the consumption of private goods and services, and to the level of an environmental quality indicator. Thus there are nine commodities (pork, other food, non-food, NPFs, peas, feed, labour, capital and land) and one non-rival good (expressed by an environmental quality indicator) in the model. All the goods and services can be exported or imported based on the comparative advantages of each region under free trade. In our application the factors of production are immobile between two regions. For simplicity, the model is comparative static.

Objective function and utility functions

The objective function of the welfare program in Negishi format is:

$$W = Max[\alpha_{EU} \cdot logU_{EU} + \alpha_{ROW} \cdot logU_{ROW}] \tag{5-1}$$

where W is the total welfare, U_{EU} and U_{ROW} are the utility of the EU and ROW, α_{EU} and α_{ROW} are the Negishi weights of the EU and ROW respectively. For the equilibrium solution of the model, the Negishi weights have to be found such that the budget constraints hold. Analytically in the sequential joint maximization (SJM) method, the Negishi weights are the respective shares in total income in the economy when Cobb-Douglas utility functions and production functions are chosen (Ermoliev *et al.* 1996; Rutherford, 1999).

The utility function in our model is a nested function of three levels. The substitution structure of the consumption of goods is shown in Figure 5-2. At Level 1, it is a Cobb-Douglas function with substitution between the consumption of rival goods and a non-rival good (environmental quality). At Level 2, it is also a Cobb-Douglas function with substitution between proteins, other food, non-food and peas for the consumption of rival goods. At Level 3, it is a CES function with substitution between pork and NPFs for the consumption of proteins.

The demand function (Shoven and Whalley, 1992) for pork and NPFs will then be[2]:

$$C_{EU,pork} = \frac{(1-\delta)E_{pr,EU}}{p_{pork}^{\sigma} \cdot [(1-\delta)p_{pork}^{(1-\sigma)} + \delta p_{NPFs}^{(1-\sigma)}]}$$

$$C_{EU,NPFs} = \frac{\delta E_{pr,EU}}{p_{NPFs}^{\sigma} \cdot [(1-\delta)p_{pork}^{(1-\sigma)} + \delta p_{NPFs}^{(1-\sigma)}]}$$

where $C_{EU,NPFs}$ is the consumption of NPFs, $C_{EU,\, pork}$ is the consumption of pork in the EU, σ is the elasticity of substitution between pork and NPFs, δ is the expenditure share of NPFs in protein budget, $E_{pr,EU}$ is the expenditure of the consumers on protein consumption in the EU (the protein budget), p_{pork} and p_{NPFs} are prices of pork and NPFs respectively. Therefore

[2] The demand function of pork and NPFs are based on the CES utility function in Level 3 for the protein consumption: $U(protein) = [(1-\delta) \cdot C_{EU,pork}^{\frac{(\sigma-1)}{\sigma}} + \delta \cdot C_{EU,NPFs}^{\frac{(\sigma-1)}{\sigma}}]^{\frac{\sigma}{\sigma-1}}$.

according to the substitution effects and expenditure share of the two proteins, the following relation exists[3]:

$$C_{EU,NPFs} = \frac{\delta}{1-\delta}\left(\frac{p_{pork}}{p_{NPFs}}\right)^{\sigma} \cdot C_{EU,pork} \tag{5-2}$$

The protein consumption in the EU $C_{EU,pr}$ and in the ROW $C_{ROW,pr}$ is as follows.

$$C_{EU,pr} = C_{EU,pork} + C_{EU,NPFs} \tag{5-3}$$

$$C_{ROW,pr} = C_{ROW,pork} \tag{5-4}$$

where $C_{ROW,pork}$ is the pork consumption in the ROW.

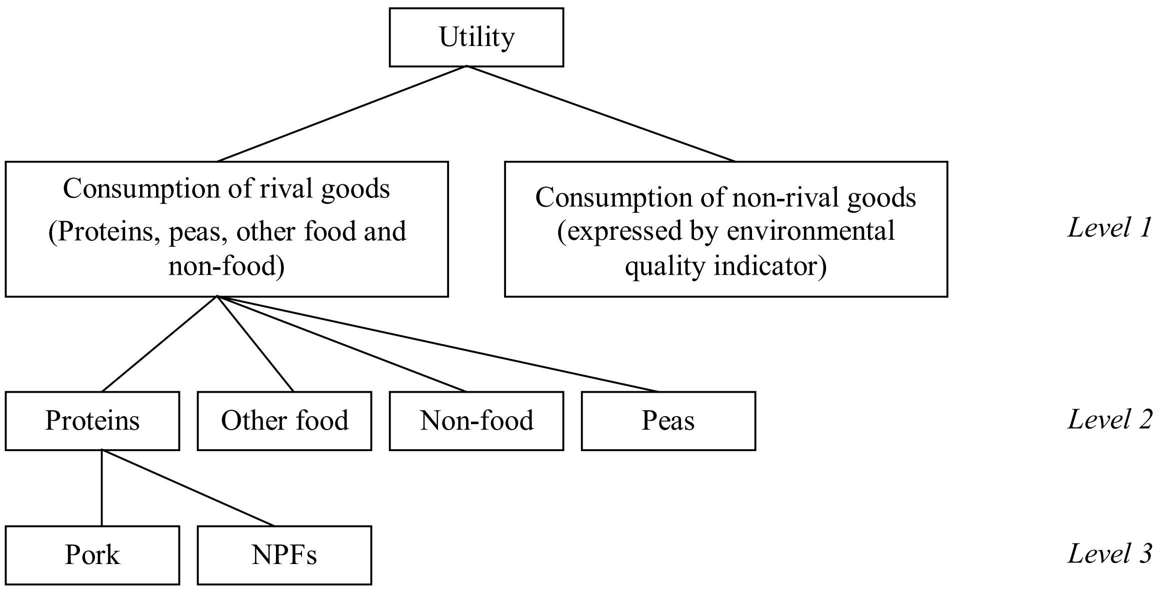

Figure 5-2 Nesting structure in utility function in EU

For the use of the environment, we consider the simple case in which environmental services are used as input in the production process. The use of environmental inputs decreases the utility of the consumers by reducing environmental quality that we express in the model by means of an environmental quality indicator. In this manner environmental quality is affected by the use of the environmental services in production and by preferences of the consumers for the non-rival good 'environmental quality'. The utility function $u_i(x_i, g_i)$ is continuous, concave, increasing in (x_i, g_i) and satisfies: $u_i(0, g_i) = 0$, where x is the vector of

[3] If σ =1.0, this relationship between pork demand and NPFs demand does not hold any more. Then the consumption of both goods is dependent on the protein balance function and the utility function. The consumer will only consume the cheaper one.

consumption goods, g is the non-rival consumption of environmental quality and i is the consumer. This results in the following utility functions with C_s as the consumption of rival good s, s = proteins (pork +NPFs), other food, non-food and peas, and g as the non-rival consumption of an environmental good (expressed by the environmental quality indicator):

$$U_i = g_i^{\varepsilon_i}(f(C_{si}))^{1-\varepsilon_i} = g_i^{\varepsilon_i}(\prod_s C_{si}^{\beta_{si}})^{1-\varepsilon_i}, \tag{5-5}$$

where i indicates the consumer (i= EU, and ROW), ε is the utility elasticity for environmental quality, β_s are the utility elasticities for consumption of rival goods without considering the environment, and $\sum_s \beta_{si} = 1$. The utility functions used in the applied model are given in Appendix 5-B.

Production functions

A production function describes the technical relationship between the inputs and outputs of a production process represented by a mathematical function. The production of pork, or animal protein products (processed pork) and NPFs can be described by the production chains because the agriculture process is very different from the industrial production. The two representative chains are shown in the Figure 5-3 (a) and (b).

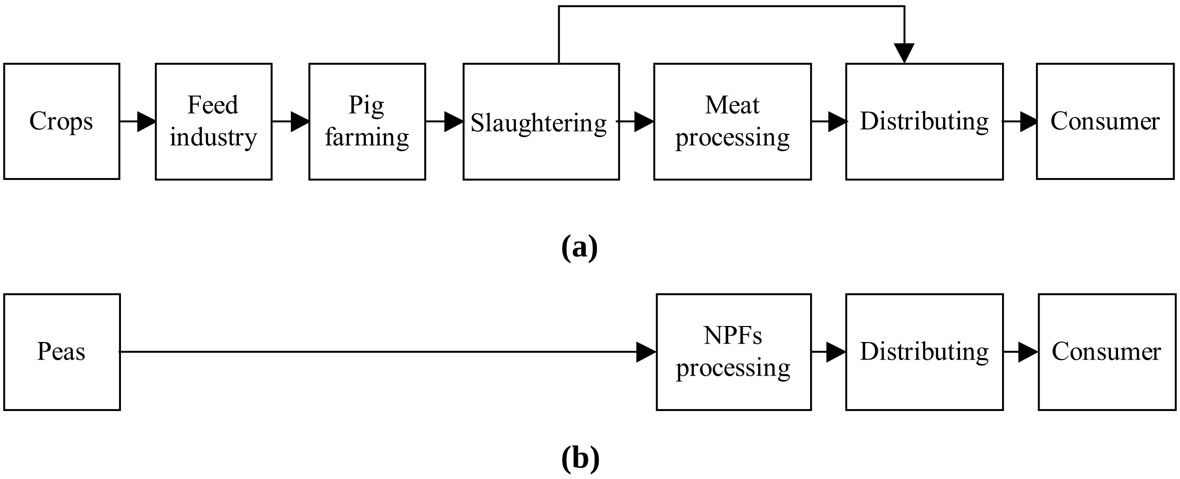

Figure 5-3 Production and consumption chains of pork (a) and Novel Protein Foods (b)

Along the chains, many inputs and outputs (including the environmental emissions) are involved. It is impossible to include all the inputs along the chains in the production function of the pork and NPFs production, and simplification is necessary. As we have noticed, the production processes not only use production factors as inputs but also generate the emissions from production. For technical reasons *pollution* in our model is not viewed as a negative externality but as the use of a natural resource. The production inputs of pork include labour, capital, land, the intermediate good 'feed' and an environmental input (e.g. emission). For the production of all the goods, an environmental input is also used. The Cobb-Douglas production function for production of good *j* with environmental input can in general be presented as follows:

$$Y_j = EM_j^{\xi_j} F(LB_j, LD_j, K_j, FD_j, PI_j)^{1-\xi_j}$$

where *j* is the production good (*j* = pork, NPFs, other food, non-food, peas and feed), *Y* is the production, *EM* is the environmental input, ξ is the exponent of the emission in the production function indicating the cost share of the emission *EM* for production, $0<\xi<1$, *LB* refers labour input, *LD* land input, *K* capital input, *FD* the feed input and *PI* the pea input. One can consider *EM* as the use of 'environmental services', which reflects that the firm must release its emissions to the environment. We can think of the firm as requiring *EM* emission permits in order to produce (Copeland and Taylor, 2003). Therefore when environmental services are treated in the production function in this way, an emission permit system reflecting the annual endowment of environmental services for each region is necessary for the modelling. Thus the following relationship holds

$$\sum_j EM_{ij} \le \overline{EM_i}, \tag{5-6}$$

where EM_{ij} is the use of environmental services in region *i* for good *j*, and $\overline{EM_i}$ is the number of emission permits in region *i*.

The production function for good *j* is then:

$$Y_j = EM_j^{\xi_j} [(LB_j)^{\eta_{1j}} (LD_j^{\eta_{2j}} (K_j)^{\eta_{3j}} (FD_j)^{\eta_{4j}} (PI_j)^{\eta_{5j}}]^{1-\xi_j} \tag{5-7}$$

where η_1, η_2, η_3, η_4 and η_5 is the cost share of each input (*LB*, *LD*, *K*, *FD*, *PI*) for production without considering the cost of emissions, with $\eta_1 + \eta_2 + \eta_3 + \eta_4 + \eta_5 = 1$.

For the parameters of the production functions, we use information from other studies. For example, the feed costs amount to 60% of the total production costs in the Netherlands (Jogeneel, 2000). For the EU an average of 45% of the feed costs is used in the pork production function. The technological parameters in the production functions of the EU and the ROW are 1.0 and 0.6 respectively[4]. The production functions in this manner *grosso modo* reflect the production technology for the region that we distinguish in our study. The production functions and balance equations are reported in Appendix5-B.

Environmental quality

The balance equation for environmental goods (e.g. clean air), which are inputs to the production process, is assumed to be determined by the initial stock and production inputs as

[4] These technological parameters are chosen to the best of our knowledge but require further research. The model specification in GAMS is available on request from the authors and the impact of different parameter values can be easily established.

shown in equation (5-A2) of Appendix 5-A. But the initial stock of 'environmental services' is hard to know and the link between output and the use of environmental goods in the production process is hard to establish. With the emission permit system, we established the relationship in equation (5-6) for producers. For consumers, the environment is valued in terms of environmental service which is constrained by equation (5-A2)' of Appendix 5-A. For our applied model, we only consider a one-dimensional (e=1) environmental service g, which reflects a number of environmental issues that are related to the energy use and the release of pollutants like NO_x and SO_2 or greenhouse gases. As a proxy for energy use and related emissions we use the level of CO_2 emissions in the respective regions. Then we can define the 'environmental quality indicator' to be determined by the level of emissions. If the emissions are above a critical level, the environmental quality indicator will decrease. We next use the environmental quality indicator as the non-rival consumption of environmental goods in the utility function. Of course, the model can be easily expanded to include more dimensions of environmental goods g, by explicitly modelling emissions of nitrogen oxides and other pollutants as long as the data are available.

Obviously, the environmental quality that consumers face in region i is determined by the total use of the environmental services of all the producers in region i. In the present model version we approximate this relation by means of a linear function in the use of the environmental services:

$$g_i = \overline{\psi}_i - \sum_{j=1}^{n} EM_{ij} \qquad (\phi_i) \tag{5-8}$$

where $\overline{\psi}_i$ is the intercept and $\sum_{j=1}^{n} EM_{ij}$ is the total emissions of all the producers in region i.

This relationship shows that the higher the emissions the lower the environmental quality. Since consumers will enjoy and pay for this environmental quality, it can be seen as a product produced by a certain environmental sector.

Budget constraints

Under constant return to scale, profits are zero so that income is the value of initial endowments, which are employed in the production. According to the endowments of production factors and emission permits the income is:

$$h_i = rl_i \cdot LD_i + w_i \cdot LB_i + rk_i \cdot K_i + p_{mi} \cdot EM_i$$

where rl is the price of land, w is the wage, rk is the price of capital and p_m is the price of emission permit. It should be equal to the total revenue of the production sectors and the 'environmental sector':

$$h_i = \sum_j p_j \cdot Y_{ij} + \phi_i g_i \,, \tag{5-9}$$

where p_j is the price scalar of good j, the first item of the right-hand side $\sum_j p_j \cdot Y_{ij}$ is the revenue of the production sectors, and the second item $\phi_i g_i$ is the revenue of the 'environmental sector' which maintains certain environmental quality demanded by the consumer.

Budget constraints say that the expenditure of the consumer should be equal to his income. Now that the non-rival environmental quality is one of consumption goods, the consumer has to pay for his consumption. Just like that the producer has to pay for the emission permit for production, the consumers who simply enjoy the presence of the resource or environmental quality should pay to the 'environmental sector' for the environmental services. The budget constraint of the consumer now looks like:

$$\sum_s p_s \cdot C_{si} + \phi_i g_i = h_i \qquad (5\text{-}10)$$

where p_s is the price scalar of good s, s = proteins (pork + NPFs), other food, non-food, and peas, C_{si} is the consumption of good s in region i, $\sum_s p_s \cdot C_{si}$ is the total expenditure on the consumption of all rival goods and $\phi_i g_i$ is the payment by the consumers for the environmental quality g, and h is income.

In this welfare program, where both the consumers and producers have to pay for the environmental use, the Lindahl equilibrium is reached (GK, 2002).

5.3 THE MODEL APPLICATION AND RESULTS

Data and scenarios

The base run and scenarios

We have applied the model to develop the base run, a scenario for the enhanced consumption for NPFs and some scenarios of sensitivity analysis.

Base run

There are no NPFs, the environmental concern is indicated by the utility elasticity for environmental quality ε, which is assumed to be 0.05 for both regions.

NPF scenario

For the simulation of the new scenarios, we assume that the substitution elasticity of the NPFs for pork is $\sigma = 0.8$ and we simulate a situation where the expenditure share of NPFs in the protein budget is increased to 30% (δ = 0.3) after enhanced introduction of NPFs. We do not assume NPFs as *perfect* substitutes of pork (σ =1) because we think in the short run it is impossible to replace all the animal protein products by NPFs. In this scenario, we use the same value for the utility elasticity for the environment (*ε=0.05*) as in the base run.

<u>*Sensitivity analysis*</u>

As a consumer-driving economy, the sensitivity of the results to the parameters in the utility functions is a very interesting issue. We carry out the sensitivity analysis for the value of parameter *ε*. The values of 0.1 and 0.2 for *ε* are simulated under two cases of four runs where (*i*) different values for the EU and ROW and (*ii*) similar values for the EU and ROW are used, respectively. The results of all these scenarios are compared with the results of the base run. The comparison gives an impression of some potential impacts of the enhanced introduction of the NPFs in the EU on the economy and the environment.

The data

As stated, the model is applied to the economy with two regions: the EU and ROW. The data for labour, land and capital are based on the database of FAO (2002) and Penn World Table (2002). The labour force in 1998 in the EU is 252 millions and 3323 millions in the ROW. The total land area in 1998 in the EU is 313 thousand ha and 12149 thousand ha in the ROW. Non-residential capital stock per worker in the EU is approximately 30000 € per worker and 5000 € per worker in the ROW according to the Penn World Table. The total capital stock in the EU is 7560 billion € and the ROW is 16615 billion €. The data for emissions is based on the little Green Data Book (World Bank, 2000). The EU contributes about 12% of the global CO_2 emissions (3000Mt in the EU and 22000Mt in ROW in 1998). As we have already mentioned, emission permits should be given when the emissions are taken as an input for the production function. In the model run, we initially allocate emission permits to the EU and ROW according to the emission levels of 1998. The initial endowments are shown in Table 5-1. Those data are used for the model applications.

Table 5-1 Factor endowments of labour, land, capital and CO_2 emission permits

	Labour (millions)	Land (ha×1000)	Capital (billion €)	Emissions (Mt)
EU	252	313	7560	3000
ROW	3323	12149	16615	22000

The results

<u>*The results for the base run*</u>

When there are no NPFs, and *ε*=0.05, we run the model as the base case. The results for the 'base run' are reported in Table 5-2. Firstly for production the table shows that the EU is basically the major producer of pork and non-food. It exports pork and non-food to the rest of the world and imports other food, peas and feed from the rest of the world. Secondly for the use of environmental services, the entry 'emissions' in Table 5-2 shows that the EU emits 12 % of the global emissions, which is consistent with the endowment of environmental services that we used. Pork is, in our analysis, the most polluting product with the highest environment input in the production function. Pork is more expensive, because its production needs more factor inputs, including feed as an extra intermediate input. Finally Table 5-2 shows that income per worker in the EU is five times higher than the rest of the world.

Table 5-2 Baseline: Production, Consumption, Trade, Emissions and Income

	Production					Consumption				
	Pork	Other food	Non food	Peas	Feed	Pork	Other food	Non-food	Peas	Feed
EU	304	0	1283	0	0	94	668	1218	3	301
ROW	39	2422	3163	43	340	249	1754	3229	40	39
Total	343	2422	4447	43	340	343	2422	4447	43	340
	Trade (+ = export - = import)					Emissions		Income per worker		Utility (welfare)
EU	210	-669	66	-3	-301	1162		12.4		779
ROW	-210	669	-66	3	301	8188		2.5		2140
Total	0	0	0	0	0	9350				(7.39)

The results for the NPF scenario

By introducing an exogenous increase in the consumption of NPFs in the EU by increasing the expenditure share of NPFs in protein budget, with the same environmental concern in the two regions as the base run (ε=0.05), a new equilibrium will be reached. The results are reported in Table 5-3.

Table 5-3 NPFs scenario: Production, Consumption, Trade, Emissions and Income

	Production						Consumption					
	Pork	NPFs	Other food	Non-food	Peas	Feed	Pork	NPFs	Other food	Non-food	Peas+ input	Feed input
EU	289	52	0	1281	0	0	68	52	662	1205	3 +66	284
ROW	30	0	2421	3164	109	313	251	0	1759	3240	40	29
Total	319	52	2421	4445	109	313	319	52	2421	4445	109	313
	Trade (+ = export - = import)						Emissions			Income per worker		Utility (welfare)
EU	221	0	-662	77	-69	-283	1153			12		794
ROW	-221	0	662	-77	69	283	8170			2.5		2148
Total	0	0	0	0	0	0	9323					(7.4)

Comparing Tables 5-2 and 5-3, we observe the implications of the enhanced introduction of NPFs in the EU to the economy. The budget share of 30% for NPFs results in a reduction of consumption of pork in the EU by 28%. Pork production in the EU will be decreased by 5% (15 units) from 304 to 289 units. The reduction in consumption of pork is more than the decrease of the pork production in the EU because the EU will benefit from exporting pork to the rest of the world. The international trade of pork is increased by 5 % from 210 to 221 units.

Since the production of NPFs is less polluting than that of pork production, the total emissions will decrease by about 0.8% in the EU. As for the rest of the world, the emissions are decreased by 0.2% because they produce less pork by importing from the EU. The total emissions are reduced by about 0.3% because the emissions of the EU are much lower than those of the ROW.

For income related to the remuneration of factors, we observe that income for the EU falls slightly because the production of NPFs needs simpler process than pork and thus less primary inputs. Therefore the factors are less demanded than before the enhanced introduction of NPFs, and prices of factors are lower. Given the fixed volume of factors, the remuneration will be lower.

The utility is increased slightly because in our model the utility depends on both the consumption of rival goods and the environmental quality indicator. The environmental quality indicator is linear and declining in the level of emissions. The consumers have to make a tradeoff between more consumption of the rival goods with lower environmental quality and better environmental quality with less consumption. The more consumption of the rival goods means more pollution but more pollution implies the lower environmental quality. In this manner the preference of the consumers for environmental quality give feedback to consumption of rival and non-rival goods and then to production.

Sensitivity analysis

As the preferences of consumers for environmental quality will have a feedback on the production and consumption in a competitive model, the interesting question is how the consumers value this environmental quality. We carry out some sensitivity analysis for the valuation of the consumer for the environmental quality, because little information is available on the role of the environment in utility function of the consumers. In the above two applications of the model, a modest value of 0.05 for the utility elasticity for the environment is used for both regions. This means that the consumers are willing to pay 5% of their expenditure for a good environment. But in reality different people have different willingness to pay for the non-rival consumption of environmental goods. Therefore, it will be interesting to see how the attitude of the consumers will influence their consumption bundle. Under the first case, we consider the different environmental concerns in different regions. The market for environmentally friendly goods is located mainly in the member countries of OECD, where during the last few years consumers have started to articulate strong environmental concerns. These concerns have been translated into both individual purchasing decisions and government regulations (Bharucha, 1997). Under the second case, we will increase the value of ε from 0.05 to 0.1 and 0.2 for both regions. Therefore we will carry out sensitivity analysis under these two cases of the four runs which are shown in Table 5-4.

Table 5-4 Runs for sensitivity analysis of ε

	Model runs	Values of ε
Case 1	Run 1	$\varepsilon_{EU} = 0.1,\ \varepsilon_{ROW} = 0.05$
	Run 2	$\varepsilon_{EU} = 0.2,\ \varepsilon_{ROW} = 0.05$
Case 2	Run 3	$\varepsilon_{EU} = 0.1,\ \varepsilon_{ROW} = 0.1$
	Run 4	$\varepsilon_{EU} = 0.2,\ \varepsilon_{ROW} = 0.2$

Under Case 1, we fix the value of the utility elasticity for the environment ε in ROW at 0.05, and increase the value for the EU from 0.05 to 0.1 and 0.2 respectively. See Tables 5-A1 and 5-A2 in Appendix 5-C for the detailed results. With the increased value for the EU, pork production in the EU will decrease. If the value increases to 0.2, pork production in the EU will be hampered severely and at the given technology will eventually disappear, because pork is the most polluting product. The price of pork decreases because it is less demanded. Non-food production will increase in the EU because the EU has comparative advantage and is less polluting than the other products. As a result, the export of non-food to the rest of the world will increase and the price of non-food falls because more production takes place. The emissions in the EU decrease as the increase of consumer's valuation to the environmental goods in the EU, because the EU switches to produce more non-food and less pork. As a contrast, pork production in the ROW will increase as a result of the increase in the value of the environmental good in the EU, because the EU will reduce the production and the export of pork. Since pork and non-food become cheaper as the increase of ε, the ROW is also better off. The emissions in the ROW increase, however, because the ROW has to produce of the polluting product 'pork' for its own consumption and exports to the EU.

Under Case 2, we have increased the value of ε for both regions from 0.05 to 0.1 and 0.2 for both regions. The simulation results are reported in Tables 5-A3 and 5-A4 in Appendix 5-C. The results show that pork production for both regions decreases and the emissions decrease greatly.

5.4 Conclusions and discussion

In this chapter we has sketched some important aspects and possible implications of an enhanced demand for NPFs, by means of an AGE model. Although we are aware that the model is far from perfect and that it is formalized at a high level of aggregation, we think it is worthwhile to discuss some of the characteristics, the assumptions and the results of the analysis. The model considers both the utility from the consumption of goods and the disutility from environmental pollution. The emissions from production give a feedback on utility and on the bundle of rival and non-rival consumption, and then indirectly on production. For a value of 0.05 for the utility elasticity for the environment, the enhanced introduction of NPFs decreases the emissions from pork production in EU and decreases the total emissions slightly (0.8 %). The EU will consume less pork by consuming some NPFs and will export more pork than before. Moreover, pork production in the rest of the world will decrease slightly (0.2 %) because slightly more pork can be imported from the EU. Thus the introduction of NPFs decreases in this setting the emissions in the ROW slightly. As a result, the total emissions in the world will *decrease* slightly (0.3%) too.

Nevertheless, the model results are sensitive to the value of the utility elasticity for the environment. If the EU has a higher utility elasticity for the environment than the ROW (0.1 versus 0.05) pork production in the EU will decrease more strongly and the export of pork to the rest of the world will decrease. As a result, the rest of the world has to increase the pork production for their high demand for pork. The emissions in the ROW will *increase* by 1.7% from 8188 to 8328 units. If the utility elasticity for the environment in the EU increases to 0.2, then a stronger trend will occur. The EU will stop to produce pork and will import some pork from the rest of the world. Then the emissions in the rest of world will *increase* by 2.7% (to 8413 units). To summarize, if only consumers in the EU increase their environmental concern, the introduction of NPFs does not reduce the emissions in the rest of the world. But switching to produce more NPFs and less pork in the EU is helpful to reduce the unevenness of the income distribution by improving the income share of the ROW.

If the two regions have the same concern for the environment, the increase of the value of ε will limit the pork production in both regions and limit the emissions globally. The model strongly suggests that the enhanced introduction of NPFs is meaningful for global environmental improvement by emission reduction, only if both regions increase their preferences for environmental quality.

The chapter presented an AGE model that captures the environmental concerns in the utility function. The model presented in this chapter shows how the economy can be modelled by general equilibrium modelling when facing some changes in preferences. Despite its simplicity, it illustrates some of the most important fundamental environmental economic mechanisms that might occur as a result of the enhanced introduction of NPFs based on the classification of the goods and their production functions of our model. The model provides a useful framework for further empirical studies on the role of biotechnology in the economy and for studies on the environmental concerns of the consumers. The inclusion of the agricultural elements, like land use, water use and agricultural-chemicals use, effects of the common agricultural policy (CAP) and other environmental issues (like environmental policy measures) are important aspects for expansion and application of the model. At the theoretical level, embodying the dynamic properties of the environment and introducing the explicit environmental feedback on the production and consumption in the AGE model is an interesting challenge.

APPENDIX 5-A THE THEORETICAL AGE MODEL WITH ENVIRONMENTAL CONCERNS — THE NEGISHI FORMAT

Consider an economy consisting of *m* consumers, indexed by *i*, $i = 1, 2,\dots, m$ and *n* producers, indexed by *j*, $j = 1, 2,\dots, n$. There are *r* commodities (goods and factors), indexed by *k*, $k = 1, 2, \dots, r$. Environmental goods indexed by *g* ($g = 1, 2, \dots, e$) are involved in the economy for consumption and production. The welfare program in Negishi format, which allocates the resources in the economy optimally (Gunning and Keyzer, 1995; GK, 2002), is as follows[5].

$$\underset{x_i, g_i \geq 0, y_j, \forall i,j}{Max} \sum_i \alpha_i u_i(x_i, g_i) \qquad \text{(5-A1)}$$

subject to the balances of rival commodities and environmental goods:

$$\sum_i x_i + x_g \leq \sum_j y_j + \sum_i \omega_i \qquad (p) \qquad \text{(5-A2)}$$

$$g_i \leq x_g \qquad (\phi_i) \qquad \text{(5-A2)'}$$

Production technology:

$$y_j \in Y_j \qquad \text{(5-A3)}$$

With welfare weights α_i, such that

$$px_i + \phi_i g_i = p\omega_i + \sum_j \theta_{ij} \Pi_j(p) \qquad (\lambda_i) \qquad \text{(5-A4)}$$

and

$$\alpha_i = \frac{1}{\lambda_i} \qquad \text{(5-A5)}$$

In this model, equation (5-A1) is the objective function of the model, where u_i is the utility function of each individual *i* ($i = 1, 2, \dots, m$), *x* is the vector of consumption goods with *k* dimension, and *g* is the vector of consumption of non-rival environmental goods with *e* dimension. The objective of this welfare program is to maximize the total welfare, which is a weighted sum of the utility of all the *m* consumers in the economy, the Negishi weight of consumer *i* is given by α_i.

Equation (5-A2) are the balance equations for each commodity *k* (k=1,…, *r*) and each environmental good *g* (g=1,2,…, *e*). In this equation, x_g is the vector of consumption of environmental goods with *e* dimensions, y_j is the vector of the net output of a producer *j* with k+e dimension if each producer produce only one good, and ω_i is the vector of initial

[5] In this annex we follow the original notation of GK, 2002.

endowments (including the environmental goods) of consumer i with k+e dimensions. Positive y_j indicates the output of a production process and negative y_j indicates the input of the production process. A vector of Lagrange multipliers associated with the balance constraints, i.e., a vector of the shadow prices of each commodity or environmental good is indicated by p in the bracket. The commodity can be a final product, a production factor or an intermediate good. This equation states that the consumption of a commodity or environmental good must be smaller than or equal to its production plus its initial endowments.

Equation (5-A2)' is the balance equation of non-rival environmental consumption goods, where consumer's individual consumption should not exceed the common consumption of all the consumers. This also makes it possible to obtain explicit Lagrange multipliers for the value that each consumer attributes to the environmental consumption x_g. Vector of Lagrange multiplier ϕ_i in the bracket with e dimension, is the price vector that each consumer has to pay for the consumption of environmental goods.

Equation (5-A3) shows that production plan must belong to some feasible set, or is constrained by the production technology. Y_j is the production set of firm j reflecting its feasible technology.

Equation (5-A4) states that the expenditure of the consumer must be equal to his income, where the left-hand side shows the total expenditure and the right hand side shows the income of the consumer. The total expenditure includes the total expenditure on the consumption of all rival goods px_i and the payment for the environment $\phi_i g_i$. The income of consumer i includes the value of his initial endowments $p\omega_i$ and his total profit, which he receives from firm j (j=1,2, …, n). θ_{ij} is the profit share of consumer i in firm j, $\prod_j(p)$ is the profit of firm (producer) j.

Equation (5-A5) shows how welfare weights are related to the budget constraints in this welfare program. The Lagrange multiplier associated with the budget constraint of consumer i is indicated by λ_i, its inverse is the welfare weight that is attributed to consumer i such that the equilibrium of the economy exists. The allocation resulting from the equation system from equation (5-A1) through (5-A5) is called Lindahl equilibrium.

APPENDIX 5-B UTILITY AND PRODUCTION FUNCTIONS, AND BALANCE EQUATIONS OF THE APPLIED MODEL

Utility functions

$$U_{EU} = (g_{EU})^{0.05} \cdot (C_{EU,pr}^{0.12} \cdot C_{EU,otf}^{0.299} \cdot C_{EU,peas}^{0.001} \cdot C_{EU,nf}^{0.58})^{0.95}$$

$$U_{ROW} = (g_{ROW})^{0.05} \cdot (C_{ROW,pork}^{0.12} \cdot C_{ROW,otf}^{0.295} \cdot C_{ROW,peas}^{0.05} \cdot C_{ROW,nf}^{0.58})^{0.95}$$

Production functions

Here *Y* indicates the production quantity, *LB* the labour input, *LD* the land input, *K* the capital input, *FD* the feed input, and *EM* the emission input.

1) Pork

$$Y_{EU,pork} = EM_{EU,Pork}^{0.05} [LB_{EU,pork}^{0.2} \cdot LD_{EU,pork}^{0.15} \cdot K_{EU,pork}^{0.20} \cdot FD_{EU,pork}^{0.45}]^{0.95}$$

$$Y_{ROW,pork} = 0.6 EM_{ROW,Pork}^{0.05} [LB_{ROW,pork}^{0.2} \cdot LD_{ROW,pork}^{0.15} \cdot K_{ROW,pork}^{0.20} \cdot FD_{ROW,pork}^{0.45}]^{0.95}$$

2) Other food

$$Y_{EU,otf} = EM_{EU,otf}^{0.04} [LB_{EU,otf}^{0.30} \cdot LD_{EU,otf}^{0.35} \cdot K_{EU,otf}^{0.35}]^{0.96}$$

$$Y_{ROW,otf} = 0.6 EM_{ROW,otf}^{0.04} [LB_{ROW,otf}^{0.3} \cdot LD_{ROW,otf}^{0.4} \cdot K_{ROW,otf}^{0.3}]^{0.96}$$

3) Non-food

$$Y_{EU,nf} = EM_{EU,nf}^{0.02} [LB_{EU,nf}^{0.45} \cdot K_{EU,nf}^{0.55}]^{0.98}$$

$$Y_{ROW,nf} = 0.6 EM_{ROW,nf}^{0.02} [LB_{ROW,nf}^{0.45} \cdot K_{ROW,nf}^{0.55}]^{0.98}$$

4) Feed or peas

Here feed is the yield of feed crops. The following production functions are used for feed crops and peas:

$$Y_{EU,feed} = EM_{EU,ROW}^{0.03} [LB_{EU,feed}^{0.3} \cdot K_{EU,feed}^{0.3} \cdot LD_{EU,feed}^{0.4}]^{0.97}$$

$$Y_{ROW,feed} = 0.6 EM_{ROW,feed}^{0.03} [LB_{ROW,feed}^{0.4} \cdot K_{ROW,feed}^{0.3} \cdot LD_{ROW,feed}^{0.3}]^{0.97}$$

$$Y_{EU,peas} = EM_{EU,peas}^{0.03} [LB_{EU,peas}^{0.4} \cdot K_{EU,peas}^{0.3} \cdot LD_{EU,peas}^{0.3}]^{0.97}$$

$$Y_{ROW,peas} = 0.6 EM_{ROW,peas}^{0.03} [LB_{ROW,peas}^{0.4} \cdot K_{ROW,peas}^{0.3} \cdot LD_{ROW,peas}^{0.3}]^{0.97}$$

5) NPFs in EU

$$Y_{EU,NPFs} = EM_{EU,NPFs}^{0.015} [LB_{EU,NPFs}^{0.1} \cdot K_{EU,NPFs}^{0.2} \cdot Pea_{EU,NPFs}^{0.7}]^{0.985}$$

Balance equations

Feed balance

The production of feed crops Y_{feed} is equal to the intermediate input for pork production FD_{pork} plus its net export X_{feed}.

$$Y_{feed} = FD_{Pork} + X_{feed}$$

Balance of peas

Peas are produced for direct use and production of NPFs, and NPFs are only produced in the EU[6].

$$Y_{EU,peas} = C_{EU,peas} + PI_{EU,NPFs} + X_{EU,peas}$$

$$Y_{ROW,peas} = C_{ROW,peas} + X_{ROW,peas}$$

where C is the direct consumption of peas, PI is the intermediate input of peas for production of NPFs and X is the net export of peas.

Balance of pork, other food and non-food

The production of a good in one region Y_{ij} equals the consumption of a good C_{ij} plus its net export X_{ij}.

$$Y_{ij} = C_{ij} + X_{ij}$$

where j = pork, other food, non-food, but $j \neq$ feed, peas.

Balance of NPFs

The production of the NPFs equals its consumption.

$$Y_{EU,NPFs} = C_{EU,NPFs}$$

Trade balance

$\sum_i X_{ij} = 0$, for j= pork, other food, non-food, feed and peas, but $j \neq$ NPFs.

Balance of factors

$$\sum_j LB_{ij} \leq \overline{LB_i}$$

[6] We assume that NPFs are particularly developed in the European market and that in the short run they will mainly be produced within Europe.

$$\sum_j LD_{ij} \le \overline{LD_i}$$

$$\sum_j K_{ij} \le \overline{K_i}$$

where *j* includes pork, other food, non-food, feed, peas, and NPFs, *LB* is the labour usage, *LD* is the land usage and *K* is the capital usage for production. $\overline{LB_i}$, $\overline{LD_i}$ and $\overline{K_i}$ are the factor endowments of region *i*.

APPENDIX 5-C RESULTS FOR SENSITIVITY ANALYSIS

Table 5-A1: Production, Consumption, Trade, Emissions and Income ($\varepsilon_{EU} = 0.1, \varepsilon_{ROW} = 0.05$)

	Production						Consumption					
	Pork	NPF	Other food	Non-food	Pea	Feed	Pork	NPFs	Other food	Non-food	Peas+ input	Feed input
EU	223	49	0	1334	0	0	64	49	619	1133	3+62	207
ROW	95	0	2400	3103	105	301	254	0	1781	3304	40+0	94
Total	318	0	2400	4437	105	301	318	49	2400	4437	105	301
	Trade						Emissions	Income per worker		Utility (welfare)		
EU	159	0	-618	201	-65	-207	669	10.7		802		
ROW	-159	0	618	-201	65	207	8328	2.4		2181		
Total	0	0	0	0	0	0	8997			7.43		

Table 5-A2: Production, Consumption, Trade, Emissions and Income ($\varepsilon_{EU} = 0.2, \varepsilon_{ROW} = 0.05$)

	Production						Consumption					
	Pork	NPFs	Other food	Non-food	Peas	Feed	Pork	NPFs	Other food	Non-food	Peas+i nput	Feed input
EU	0	35	0	1410	0	180	46	35	445	827	2+45	0
ROW	319	0	2354	3001	90	138	273	0	1909	3584	43+0	318
Total	319	35	2354	4411	90	318	319	35	2354	4411	90	318
	Trade						Emissions	Income per worker		Utility (welfare)		
EU	-46	0	-445	583	-47	180	311	7.0		719		
ROW	46	0	445	-583	47	-180	8413	2.3		2345		
Total	0	0	0	0	0	0	8724			7.54		

Table 5-A3: Production, Consumption, Trade, Emissions and Income ($\varepsilon_{EU} = 0.1$, $\varepsilon_{ROW} = 0.1$)

	Production						Consumption					
	Pork	NPFS	Other food	Non-food	Peas	Feed	Pork	NPFs	Other food	Non-food	Peas+input	Feed input
EU	280	51	0	1268	0	0	66	51	648	1193	3+65	280
ROW	28	0	2371	3131	107	308	242	0	1723	3206	39+0	28
Total	308	51	2371	4399	107	308	308	51	2371	4399	107	308
	Trade						Emissions		Income per worker			Utility (welfare)
EU	214	0	-648	75	-68	-280	702		12			837
ROW	-214	0	648	-75	68	280	4883		2.5			2385
Total	0	0	0	0	0	0	5585					7.50

Table 5-A4: Production, Consumption, Trade, Emissions and Income ($\varepsilon_{EU} = 0.2$, $\varepsilon_{ROW} = 0.2$)

	Production						Consumption					
	Pork	NPFs	Other food	Non-food	Peas	Feed	Pork	NPFs	Other food	Non-food	Peas+input	Feed input
EU	369	50	0	1250	0	0	63	50	631	1177	3+64	274
ROW	27	0	2307	3088	105	302	233	0	1676	3161	38+0	28
Total	296	50	2307	4338	105	302	296	50	2307	4338	105	302
	Trade						Emissions		Income per worker			Utility (welfare)
EU	205	-631	73	-274	-66	-274	380		12			945
ROW	-205	631	-73	274	66	274	2525		2.5			2994
Total	0	0	0	0	0	0	2905					(7.69)

APPENDIX 5-D A LIST OF THE SYMBOLS

Notation: a bar above a variable indicates that it is exogenous.

Variables:

C = consumption

E = expenditure

EM = emission

$\overline{EM}$ = emission permits (exogenous)

FD = feed input in the production of pork

h = income
g = vector of consumption of environmental goods in general model, or environmental quality indicator in applied model
K = capital
$\overline{K}$ = capital endowment (exogenous)
LB = labour
$\overline{LB}$ = labour endowment (exogenous)
LD = land
$\overline{LD}$ = land endowment (exogenous)
PI = peas input for the production of NPFs
u or U = utility of the consumer
W = total welfare (Negishi welfare)
X = net export
x = vector of consumption goods
Y = production sets or production quantity
y = vector of net production of goods

Parameters:
α = welfare weights
β = parameter in the utility function
γ = parameters in Cobb-Douglas production function
δ = expenditure share of NPFs in protein budget
ε = utility elasticity for the environment (in utility function)
η = parameter in the utility function
θ = profit share
ξ = cost share of the emission input in the production
Π = profit
σ =substitution elasticity
$\overline{\psi}$ = environmental standard
ω = vector of initial endowments

Shadow prices:
λ = Lagrange multipliers associated with the budget constraint of the consumer
ϕ = shadow price of the environmental goods
p = shadow price vector of commodities
p_j = shadow price (scalar) of production good j
p_s = shadow price (scalar) of consumption good s
p_m = shadow price of emission permit
rk = shadow prices of capital
rl = shadow prices of land
w = shadow prices of labour

Subscripts:

g	= environmental goods, g =1,2,…,e
i	= consumers, i =1, 2, …, m for theoretical model, and i=EU and ROW for applied model
j	= goods or products, j =1, 2, …, n for general model, and j = pork, other food, non-food, NPFs, peas and feed for the applied model
k	=commodities, k =1,2,…, r for general model
s	= consumption goods in applied model, s = proteins (pork + NPFs), peas, other foods and non-food
EU	= the European Union
ROW	= the rest of the world.

Chapter 6 Modelling consumers' preferences for Novel Protein Foods and environmental quality

6.1 Introduction

Some studies (e.g. MAF, 1997; Miele, 2001; Jin and Koo, 2003) indicate that health and food safety concerns have become pivotal when purchasing food products. For a large number of consumers, these concerns manifest themselves in the selection of products, as seen in increased purchases of diet and low-fat foods. This tends to increase the demand for meat substitutes, or for meat products that are produced in an animal-friendly way. For example, consumers' expenditures on plant protein products in the Netherlands are increasing over time (Aurelia, 2002). Fonk and Hamstra (1995) suggest that the consumption of NPFs in the next 30 years will replace almost 40% of meat in the Western diet in terms of protein expenditure. This trend indicates that consumers may shift their preferences for the consumption of proteins from meat to NPFs. This will have clear impacts on the economy and the environment.

Some other studies (e.g. Hökby and Söderqvist, 2003; Latacz-Lohmann and Hodge, 2003) indicate that increasing income tends to influence willingness to pay for environmental services positively and significantly. Because the environment provides amenity services for consumers, it is economically necessary to consider the willingness to pay of consumers for the enjoyment of the environmental services. These changes in willingness to pay for the environmental amenity will have impacts on the choice of consumption and the environmental quality.

Chapter 5 has already shown the method of how to apply a model with the amenity value of environmental quality in the utility function in a real world, but its empirical basis is still weak due to the predetermined production and utility functions. Therefore there is a need for the empirical improvement in the model application. Although both chapters are based on the same welfare program, there are some distinctions between this chapter and the previous one. Firstly, we calibrate the parameters in production functions and utility functions using the data source of GTAP model. Secondly, we have divided the world into three relevant regions, i.e. the EU, Other OCED countries (OOECD) and rest of the world (ROW), instead of two (i.e. EU and ROW). This refines the results because the regions are more balanced in size. Thirdly, we use different pollutants in the application of the model. In this chapter we use NH_3 for its relevance for protein production, whereas CO_2 was used in the previous chapter.

This chapter thus aims to investigate economic and environmental consequences of changes in consumer preferences for NPFs and environmental amenity. The first contribution is to construct a theoretical AGE model that explicitly includes the emission input in production functions and the environmental amenity in utility functions. The second contribution is to empirically apply the model to obtain some insights into the effects of the enhanced consumption of NPFs and of the changes in consumers' willingness to pay for the environmental amenity.

We have specified a three-region AGE model that allows for substitution between pork and NPFs and that includes consumer environmental concerns. For simulation of enhanced consumption of NPFs, we consider an *exogenous shift* of consumption from meat to NPFs, driven by consumer health and food safety concerns for animal products. Since pork, which comprises 45% of the EU meat consumption in 1999 (European Commission, 2002), is the most common protein product, the enhanced consumption of NPFs is assumed to replace part of pork. The exogenous shift is represented by a higher share of expenditures of NPFs in the total protein budget. The substitution effect between pork and NPF consumption is represented by the substitution elasticity[1], which reflects the ease of substitution between two goods due to the change of relative prices. The consumer environmental concerns for environmental quality are represented by the willingness to pay for the environmental amenity, or more specifically, by the utility elasticity with respect to environmental quality if environmental quality is included in a Cobb-Douglas utility function.

The chapter is organised as follows. Section 6.2 presents the theoretical structure of the AGE model with environmental concerns, while Section 6.3 specifies the model for our study. Section 6.4 concerns the data and model calibration. Section 6.5 is the model application. Here we examine the effects of NPFs and environmental concern on the economy, and perform the sensitivity analysis for the substitution elasticity between pork and NPFs and the utility elasticity with respect to environmental quality. Finally, we draw conclusions in Section 6.6.

6.2 Theoretical structure of an AGE model with environmental concerns

We use the welfare program (2-3) presented in Chapter 2. The model structure of the Negishi format including environmental concerns (cf. GK, 2002) is given in equation (6-1) to (6-5):

[1] The formal definition of substitution elasticity between two goods (1 and 2) is:

$$\xi_{12} = -\frac{\dfrac{\partial(x_1/x_2)}{x_1/x_2}}{\dfrac{\partial(p_1/p_2)}{p_1/p_2}},$$

where x indicates the demand and p the price (Mas-Colell, 1995).

$$\max \sum_i \alpha_i u_i(x_i, g_i) \tag{6-1}$$

$$x_i \geq 0, g_i \geq 0 \text{ all } i, y_{e\,j}^- \geq 0, y_j \text{ all } j, y_g^+ \geq 0$$

subject to

$$\sum_i x_i \leq \sum_j y_j + \sum_i \omega_i \qquad (p) \tag{6-2}$$

$$\sum_j y_{e\,j}^- \leq \sum_i \omega_e \qquad (p_e) \tag{6-2'}$$

$$g_i = y_g^+ \qquad (\phi_i) \tag{6-2''}$$

$$F_j(y_j, -y_{e\,j}^-) \leq 0 \tag{6-3}$$

$$F_g(y_g^+ - \sum_j y_j^+) \leq 0 \tag{6-3'}$$

with welfare weights α_i, such that

$$px_i + \phi_i g_i = p\omega_i + \sum_j \theta_{ij} \Pi_j(p) \qquad (\lambda_i) \tag{6-4}$$

and

$$\alpha_i = \frac{1}{\lambda_i}, \tag{6-5}$$

where x_i is the vector of consumption goods, and g_i is the vector of non-rival consumption (environmental quality) for consumer *i* (*i* = 1, 2, …, *m*). y_g^+ is provided by an environmental process according to a transformation function $F_g(.)$, using total emission $\sum_j y_{e\,j}^-$. y_j is the vector of netput of producer *j* (*j* =1,2, …, *n*); positive one indicates outputs and negative one indicates inputs. $y_{e\,j}^-$ is the vector of emission input for producer *j*. ω is the vector of initial endowments and ω_e is the vector of emission permits. Parameters (p), (p_e), (ϕ) give the vectors of shadow prices of the *rival* goods, emission permits and environmental quality. For notational convenience, we assume that vectors x_i, g_i, y_j, y_g^+ and $y_{e\,j}^-$ refer to the same commodities space R^r, but they usually have different entries for the same *k* (*k* =1,2,…, *r*). Finally, α_i is the welfare weight of consumer *i*.

In this model, equation (6-1) is the objective function, where u_i is the utility function of each individual *i*. The objective of this welfare program is to maximise total welfare, which is a weighted sum of the utility of all the *m* consumers in the economy, and the Negishi weight of consumer *i* is given by α_i.

Since there are r commodities (including environmental goods) in our model, balance equation (6-2) includes r equations for r commodities (i.e. goods and production factors). $\sum_i x_i$ is the total consumption, $\sum_j y_j$ is the total production, and $\sum_i \omega_i$ is the total initial endowment of the commodities. A vector of Lagrange multipliers associated with the balance equations, or, a vector of the shadow prices of commodities including environmental goods, is indicated by p within brackets. The commodity can be a final product, a production factor, or an intermediate good. This equation states that the consumption of a commodity must be smaller than, or equal to, its production plus its initial endowments.

Equation (6-2)' refers to the balance of emission permits. The total emission inputs in all production processes should not exceed the total endowments of emission permits. Langrange multiplier p_e is the vector of shadow prices of the emission permits.

Equation (6-2)'' is the balance equation for a vector of environmental quality indicators, which indicates each individual's consumption equals to the total supply of the non-rival environmental quality. This constraint also makes it possible to obtain explicit Lagrange multipliers for the value that each consumer attributes to the environmental consumption. The vector of Lagrange multipliers ϕ_i, is the vector of prices that consumers have to pay for the consumption of environmental goods as if the markets for environmental goods existed or institutional arrangements were made.

Equation (6-3) shows that the production plan must belong to some feasible set, which is constrained by production technology. F_j is the transformation function of firm j, which uses emission $y_{e\,j}^{-}$ as input for producing y_j.

Equation (6-3)' shows the production technology of environmental quality. Environmental quality is produced by a specific technology according to a transformation function $F_g(.)$. As such, the technology can also be viewed as an exogenous environmental process that transforms emission into a certain level of environmental quality y_g^{+}.

Equation (6-4) states that the expenditure of the consumer must be equal to income; the left-hand side shows the total expenditure and the right-hand side shows the income of the consumer. The total expenditure includes the expenditure on the consumption of all rival goods px_i and the payment for the environmental quality $\phi_i g_i$. The income of consumer i includes the remuneration for his initial endowments ($p\omega_i$), and profits received from firm j ($\sum_j \theta_{ij} \Pi_j(p)$). θ_{ij} is the profit share of consumer i in firm j, and $\prod_j(p)$ is the profit of firm (producer) j, defined as $\Pi_j(p) = \max_{y_j} \{py_j \,|\, y_j \in Y_j\}$.

Equation (6-5) shows how welfare weights are related to the budget constraints in this welfare program. The Lagrange multiplier associated with the budget constraint of consumer *i* is indicated by λ_i, and its inverse is the welfare weight attributed to consumer *i* such that an equilibrium exists (GK, 2002). The optimal allocation resulting from the equation system from equation (6-1) through (6-5) is called the Lindahl equilibrium. This is an equilibrium without transfers, in which welfare weights are such that each consumer satisfies his budget constraint, including payment to the environmental consumption. In this model economy, the consumers reveal their real preferences and will pay for the non-rival consumption of environmental quality, i.e. no free-riding.

The mechanism of the Lindhal equilibrium requires that users pay for their consumption, while nonusers and satiated users do not pay. We have to emphasise that the Lindhal equilibrium does not ensure equity. However, the second welfare theorem can come into play. Once the level of demand for non-rival commodities has been set optimally and cost sharing rules are specified, the contribution can be levied as a direct tax (GK, 2002).

6.3 Specification of the AGE model

Following the theoretical structure in Section 6.2, we have specified the model for our study by explicitly considering producers, consumers, production goods, consumption goods, intermediate goods, and environmental quality.

Characteristics of the model

In our AGE model, the world is divided into three regions: the EU, OOECD and ROW. In each region, there is one representative consumer. There are six producers who produce totally six products in each region. The products are distinguished as pork, peas, other food, NPFs, non-food and feed. Pork, other food, non-food, and NPFs are the consumption goods. Peas are used for both direct consumption and intermediate input for production of NPFs and feed. Feed is the intermediate good for pork and other food because other animal products are included in the category other food. There are three production factors: labour, capital and land. In this specific study we only consider the emissions of ammonia (NH_3), which is a serious problem in animal protein production. The level of NH_3 emissions determines the environmental quality.

In the model the environmental quality is specified in three steps. Firstly, the utility of the representative consumer in each region is determined by the consumption level of private goods and services, and the level of an environmental quality indicator. Secondly, we consider emissions to be the depletion or use of clean environmental resources. We can thus treat emissions from production as the input for production. Therefore, in this study NH_3 is treated as input for production. Thirdly, total emissions are constrained by emission permits. As such, (shadow) prices for emission permits can be determined.

The objective function and utility functions

The objective function of the welfare program in Negishi format is:

$$W = Max\sum_i \alpha_i log U_i \quad (6\text{-}6)$$

where W is the total welfare, U_i is the utility of region i, α_i is the Negishi weights of region i, and i represents the EU, OOECD and ROW, respectively. For the equilibrium solution of the model, the Negishi weights have to be found such that the budget constraints hold. Sequential Joint Maximisation (SJM) method show that the Negishi weights are the respective shares in the total income of the economy (Manne and Rutherford, 1994; Ermoliev *et al.* 1996; Rutherford, 1999).

The utility function in our model is a nested function combining Constant Elasticity of Substitution (CES) function and Cobb-Douglas (C-D) function with three levels (see Figure 6-1). At level 1, it is a C-D function with substitution between the consumption of a composite of rival goods (i.e. proteins, other food, non-food and peas) and a non-rival good (i.e. environmental quality). At level 2, it is a C-D function of a composite of rival goods with substitution among proteins, other food, non-food and peas. At level 3, it is a CES function of a composite of proteins with substitution between pork and NPFs. The utility function can be written as:

$$U_i = g_i^{\varepsilon_i}((\prod_s C_{si}^{\beta_{si}})^{1-\varepsilon_i} \quad (6\text{-}7)$$

where i indicates the consumer (i= EU, OOECD, ROW), g is the environmental quality, and C_s is the consumption of rival good s (s = proteins, other food, non-food and peas), ε is the elasticity of utility with respect to environmental quality, and β_s is the utility elasticities with respect to consumption of rival goods s. Consumption of a composite of proteins is defined as a CES function, with substitution between pork and NPFs. It is specified as follows:

$$C_{proteins,i} = [\delta_i^{\frac{1}{\sigma}} C_{NPFs,i}^{\frac{\sigma-1}{\sigma}} + (1-\delta_i)^{\frac{1}{\sigma}} C_{pork,i}^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} \quad (6\text{-}8)$$

where σ is the elasticity of substitution between pork and NPFs, δ is the expenditure share of NPFs in protein consumption[2], and C_{NPFs} and C_{pork} are the consumption of NPFs and pork.

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[2] For the model calibration, we use $C_{proteins} = B[SC_{NPFs}^{\frac{\sigma-1}{\sigma}} + (1-S)C_{pork}^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}$, where S is the share of NPFs in CES function, $S = \frac{\delta^{\frac{1}{\sigma}}}{\delta^{\frac{1}{\sigma}} + (1-\delta)^{\frac{1}{\sigma}}}$ (Shoven and Whalley, 1992), and B is the scaling term which will be used to ensure that the price of the composite good is equal to the cost of the amounts of C_{NPFs} and C_{pork} that have produced it, $B = [S^{\sigma} + (1-S)^{\sigma}]^{\frac{1}{\sigma-1}}$ for a nested CES (Reed and Blake, 2003). But if this composite is nested in a Cobb-Douglas utility function, B does not influence the results, thus B can be chosen as one.

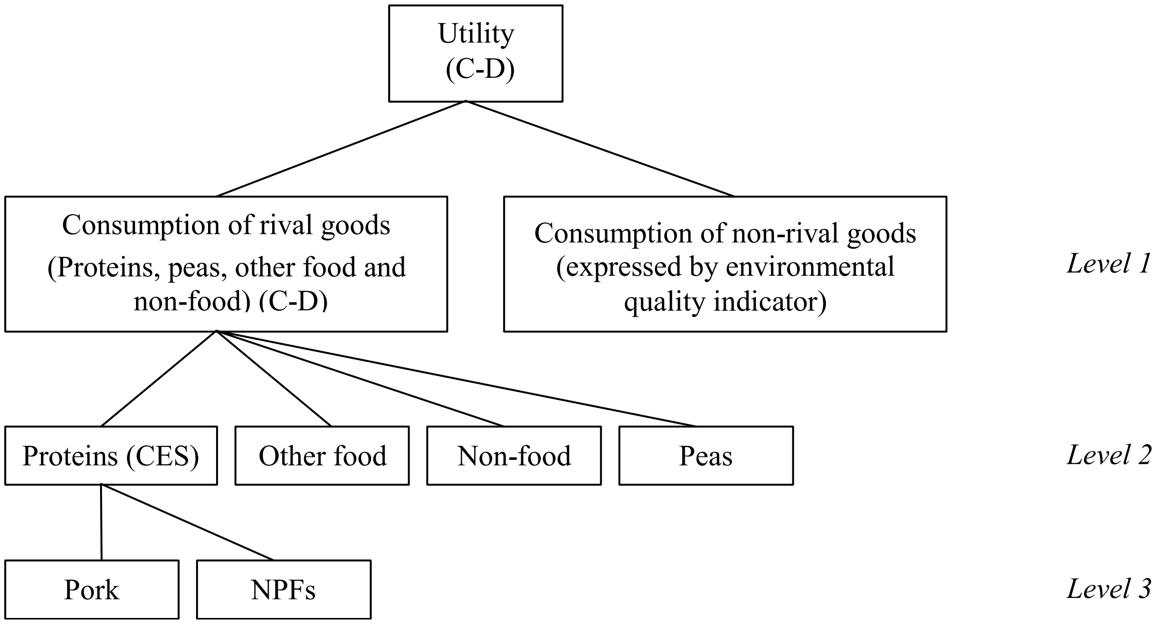


Figure 6-1 Nesting structure of the utility function

Environmental quality

The environmental quality indicator should indicate the state of the environment. How environmental quality is influenced by emissions depends on the related environmental processes. A real environmental process model describing environmental quality is very complicated because environmental processes follow biophysical laws. We try to simplify it in economic model. From a consumer perspective, the perception of the environment can be directly linked to emissions to the environment. These emissions can be from, for example, industrial and agricultural processes. The utility of consumers is influenced by emissions, which we can aggregate into an indicator for environmental quality. For this specific study, we only consider the emissions of ammonia (NH_3), which is a large concern when dealing with animal protein production. Therefore, we can define the 'environmental quality indicator' to be determined by the level of emissions. Specifically, we call it 'air quality' for its atmospheric impacts, such as acid rain and unpleasant odour.

We have specified the model as such that the environmental quality, or air quality, that consumers encounter is determined by the total emissions of NH_3. In the model we approximate this relation by means of a linear function:

$$y_g^+ = \overline{\psi} - TM \tag{6-9}$$

where $\overline{\psi}$ is the intercept and *TM* is the total level of emissions from all producers in region *i*. The intercept can be given by the tolerable emission level which also determines the emission bounds or emission permits. The total level of emissions can be viewed as a by-product of the total production. This relationship shows that the higher the emissions the lower the environmental quality (or air quality). We would like to keep the applied model as simple as possible. As such, the linear relation is assumed due to the consideration of convexity. This convex constraint enters the model without changing the convexity of the model and thus to ensure a unique equilibrium solution. The environmental quality can be viewed as a product produced by an exogenous environmental process and possessed by consumers. In each region, there are different specifications for the intercept in equation (6-9) depending on the local environmental capacity. We use two times the base year NH_3 emission level for this intercept for each region. For a better comparison of air quality change among different scenarios in Section 6.5, we specify air quality as:

$$y_g^{+} = 100 \times \frac{(2TM_0 - TM)}{TM_0}, \tag{6-10}$$

where TM_0 is the total NH_3 emission in specific region in the base year, *TM* is the real emission in scenarios. In the base year, *TM* equals TM_0, therefore $y_g^{+} = 100$.

Production functions

In our model emissions are viewed as the use of a natural resource since producers use the environmental resources when they emit pollutants. To price use of these environmental goods, emission permits are attributed and as a result users have to pay for emissions. This treatment provides us the price signals of the emissions and tools to implement proper environmental policy. When emissions are treated as the use of the environmental goods, they are, in fact, input for the production process. As such, we have to include this input in addition to the normal factor inputs and other intermediate inputs in the production function. The production function of producer *j* looks like:

$$Y_{i,j} = A_{i,j} EM_{i,j}^{\xi_{i,j}} [(LB_{i,j})^{\eta_{1i,j}} (KL_{i,j})^{\eta_{2i,j}} (LD_{i,j})^{\eta_{3i,j}} (IFD_{i,j})^{\eta_{4i,j}} (IP_{i,j})^{\eta_{5i,j}}]^{1-\xi_{i,j}} \tag{6-11}$$

where *Y* is the production quantity, *EM* is the emission input, ξ is the cost share of the emissions with $0<\xi<1$, $\eta_f (f = 1,2,...,5)$ is the cost share of each input without considering the cost of emission permits, and $\sum_{f=1}^{5} \eta_f = 1$. *LB* reflects labour input, *LD* land input, *KL* capital input, *IFD* the feed input and *IP* the pea input for production. Some of these inputs can be zero if not used in production. *EM* can be thought of as the use of 'environmental services', as a firm must dispose of its emissions in the environment. Alternatively, we can think of the firm as requiring emission permits in order to produce (Copeland and Taylor, 2003).

Balance equations

In the applied model we consider factors to be mobile between different sectors, but immobile factors among the three regions. We note C for consumption, X for net export, and

Y for production. Variables with a bar stand for exogenous ones. The balance equations for goods without intermediate use are as follows,

$$C_{i,j} + X_{i,j} \le Y_{i,j}, \quad j = \text{pork, other food, non-food and NPFs} \tag{6-12}$$

Peas are used both for direct consumption and intermediate use for production of NPFs and feed. The balance equation for the peas is as follows:

$$C_{i,peas} + \sum_j IP_{i,j} + X_{i,peas} \le Y_{i,peas}. \tag{6-13}$$

Feed is used for production but not consumption. The balance equation for feed looks like:

$$\sum_j IFD_{i,j} + X_{i,feed} \le Y_{i,feed} \tag{6-14}$$

Similarly, factor balance equations can be written as,

$$\sum_j LB_{ij} \le \overline{LB_i} \tag{6-15}$$

$$\sum_j KL_{ij} \le \overline{KL_i} \tag{6-16}$$

$$\sum_j LD_{ij} \le \overline{LD_i}. \tag{6-17}$$

Emissions in this model are treated as input in the production function, and an emission permit system for each region can be implemented. Thus, the following relationship holds

$$\sum_j EM_{ij} \le \overline{EM_i}, \tag{6-18}$$

where EM_{ij} is the use of emission input in region i for good j. $\overline{EM_i}$ is the permitted level of total emissions in region i. This permitted emission level can be an emission permit for a specific environmental policy, or the real level of emissions in base year depending on the study purpose. For example, when benchmarking, it is the emission level in the base year. For an environmental policy study, it can be an exogenous emission permit, which is in fact determined by the ecological limit. For the regeneration of the environment, emissions should not be above a certain level. Since the ecological limit for NH_3 emission is very much location-dependent, and our focus is not on an exogenous environmental policy analysis, we will not implement exogenous emission permits in our study. Instead we use the emission levels in 1998 for the benchmark, and we use the real emission level in scenario studies to get a proper shadow price of emission permits. Based on the emission factors determined by the base year emissions and production levels, we can get the real emission level in the feedback program when the model is applied to different circumstances.

The balance of environmental quality considering its non-rivalry is:

$$g_i = y_g^{\ +} . \qquad (6\text{-}19)$$

The equality indicates the non-rivalry of the environmental quality. It means that the consumption by one agent does not limit the consumption by another.

Budget constraints

Budget constraints say that the expenditures of the consumers should not exceed their income:

$$\sum_r (p_r \cdot C_{i,r}) + \phi_i g_i \le h_i , \quad r = \text{pork, NPFs, other food, non-food and peas} \qquad (6\text{-}20)$$

where $\sum_r (p_r \cdot C_{i,r})$ is the total expenditure on the consumption of all rival goods, $\phi_i g_i$ is the payment for the environmental quality, and *h* is income. Income consists of remuneration of endowments. Non-rival environmental quality is entitled to the consumer. When emissions are used as input, income from emission permits should also be accounted. The income is:

$$h_i = w_i \overline{LB_i} + r_i \overline{KL_i} + r_{N\,i} \overline{LD_i} + p_{mi} \overline{EM_i} + \phi_i g_i . \qquad (6\text{-}21)$$

Under constant returns to scale, profits are zero so that income is the value of initial endowments, which are employed in production. The income should be equal to the total revenue of the production sectors and the entitled 'environmental sector':

$$h_i = \sum_j (p_j \cdot Y_{ij}) + \phi_i g_i , \qquad (6\text{-}22)$$

where p_j is the price scalar of good j. The first item $\sum_j (p_j \cdot Y_{ij})$ on the right-hand column is the revenue of all the production sectors, and the second item $\phi_i g_i$ is the revenue of the 'environmental sector' which produces environmental quality g_i.

6.4 DATA AND CALIBRATION

The data

For calibrating the model, we mainly use the GTAP data source (GTAP, 2004) for the economic data in 2000. For our purpose we construct three Social Accounting Matrix (SAM) tables for three regions by aggregation. Based on the GTAP data source, we aggregate the data according to the structure of the production functions. Except for the factor inputs for production, the original input-output tables also contain other inputs, usually from other production sectors. These inputs are the so-called 'intermediate inputs'. In our study we only consider feed as the intermediate input for production of pork and other food, and peas as intermediate input for production of NPFs and feed, but we aggregate all the other intermediate inputs into 'capital'. The three SAM tables are included in Table 6-A1 to A3 of Appendix 6-A. Positive entries refer to supply and negative ones refer to use of the commodities in the tables.

The total NH_3 emissions in 2000 for each region and the emission distribution over production sectors are based on RIVM (2004). The emission distribution is included in Table 6-A4 of Appendix 6-A. Since the emission in our model is used as input for production, we also present the total endowments and levels of NH_3 emissions in Table 6-1.

Table 6-1 Total endowments in billion € and NH_3 emissions in million tons

	Labour	Capital	Land	NH_3 emissions
EU	4240.820	11575.894	41.741	2.879
OOECD	9082.629	19955.044	99.314	7.776
ROW	2871.850	10434.586	204.483	32.385

Calibration

The entries in the SAM are in value terms. When we calibrate the model, we follow the commonly used units convention, the Harberger convention. That means we set all the prices equal to unity in the benchmark (Shoven and Whalley, 1992). According to the cost shares of production inputs in total output of production goods and expenditure shares of consumption goods, we calibrate the parameters in production functions and utility functions.

Since the real SAM does not contain emissions, we have to modify it by including the emission input in each sector. In calibration, the total emission levels in each region are considered as the emission permits for each region in the base year. Then we run the model and get artificial units for the 'quantities' of all goods (this is called the base run). The emission input, together with other inputs (e.g. production factors, and intermediate inputs of peas and feed) from the production process will be transformed into final products. The final product embodied with emission input is a value-added product and thus all products with emission input produce a modified SAM. The base run equilibrium is then the benchmark. When the model is applied to specific scenarios, the results are also in those artificial units (in quantity) and we can compare the results with these 'units' to the benchmark. The parameters, in production functions and utility functions, are included in Tables 6-A5 and -A6 of Appendix 6-B.

6.5 MODEL APPLICATION TO SCENARIOS AND RESULTS

Scenarios

As we mentioned in the introduction, there are two trends of consumer preference: a life style change towards less meat and more NPFs in the EU, and a higher willingness to pay for environmental services (or amenity). Therefore we wish to assess the impacts of these changes by applying the model to the following scenarios.

In the *first* scenario, we simulate an exogenous shift from pork to NPFs due to the technological possibility of NPF production and consumer acceptance of NPFs. This will increase the consumption of NPFs. The parameter changes under this scenario, relative to the base run, are the share of NPFs in the consumption of protein foods (including pork and NPFs in this model) (δ) and increased substitution elasticity between pork and NPFs (σ). For detailed numbers see Table 6-2. Thus, we apply the model to analyse the impacts of exogenously enhanced consumption of NPFs.

On the basis of this scenario, we consider in the *second* scenario a more ambitious case where consumers are willing to pay for the enjoyment of good environmental quality. Since exogenous environmental policies, such as an emission bound, bring inefficiency, we consider an efficient mechanism: users pay for the environmental resource use. If this mechanism can be implemented, efficiency can be achieved. In this applied model, we introduce a small value of willingness to pay for environmental quality, or the marginal utility with respect to environmental quality. This parameter is embodied in the utility function and if it is the Cobb-Douglas functional form (see equation (6-7)), it is also called utility elasticity with respect to the environmental quality (ε). This parameter reflects the budget share used for the payment of environmental quality in the total expenditure for both environmental quality and rival goods. In this scenario we consider 1% of the budget to be spent for air quality determined by ammonia emissions. We analyse how this value affects the economic variables and environmental emissions.

However, the values of the two parameters (σ and ε) can not be observed from existing data. Therefore, we perform a *sensitivity analysis* for the values of these parameters for the impact analysis of NPFs and willingness to pay for protection of air quality. For σ, we consider a range of the values $0.5 < \sigma < 1.5$ because we do not think NPFs are *perfect* substitutes for pork. For ε, we consider a range of 0 to 10% because we do not expect consumer willingness to pay for air quality to exceed 10% of their total expenditure considering the present level of 3% of total environmental expenditures in GDP. Thus, in the sensitivity analysis we change the value for σ from 0.5 to 1.5 and for ε from 0 to 0.10. Table 6-2 gives the detailed description of the parameters for the scenario studies and sensitivity analysis.

Table 6-2 Parameters under scenarios and sensitivity analysis

Scenarios	Contents
Base run	Substitution elasticity between NPFs and pork is σ = 0.56 in the EU, 0.58 in the OOECD and 0.5 in the ROW. Expenditure share of NPFs in protein δ=2.5% in EU
Scenario 1: Enhanced consumption of NPFs in the EU	Expenditure share of NPFs in protein δ=25%, substitution elasticity between NPFs and pork σ =0.9 in EU.
Scenario 2: Environmental willingness to pay in the EU	Under scenario 1, σ =1.5, willingness to pay for the environmental quality ε =1% in EU.
Sensitivity analysis	The range of σ is from 0.5-1.5 and for ε is 0 to 10%.

The model was solved by GAMS (Brook *et al.*, 1997) for different scenarios. The results of all simulations for the scenarios are compared with the benchmark. The comparison gives the implications of the enhanced demand for NPFs in the EU with the different levels of environmental concerns to the economy and environmental quality.

The results

Base run: Quantities of production, consumption and international trade

After the model parameters are fully calibrated by the base year data, we rerun the model considering the emissions as input in production (i.e. the base run). The results for quantities of production, consumption and international trade in the base run are shown in Table 6-3. This is our benchmark. In the benchmark, the trade pattern is that the EU exports some pork and non-food and imports peas, other food, non-food and feed. Though not reported in the table, air quality in each region is 100 in the base run.

Table 6-3 Quantities (units) of production, consumption and international trade in the base run

		Pork	Peas	Other food	NPFs	Non-food	Feed
Production	EU	39.1	35.0	1028.6	1.0	14767.1	47.4
	OOECD	75.0	121.1	1622.0	1.4	27333.0	91.8
	ROW	179.8	259.6	1663.9	2.1	11429.4	131.0
Consumption	EU	38.8	42.2	1042.3	1.0	14675.7	
	OOECD	77.8	124.2	1679.7	1.5	27404.5	
	ROW	177.3	242.5	1592.5	1.9	11450.3	
Trade*	EU	+0.3	-7.9	-13.8	-0.0	+91.4	-8.8
	OOECD	-2.8	-4.9	-57.7	-0.1	-73.5	-5.0
	ROW	+2.5	+12.8	+71.5	+0.1	-17.9	+13.8

*Note for trade, '-' means imports and '+' exports.

Scenario 1: Impacts of enhanced demand for NPFs

In Scenario 1, the expenditure share of NPFs in protein consumption is increased from 2.5% to 25% and the substitution elasticity is increased from 0.5 to 0.9. These changes reflect the enhanced demand for NPFs. The impacts of such changes can be seen from both production and consumption sides (Table 6-4).

Table 6-4 Percentage changes of production and consumption, and real quantities in trade due to enhanced demand of NPFs (δ=25%, σ =0.9), as compared to the base run

		Pork	Peas	Other food	NPFs	Non-food	Feed
Production	EU	-7.5	0.6	-0.5	935.6	0.0	-11.1
(%)	OOECD	-8.3	0.8	-0.3	-89.9	0.0	-6.0
	ROW	-0.0	-0.4	-0.2	65.0	-0.0	6.8
Consumption	EU	-23.4	0.0	-0.3	898.0	0.0	
(%)	OOECD	-0.1	-0.0	-0.2	-0.1	0.0	
	ROW	-0.0	-0.0	-0.4	-0.0	0.0	
Net export	EU	6.5	-7.8	-16.1	-0.2	91.8	-13.5
(units)	OOECD	-9.0	-3.7	-58.3	-1.3	-66.0	-9.1
	ROW	2.6	11.4	74.5	1.5	-25.8	22.6

Note in the table, for the production and consumption '-' means a decrease and '+' means an increase, but for the net export, '-' means imports and '+' exports. This also holds for Table 6-5.

On the consumption side, the EU will increase the demand for NPFs by a factor of about 9.0 and decrease pork consumption by 23%. This is determined by the exogenous shift of expenditure. This change has almost no impacts on the consumption of the other goods (peas, other food, and non-food) in the EU and nor the overall consumption in the other two regions. There are, however, impacts on the production pattern due to the possibility of international trade. In this case each region will produce using its comparative advantage.

Table 6-4 shows that production of NPFs in the EU will increase to about 9.4 times, and production of pork will decrease by 7.5%. Accompanying the increase in production of NPFs, production of peas will increase by 0.6%. Feed production will decrease by 11% because less pork is produced. The impacts on non-food and other food are very small. Observing the enhanced demand for NPFs, ROW will increase its production of NPFs by 65% for exporting to the EU, but can not cover all the EU demand because it still has to increase it production of feed. As such, the EU still has to produce most of the NPFs.

There are also some impacts on the international trade. The EU will increase its pork export from 0.3 units to 6.5 units. Due to the comparative advantage of pork production in the EU, the EU will export more pork to the OOECD. The import of NPFs in the EU will be increased from 0.1 to 0.2 units. The import of feed will increase from 8.8 units to 13.5 units because, by switching to more production of NPFs, less feed is domestically produced. There are almost no impacts on the non-food sector and other food sector. To summarise, the major impact of Scenario 1 is on the sectors of NPFs and pork as well as the related feed and pea sectors.

For air quality, it will be 103 in the EU, 102 in the OOECD, and 99 in ROW. That means emissions of NH_3 will decrease in the EU from 2.88 to 2.79 million tons, in the OOECD, emissions decrease from 7.77 to 7.58 and in the ROW will increase from 32.38 to 32.67 million tons. The enhanced consumption in the EU will change the emission levels for other regions because of international trade. Now more feed has to be produced in the ROW, which will increase emissions there. The OOECD has lower emissions because it decreases the production of pork and feed. Although the EU has changed its emission through production, the impacts on emissions also happen in other regions because of international trade.

Scenario 2: Impacts of environmental concern and enhanced demand for NPFs

When consumers highly value the air quality, they are certainly willing to pay for a high level of air quality. As well, we can also expect a higher value of substitution elasticity between NPFs and pork when consumers are more concerned about air quality. In this scenario we check how emissions, and production and consumption will adjust if the EU consumers are willing to pay 1% of their income for air quality (determined by NH_3 emissions), and if substitution elasticity is simultaneously increased to 1.5 (see Table 6-5).

Table 6-5 Percentage changes of production and consumption, and real quantities in trade due to enhanced demand of NPFs and environmental concern (σ =1.5, ε =1%)

		Pork	Peas	Other-food	NPFs	Non-food	Feed
Production (%)	EU	-61.9	12.0	-0.1	935.6	0.1	-16.6
	OOECD	5.4	-1.2	-0.1	0.5	0.0	0.1
	ROW	5.1	-0.9	-0.1	3.0	-0.1	4.4
Consumption (%)	EU	-24.4	0.2	0.1	898.0	0.1	
	OOECD	-0.6	0.0	-0.1	-1.3	0.0	
	ROW	-0.6	0.0	-0.2	-1.1	-0.1	
Net export (units)	EU	-14.5	-3.9	-14.9	-0.2	92.0	-12.0
	OOECD	1.7	-6.3	-57.4	-0.1	-73.6	-5.5
	ROW	12.7	10.2	72.2	0.2	-18.5	17.5

In this scenario the production of NPFs in the EU will increase by a factor of 9.4 due to the exogenous shift from meat to NPFs and the environmental concerns of the consumers. The pork production will then decrease by 62% because of the resulting high emissions of NH_3. Meanwhile the production of peas will increase by 12% because remaining production factors from pork production will be used for producing low-emission products and more NPFs production needs more peas. The feed production will decrease by 16% because less pork is produced.

On the consumption side, the consumption of NPFs will be about 9 times more than the benchmark, while the pork consumption will decrease 24%. The pork consumption is lower than Scenario 1 because as air quality is directly determined by emissions, it is logical to reduce production and consumption with high emission factors when expenditure on air quality is increased. The price of pork slightly increases due to the restriction of production, which also leads to lower consumption in other regions. The impact on the consumption of other goods (peas, other food and non-food) is very small.

Concerning international trade, the EU must import pork when the expenditure on air quality is increased. Pork is the first product to be reduced given its high emission factors (see Table 6-A7 in Appendix 6-B). In the base year, almost 1% of pork production in the EU is exported but under Scenario 2, 50% (14.5 units of pork) of its total consumption (29 units) of pork is imported. Accompanying the increase in the production of NPFs, pea imports decrease by 50% because more peas are produced in the EU. To summarise, the major impact of Scenario 2 is on pork, NPFs, pea and feed sectors. The impact on international trade of pork and peas is larger than under Scenario 1.

Regarding air quality, there is a dramatic change in the EU, though little change in other regions. It is 190 in the EU, and 99 in the OOECD and in ROW. That means emissions in the EU will decrease by 90% from 2.879 to 0.288 million tons, but there is a slight increase (about 1%) in other regions (from 7.776 to 7.834 in OOECD and from 32.385 to 32.816 in ROW). Due to the value of air quality in the EU, reducing emission can increase utility. Therefore, there is a trade-off between high air quality (with low production of pork) and high consumption of pork (with low air quality). The environmental concerns with enhanced consumption in the EU will change the emission levels for other regions because of international trade. Since the EU will even import some pork from other regions, more pork has to be produced in the OOECD and ROW, which will increase emissions there.

Sensitivity analysis for substitution elasticity σ and utility elasticity ε

Results are calculated for different values of σ and ε. Since the value of substitution elasticity between pork and NPFs in Scenario 1 (σ =0.9) is only an estimate, we carry out a sensitivity analysis for this value. We thus change the value of σ from 0.5 to 1.5 for Scenario 1 for the sensitivity analysis of σ. Figure 6-2 shows that pork consumption will decrease compared to the base run, but will not change regarding the value of σ in Scenario 1. In Scenario 1 we have a fixed expenditure share of NPFs for the consumption of pork and NPFs, thus the substitution elasticity will not change pork and NPFs consumption.

Figure 6-3 shows that pork production in the EU decreases after the enhanced introduction of NPFs, and the extent of this a change increases with the increase of the values of σ. Production level will change, because the substitution elasticities will change the relative prices of pork and NPFs, and the producer will react to such a price change. As σ increases, the price ratio of NPFs to pork increases, therefore pork becomes cheaper and less will be produced. We also observe from the figure that pork production is higher for σ <1 and lower for σ >1. There is an abrupt jump around σ =1. This is due to the CES function: when σ is close to one, the function becomes undefined. Therefore the figure shows the irregularities around σ =1.

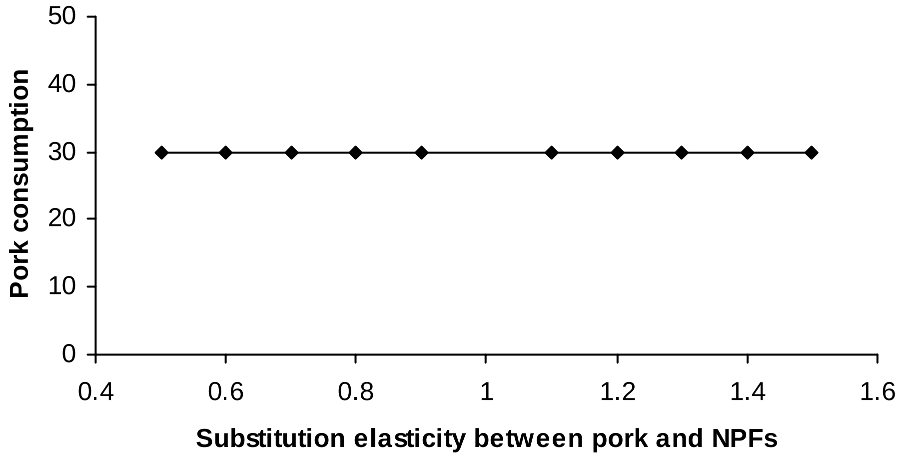


Figure 6-2 Pork consumption in the EU under different values of σ for Scenario1

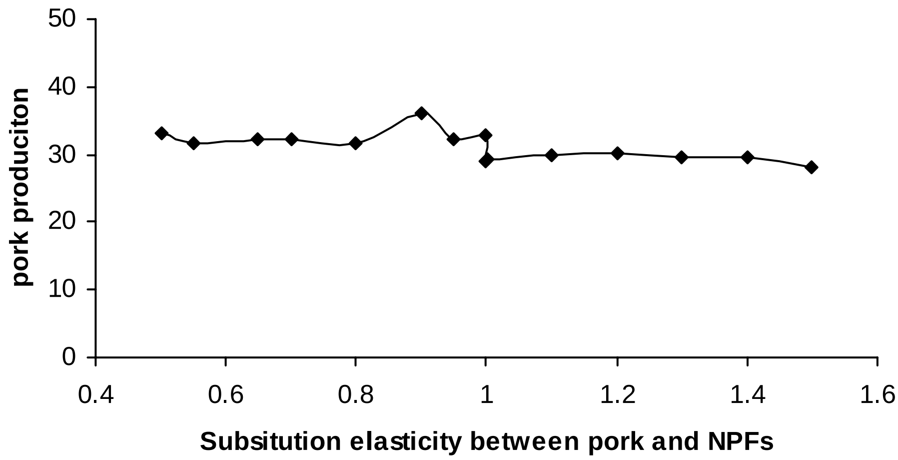


Figure 6-3 Pork production in the EU under different values of σ for Scenario1

We change the value of ε from 0 to 0.10 under Scenario 2 for the sensitivity analysis. Figure 6-4 shows that the enhanced introduction of NPFs, in combination with a willingness to pay for the environmental quality, will decrease the production of pork in the EU, but such a decrease is sensitive to the value of ε. As ε increases from zero to a very low value, there will be a drop in pork production. If air quality is paid for, there will be an adjustment in production patterns because the emission factors are very different. The dirtiest good will be the first to be reduced in production. We can, however, observe from the figure that when the value of ε is small (<3%), the results are very sensitive to the value of ε. This is because when the consumer has to pay for air quality, the model can choose shifting between low pork production with high air quality and high pork production with low air quality for the highest utility. Therefore, the pattern of pork production, with respect to environmental payment, shows non-smoothness. If ε is larger than 3%, substantial pork will be replaced by NPFs and the model results will become stable and reach a point at which pork production becomes low and stable.

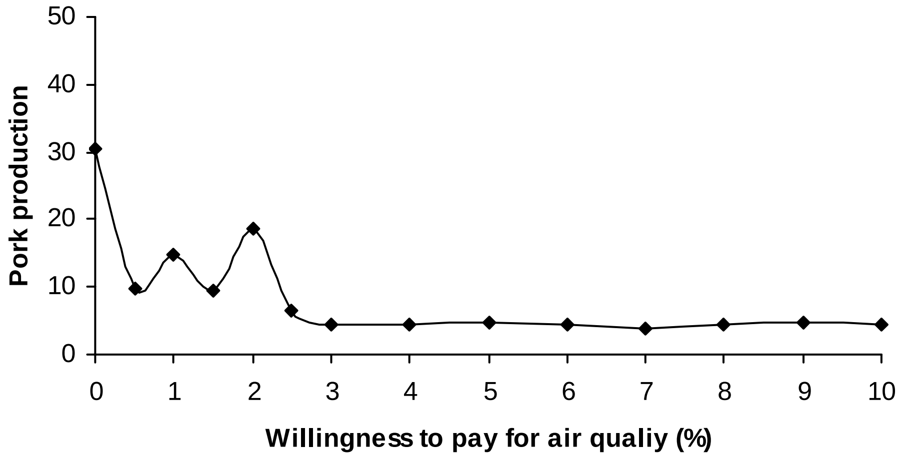


Figure 6-4 Pork production in the EU under different values ε for Scenario 2

<u>*Qualification of the results*</u>

The model results are dependent on the model structure. Firstly, the model introduced a concept of air quality that is a function of emission. This is an arbitrary relation therefore the results are only valid for this relationship. If another relationship between emission and air quality is specified, different results can be expected. The model is also flexible to the change of the values of parameters such as substitution elasticity and utility elasticity.

Secondly, the results are based on an aggregate model thus they only provide some general insights into the tendencies of any change that might occur. The model does not consider the possible trade barriers and transportation costs of international trade, thus they may over estimate the extent of changes. In reality, more factors prevent such a strong reaction to some variations in a small sector. For example, the skills of the labour forces restrict the movement from one sector to another. Therefore interpretation of the model results should be cautious.

6.6 CONCLUSIONS AND DISCUSSION

This chapter presents an AGE model that captures environmental concerns in the utility functions and the production functions. The model is applied to two scenarios: an exogenous shift of the consumption of proteins from pork to NPFs represented by a higher expenditure share of NPFs and an environmental concern represented by a higher willingness to pay for the environmental amenity. Under the first scenario, we found that enhanced demand for

NPFs will impact the pork production in the EU. The other related sectors, such as feed, and peas are also affected. The EU will decrease its pork production by 8% and feed production by 11%. The ROW will increase the production of NPFs by 65% for exporting to the EU, and increase feed production because the EU will import feed. The pork consumption in the EU decreases by 23%. The export of pork is increased due to the demand in the OOECD countries. The impacts on other food and non-food sectors are very small. Introducing NPFs in the EU will not change the consumption pattern in other regions but will change the production patterns through international trade. For example, OOECD will increase production of peas, while ROW will increase production of NPFs. For the emissions, the EU will have a 3% decrease through less pork production. The OOECD will have a 2% decrease of ammonia emission due to the import of pork from the EU, whereas the ROW will have a 2% increase of emission from its increased feed production.

Under the second scenario, the pork production will decrease further due to the associated high emission factor if the mechanism that users pay for the use of environmental resources is implemented. The EU will enjoy a much higher air quality if consumers are really paying for good air quality. The EU will reduce its pork production by 62% and feed production by 16%. It will increase production of NPFs by about 9 times and increase 12% of pea production. The consumption of pork is decreased by 24%, which is not very different from Scenario 1. This is because pork can be imported from other regions. The impacts on sectors of other food and non-food are very small. The major impacts are on the pork and NPFs sectors, as well as on related sectors like feed and peas. Emissions in the EU will decrease by 90%, but there is a slight increase (about 1%) in other regions.

The model has also been applied to examine the impacts of NPFs in the EU under different values of the elasticity of utility with respect to environmental quality and substitution elasticity between pork and NPFs. The study shows that an increase in the values of both parameters will generally increase the production and consumption of NPFs and decrease pork consumption in the EU. Pork production in the EU decreases with the increase of substitution elasticity. Pork production in the EU in general decreases with an increase of the value of the willingness to pay for the air quality. The results are, however, more sensitive to the latter than to the former, that is, the value of elasticity of utility with respect to environmental quality is more responsive to the results than to that of the substitution elasticity. Especially when willingness to pay is around 1%, the model results are very sensitive. Until it achieves about 3%, it becomes stable and as it increases, the results do not change a lot because pork production reaches a lower bound.

The implication of the study is that the elasticity of utility with respect to environmental quality is very important for determining the results. The elasticity of utility with respect to the environment is related to consumers' attitudes towards environmental quality. Stimulating the environmental concerns of consumers and providing them with information about the environmental performance of the products are important for a sustainable consumption pattern. As well, the substitution effect depends on the relative prices of NPFs to pork. Lowering the price of NPFs helps to raise the replacement of pork by NPFs.

APPENDIX 6-A SOCIAL ACCOUNTING MATRICES FOR ALL REGIONS

Table 6-A1 SAM in 2000 for the EU

	Pork	Peas	Other food	NPFs	Feed	Non-food	Consumer	Export	Import	Total
Pork	39080	0	0	0	0	0	-38781	-6651	6352	0
Peas	0	35029	0	-21	-580	0	-42172	-13885	21629	0
Other food	0	0	1027232	0	0	0	-1039722	-187593	200083	0
NPFs	0	0	0	989	0	0	-1005	-182	198	0
Feed	-7719	0	-49749	0	48542	0	0	0	8926	0
Non-food	0	0	0	0	0	14765651	-14674625	-2460011	2368985	0
Factor input										
Labour	-5688	-14299	-187394	-162	-9390	-4023886	4240819			0
Capital	-25249	-18301	-753533	-806	-36240	-10741765	11575894			0
Land	-424	-2429	-36556	0	-2332	0	41741			0
Trade							-62149	2668322	-2606173	0
Total	0	0	0	0	0	0	0	0	0	0

Table 6-A2 SAM in 2000 for other OECD countries

	Pork	Peas	Other food	NPFs	Feed	Non-food	Consumer	Export	Import	Total
Pork	75198	0	0	0	0	0	-77663	-5569	8034	0
Peas	0	121500	0	-51	-1997	0	-124097	-11075	15720	0
Other food	0	0	1618586	0	0	0	-1675085	-130279	186778	0
NPFs	0	0	0	1389	0	0	-1465	-85	161	0
Feed	-17153	0	-83038	0	93384	0	0	0	6807	0
Non-food	0	0	0	0	0	27329170	-27402701	-2335386	2408917	0
Factor input										
Labour	-9670	-37585	-242224	-239	-15717	-8777195	9082630			0
Capital	-45766	-64101	-1221305	-1099	-70798	-18551975	19955044			0
Land	-2609	-19814	-72019	0	-4872	0	99314			0
Trade							144023	2482394	-2626417	0
Total	0	0	0	0	0	0	0	0	0	

Table 6-A3 SAM in 2000 for the ROW

	Pork	Peas	Other food	NPFs	Feed	Non-food	Consumer	Export	Import	Total
Pork	178804	0	0	0	0	0	-176637	-14274	12107	0
Peas	0	258616	0	-221	-4455	0	-241552	-25243	12855	0
Other food	0	0	1651954	0	0	0	-1582965	-235616	166627	0
NPFs	0	0	0	2011	0	0	-1919	-326	234	0
Feed	-44178		-70388		130299	0	0	-23347	7614	0
Non-food	0	0	0	0	0	11408477	-11425972	-1834204	1851699	0
Factor input										
Labour	-34559	-85415	-293885	-202	-18974	-2438815	2871850			0
Capital	-83774	-121710	-1158882	-1588	-98970	-8969662	10434586			0
Land	-16293	-51491	-128799	0	-7900	0	204483			0
Trade							-81874	2133010	-2051136	0
Total	0	0	0	0	0	0	0	0	0	

Table 6-A4 NH_3 emissions and distribution in three regions

		Pork	Peas	Other food	NPFs	Feed	Non-food	Total
Distribution (%)	EU	0.2	0.001	0.579	0	0.12	0.1	1
	OECD	0.17	0.001	0.5	0	0.14	0.18	1
	ROW	0.15	0.001	0.49	0	0.15	0.2	1
Emissions (ton)	EU	575.74	2.879	1666.767	0	345.444	287.87	2878.7
	OECD	1321.886	7.776	3957.882	0	1088.612	1399.644	7775.8
	ROW	4857.78	32.385	16160.22	0	4857.78	6477.04	32385.2

Source: based on RIVM (2004).

APPENDIX 6-B PARAMETERS IN PRODUCTION AND UTILITY FUNCTIONS

Production function

$$Y_{i,j} = A_{i,j} EM_{i,j}^{\xi_{i,j}} [(LB_{i,j})^{\eta_{1i,j}} (KL_{i,j})^{\eta_{2i,j}} (LD_{i,j})^{\eta_{3i,j}} (IFD_{i,j})^{\eta_{4i,j}} (IP_{i,j})^{\eta_{5i,j}}]^{1-\xi_{i,j}} .$$

The parameters are presented in Table 6-A5.

Table 6-A5 Parameters in production functions

		Pork	Peas	Other food	NPFs	Feed	Non-food
A	EU	2.70340	2.43700	2.25630	1.72440	2.16310	1.79670
	OOECD	2.97230	2.70930	2.23180	1.83940	2.22650	1.87440
	ROW	3.76620	2.83790	2.54770	1.93480	2.46400	1.68780
ξ	EU	0.014518	0.000082	0.001620		0.007066	0.000019
	OOECD	0.017275	0.000064	0.002439		0.011523	0.000051
	ROW	0.026450	0.000125	0.009688		0.035942	0.000567
η_1	EU	0.1455	0.4082	0.1824	0.1638	0.1934	0.2725
(labour)	OOECD	0.1286	0.3093	0.1497	0.1721	0.1683	0.3212
	ROW	0.1933	0.3303	0.1779	0.1004	0.1456	0.2138
η_2	EU	0.6461	0.5225	0.7336	0.815	0.7466	0.7275
(capital)	OOECD	0.6086	0.5276	0.7546	0.7912	0.7581	0.6788
	ROW	0.4685	0.4706	0.7015	0.7897	0.7596	0.7862
η_3	EU	0.0108	0.0693	0.0356		0.048	
(land)	OOECD	0.0347	0.1631	0.0445		0.0522	
	ROW	0.0911	0.1991	0.078		0.0606	
η_4	EU	0.1975		0.0484			
(feed)	OOECD	0.2281		0.0513			
	ROW	0.2471		0.0426			
η_5	EU				0.0212	0.0119	
(peas)	OOECD				0.0367	0.0214	
	ROW				0.1099	0.0342	

Utility function

$$U_i = g_i^{\varepsilon_i} ((\prod_s C_{si}^{\beta_{si}})^{1-\varepsilon_i}$$, s= proteins, other food, non-food and peas.

The parameters are presented in Table 6-A6.

Table 6-A6 Parameters in utility functions

	ε	β			
		Peas	Other foods	Non-food	Proteins
EU	0 or 1%	0.00266974	0.06582058	0.92899099	0.00251869
OOECD	0	0.00423811	0.05720721	0.93585228	0.00270240
ROW	0	0.01798728	0.11787622	0.85084025	0.01329625

Table 6-A7 Emission factors of different products in different regions

	Pork	Peas	Other food	NPFs	Non-food	Feed
EU	14.587	0.083	1.624	0	0.02	7.11
OECD	17.278	0.064	2.45	0	0.051	11.543
ROW	26.773	0.127	9.809	0	0.576	36.459

CHAPTER 7 IMPACTS OF NOVEL PROTEIN FOODS ON SUSTAINABLE FOOD PRODUCTION AND CONSUMPTION: LIFE STYLE CHANGE AND ENVIRONMENTAL POLICY*

7.1 INTRODUCTION

Environmental problems associated with animal production call for alternative protein foods with lower emissions. Consumers are changing their attitudes towards food consumption due to animal diseases, and turning more to meat substitutes (MAF, 1997; Miele, 2001; Jin and Koo, 2003). That is, the consumers' lifestyle concerning consumption meat is changing. Chapter 4 showed that NPFs are more environmentally friendly than pork. Replacing animal protein food with NPFs seems a good option for reducing emissions related to animal protein production and consumption. Therefore, in Chapters 5 and 6 we simulated a voluntary shift to NPFs in the model by an *exogenous* shift in consumer demand (i.e. by increasing the expenditure share of NPFs in the protein budget to partially replace the consumption of pork) to study the impacts of NPFs. In literature (e.g. CAST, 1999; Delgado *et al.*, 1999; Keyzer *et al.*, 2003), it has been indicated that meat consumption is related to income level. Therefore, we might also consider an *endogenous* lifestyle change related to meat consumption in modelling to study the impacts of NPFs. In this chapter, meat demand functions related to income will be included in the AGE model for various income levels and regions. Concerning the replacement level of meat by NPFs, we use 'scenarios' in our study. Another possible option to reduce emissions related to food production and consumption is to implement environmental policy. As such, we also study the impacts of environmental policies with the same emissions target as the lifestyle change scenario. For this purpose, we introduce a system of tradable permits for greenhouse gases (GHGs), in combination with emission restrictions for acidifying pollutants. Main environmental problems associated with meat production are related to the production system used (i.e. intensive production versus mixed farming or grass-based systems). Therefore, the introduction of incentive-based tradable emission permits for GHGs and emission restrictions for acidifying compounds should subsequently influence the way meat is produced, inducing a shift away from intensive production and towards mixed farming and grazing systems.

Compared to Chapters 5 and 6, we now use a more disaggregated model that includes more detailed agricultural sectors and we consider more pollutants (i.e. NH_3, CH_4 and N_2O) for

* This Chapter is in collaboration with Lia van Wesenbeeck from SOW-VU.

analysis. Another difference is that in this chapter we do not consider the amenity service of the environment in the utility functions, but rather use the emission input in the production functions. Here we focus on the economic impacts of NPFs and the resulting changes of the emissions in a four-region world model. In such a model, it is difficult to obtain and include a relevant environmental process model with an explicit spatial dimension because regions are divided according to income rather than geography. Therefore, we simplify the model setting, because we restrict the analysis to changes in lifestyle and to imposing limits on emissions of GHGs and acidifying gases. We use more detailed region-specific economic sectors, and we have to give up the detailed representation of the environmental processes.

The main contribution of this chapter is to address questions related to achieving less environmental emissions concerning meat consumption. We analyse the impacts of a change in consumer preference for NPFs and the impacts of environmental policies on the sustainability of food production and consumption. The impacts are not straightforward. For example, even if EU consumers accept NPFs, pork production in the EU may not be reduced due to the high demand in developing countries, especially China. If so, the environmental problems caused by animal production in the EU will remain. The impacts on the production structure are not obvious either because of the international trade of commodities. As a result, we expect changes in economic variables (e.g. production, consumption and international trade) and environmental variables (i.e. emissions of greenhouse gases such as CH_4, and N_2O and of ammonia NH_3), accompanying the introduction of NPFs and environmental policies. Our model includes a lifestyle change of consumers related to income level, different production systems, emissions and incentive-based emission permits. Using these variables we hope to aim to obtain insights into sustainable food consumption and production.

The chapter is organised as follows. Section 7.2 provides a general discussion on the theoretical framework and on different lifestyles of meat consumption, that is, three different meat consumption levels with respect to three income levels. Section 7.3 contains the implementation of these lifestyles, the selection of environmental pollutants and the implementation of emission permits as well as local emission bounds in an applied model. Section 7.4 provides the information including the economic data and environmental data. In Section 7.5, we formulate scenarios of lifestyle change and emission permits, present the parameters for each scenario, and discuss the model results. Section 7.6 presents the main conclusions.

7.2 THEORETICAL FRAMEWORK

AGE models have become a standard tool for the analysis of environmental issues and the determination of optimal policies to reduce environmental pressure (Copeland and Taylor, 2003). For our analysis, we rely on a stylised AGE model which focuses on describing agricultural production, consumption, and trade (GEMAT[1], see Appendix 7-A for the model equations). In this chapter, we have added the environmental aspects related to our study in the model including emissions and environmental policy instruments. Here we briefly describe the main characteristics of the model and the adjustments for analysing the impacts of changing consumption patterns, especially with respect to protein foods, and the inclusion of environmental emissions related to proteins in the model.

The model covers two time periods (1999/2000 and 2020), in which agents are assumed to make fully informed decisions on consumption and production. The representation of the future includes exogenous trends on population growth, technical progress, and yield increases. In terms of geographical coverage, the model distinguishes four different regions (i.e. low-income countries, middle income countries, the EU-15 and other high-income countries). The model distinguishes 14 agricultural sectors[2] and three industrial sectors (i.e. NPFs, industrial products and industrial services). In addition, the model includes different land types. In utility functions we distinguish between protein-related items (i.e. meat and NPFs), and other consumption items.

There are also two adjustments to the GEMAT model. Firstly, lifestyle change related to meat consumption is included in the model. Per capita demand for meat is not a concave function of per capita income, instead there are three different income-dependent lifestyles with respect to meat consumption (Keyzer *et al.*, 2003). For low income, both consumption and income elasticity are low. Then, after income crosses a certain threshold $\underline{y}$, meat demand 'takes off' and rises rapidly with the increase of income. Finally, after income crosses another critical threshold $\overline{y}$, consumers become satiated with meat, and the income elasticity of meat demand is low again but at high levels of consumption (Figure 7-1). Accordingly, we name these different meat consumption patterns as 'poor', 'intermediate' and 'rich' lifestyles.

Secondly, the model distinguishes three possible production systems for livestock, namely grazing systems, mixed farming systems, and intensive livestock keeping, in terms of the classification by Seré *et al*. (1995) and de Haan *et al*. (1997). Whereas grazing systems rely predominantly on the availability of grazing area, crop residuals, and household wastes, intensive livestock keeping represents the opposite with an almost exclusive reliance on commercially bought feed (mainly cereals, root crops, and oilseed cakes). Mixed farming systems represent an interesting intermediate case, where livestock keeping and crop farming are integrated as much as possible, and additional feed is sometimes brought into the system. In our model, the choice for a particular production system is endogenous, depending on the availability and prices of grassland and residuals for feed to optimise the profits of producers.

[1] General Equilibrium Model of Agricultural Trade and production (van Wesenbeeck and Herok, 2002). For more background information, see Folmer *et al*., 1995; Keyzer and Mebis, 2000 and Keyzer *et al*., 2002.

[2] These are: grass, grains, roots/tubers, oil crops, pulses, other agriculture, ruminants, monogastrics excluding pigs, pig meat, meat products, vegetable oil and fats, other agricultural products, oilseed cakes and grain brans.

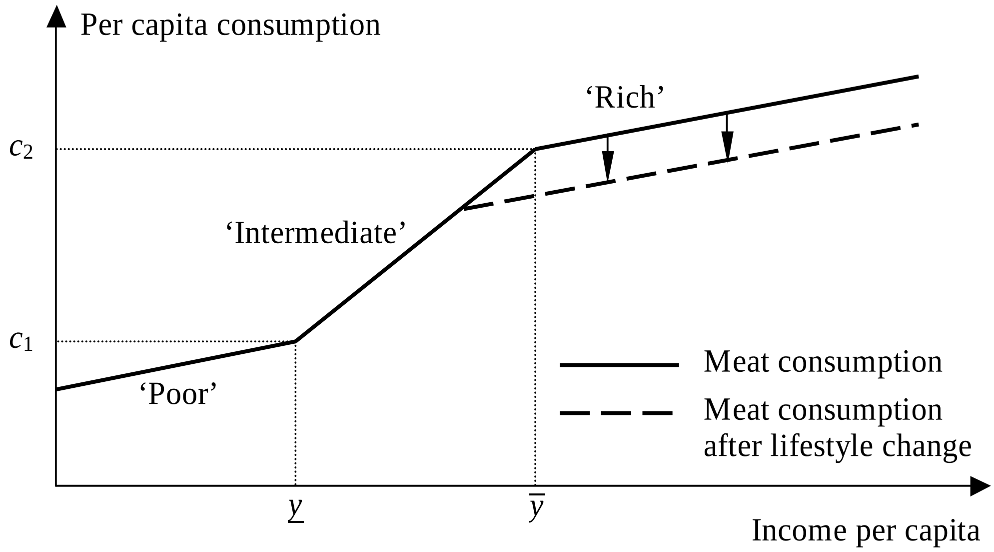


Figure 7-1 A stylised Engel curve for meat and life style shift of 'rich' consumers

In addition to considering the economic output from agriculture, we also consider the environmental output in terms of emissions to the environment, which may lead to environmental problems. In this study we focus on emissions and the effects of emission permits to analyse the environmental aspects of proteins.

7.3 IMPLEMENTATION

Economic aspects

The stylised structure of our model includes a welfare program and a feedback program (see GK, 2002). A welfare program is a centralised representation of an economy, where the objective is to maximise the weighted sum of utilities of consumers in the economy, subject to constraints on resource and technology. In the feedback program, parameters of the welfare program are adjusted such that: (1) all individual budgets of the consumers hold (adjusting the welfare weights of the individuals in the objective), and (2) the percentage of consumers in a certain lifestyle is updated following the changes in average per capita income. An equilibrium of this system is then defined as a situation where a welfare optimum is found, all budgets hold, and the percentage of consumers within a region in a certain lifestyle is consistent with the average per capita income in that region.

Lifestyles

Regarding the representation of lifestyles, the best one of choosing one of the three lifestyles ('rich', 'intermediate' and 'poor') would be to use a migration[3] approach (see Keyzer, 1995).

[3] The term 'migration' here differs from the common use of people moving from one location to another. Instead, we take a broader meaning of individuals moving between lifestyle classes.

For each individual consumer, this would imply formulating an optimisation program that reads,

$$max_{m_l, x_l, n_l} \sum_l n_l u_l(x_l, m_l),$$

subject to

$$p \sum_l (n_l x_l + n_l m_l + n_l \hat{m}_l) = H ,$$

$$n_l \bar{q}_{l-1} \leq n_l m_l + n_l \hat{m}_l ,$$

$$n_l m_l + n_l \hat{m}_l \leq n_l \bar{q}_l ,$$

$$\sum_l n_l = 1,$$

where the subscript *l* is used to represent the different lifestyles 1 (poor), 2 (intermediate), and 3 (rich), and (*l*-1) refers to the lifestyle of the income group just below lifestyle *l*. $u_l(x_l, m_l)$ is the utility function associated with lifestyle *l*, which depends on the consumption of meat (m_l) and other consumption goods (x_l). $\hat{m}_l$ represents the committed consumption of meat for every lifestyle, $\bar{q}_l$ is the upper bound on meat consumption in every lifestyle, and H represents the given income of the consumer and *p* the given prices for meat and other consumption goods. n_l is the share of lifestyle *l*. Finally, the choice between different lifestyles is modelled as such that the share of n_l is summed to 1.

In the application we use fixed lifestyle shares in the main program and update them in the feedback program. The general idea is to use the incomes and prices from the equilibrium solution of the welfare program to solve the migration problems. 700 income classes are distinguished. For each of these classes, an individual optimisation is done to determine the share of consumers in this class that would migrate to a rich, poor, or intermediate lifestyle. Then, after multiplying these shares with the number of people in each income class and aggregating them over all income classes, we find the total number of people that follows a specific lifestyle. This share is then used in another round of the main welfare program.

The upper and lower bounds on meat consumption and the committed consumption for each lifestyle are set following Keyzer *et al*. (2003). Since the distribution of income depends on the level of the average income, it is clear that if no additional assumptions are made, the homogeneity of degree zero in prices is lost. To clarify, if all prices are multiplied by some factor *A*, incomes would rise with a factor *A*. This would lead to another income distribution with another pattern of lifestyles, and thus another consumer demand pattern. To overcome this problem, we first calibrate the model such that incomes are in the same range as the actual incomes on which the distributions are based, and then use the normalisation of prices used in this benchmark model as the base normalisation. For all other normalisation, corrections are made in the prices and income reported by the main program.

Production function and utility function

For the functional forms of agricultural production, we use a nested production function with a CES technology at the highest level and a Leontief technology at the lowest level regarding the specific agricultural production characteristics. The Leontief technology captures upper bounds on yields and carcass weights. Furthermore, some important feed items, such as grain brans and oilcakes are represented as by-products of the production of other agricultural goods. The utility function is chosen as a CES function that allows substitution between different types of consumption goods.

Regional specifications

The model includes four regions: low-income region (denoted as Lowinc), middle income region (Midinc), other high- income region (Highinc) and the EU. In each region, there are region-specific production functions, utility functions, and committed meat consumption levels for each income level.

Environmental aspects

In our study, we focus on the environmental emissions from the agricultural sector. Agricultural activities (including manure storage, soil fertilising and animal husbandry) are important sources of ammonia (NH_3), methane (CH_4) and nitrous oxides (N_2O) emissions. NH_3 emissions contribute to acidification, while GHGs (CH_4 and N_2O) to global warming. Other important greenhouse gas is carbon dioxide (CO_2) and acidifying gases are sulphur dioxide (SO_2) and nitrogen oxides (NO_x). The CO_2 emissions from agricultural processes are not covered in this study as agriculture itself is considered as both a source and a sink. For example, in the Netherlands the CO_2 emission from agriculture is only 4% of the total national CO_2 emissions in 1998 (CBS, 1999). For the same reason, SO_2 and NO_x emissions are not considered because NO_x emissions from agriculture are only 2% of the total emission, and SO_2 from agriculture is negligible (CBS, 1999). Therefore we only consider three pollutants: NH_3, CH_4 and N_2O.

For reasons of economic efficiency, we introduce economic incentive-based instruments for environmental management. There is a wide range of alternative instruments like taxes on emissions, subsidies for pollution abatement, a marketable permit for emissions of pollutants, etc. (Costanza *et al*., 1997). In terms of the effects of emissions, we consider two environmental policy instruments: tradable permits for GHGs (CH_4 and N_2O) and emission bounds for regional pollutants (NH_3). For the two GHGs, it is the total emission volume that counts and restrictions are set at a global level, because global warming caused by GHGs has a global effect. Since the damage caused by the emissions of NH_3 is local, the relevant bound is the emission of NH_3 per unit of area in this model[4].

[4] We have to acknowledge that the emission bounds for acidifying substances should be determined by the soil sensitivity, such as in the RAINS model (Alcamo *et al*., 1990). Therefore, the emission bounds should be more location-specific, which is not considered in this chapter.

7.4 THE DATA

In this section we report the data used for calibration of the model and the emission coefficients for emission calculations. The base year is 1999/2000. The economic data includes general regional characteristics, land use, labour working hours, and expenditure shares. The environmental data includes the base year emissions for NH_3, CH_4, and N_2O, and the emission factors from animal farming and crop production.

Economic data

For the definition of the low income (Lowinc), middle income (Midinc), and high income (Highinc) regions, the classification of the World Bank (2001) was used in terms of income in 1998, with an additional breakdown of the high-income region into the EU-15 and other high-income region. Since an urban-rural distinction seems warranted for our purposes, the population is divided into these two groups, and migration tendencies are accounted for by including urban and rural population growth. Table 7-1 gives the important characteristics of the regions.

Table 7-1 Main characteristics of the regions

	Lowinc	Midinc	Highinc	EU
Population in millions (2000)[b]	3771.59	1234.55	487.42	375.51
Urban population in millions (2000)[b]	1257.72	851.60	380.29	295.87
Rural population in millions (2000)[b]	2513.88	382.94	107.12	79.64
Population in millions (2020)[b]	4825.18	1507.72	536.85	371.39
Urban population in millions (2020)[b]	2208.94	1146.09	443.94	308.74
Rural population in millions (2020)[b]	2616.25	361.63	92.91	62.66
Average yearly population growth	0.012	0.010	0.005	-0.001
Average yearly population growth urban	0.028	0.015	0.008	0.002
Average yearly population growth rural	0.002	-0.003	-0.007	-0.012
GDP in billions PPP US$ (1999)[a]	10676.71	7339.337	14285.53	8338.689
GDP per capita in PPP US$ (1999)[a]	2911.574	6187.908	28670.72	22209.37
GDP in billions PPP US$ (2020)[c]	28328.49	17587.8	23869.52	13933.01
GDP per capita in PPP US$ (2020)[c]	5870.973	11665.18	44462.42	37515.75

Sources (a) World Bank, 2001; (b) FAOSTAT, 2001; (c) EIA, 2001.

With respect to land use, three types of land are distinguished according to the FAO classification: grassland, cropland and cityland. Grassland is defined as the element ‘permanent pasture’, while cropland is defined as ‘arable land and permanent crop land’. For cityland, there is no data in the FAOSTAT database, so we use assumed population densities for urban areas. For 1999, we assume that the average population density in cities in Lowinc is 7 per ha; in Midinc 8 per ha; in other-Highinc 8.5 per ha, and in the EU 10 per ha (these figures are loosely based on World Bank (2001)). Then the total urban area consistent with the assumptions is labelled as ‘cityland’. The difference between the sum of the three types of land, and the total land area per region, is assumed to be unsuitable for economic activity (e.g. rocks or inland waters). This area is thus not included in the model.

In the past, the reclamation of land was one of the ways in which agricultural production increased. As such, we apply exogenous trends for land use change, based on FAOSTAT data on land use for the period 1961 to 1999. Furthermore, we assume that through increased urbanisation the population density in urban areas will rise to 8/ha, 9/ha, 9/ha, and 10.5/ha, for the Lowinc, Midinc, Highinc, and the EU regions, respectively. There are also changes in grassland and cropland from 1999 to 2020. We assume that the area for grassland in Lowinc in 2020 is 1% larger than in 1999, and cropland 8%. For Midinc, grassland increases by 1% and cropland by 3%. In Highinc, the area of grassland in 2020 is 2% lower than in 1998, and the area for cropland remains constant. In the EU, there is a decrease of 1% for grassland and 0.5% for cropland. The land use overview is included in Table A1 of Appendix 7-B.

Available rural and urban labour is expressed in total working hours based on total workforce (aged 15-64), workforce share of total population, and urban and rural workforce numbers. We assume that in the EU and Highinc regions, 300 days can be worked yearly for 8 hours a day. For Midinc, this is 280 days per year, 6 hours a day, and for Lowinc, 260 days/year, 5 hours a day. The difference in days/year and hours/day between the regions reflects differences in, for example, the health status of the workers, and the differences in education. Because of increases in productivity, we assume 310 days/year and 8 hours/day in 2020 in the EU and Highinc, 300 and 7 in Midinc, and 270 and 6 in Lowinc. The labour force and working hours are given in Appendix 7-B, Table A2.

Production, consumption, and input use of all agricultural commodities including meat products and agricultural products were taken from FAOSTAT in 1999. For the estimation of meat production parameters by livestock system, we used the data reported in Annex 3 of Seré *et al.* (1995) and Annex 2 of de Haan *et al.* (1997), which were mapped to the regional aggregation in the model.

For consumption data for the EU-15 concerning food items, industrial services and industrial products, we used data from the European Commission (2002). Data for expenditure shares of other regions were taken from Regmi (2001), Blisard (2001), and Banse and Grings (2001) (see Table 7-2).

Environmental data

The environmental data reported in this section is useful for the calculation of NH_3, CH_4 and N_2O emissions from the agriculture sector. Therefore, the distribution of emissions in production of different products, emission factors from different sources (i.e. animals, plants), and manure management systems are necessary.

Table 7-2 Expenditure shares of all consumption goods

Items	Lowinc	Midinc	Highinc	EU
Grains (cereals) [a)]	0.132	0.058	0.021	0.021
Roots and tubers (potatoes)[b), c)]	0.009	0.006	0.001	0.001
Pulses (beans, peas) [b)]	0.005	0.003	0.001	0.001
Other agriculture (fruit and vegetables) [a)]	0.108	0.061	0.026	0.026
Meat products [a)]	0.085	0.064	0.033	0.033
Vegetable oil (oil and fats) [a)]	0.033	0.014	0.005	0.005
Other agriculture products (flour, beverages, juices etc.)	0.099	0.084	0.043	0.041
Industrial products [a)]	0.33	0.42	0.49	0.49
Industrial services [a)]	0.20	0.29	0.38	0.38
Novel Protein Foods [d)]	0	0	0	0.002
Total	1.000	1.000	1.000	1.000

Source: a) Regmi, 2001, European Commission, 2002; b) Blisard, 2001, and c) Banse and Grings, 2001, and d) Aurelia, 2002.

NH_3 emissions come from both animal and crop production. NH_3 emissions from animal production depend on the type of animals. The NH_3 emission from ruminants is 14.3 kg/animal, from pigs 6.39 kg/animal and from poultry 0.28 kg/animal (EEA, 2002). The NH_3 emissions from arable agriculture (i.e. crop production) generally include the emissions from fertiliser application and from plants. The emission factor from N-fertiliser and plants is 0.02kg NH_3-N/ kg fertilisers applied (EEA, 2002). The fertiliser use rate for plants (kg/ha per year) is based on IFA, IFDC and FAO (1999), which is given in Appendix 7-B, Table A3. By the land area used for plants and the emission factors, we can obtain the NH_3 emissions from crop agriculture.

N_2O emissions in agriculture are associated with animal production (manure management) and crop production (emissions from agricultural soils due to nitrification and denitrification). The N_2O emissions can be calculated in three parts: N_2O emissions from manure management, direct N_2O emissions from agricultural soils and indirect N_2O emissions due to agricultural activities (nitrogen use in agriculture). For calculating the N_2O emissions from manure management, regional information is obtained from IPCC (1997): nitrogen excretion from animals (Appendix 7-B: Table A4), the animal waste management systems (Appendix 7-B: Table A5) and emission factors for each system (Appendix 7-B: Table A6). The direct N_2O emissions come from agricultural soils due to the N-inputs e.g. synthetic fertilisers, animal excreta nitrogen used as fertiliser, biological nitrogen fixation, crop residue or sewage sludge. According to IPCC (1997), synthetic fertilisers are an important source of N_2O. The emission factor of the applied nitrogen fertilisers is 0.0125 kg N_2O /kg N-fertiliser (Brink, 2003). Through the fertiliser use and emission factor, the quantity of direct N_2O emissions can be obtained. The indirect N_2O emissions come from the pathways for synthetic fertiliser and manure input due to the volatilisation and subsequent atmospheric deposition of NH_3 and NO_x, as well as nitrogen leaching and runoff. The emission factors for deposition are 0.01 kg N_2O-N/kg (NH_3-N and NO_x-N) emitted, and for leaching and runoff are 0.025 kg N_2O-N/kg N leaching /runoff. As for the NO_x volatilisation, it is 0.1 kg nitrogen /kg synthetic fertiliser and 0.2 kg nitrogen /kg of nitrogen excreted by livestock. The leaching of nitrogen world-wide is 0.3 kg/kg of fertiliser or manure *N* (IPCC, 1997)[5].

The major agricultural source of CH_4 emissions is animal husbandry, which contributes 96% of the total agriculture CH_4 emissions (EEA, 2002). Thus we only consider the CH_4 from animal husbandry and omit CH_4 emissions from the production of other agricultural products in this study. CH_4 emissions from animal husbandry include the emissions in enteric fermentation and manure management. We use data from IPCC (1997) for CH_4 emission factors from both enteric fermentation (Appendix 7-B: Table A7) and manure management (Appendix 7-B: Table A8).

7.5 Scenario formulation and results

Introduction

As mentioned previously, there are two important ways towards more sustainable food consumption patterns for reducing emissions: one is a lifestyle change towards less meat and more NPFs, and the other is the implementation of environmental policy.

We first explore the possibility to reduce environmental emissions from meat production by changing consumer lifestyles with respect to meat consumption. If consumers change their behaviour, then the demand for animal products will change. Therefore, we study the effects of the lifestyle changes on production structure and emissions. More specifically, we want to show how lifestyle changes, through different levels of NPFs replacement for meat (i.e. an increase of NPFs and a decrease of meat in the range of 0 to 30 kg per capita per year), influence the emissions.

In order to show the implications of different ways towards sustainability of food consumption and production, we carry out the following three scenario studies. We define a lifestyle change scenario as the *first* scenario (denoted as ‘lifestyle’), in which 10 kg of NPFs per capita per year are consumed by the ‘rich’ consumers to replace the same quantity of meat.

The same level of emissions reduction from a life style change in the first scenario may also be achieved by implementing environmental policy instruments. In the *second* scenario (denoted as ‘permit Grand’), we introduce tradable emission permits for the two GHGs (CH_4

[5] Indirect N_2O emission is thus calculated as: 0.01*(0.1*fertilizer use + 0.2*manure)+0.025*0.3* (fertilizer use +manure).

and N_2O), a policy that leads to a reduction of emissions by pricing the free environmental emissions. The permits are divided according to the 'grandfathering system', or that the permits are distributed according to the share of emissions in base year 1999/2000.

Emissions of NH_3 cause local environmental problems like acidification, thus we need a local limit per unit of land to avoid high concentrations in some areas. The EU has introduced the Gothenburg protocol, where emission bounds of acidifying gases are 83% of the 1990 level. Since, in our simulations, we want to compare the impacts of lifestyle changes with those of environmental policies, we use the NH_3 emission level of the first scenario divided by the total area in the second scenario as the upper bound for the EU.

In the *third* scenario (denoted as 'permit Pop'), we distribute the initial emission permits according to population size for the same emission targets as in Scenario 2, which should be more conducive to the development of developing countries. Table 7-3 describes the main characteristics of the three scenarios.

Table 7-3 Parameters under three scenarios

Scenarios	Contents
Scenario 1 ('lifestyle')	'Rich' consumers will replace meat by NPFs: 10 kg per year per capita; No environmental policy.
Scenario 2 ('permit Grand')	Emission permits of N_2O, CH_4 are the same as the emission levels under Scenario 1, division of permits is according to regional shares in base year 1999/2000, permits are tradable; Regional NH_3 emission permit for the EU is the same as the emission level under Scenario 1, permit is non-tradable, an upper bound of NH_3 emission per ha in the EU is imposed; No lifestyle change.
Scenario 3 ('permit Pop')	The same as Scenario 2 but division of permits is according to population size in each region.

Discussion of results

The model was run for each scenario in GAMS. In this section, we first report the model results for three scenarios. Then we compare the impacts of lifestyle change and environmental policy instruments on production structure. The comparison between Scenario 2 and 3 can also show some implications of the environmental policy instruments.

Impacts of lifestyle change

We simulated the different levels of NPFs replacement for meat by 'rich' consumers in all regions. The switch of 'rich' consumers from meat to more NPFs will definitely influence the demand for meat, and will therefore have an impact on production structures and emissions. Accompanying the increased consumption of NPFs, meat demand will change because of substitution and income effects. The substitution of NPFs for meat, as a preference change, will decrease the meat demand. This substitution will also change the relative prices of meat and NPFs and thus the income of consumers will alter. Therefore, the substitution from a preference change has an income effect. As an overall effect, the meat demand in the EU, other high-income, middle-income and low-income regions will decrease (see Figure 7-2). The extent of the change is greater in the EU and other high-income regions than the other two regions because there are more 'rich' consumers in the former than in the latter. We can observe from Figure 7-2 that after a certain level of NPF replacement by 'rich' consumers, the meat demand in the middle income region will exceed the meat demand in the EU and the other-high income region. This is because of the substantial substitution of NPFs for meat by more 'rich' consumers in the EU and the other-high income region. For a shift of 10 kg/capita per year of meat replacement with NPFs by 'rich' consumers, the per capita meat consumption in the EU will decrease by 8.6% (from 97.84 to 89.40 kg), and the world average meat consumption per capita will decrease by 4.9% (from 85.7 to 81.5 kg).

A change of meat demand could influence the production level of meat. For example, if worldwide 'rich' consumers consume 10kg NPFs per capita per year to replace meat, the total meat production in the EU will decrease by 3.9% (from 60.5 to 58.1 million mt) and global meat production will decrease by 25% (from 258.0 to 192.7 million mt).

A change of meat demand could influence the production structure of meat production, as there are three different livestock production systems. However, the effect is not profound. Although the share of grazing technology increases as the share of NPFs increases, this share remains very low and the largest share of production of meat still occupy in the intensive livestock production systems. This is because the meat demand is still too high to be satisfied by more extensive livestock systems that require a larger amount of land.

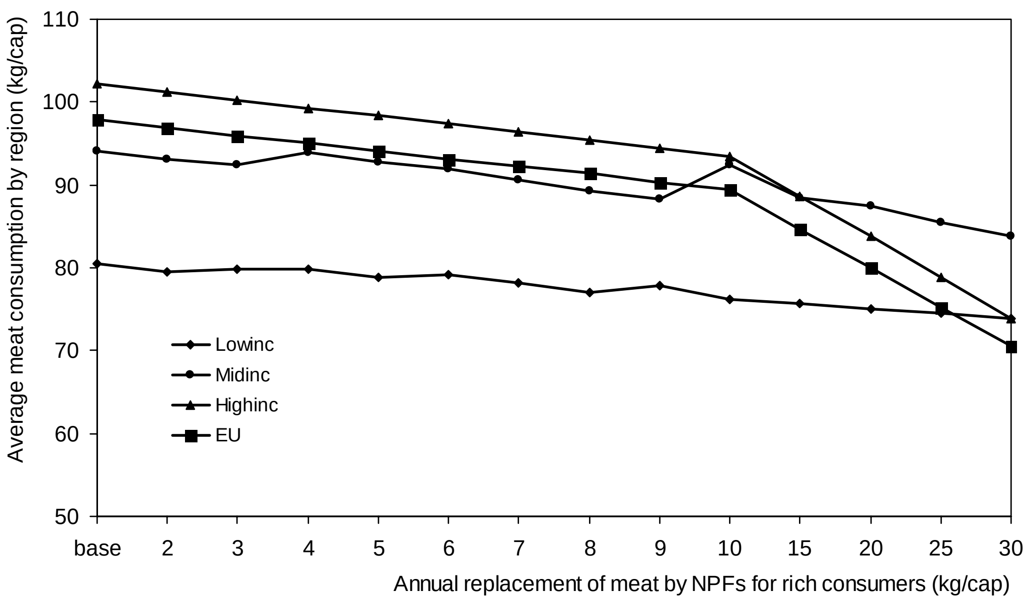


Figure 7-2 Development of average annual meat demand per capita in 2020 in response to an increasing replacement of meat by NPFs by 'rich' consumers

Figure 7-3 shows the emission levels for different levels of NPFs. It shows that generally the higher the replacement of meat by NPFs, the lower the NH_3 emission. For the emissions of N_2O and CH_4, the same trend holds. The reason is obvious; emissions are lower for the production of peas (the primary product from which NPFs are made) than for meat. If ‘rich’ consumers eat 10kg/capita per year NPFs to replace meat consumption, the global emission reduction will be 4% (from 76248 to 73239 million kg) for NH_3, 0.2% (from 16026 to 15997 million kg) for CH_4 and 3.7 % (from 4294 to 4135 million kg) for N_2O. However, this emission reduction does not necessarily happen in the regions where more NPFs are consumed, rather it happens in the regions that switch to produce more NPFs and less animal products for their comparative advantages and possibility of international trade. For example, the agricultural emissions in the EU will be reduced by 2.9 % for N_2O and increased by 6 % for CH_4. There is no change in NH_3 emission in the EU. The emission reduction of NH_3 mainly occurs in the other high-income region because this region will produce fewer ruminants, and the emissions for NH_3 are higher in ruminants than in pork production.

Figure 7-3 also shows a fluctuating trend for NH_3 emissions. At low levels of NPFs, emission decreases first and then increases, though it is always lower than the ‘business as usual’. This is because the NH_3 emission comes from both production of plant and animals. As we have discussed, the demand change will have an impact on the production structure. Around 8-10 kg of replacement by the ‘rich’, the emission reduction of NH_3 is not obvious, because still increasing amount of meat is demanded by other categories of consumers. Of course, if a substantial replacement (more than 15 kg per capita per year) takes place for ‘rich’ consumers, the impacts are obvious again.

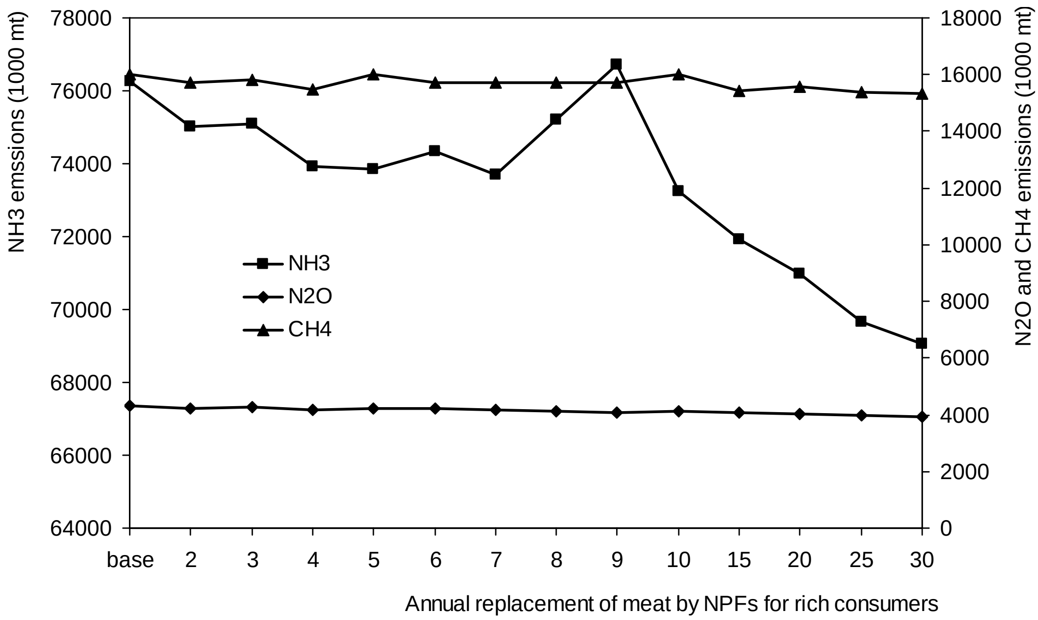


Figure 7-3 Development of emissions in 2020 under different replacement levels of meat by NPFs by ‘rich’ consumers

Despite the fact that the assumption of a 10kg replacement of meat by NPFs may be heroic, the emission reduction of CH_4 and N_2O through lifestyle change is very limited for a lower level of replacement of meat by NPFs. This result can be explained by the assumption that only 'rich' people will switch to NPFs. Even in 2020, the share of people with the rich lifestyle in the total population is still low compared to that of the intermediate lifestyle. For example, in the low-income region with the highest population, 56% is still in the 'intermediate' lifestyle in 2020, and only 13% reaches the rich lifestyle income range. Therefore, the number of people with decreasing meat demand is relatively low, especially since the largest increase in meat demand stems from people in the 'intermediate' lifestyle.

Impacts of emission permits and comparison between scenarios

The results show that developing countries (i.e. low-income and middle-income regions) are relatively better off according to the utility levels in the scenario where permits are divided according to population size than in the grandfathering scenario. Although it would be interesting to compare welfare effects under different scenarios for the same emission targets for the GHGs, it is very difficult because the preferences have changed under Scenario 1. Therefore, we turn to the interpretation of the other variables of the different scenarios, such as the change of production structure and emission distribution.

The tradable emission permits of CH_4 and N_2O, and emission bounds of NH_3 per ha, will redistribute the production patterns and thus have impacts on the distribution of emissions. Figure 7-4 gives the composition of world production structure in different scenarios. It shows that the production structure is changing towards more grazing system and less intensive production under environmental policy scenarios than the lifestyle change scenario, because emission bounds are imposed and it is more efficient to use a more extensive farm system.

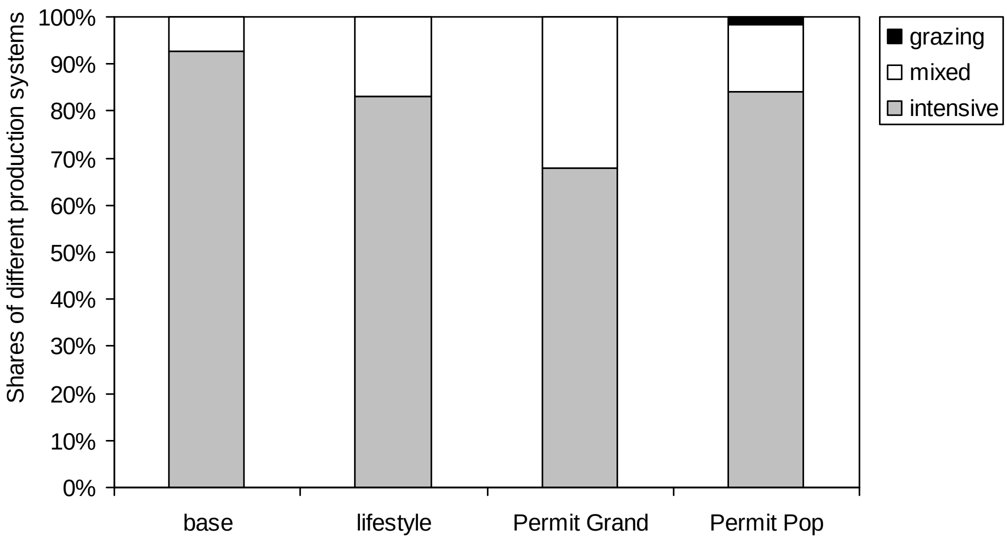
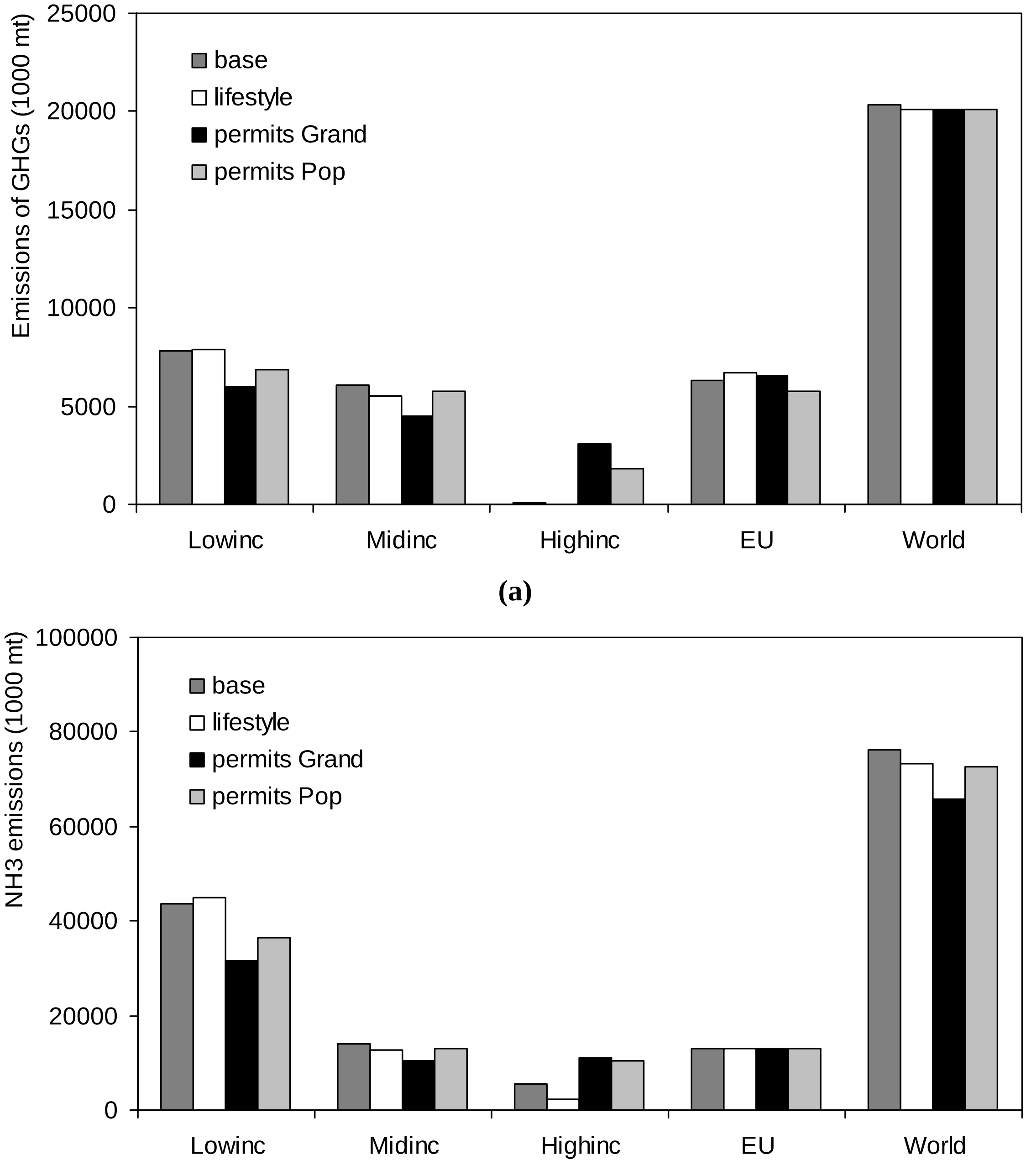


Figure 7-4 Structure of production systems in 2020 under different scenarios

Figure 7-5 shows emission distributions over different regions under different scenarios. The emissions are lower under three scenarios than under 'business as usual' because of the design of the scenarios. For GHGs, more emission will take place in the EU and middle-income regions under three scenarios because the EU will keep its meat production for export and the middle-income region will increase their meat consumption as well as production. The low-income and other high-income regions will import more meat from the EU and middle-income regions, thus the emissions are lower in low- and other high-income regions.



(b)

Figure 7-5 a) GHG (CH_4 and N_2O) emissions 2020 for different scenarios; b) NH_3 emissions 2020 for different scenarios

NH_3 emissions are lower in the lifestyle scenario than the 'business as usual'. Since we imposed a per hectare emission bound (kg/ha) for the EU considering the real problem in the EU under Scenarios 2 and 3, emissions of NH_3 are reduced. This is achieved by a more extensive production system. Such a system reduces the NH_3 emissions in the EU though not the GHGs. This is because different emission coefficients apply to different animals. For example, the ratio of CH_4 emission coefficient for cattle and CH_4 emission coefficient for pigs is 32. The ratio of NH_3 emission coefficient of cattle and NH_3 emission coefficient for pigs is 2.3. That means that a pig emits more NH_3 than CH_4 compared to cattle. Since the present cattle production is relatively extensive compared to pig production, much extensification will take place in pig production. Therefore, more NH_3 emissions can be reduced by a more extensive production system.

Qualification of results

We have to emphasise that the results should be considered cautiously. Firstly, we have a stylised model, which means that a lot of simplifying assumptions have been made. For example, we have a very aggregate non-agricultural sector. Even for the agricultural sector we have limited information for production and consumption in various parts of the world. Secondly we have limited data on emissions for non-EU regions. From authorative data sources like European Environmental Agency and IPCC, data on emissions are available only for a limited number of countries. Thirdly, lifestyle change is only an observed phenomenon. Detailed information about how and to what extent it is changing is hard to find thus far. Therefore, in the model simulation we have to assume a range of changes in relevant parameters, for example in the committed level of meat consumption for 'rich' consumers.

7.6 CONCLUSIONS AND DISCUSSION

This chapter has focused on studying the impacts of NPFs through lifestyle change of consumers and emission permits system through production structure change on sustainable food production and consumption. The following are our conclusions.

Firstly, NPFs indeed help to reduce environmental pressure if consumers change their lifestyle by consuming more NPFs and reducing meat consumption. This is because emissions originating from the production of NPFs are lower than those associated with meat production. If 'rich' consumers consume 10kg NPFs per capita per year to replace meat, the global emission reduction for NH_3 will be 4%, for CH_4 0.2% and for N_2O 3.7%. But this emission reduction does not necessarily happen in the regions where more NPFs are consumed. It happens to the regions that switch to produce fewer ruminants using their comparative advantages in the regime of free international trade. For example, the agricultural emissions in the EU will be reduced by 2.9% for N_2O and increased by 6% for

CH_4. There is no change in NH_3 emission in the EU. In this case, it is the other high-income region that reduces the most NH_3 emissions.

Secondly, to achieve a similar emission reduction as that of a lifestyle change, we can also use environmental policy instruments. Lifestyle change leads to emission reduction through production reduction in meat sectors because less meat is demanded and production will increase in the NPFs sector, which impacts other related sectors such as feed and pulses. This change will make the production structure more extensive. Nonetheless, environmental policies reduce the emissions through using a more extensive production system, or by production reduction in high emission sectors, which increases prices and therefore consumers suffer a welfare loss. However, the environmental emission reduction through a lifestyle change is limited because meat consumption is related to income. It is a culture-related issue. A cultural change will be more difficult to implement than a policy change. Therefore, it is difficult to make a substantial change by NPFs in meat consumption. The assumption of a 10kg replacement of meat by NPFs may be ambitious, and the emission reduction through life style change is very limited for a lower level of replacement of meat by NPFs. It would be more effective to achieve *high* emission reduction by environmental policy than a life style change. For example a modest lifestyle change (10kg NPFs per capita per year for rich consumers) is not sufficient to achieve an NH_3 emission target in the EU such as the target set by Gothenburg protocol. Then we have to rely on the local environmental policy in the EU to solve the local environmental problems caused by NH_3 emissions.

Thirdly, to achieve the similar environmental emission reduction, environmental policy instruments are implemented through tradable emission permits for GHGs and an emission bound (kg/ha) in the EU for NH_3. The study has investigated the impacts of environmental policy instruments that would achieve similar emission levels as a lifestyle change on the production structure. With respect to the emission permits we have two different mechanisms to distribute the initial permits under a grandfathering scheme: based on historical emission share or population size. Since the policy targets are the same for these two measures of distributing permits, the impacts are on the welfare distribution. The results show that developing countries are relatively better off if the permits are divided according to population size than historical emission shares.

Based on the study we can make the following policy recommendations. Introducing a small amount of NPFs is only part of the measures to reduce environmental pressure. As the consumption of NPFs becomes higher, the emissions become lower, and as such, promoting sustainable consumption patterns becomes important. Our simulations also show that the group to be targeted should be larger and not only the richest ones, though a transition could start there and spread to other lifestyle groups.

Concerning the methodology used in the chapter, we have the following conclusions. Firstly, we have showed that the inclusion of a meat demand function is possible and adds richness to the modelling of meat consumption. In our application, this is especially important because it allows us to include the lifestyle scenario. Secondly, the inclusion of emissions into an AGE model is possible and relatively straightforward, and it enables us to calculate the impacts of changes in lifestyle and environmental policies and to ultimately compare the results.

APPENDIX 7-A MODEL EQUATIONS AND SYMBOLS

The model is written as a full format. The complete welfare program reads as:

$$\max \sum_r \sum_i \sum_l \alpha_{r,i} \left\{ \begin{array}{l} \delta_{r,i,l}^{1999} \left[\left(\sum_{nk1} \left(\beta_{r,i,l,nk1} x_{r,i,l,nk1} \right)^{\rho_{r,i,l}} + \sum_{ckn1} \left(\beta_{r,i,l,ckn1} x_{r,i,l,ckn1} \right)^{\bar{\rho}_{r,i,l}} \right)^{\rho_{r,i,l}/\bar{\rho}_{r,i,l}} \right]^{1/\rho_{r,i,l}} + \\ \delta_{r,i,l}^{2020} \left[\left(\sum_{nk2} \left(\beta_{r,i,l,nk2} x_{r,i,l,nk2} \right)^{\rho_{r,i,l}} + \sum_{ckn2} \left(\beta_{r,i,l,ckn2} x_{r,i,l,ckn2} \right)^{\bar{\rho}_{r,i,l}} \right)^{\rho_{r,i,l}/\bar{\rho}_{r,i,l}} \right]^{1/\rho_{r,i,l}} \end{array} \right\}$$

$$- \sum_r \sum_{tg} (\tau_{r,tg} + \varsigma_{r,tg}) z_{r,tg}$$

subject to

$$\sum_g a_{k,r,j,g} \left(q_{r,j,g} - \bar{y}_{r,j,g} \right) + \sum_g \bar{a}_{k,r,j,g} \bar{y}_{r,j,g} = y^-_{k,r,j} \, ,$$

$$\sum_r z_{r,tg} \le 0 \, ,$$

$$\sum_i \sum_l \left(x_{r,i,l,tg} + \gamma_{r,i,l,tg} \right) + \sum_j y^-_{tg,r,j} \le \sum_j \left(y^+_{r,j,tg} + \bar{y}_{r,j,tg} \right) + \sum_i \omega_{t,i,tg} + z_{r,tg} \, ,$$

$$\sum_i \sum_l \left(x_{r,i,l,sc} + \gamma_{r,i,l,sc} \right) + \sum_j y^-_{sc,r,j} \le \sum_j \left(y^+_{r,j,sc} + \bar{y}_{r,j,sc} \right) + \sum_i \omega_{t,i,sc} \, ,$$

$$\sum_i \sum_l \left(x_{r,i,l,sf} + \gamma_{r,i,l,sf} \right) + \sum_j y^-_{sf,r,j} \le \sum_i \omega_{t,i,sf} \, ,$$

$$y^+_{r,j,g} + \bar{y}^+_{r,j,g} = q_{r,j,g} \, ,$$

$$y^+_{r,j,cakes} \le \sum_j \zeta_{cakes,r,j,fats} y^+_{r,j,fats} \, ,$$

$$y^+_{r,j,brans} \le \sum_j \zeta_{brans,r,j,grains} y^+_{r,j,grains} \, ,$$

$$y^+_{r,j,residu} \le \sum_j \zeta_{residu,r,j,grains} y^+_{r,j,grains} + \sum_j \zeta_{residu,r,j,roots} y^+_{r,j,roots} + \sum_j \zeta_{residu,r,j,oilcrops} y^+_{r,j,oilcrops}$$
$$+ \sum_j \zeta_{residu,r,j,peas} y^+_{r,j,peas} \sum_j \zeta_{residu,r,j,othagri} y^+_{r,j,othagri}$$

$$\sum_j y^+_{r,j,cityland} \le \breve{y}_{r,cityland} \, ,$$

$$\sum_j y^+_{r,j,cropland} \le \breve{y}_{r,cropland} \, ,$$

$$\sum_{tg} \bar{p}_{tg} z_{r,tg} = 0 \, ,$$

$$\sum_l \sum_k \bar{p}_{r,k} \left(x_{r,i,l,k} + \gamma_{r,i,l,k} \right) = \sum_k \bar{p}_{r,k} \omega_{r,i,k}$$
$$+ \sum_j \pi_{r,i,j} \left(\sum_g \bar{p}_{r,g} \left[y^+_{r,j,g} + \bar{y}_{r,j,g} \right] - \sum_k \bar{p}_{r,k} y^-_{k,r,j} \right) + \theta_{r,i} T_r$$

where, parameters

$\bar{p}_{r,k}$	price used in individual budget constraints
$\bar{p}_{tg}$	world price used in balance of payments constraint
$a_{k,r,j,g}$	Input-output constants by producer, updated in feedback using Shephard's Lemma
$\alpha_{r,i}$	Welfare weights of agents
$\beta_{r,i,l,k}$	LES parameters utility function
$\gamma_{r,i,l,k}$	Committed consumption

$\breve{y}_{r,cityland}$	Upper bound on cityland
$\delta^{1999}_{r,i,l}, \delta^{2020}_{r,i,l}$	Weights for lifestyles 1999, and 2020
$\zeta_{k,r,j,k}$	Joint output parameter
$\breve{y}_{r,cropland}$	Upper bound on cropland use
$\pi_{r,i,j}$	Share in profits by consumer and producer
$\omega_{i,k}$	Endowments by consumer
$\rho_{r,i,l}$	Elasticity of substitution in CES function consumers
$\breve{\rho}_{r,i,l}$	Elasticity of substitution for protein goods
$\tau_{r,tg}$	Tariffs on net imports of goods by region
$\varsigma_{r,tg}$	Average transport costs by region
$\theta_{r,i}$	Share in direct taxes by group and region
$\bar{y}_{r,j,g}$	Setup production

Variables

$y^{+}_{r,j,g}$	Output by good and producer
$y^{-}_{k,r,j}$	Input by commodity and producer
$q_{r,j,g}$	Activity level by producer and good
$x_{r,i,l,k}$	Consumption by class and lifestyles
$z_{r,tg}$	Net imports by region

Indices

1	year 1999
2	year 2020
r	Regions
i	Consumers
j	Producers
l	Lifestyles
k	All commodities
ckn	Protein commodities
nk	Non-protein commodities
g	Goods
sc	Non tradable goods
tg	Tradable goods
f	Factors
sf	Non tradable factors

APPENDIX 7-B SOME DATA

Table 7-A1 Land use (1000 Ha)

	Lowinc	Midinc	Highinc	EU
Grassland (1998)	1,320,302	1,233,879	701,615	56,284
Grassland (2020)	1,333,505	1,246,218	687,583	55,721
Cropland (1998)	592,887	502,860	283,664	85,906
Cropland (2020)	640,318	517,946	283,664	85,476
Cityland (1998)	198,096	114,771	45,415	29,801
Cityland (2020)	276,117	127,344	49,327	29,404
Natureland (1998) not included in model	2,103,539	3,352,471	1,700,009	141,196
Natureland (2020) not included in model	1,964,884	3,312,473	1,710,129	142,586
Total land area (1998)	4,214,824	5,203,981	2,730,703	313,187
Total land area (2020)	4,214,824	5,203,981	2,730,703	313,187

Source: FAOSTAT, 2002 and own projections.

Table 7-A2 Urban and rural work force

	Lowinc	Midinc	Highinc	EU
Work force in millions (2000)	2,244	755	324	252
Work force as % of population (2000)	61.73	63.01	66.92	67.14
Urban work force in millions (2000)	722	502	253	200
Rural work force in millions (2000)	1,523	242	70	52
Urban work force in millions (2020)	1,364	722	297	207
Rural work force in millions (2020)	1,615	228	62	42
Total urban working hours in millions (2000)	938,957	843,388	607,854	479,392
Total rural working hours in millions (2000)	1,980,100	406,212	169,260	124,620
Total urban working hours in millions (2020)	2,208,997	1,516,417	736,770	514,094
Total rural working hours in millions (2020)	2,616,318	478,481	154,195	104,337

Source: World Bank, 2001, and own projections.

Table 7-A3 Fertiliser use per crop per region (kg/ha·yr^{-1})

	EU	Highinc	Midinc	Lowinc
Grass	120	120	80	0
Grains	120	150	80	130
Roots & tubers	120	200	80	125
Oil crops	120	65	80	60
Other-agriculture	120	35	80	75
Pulses	0	0	0	0

Source: IFA, IFDC and FAO, 1999.

Table 7-A4 Nitrogen excretion from animals (kg N/animal/yr)

Regions	Type of animals		
	Ruminants	Pigs	Poultry
EU	70	20	0.6
High Income	70	20	0.6
Middle income	50	16	0.6
Low income	40	16	0.6

Source: IPCC, 1997.

Table 7-A5 Animal waste management systems per region

Regions	Animal types	Percentage of manure production per animal waste management systems						
		Anaerobic lagoon	Liquid system	Daily spread	Soil storage & drylot	Pasture range & paddock	Used fuel	Other system
EU	Cattle	0	55	0	2	33	0	9
	Swine	0	77	0	23	0	0	0
	Poultry	0	13	0	1	2	0	84
Highinc	Cattle	0	1	0	14	84	0	1
	Swine	25	50	0	18	0	0	6
	Poultry	5	4	0	0	1	0	90
Midinc	Cattle	4	19.5	0	26	49.5	0	1
	Swine	0	18.5	1	25.5	13.5	0	42.5
	Poultry	0	28	0	0	1	0	71
Lowinc	Cattle	0	0	8.5	8.5	62.5	20	0
	Swine	0.5	22.5	0.5	73	0	3.5	0
	Poultry	0.5	1	0	0	62.5	0.5	35.5

Source: IPCC, 1997.

Table 7-A6 Emission factors (kg N_2O-N/kg nitrogen excreted)

Animal waste management system	Emission factor
Anaerobic lagoons	0.001
Liquid systems	0.001
Daily spread	0.0
Solid storage and drylot	0.02
Pasture range and paddock	0.02
Used as fuel	0.0
Other system	0.005

Source: IPCC, 1997.

Table 7-A7 CH_4 emission factors from enteric fermentation (kg CH_4/animal)

	Cattle	Swine	Poultry
EU	48	1.5	0
Highinc	47	1.5	0
Midinc	52.5	1.0	0
Lowinc	38	1.0	0

Source: IPCC, 1997.

Table 7-A8 CH_4 emission factors (Kg CH_4/animal/yr) from manure management

Region	Animal type	Emission factors
EU	Cattle	20
	Swine	10
	Poultry	0.117
Highinc	Cattle	2
	Swine	14
	Poultry	0.117
Midinc	Cattle	7
	Swine	4
	Poultry	0.0675
Lowinc	Cattle	1.5
	Swine	4.5
	Poultry	0.023

Source: IPCC, 1997.

CHAPTER 8 DISCUSSION AND CONCLUSIONS

8.1 INTRODUCTION

Population growth and affluence in the past century have increased the demand for proteins, especially animal proteins. The livestock production pattern, especially in the Western world, has changed into an intensive production system by using highly concentrated feed, which is related to international trade of feedstuffs. Pigs (belonging to the category of monogastrics) are among the most efficient domestic animals in converting feedstuffs and organic wastes into edible meat. Pork production has been intensified by the use of concentrated and better-balanced feed, and by the introduction of advanced technologies, such as sophisticated housing and confinement systems. The intensification and international dimension of the pork production system in Europe, particularly in the Netherlands has resulted in a series of problems.

Firstly, it causes environmental problems due to manure surplus. A large amount of the minerals in manure affect the quality of soil, water, and air. The odour from intensive livestock farming can be a nuisance in populated areas. Volatilisation of ammonia (NH_3) to the air from manure causes N-deposition, and eutrophication and acidification of sensitive ecosystems. Methane (CH_4) from manure contributes to global warming. Secondly, large-scale imports of feed make the problems related to pork production in Europe not only local but also global. Large quantities of feed crops imported from developing countries such as Thailand, Brazil and Argentina result in large-scale deforestation and impose a big pressure on the land. Thirdly, intensive animal production systems, especially in densely populated areas, result in increased risks of disease infection to livestock, as well as human beings. Finally, intensive livestock production is likely to induce the use of livestock rearing techniques unfriendly to animals, reducing animal welfare.

This thesis has aimed to make contributions to identifying solutions to the problems related to protein issues. The first contribution concerns the theoretical modelling of environmental problems. This includes how to represent the environmental impacts in economic models considering the interactions between the economic system and the environmental system, and how to deal with the relevant non-convexities in models. The second contribution is a systematic analysis of protein chains, which provides information on their environmental pressures. The third contribution is the empirical application of AGE models to analyse the economic and environmental impacts of enhanced consumption of NPFs in a global context.

The five theoretical and empirical research questions were formulated in Chapter 1. This chapter provides the most important results of the study and highlights our findings.

8.2 Economic modelling of environmental problems

Research question 1:

How can we theoretically model environmental issues in welfare optimisation and equilibrium models in order to identify solutions to the environmental problems? More specifically, how can we model the interactions between the economic system and the environmental system in a welfare program, which can represent policy objectives?

Environmental problems are the negative impacts on the economic system, which are caused by the interactions between the economic system and the environmental system, and the intrinsic biophysical processes in the environmental system. Economic modelling in order to identify solutions to environmental problems requires consideration of the economic functions of the environment, the environmental processes, and the feedbacks between the economic system and the environmental system.

A welfare program can be thought of as a central plan that allocates goods over agents. An allocation that is an optimal solution to a welfare program is called a welfare optimum. The first welfare theorem tells us that every competitive equilibrium is Pareto-efficient. Therefore, every competitive equilibrium can be represented as a welfare optimum and a competitive equilibrium model can be represented by a welfare program. A welfare program can be used for modelling environmental problems in order to allocate the environmental resources efficiently.

Conclusions
We can represent the economic functions of the environment, the environmental processes and the feedbacks in a welfare program. This can be done through: 1) input function of the environment in production functions; 2) amenity services of the environment in utility functions; 3) relevant environmental processes reflecting the feedbacks to the two systems (e.g. damages to the production and utility, and change of the environmental state).

It is important to check the non-convexities of the model by analysing the characteristics of the Hessian matrix and deal with non-convexities properly, because non-convexities may arise from the incorporated environmental processes, and may have serious implications for the resulting policy recommendations. We found that the DICE model is a non-convex program and the numerical solution to the model is not an optimum because the second order condition for the optimal solution is not satisfied.

Research question 2:

Which complications do we face if we introduce an environmental process (biophysical) model into a mathematical program for a specific analysis; and how can we deal with non-convexity?

Standard economic theory assumes a convex production set and preference set, which ensures that the equilibrium is the welfare optimum. Prices give sufficient information for the maximisation problem of each agent in a competitive market, which coincides with the maximisation of social welfare (e.g. Pareto optimality of the competitive equilibrium). When we incorporate an environmental process model into an economic model (i.e. a welfare model) for a good representation of the environmental problems, non-convexities may arise due to the characteristics of related environmental processes and the positive or negative environmental impacts on production and/or utility. Although non-convexity never causes non-existence of a welfare optimum, the equilibrium may not be the welfare optimum (i.e. social optimum). If we simply plug the non-convex environmental model into an economic model and solve it as if it were a convex problem, we may not obtain an optimal solution because of the possible existence of multiple local maxima. If more than one local maximum exists, a central planner has to choose the welfare optimum from a set of local maxima and implement policies that will lead to this optimum. The problem of non-convexities is the difficulty of decentralisation of the optimal solution. For a non-convex program, the prices do not tell us whether we are at welfare maximum or minimum, whether a maximum is local or global, or in which direction the economy should move to secure an increase in welfare. As such, non-convexities bring complication for decentralising the optimal solution and may need policy intervention.

Other special features of environmental problems are non-rivalry and non-excludability. Non-rivalry and non-excludability of environmental goods, in the absence of environmental management, generate externalities. If these two properties do not generate non-convexities, the standard approach of internalising the externalities using a Pigovian tax or Lindhal prices for non-rival goods can be used. Then the environmental problems can be solved efficiently.

Conclusions

Many environmental problems are characterised by non-convexities. The production set of natural resources often does not have the property of ‘convexity’ because a process generating natural resources follows biophysical laws, which usually do not fulfil convexity conditions (e.g. divisibility). Non-convexities may also be caused by the feedback of environmental change to the economic system (i.e. the damages on production and consumption). For example, we have analysed that non-convexity is caused by the lack of free disposal of manure, which influences the crop production via adverse effects of a soil acidification process. Manure cannot be disposed of freely because crops have a locally decreasing response to manure due to soil acidification and/or other adverse effects. The feedback of the environmental processes on the economic systems may cause non-convexity of the production technology in the form of non-concave production functions.

Non-convexities may also exist in the economic system. On the production side, there are two specific issues related to non-convexity at firm level: set-up costs and increasing-return to scale. On the consumer side, the non-convexity may arise as a result of a non-concave utility function, or because the commodities are indivisible, or because consumers switch preferences.

Non-convexity requires special treatment because it causes market failures, i.e. the competitive market condition cannot achieve an efficient allocation. It may lead to multiple local maxima, and this is why it may undermine efficient decentralisation. Therefore a check of the decentralisability of the optimal solution becomes important for non-convex programs. In addition, we need special techniques to solve a non-convex problem. Finding optimal solutions to welfare programs with non-convexities requires special mathematical techniques for different types of non-convexities, such as the graphical approach or the parametric approach.

For simple models we can use a graphical method that represents the total welfare and choice variables in a graph and spot the optimal solution. We have shown the graphical method in an aquatic model in Chapter 2. We can also solve non-convex programs by convexification. *Parameterisation* is one important technique of convexification for solving non-convex programs numerically. By setting the non-convex elements into parameters, the non-convexities become irrelevant. The practical way is to use GAMS and scan the possible range of the non-convex elements to find all local optima for each value of the parameters. It is then possible to compare all the local optima and spot the optimal solution with the highest welfare. In Chapter 3 we have shown how non-convex problems can be solved by scanning the non-convex element of soil fertility and by scanning the choice variable (e.g. emission) in different cases. We have made several exercises to show how to solve different cases, reflecting different types of economies that contain non-convexity in welfare programs and equilibrium models. This also includes the check of the decentralisability of the welfare optimum to each agent (i.e. consumers and producers). If the consumers receive income and spends it on consumption of goods, and if the producers obtains non-negative aggregate profit and non-negative individual profit, then the welfare optimum is decentralisable. This implies we do not need policy intervention but a competitive market condition. Otherwise, we need policy intervention, such as quantity control, to achieve the welfare optimum.

8.3 Impacts of Novel Protein Foods

Research question 3:

What are the main environmental pressures of pork production compared with NPFs?

We compared the environmental impacts of two different protein chains using an environmental life-cycle assessment (LCA). We defined two types of environmental pressure indicators for comparison: *emission* indicators and *resource use* indicators. Considering the diversity of the emissions and their environmental impacts, we define emission indicators based on 'environmental themes' because many environmental emissions have the same effect on the environment. We define five emission indicators: CO_2 equivalents for global warming, NH_3 equivalents for acidification, N equivalents for eutrophication, pesticide use, and fertiliser use. We also define resource use indicators, such as land use and water use, because agriculture requires land and water inputs.

Conclusions
The results of the LCA show that the pork chain contributes to acidification 61 times more, to global warming 6.4 times more, and to eutrophication 6.0 times more than the NPFs chain. The pork chain also needs 3.3 times more fertilisers, 1.6 times more pesticides, 3.3 times more water and 2.8 times more land than the NPFs chain.

Using the reported environmental indicators, we conclude that the NPFs chain is environmentally more friendly than the pork chain. This is an interesting result because producing plant proteins, using only crops, is less damaging to the environment than via an additional step from crops to animals. Replacing animal protein by plant protein is promising in reducing environmental pressures, especially acidification. Since NPFs need less land, introducing NPFs can reduce the pressure on land for the production of food and feed. Thus, from an economic perspective it gives the opportunity to grow other crops on available land.

Research question 4:

What will be the expected effects of a shift from animal protein to plant protein foods on the economy and the environment?

The international dimension of Dutch pig production, related to the import of feed and export of meat, means that substantial changes in the pork sector have a direct impact on agricultural producers and traders elsewhere in the world. Following the theoretical studies on economic modelling of environmental problems, we have specified a welfare program as a general equilibrium (GE) model for analysis.

Specifically in Chapter 5 and Chapter 6, we constructed an AGE model that explicitly includes consumer preference for environmental quality in the utility functions and emission input in the production functions. Although we use the same welfare program, in both chapters, we have different purposes and present different details (i.e. regions and emissions).

The model in Chapter 5 is characterised by two regions (i.e. the EU and ROW), six sectors (i.e. peas, pork, NPFs, other-food, non-food and feed) in each region, and one environmental quality indicator determined by CO_2 emissions. The model in Chapter 6 is characterised by three regions (i.e. the EU, OOECD and ROW), six sectors, and one environmental quality indicator determined by NH_3 emissions. For an applied model in Chapter 5, we used predetermined production functions, utility functions and endowments to produce a benchmark. Therefore Chapter 5 is more methodological than empirical. Whereas we calibrated the model in Chapter 6 using the GTAP data source and thus Chapter 6 has a more empirical focus. We draw our main conclusions on the effects of a shift from animal protein to plant protein foods on the economy and the environment based on Chapter 6. The model in Chapter 6 was applied to two scenarios: exogenous shift from pork to NPFs and environmental concern (i.e. the willingness to pay for the environmental quality). The exogenous shift from pork to NPFs in the model was represented by increase of expenditure share of NPFs (from 2.5% to 25%) in protein consumption budget. The environmental concern in the model was represented by a willingness to pay for the air quality. If the mechanism that users pay for the use of environmental resource is implemented, then the consumer pays for the air quality. We assumed that 1% of consumer budget would be paid to improve air quality.

Conclusions

For the first scenario, we have the following results. Pork consumption decreases by 23% in the EU. There are hardly impacts on the consumption of other goods and hardly impacts on the consumption side in other regions. Introducing NPFs in the EU will not change the consumption pattern in other regions but will change the production patterns through international trade. Pork production in the EU decreases by about 8% accompanying an 11% decrease in feed production. The ROW will increase production of NPFs by 65% for exportation to the EU. The export of pork in the EU is increased due to the demand in the OOECD countries. The impacts on the other food and non-food sector are very small. For example, OOECD will increase production of peas and ROW will increase production of NPFs. The major impacts are on the pork and NPFs related sectors such as the pea and feed sector. Concerning the emissions, the EU will have a 3% decrease through less pork production. The OOECD will have a 2% decrease of ammonia emission due to the import of pork from the EU, while the ROW will have a 2% increase of emission from its increased feed production.

For the second scenario, we have the following results. The EU will reduce its pork production by 62% and feed production by 16%, while increasing pea production by 12%. Again, the major impacts are on the pork, NPFs and related sectors such as feed and peas. The EU will also enjoy a much higher air quality if consumers are paying for the good air quality. Emissions in the EU will decrease by 90%, but there is a slight increase (about 1%) in other regions.

The implication of the study is that the elasticity of utility with respect to environmental quality is important in determining the environmental results. The elasticity of utility with respect to the environment is related to consumer attitudes towards environmental quality. Stimulating the environmental concerns of consumers and providing them with information about the environmental performance of the products are important for a sustainable consumption pattern. The substitution effect is influenced by the relative prices of NPFs to pork. Lowering the price of NPFs helps to raise the replacement of pork by NPFs.

Research question 5:

What scenarios can be designed to assess the impact of changes in protein chains on society and the environment?

We have found that two important issues were raised with respect to sustainable food production and consumption: the environmental pressure resulting from higher demand for animal protein, and the changing consumer attitudes towards food consumption. For an analysis of future directions of change in the food production system and of the effects of policy interventions to achieve sustainability of food production and consumption, we should consider both of these trends.

Conclusions

We can consider two types of scenarios to achieve lower emissions through protein chains. The first type is related to a consumer lifestyle change in meat consumption by replacing meat with NPFs. The second type is to use environmental policy instruments to achieve the similar emission reduction as in the scenario for lifestyle change. Using a more disaggregated AGE model, we have checked the impacts of different parameter values of these two scenarios and obtained the following results.

Firstly, NPFs indeed help to reduce environmental pressure if consumers change their lifestyle by consuming more NPFs and less meat since the emissions originating from the production of peas are lower than those associated with meat production. If 'rich' consumers consume 10kg NPFs per capita per year to replace meat, the global emission reduction for NH_3 will be 4%, for CH_4 0.2% and for N_2O 3.7%. However, this emission reduction does not necessarily happen in the regions where more NPFs are consumed, but rather happens in the regions that switch to produce fewer ruminants using their comparative advantages in the regime of free international trade. For example, the agricultural emissions in the EU will be reduced by 2.9% for N_2O and increased by 6% for CH_4. There is almost no change in NH_3 emissions in the EU. In this case, it is the other high-income region that reduces the most NH_3 emissions.

Secondly, to achieve similar environmental emission reduction we can also use the environmental policy instruments. *Lifestyle change* contributes to emission reduction through production reduction in meat sectors because less meat is demanded. Production in the NPF sector will increase, which impacts other related sectors such as feed and pulses. This change will make the general production structure more extensive. *Exogenous environmental policies* reduce the emissions through production reduction in high emission sectors, which increases prices which cause consumers to suffer a welfare loss. However, the environmental emission reduction through lifestyle change is very limited, because meat consumption is related to income level and probably many people will not change their consumption pattern. Therefore, it is difficult to make a substantial change in meat consumption. The assumption of a 10kg replacement of meat with NPFs may be heroic, and the emission reduction through lifestyle change is very limited for a lower level of replacement of meat by NPFs. It would be more effective to achieve *high* emission reduction by environmental policy than by a lifestyle change. For example a modest lifestyle change (i.e. 10kg NPFs per capita per year for rich consumers) is not sufficient to achieve an NH_3 emission target in the EU such as the target set by the Gothenburg protocol. Then we have to rely on the local environmental policy in the EU to solve the local environmental problems caused by NH_3 emission.

Thirdly, environmental policy instruments are implemented through tradable emission permits for GHGs and an emission bound (kg/ha) in the EU for NH_3, based on the emissions under the first scenario (i.e. 10kg NPFs replacement of meat per capita per year for rich consumers). The study has investigated the impacts of environmental policy instruments that would achieve similar emission levels as a lifestyle change on the production structure and welfare. Regarding the emission permits we have two different mechanisms to base the distribution of initial permits: historical emission shares or population size. Since the policy targets are the same for these two measures of distributing permits, the impacts are on the welfare distribution. The results show that the developing countries are relatively better off if the permits are divided according to population size rather than historical emission shares.

8.4 General discussion on methodology used in the thesis

In this thesis environmental life cycle assessment (LCA) is the methodology used for environmental assessment of protein chains. LCA is a system analysis method for assessing the environmental impacts of a material, product, process or service throughout its entire lifecycle. It is intended for comparative use, that is, the results of LCA studies have a comparative significance rather than providing absolute values on the environmental impact related to the product. It is an increasingly important tool for supporting choices at both the policy and industry levels. As illustrated in the sensitivity analysis in Chapter 4, changing some parameters in the chains will change the relative advantages of the different chains. It implies that modifying the protein production and consumption chain offers possibilities to enhance sustainability, by reducing inefficiency and its environmental impacts. It will be interesting to show, in future studies, how changing some inputs in chains will result in less environmental pressures.

In this thesis the methodology used for economic modelling of the environmental problems is general equilibrium modelling and welfare economics. Like any other class of models, AGE models are a simplification of reality. Theoretical analysis shows that the environmental processes are important aspects of the model considering the interactions between the economic system and the environmental system. Nevertheless, incorporating the environmental processes in economic models might bring some difficulties to find the optimum and to decentralise the welfare optimum if non-convexities are involved. In Chapter 2 we illustrated how to check the convexity of any extra constraints by an analysis of the second order conditions by means of the Hessian matrix. For the optimal solution to a non-convex program, we can convexify the non-convex constraints using parameterisation in the numerical solution. Finally, it is important to check the decentralisability of the welfare optimum by checking if the welfare optimum matches the individual's one. Specifically, we check if a consumer spends his full income on expenditure and if each producer obtains non-negative profit. This was illustrated in Chapter 3.

In applied modelling, further simplification has taken place. In Chapter 5 we use CO_2 as the environmental substances for study, and the environmental quality indicator is directly determined by CO_2 emissions. In Chapter 6 we take NH_3 as the environmental substance because it is a major pollutant from protein production. In both Chapters 5 and 6 the environmental processes are simplified by assuming a linear relation between emission and environmental quality, which gives a feedback on consumer utility. In Chapter 7, for the environmental and economic impacts of NPFs related to animal protein chains, we focus on a few pollutants, including NH_3, CH_4, and N_2O for environmental assessment. For producers, emissions of NH_3, CH_4, and N_2O are considered. This treatment is sufficient because the protein related environmental problems include acidification caused by NH_3, and global warming due to the emissions of CH_4 and N_2O. The biophysical processes are not implemented in detail because information on environmental effects caused by emissions is lacking, which limits the possibilities to model the detailed environmental processes in the context of the empirical part of this thesis.

In the model simulation we have taken a step-wise approach to analyse the economic and environmental impacts. From a two-region model in Chapter 5 we expand to a three-region model in Chapter 6 and a four-region model in Chapter 7. Also different focuses are considered in each version of the model. In the model presented in Chapter 5, we have methodologically shown how to analyse the impacts of enhanced consumption of NPFs on the economy and the environment. In Chapter 6, we use a calibrated model with three-regions to investigate the impacts of some important parameters, such as substitution elasticity between pork and NPFs, and utility elasticity with respect to environmental quality, on the results. In Chapter 7 a more detailed presentation of the agricultural sectors has been included and also some interesting scenarios have been studied. We have investigated the impacts of a consumer lifestyle change in meat consumption and the economic-incentive based environmental policy instruments. This step-wise approach in the research method is useful because modellers can focus on different aspects of the problem and obtain useful insights into different aspects of the problem.

8.5 LIMITATIONS AND RECOMMENDATIONS ON FURTHER RESEARCH

In this thesis we have used environmental pressure indicators for environmental impact assessment. This is a straightforward way of assessing environmental impacts, which avoids the difficulties of collecting data on the environmental effects. We should, however, be aware that actual environmental impacts have a spatial dimension. Although this study considered the locations of specific products (e.g. fertiliser use for feed crops), we could not give a specific indication about where this pressure is imposed. This gives a direction for further study on the assessment of spatial environmental impacts.

In the thesis, we have also attempted to represent the environmental problems in a welfare model. For example, we consider that the soil acidification is the reduction of soil fertility, which will impact the growth of crops. By linking the soil condition and input for crop growth, the environmental problems are logically included in economic modelling. However, we must acknowledge that the inclusion of an environmental process model needs sound, location-specific natural science models. In our modelling exercises, we could neither include the spatial aspect, nor the dynamic aspect of the acidification process. Instead we use the steady state on one specific site for the soil acidification process. As such, the empirical contribution of the environmental process model is limited. There are still many issues that need further research.

As shown in Chapter 3, it is possible to include a non-convex process (i.e. acidification) model in an applied model. Proper and detailed inclusion of the interactions between economic activities and the environmental system is a further research direction in order to identify solutions to environmental problems using economic modelling. Dynamics of the environmental processes are very important for real representation of the environmental problems. We need to know more about how to deal with non-convexity in combination with dynamics.

8.6 GENERAL CONCLUSIONS AND MAIN FINDINGS

This thesis has focused on economic modelling of environmental problems related to pork production and environmental assessment of protein chains. To summarise, we highlight the following main conclusions on economic modelling, impacts of NPFs, and policy recommendations.

On economic modelling

- Firstly, economic modelling of environmental problems should consider the main causes of the environmental problems. There are interactions between the economic system and the environmental system. The main economic functions of the environment are to provide input for production and amenity services for consumption. Economic activities will influence the functions of the environment by changing the environmental states. The environmental changes are also due to the intrinsic environmental processes following biophysical laws, and these changes give feedbacks on production and utility of the economic agents in the form of damages.

- The essence of the environmental problems is the impacts on human society, or on economic systems. For example, plants are killed through soil pollution or fish are killed through water pollution. The causes of environmental problems are twofold, one being the economic activities (i.e. production and consumption) which use the environmental resource or emit pollutants to the environment, and the other being the intrinsic environmental process which follows biophysical laws. Identifying solutions to environmental problems means that we want to achieve a balance between pollution and economic activities. Managing the environment does not simply mean that we stop using it, but rather we understand how to use it efficiently. This can be analysed by welfare programs, which represent the economic and environmental policy objectives. In the welfare program we need to represent the economic functions of the environment, the interactions between the economic system and the environmental system, and the relevant environmental processes. This can be done by adding: the input function of the environment in production functions, amenity services of the environment in utility function, and relevant environmental processes reflecting the feedbacks to the two systems (i.e. damages to the production and utility, and change of the environmental state) in a welfare model.

- Inclusion of the environmental process and feedbacks in a welfare program often brings non-convexities, a property that departs from standard economic assumptions. In standard economic theory, the convexity of a production set and a preference set ensures that equilibrium exits and coincides with the welfare optimum. Therefore prices provide sufficient information to each economic agent to realise his plan. A competitive market condition can achieve efficient allocation of the economy. That means decentralisation is possible. When non-convexities are involved in a welfare program, we will probably have multiple local optima. The problem is that only one of them can be chosen by the policymaker and this one may not be the same as the equilibrium. That means that each agent may choose a different level from the welfare optimum level. If the welfare optimum matches with the equilibrium, then decentralisation is possible; otherwise we need policy intervention to achieve the welfare optimum. The tasks of the environmental economists would be to provide information to the policymakers on whether policy intervention is needed, and at what level should we intervene to achieve the welfare maximisation. This involves solving a model with non-convexities and checking the decentralisability. The basic technique for solving non-convex problems is using convexification. This includes a graphical method and parametric method. A graphical method is easy but only works for one or two-dimensional non-convexities, due to the limitation of graph making. Parameterisation involves four steps: *i*) setting the non-convex elements of the model into parameters, which makes the non-convexities irrelevant, *ii*) finding a series of solutions over a relevant range of the parameters, *iii*) comparing the welfare's, and *iv*) spotting the optimal solution with the highest welfare. This is a practical way for solving a non-convex model though it only works with low dimensions. Checking the decentralisability of a welfare optimum means to check if each agent maximises his objective. That is, each consumer maximises his utility subject to the budget constraint and producers maximise (non-negative) profits.

On the impacts of Novel Protein Foods

- NPFs are environmentally more friendly than pork according to the environmental pressure indicators used in this study. The main advantages of NPFs are on the low contribution to acidification compared to pork. However, the real impacts of NPFs on the environment and the economy depend on the acceptance of consumers and their environmental concerns.

- If EU consumers increase their expenditure share of NPFs from 2.5% to 25%, pork consumption decreases by 23% in the EU. There are hardly impacts on the consumption of other goods and hardly impacts on the consumption side in other regions. Pork production in the EU decreases by about 8% accompanying an 11% decrease in feed production. For the emissions of NH_3, the EU will have a 3% decrease through less pork production. The other OECD countries will have a 2% decrease of NH_3 emission due to the import of pork from the EU, while the ROW will have a 2% increase of NH_3 emission due to its increased feed production.

- If the EU consumer is willing to pay 1% of their income to improve air quality, the EU will reduce its pork production by 62% and feed production by 16%. It will increase pea production by 12%. Again, the major impacts are on the pork, NPFs and related sectors such as feed and peas. The EU will enjoy a much higher air quality if consumers are paying to improve the air quality. Emissions of NH_3 in the EU will decrease by 90%, but there is a slight increase (about 1%) in other regions.

- If 'rich' consumers consume 10kg NPFs per capita per year to replace meat, the global emission reduction for NH_3 will be 4%, for CH_4 0.2% and for N_2O 3.7%. But this emission reduction does not necessarily happen in the regions where more NPFs are consumed, but rather in the regions that switch to produce fewer ruminants using their comparative advantages in the regime of free international trade. For example, the agricultural emissions in the EU will be reduced by 2.9% for N_2O and increased by 6%

for CH_4. There is no change in NH_3 emission in the EU. In this case, it is the other high-income region that reduces the most NH_3 emissions.

On policy recommendation

- Both an exogenous shift from pork to NPFs, and willingness to pay for good environmental quality, contribute to emission reduction, though the latter contributes more than the former. This knowledge could be used in policy design. Stimulating the environmental concerns of consumers and providing them with information about the environmental performance of products are important for a sustainable consumption pattern. From the policy-making perspective, it would be important to advocate environmental concerns of the consumers or introduce the payment system of an environmental premium for good environmental quality.

- As the consumption of NPFs becomes higher, emissions will become lower. Thus, promoting sustainable consumption patterns is important. The global emission will be reduced if consumers change their lifestyle towards more NPFs. Considering the lower emission related to the replacement of meat by NPFs, the lifestyle change towards less meat and more NPFs should be promoted.

- The reduction of environmental emissions in the EU through a lifestyle change is very limited because more meat can still be produced in the EU to meet the increasing demand in other regions in the regime of free international trade. Therefore, we have to rely on local environmental policy in the EU to solve the local environmental problems caused by NH_3 emission. From a policy-making perspective, we have to make policies which induce to reduce emissions related to meat production (e.g. quantity control on emissions or eventually on pork production) in order to solve the environmental problems.

- Introducing NPFs that have lower environmental pressures is only part of the measures for reducing environmental pressure. It should, therefore, be a common and shared responsibility of the government, society and industry to work together to promote new approaches for protein production and consumption, and to safeguard a sustainable future.

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SAMENVATTING

MILIEU-ECONOMISCH MODELLEREN VAN NOVEL PROTEIN FOODS: EEN ALGEMEEN EVENWICHTSAANPAK

INLEIDING

De intensieve veeteelt in Europa, en specifiek in Nederland, leidt tot een reeks van milieuproblemen die hoofdzakelijk verband houden met mestoverschotten. Een groot deel van de mineralen in de mest beïnvloedt de kwaliteit van het land, het water en de lucht. Dit proefschrift beoogt een bijdrage te leveren aan de identificatie van problemen die gerelateerd zijn aan de productie en consumptie van eiwitten.

De hoofdstukken 1, 2 en 3 behandelen de theoretische modellering van milieuproblemen. De wijze waarop milieueffecten in een economisch model tot uitdrukking komen met betrekking tot de wisselwerking tussen het economisch systeem en het ecologisch systeem worden hierin beschreven, evenals de wijze waarop wordt omgegaan met belangrijke niet-convexe relaties in modellen. In hoofdstuk 4 wordt een systematische analyse van de eiwitketens gegeven. Hiermee wordt informatie verkregen over de milieubelasting van de betreffende ketens. De hoofdstukken 5, 6 en 7 beschrijven de empirische toepassing van een Algemeen Evenwicht Model waarin de economische- en milieu-effecten van een toename in de consumptie van Novel Protein Foods (NPFs) in mondiaal verband worden geanalyseerd. Tot slot geeft hoofdstuk 8 de belangrijkste conclusies over economische modellering van milieueffecten, over het effect van NPFs en enkele beleidsadviezen.

ECONOMISCHE MODELLERING VAN MILIEUEFFECTEN

Er bestaat een wisselwerking tussen het economisch systeem en het ecologisch systeem. De belangrijkste economische functies van het milieu zijn het voorzien in goederen en diensten die kunnen worden aangewend in productie en consumptie. Economische activiteiten beïnvloeden ecosysteemfuncties door verandering in de toestand waarin het milieu verkeert.

Veranderingen in het milieu zijn ook het gevolg van intrinsieke ecologische processen die verlopen volgens de wetten van de natuur. Via een feedbackreactie hebben veranderingen in het milieu op hun beurt een invloed op productie en consumptie.

Economische activiteiten (productie en consumptie) die grondstoffen gebruiken en verontreinigende stoffen uitstoten, en de intrinsieke ecologische processen die verlopen volgens de wetten van de natuur, zijn de oorzaak van veel milieuproblemen. Dit betekent dat we een balans moeten vinden tussen vervuiling en economische activiteiten om tot oplossingen voor milieuproblemen te komen. Milieubeheer betekent niet slechts dat we moeten streven naar vermindering van het gebruik van het milieu, maar ook naar een beter begrip over een zo efficiënt mogelijk gebruik ervan. Dit kan worden geanalyseerd door zogenaamde welvaartsprogramma's die economische- en milieu-beleidsdoelen mee in beschouwing nemen. In zo'n welvaartsprogramma worden de economische functies van het milieu beschreven, evenals de wisselwerking tussen milieu en economie en de relevante ecologische processen.

Door ecologische processen en feedback-mechanismen te koppelen aan een welvaartsprogramma ontstaan dikwijls niet-convexe relaties – een eigenschap die afwijkt van de standaard economische aannames. Volgens de standaard economische theorie zorgen de convexiteit van de productiesets en preferentiesets ervoor dat er een evenwicht bestaat dat identiek is aan het welzijnsoptimum. In dat geval geeft de prijs voldoende informatie voor economisch agenten om hun plannen te realiseren. Competitieve marktomstandigheden kunnen een efficiënte allocatie van goederen bewerkstelligen. Dat wil zeggen dat het welvaartsoptimum wordt bereikt als alle agenten hun individuele doelen nastreven. Als niet-convexe relaties onderdeel uitmaken van een welvaartsprogramma, dan zijn er waarschijnlijk meerdere lokale optima aanwezig. Het probleem is dat de beleidsmaker slechts één optimum moet kiezen, en dat dit optimum niet noodzakelijk hetzelfde is als het evenwichtspunt. Dit betekent dat iedere agent een ander optimaal punt kan kiezen. Decentralisatie van het welvaartsoptimum is mogelijk als het welvaartsoptimum overeenkomt met het evenwichtspunt; anders hebben we aanvullend beleid nodig om het welvaartsoptimum te bereiken. Voor een programma dat niet-convexe relaties heeft, moeten we naar de optimale oplossing zoeken en nagaan of decentralisatie van de beslissingen mogelijk is.

Als een model niet-convexe relaties herbergt, dan kunnen we een *grafische*- of *parametrische* methode gebruiken om de optimale oplossing te vinden. De grafische methode is eenvoudig, maar werkt alleen voor één of twee-dimensionale niet-convexe relaties. Dit komt door de beperking bij het maken van grafieken. De grafische methode wordt getoond in een aquatisch model in hoofdstuk 2.

We kunnen niet-convexe programma's ook oplossen door convexificering. Hierbij kunnen met behulp van parameterisering niet-convexe programma's numeriek worden opgelost. Door het omzetten van de niet-convexe elementen naar parameters zijn de niet-convexe elementen niet langer relevant. De meest praktische methode is om een software programma zoals GAMS te gebruiken om het scala aan niet-convexe elementen te onderzoeken en zo de lokale optima te vinden. Daarna kan door vergelijking van alle lokale optima worden gezocht naar de optimale oplossing die resulteert in het hoogste welvaartsniveau. Vooral in hoofdstuk 3 van dit proefschrift wordt naar voren gebracht hoe niet-convexe problemen zijn op te lossen door gebruik te maken van *parameterisering* van de interactie tussen varkensproductie en gewasproductie veroorzaakt door bodemverzuring. Er bestaat bezorgdheid dat varkenshouderijen een hoge uitstoot van NH_3 veroorzaken, wat vervolgens een impact heeft op de bodemvruchtbaarheid. Gewasproductie echter, hangt af van zowel toevoeging van (kunst)mest als van de bodemvruchtbaarheid. Daarom wordt een model voor bodemverzuring opgenomen in het welvaartsprogramma. Verschillende niet-convexe mogelijkheden voor de toestand van de economie worden gespecificeerd en de optimale oplossing wordt gevonden voor elke mogelijkheid.

Nadat het welvaartsoptimum is gevonden wordt ook de mogelijkheid van decentralisatie van het welvaartsoptimum voor elke actor (consument en producent) onderzocht. Het is mogelijk het welvaartsoptimum te decentraliseren als de consument zijn inkomen krijgt en dit vervolgens uitgeeft aan de consumptie van goederen om zo zijn nut te maximaliseren en als de producenten hun niet-negatieve geaggregeerde winsten verwerven en hun niet-negatieve individuele winsten maximaliseren. Als decentralisatie mogelijk is dan zal een competitieve marktvoorwaarde leiden tot het welvaartsoptimum. Anders hebben we beleidsinterventie nodig, zoals bijvoorbeeld kwantiteitscontrole, om dit welvaartsoptimum te bereiken.

MILIEUDRUK DOOR EIWITTEN

Hoofdstuk 4 van dit proefschrift concentreert zich op de vergelijking van de milieudruk tussen de Nederlandse varkensvleesketen en die van NPF's op basis van erwten. De levenscyclus analyse (LCA) is voor deze studie gekozen. De volgende stappen worden in deze analyse onderscheiden. Allereerst worden de productie- en consumptiecyclus van een dierlijk eiwit (varkensvlees) en een plantaardig eiwit (NPFs) beschreven om de relatie tussen productie, consumptie en het milieu te begrijpen. Ten tweede worden indicatoren voor milieudruk ontworpen. Vervolgens wordt de milieu-impact van beide ketens onderzocht en vergeleken.

De bevindingen van de LCA studie tonen aan dat de bijdrage van de varkensketen, in vergelijking tot de NPF-keten, meer dan 61 keer meer bijdraagt aan verzuring, meer dan 6,4 keer meer bijdraagt aan opwarming van het klimaat en meer dan 6 keer meer bijdraagt aan eutrofiëring. Ook heeft de varkensketen, in vergelijking tot de NPF keten, meer dan 3,3 keer meer bemesting nodig, 1,6 keer meer pesticiden, 3,3 keer meer water en 2,8 keer meer land. Hieruit kan worden geconcludeerd dat NPF's milieuvriendelijker zijn per eenheid geconsumeerd eiwit dan varkensvlees.

MODEL TOEPASSING

Met betrekking tot invloeden op de gehele economie, moeten milieukundige processen in toegepaste algemene evenwichtsmodellen worden vereenvoudigd vanwege hun complexiteit en vanwege ruimtelijke verschillen. Het model is toegepast voor verschillende situaties. In hoofdstuk 5, wordt het model toegepast op een economie met twee regio's (EU en rest van de wereld), waarbij CO_2 emissies invloed hebben op de milieukwaliteit en hierdoor ook op het nut van de consumenten. In hoofdstuk 6, wordt het model toegepast op een economie met drie regio's (EU, andere OECD landen en rest van de wereld) en worden de effecten van NH_3 emissies meegenomen, een schadelijke stof bij de productie van dierlijk eiwit. In zowel hoofdstuk 5 als 6, worden de milieukundige processen vereenvoudigd door aan te nemen dat er een lineaire relatie bestaat tussen emissie en milieukwaliteit, wat vervolgens van invloed is op het nut van consumenten. Voor het model in hoofdstuk 5 worden productiefuncties, nutsfuncties en bezittingen vastgesteld die het referentiepunt representeren. Hoofdstuk 5 is meer methodologisch dan empirisch van aard. Hoofdstuk 6 is meer empirisch van aard, omdat het model wordt gecalibreerd met GTAP data. Het model uit hoofdstuk 6 is toegepast voor twee scenario's: 1) een exogene verschuiving in de consumptie van eiwitten, van varkenevlees naar NPF's en 2) bezorgdheid voor het milieu die leidt tot een grotere bereidheid tot het betalen voor milieukwaliteit. De exogene verschuiving van 'varkensvlees naar NPF's komt in het model tot uitdrukking door een vergroting van het aandeel van NPF's (van 2,5% naar 25%) van het budget voor eiwitconsumptie. De bezorgdheid voor het milieu komt in het model tot uitdrukking door een bereidheid te betalen voor de kwaliteit van lucht. Er wordt aangenomen dat 1% van het budget van consumenten wordt aangewend voor een verbetering van de luchtkwaliteit. De belangrijkste conclusies, met betrekking tot het effect van een verschuiving van dierlijk eiwit naar plantaardig eiwit op de economie en het milieu, worden uitgewerkt in hoofdstuk 6. Als de consumenten in de EU hun uitgaven voor NPF's verhogen van 2,5% naar 25% van het budget dat wordt betalt aan eiwitten, dan zal de consumptie van varkensvlees in de EU dalen met 23%. Er zijn nauwelijks veranderingen geconstateerd in de consumptie van andere goederen en in het consumptiepatroon in andere regio's. De productie van varkensvlees neemt in de EU af met 8%, en de veevoerproductie met 11%. Doordat er minder varkensvlees wordt geproduceerd nemen ook de NH_3 emissies in de EU met 3% af. In de andere OECD landen zal een vermindering van NH_3 emissies optreden met 2%, door import van varkensvlees uit de EU. In de andere landen zullen de NH_3 emissies echter met 2% groeien door een verhoging van de veevoerproductie.

Als de consument in de EU bereid is om 1% van zijn inkomen aan te wenden om de luchtkwaliteit te verbeteren, dan zal de EU haar productie van varkensvlees met 62% en haar veevoerproductie met 16% reduceren. Tegelijkertijd zal de productie van erwten met 12% worden verhoogd. Ook in dit geval zijn de gevolgen vooral merkbaar in de varkenssector, NPF sector en andere gerelateerde sectoren, zoals de sectoren die erwten en veevoer produceren. De luchtkwaliteit in de EU zal veel beter worden als de consument bereid is ervoor te betalen. De NH_3 emissies zullen in de EU met 90% dalen, maar er zal een kleine toename plaatsvinden in andere regio's (met ongeveer 1%).

In hoofdstuk 7 wordt een meer gedisaggregeerd model gebruikt met vier regio's (EU, andere regio's met een hoog inkomen, regio's met een midden inkomen en regio's met een laag inkomen) en meer gedetailleerde landbouwsectoren. Hierbij worden drie soorten emissies meegenomen (CH_4, CO_2 en NH_3). De bio-fysische processen zijn niet in detail meegenomen, omdat informatie over de milieueffecten veroorzaakt door emissies niet aanwezig was. Er worden twee typen scenario's in aanmerking genomen om tot een verlaging van emissies te komen. Het eerste scenario is gerelateerd aan de levensstijl van consumenten door een verandering van vleesconsumptie als gevolg van vervanging van vlees door NPF's. In het tweede scenario wordt geprobeerd om eenzelfde emissiereductie te bewerkstelligen als bij een verandering van levensstijl door gebruik van milieubeleid instrumenten (restrictie op emissies).

Als wereldwijd 'rijke' consumenten 10 kg NPFs per persoon per jaar consumeren in plaats van vlees, neemt de mondiale emissie van NH_3 af met 4 %, van CH_4 met 0,2 % en van N_2O met 3,7 %. Deze emissiereductie vindt niet noodzakelijk plaats in de regio's waar meer NPFs worden geconsumeerd, maar in de regio's die overstappen naar een lagere vleesproductie, waarbij zij gebruik maken van hun comparatieve voordeel in de aanwezigheid van vrije internationale handel. Ter illustratie, in de EU zullen emissies van N_2O dalen met 2,9 % terwijl CH_4 emissies stijgen met 6 %. Het niveau van NH_3 emissies in de EU blijft constant. In dit voorbeeld is het de andere regio met een hoog inkomen dat de meeste reductie van NH_3 op zich neemt. Een geringe verandering in levensstijl (10 kg NPFs per persoon per jaar voor rijke consumenten) is niet voldoende om de NH_3 emissiedoelen voor de EU, zoals beschreven in het Gothenburg protocol, te bereiken.

Veranderingen in levensstijl die zorgen voor een dalende vraag naar vlees leiden tot emissiereductie door een lager productieniveau in de vleessector. Het productieniveau in de NPF sectoren zal echter toenemen. Dit beïnvloedt gerelateerde sectoren zoals veevoer en peulvruchten. Deze veranderingen maakt de productiestructuur extensiever. Milieubeleid reduceert emissies door óf het bevorderen van extensievere productiesystemen óf het verlagen van de productie in sectoren met veel emissies. Dit leidt tot prijsstijgingen en veroorzaakt zo inkomensverlies voor de consument.

BELEIDSAANBEVELINGEN

Zowel een exogene verschuiving van varkensvlees naar NPFs als bezorgdheid voor het milieu die leidt tot een grotere bereidheid tot het betalen voor milieukwaliteit veroorzaken een reductie van emissies. Bezorgdheid voor het milieu heeft hierbij de grootse invloed. Deze kennis kan worden toegepast in het ontwikkelen van beleid. Informatievoorziening en het stimuleren van het milieubewustzijn van consumenten zijn essentieel voor een duurzaam consumptiepatroon. Vanuit de beleidsmaker gezien is het dan ook belangrijk dit milieubewustzijn te versterken of een systeem te introduceren waarbij een premie wordt betaald die afhankelijk is van de milieudruk van voedselproducten.

Wanneer de consumptie van NPFs stijgt, dalen de emissies. Dit maakt het bevorderen van duurzame consumptiepatronen belangrijk. Wereldwijde emissies kunnen worden teruggebracht wanneer consumenten hun levenstijl wijzigen door meer NPFs te consumeren. Gezien de relatie tussen emissieniveaus en het vervangen van vlees door NPFs, is het aan te bevelen deze wijziging in levensstijl te stimuleren.

De reductie van emissies in de EU door veranderingen in levensstijl is erg beperkt omdat vleesproductie in de EU nog steeds kan stijgen door de toenemende vraag naar vlees uit andere delen van de wereld, gegeven de aanwezigheid van vrije internationale handel.

De introductie van NPFs met een lagere milieudruk is slechts een kleine maatregel voor het verminderen van de totale milieudruk. Het is een algemene en gedeelde verantwoordelijkheid van overheid, maatschappij en industrie om samen te werken in het ontwikkelen van nieuwe methodes voor eiwit-productie en zo een duurzame toekomst veilig te stellen.

APPENDICES

APPENDIX A SETS, FUNCTIONS AND MATHEMATICAL PROGRAMS

This appendix is based on Avriel, 1976; Bazaraa *et al.*, 1993; Chiang, 1984 and GK, 2002.

Sets and functions

Vectors are denoted by lowercase letters, such as x, y and z. The n-dimensional *real Euclidean space*, composed of all real vectors of dimension n, is denoted by E_n.

A *set* is a collection of elements or objects. Sets are denoted by capital letters, such as S, X and E. If x is a member of S, we write $x \in S$.

A set $X \subset R^n$ is convex iff for any two points x and y contained in X, every point z given by $z = \lambda x + (1-\lambda)y$, $0 \le \lambda \le 1$ lies in X. A set is closed if it contains all its boundary points.

A set is bounded if one can specify a square (or a ball), however large, which contains all of its points.

A set $X \subset R^n$ is compact iff it can be closed and bounded.

A real-valued function f defined on a subset S of E_n associates with each point x in S a real number f(x). The notation f: S $\rightarrow$ E_1 denotes that the domain of f is S and the range is a subset of real numbers. If f is defined everywhere on E_n or if the domain is not important, the notation f: E_n $\rightarrow$ E_1 is used. A collection of real-valued functions f_1, …, f_m can be viewed as a single vector function ***f*** whose jth component is f_j.

Let f: S $\rightarrow$ E_1, where S is nonempty convex set in E_n. The function f is said to be convex on S if $f(\lambda x + (1-\lambda)y) \le \lambda f(x) + (1-\lambda) f(y)$ for each $x, y \in S$ and for $\lambda \in (0,1)$. The function is called strictly convex on S if the above inequality is true as a strict inequality for each distinct x and y in S and for each $\lambda \in (0,1)$. The function f: S $\rightarrow$ E_1 is called concave (strictly concave) on S if $-f$ is convex (strictly convex) on S.

Let S be a nonempty convex set in E_n and let f: S $\rightarrow$ E_1 be a convex function. Then the level set $S_\alpha = \{x \in S : f(x) \le \alpha\}$, where α is a real number, is a convex set.

For the twice differential functions the Hessian matrix is comprised of the second-order partial derivatives $\partial^2 f(x)/\partial x_i \partial x_j \equiv f_{ij}(x)$ for i =1, …, n, j =1, …, n and is given as follows:

$$H = \left[\frac{\partial^2 f}{\partial x_i \partial x_j}\right] = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \cdots & & \cdots & \\ f_{n1} & f_{n2} & \cdots & f_{nn} \end{bmatrix}.$$

For the Hessian determinants $|H_1|$, $|H_2|$, …, $|H_n|$, the Hessian matrix is

positive definite if $|H_1| > 0$, $|H_2| > 0$, …, $|H_n| > 0$,

positive semidefinite if $|H_1| \geq 0$, $|H_2| \geq 0$, …, $|H_n| \geq 0$,

negative semidefinte if $|H_1| \leq 0$, $|H_2| \geq 0$, …, $(-1)^n |H_n| \geq 0$, and

negative definite if $|H_1| < 0$, $|H_2| > 0$, …, $(-1)^n |H_n| > 0$.

Let S be a nonempty open convex set in E_n and let f: S $\rightarrow$ E_1 be twice differentiable on S. If the Hessian matrix is positive definite at each point in S, then f is strictly convex. Conversely, if f is strictly convex, then the Hessain matrix is positive semidefinite at each point in S.

Mathematical programs

Generally we can define a mathematical program (MP) of maximisation (cf. Avriel, 1972) as,

$$\max f(x), \tag{A1}$$

subject to

$$g_i(x) \leq 0, \qquad i = 1,...,m \tag{A2}$$

$$h_j(x) = 0 \qquad j = 1,...,p \tag{A3}$$

where x denotes the vector whose components are $x_1,...,x_n$. (MP) is the problem of finding a vector x* that satisfies (A2) and (A3) and such that $f(x)$ has a maximal, that is, optimal value. If one or more of the functions appearing in MP is nonlinear in x, we call it nonlinear program.

Convex programs are a special case of the general non-linear programming problem. If functions f and g_i in MP are concave, the h_j are linear functions of the form:

$$h_j(x) = \sum_{k=1}^{n} a_{jk} - b_j .$$

Then the program is convex. This program can also be written as

$$\phi = \max\{f(x) | g(x) \leq 0, x \geq 0\}, \tag{A4}$$

where $f(x)$ is concave and $g(x)$ is convex.

We represent the general form of a convex program according to GK (2002). Define the nonempty, closed convex set $Y \subset R^m$, the continuous functions *f*: $R_+^n \to R$ and $g: R_+^n \times Y \to R^k$, and the convex program reads as:

$$\phi = \max_{x \geq 0, y} \{f(x) \mid g(x, y) \leq 0, y \in Y\}, \tag{A5}$$

where f(x) is concave and g(x,y) is convex.

The constraint set for this convex program is:

$$Q = \{x \geq 0, y \in Y \mid g(x, y) \leq 0, f(x) \geq 0, x \geq 0\}. \tag{A6}$$

Convex programs

Assume that *f*(*x*) is concave, *g*(*x*, *y*) is convex in (A5) and set *Q* in (A6) is nonempty and compact, then the optimum value ϕ for (A5) *exists* and is bounded. The set of *optimal solutions* $Q^0 = \{x \geq 0, y \in Y \mid g(x, y) \leq 0, f(x) \geq \phi\}$ is nonempty, compact and convex. This theorem indicates the *existence of optimal solutions and possibly more than one solution for convex programs*.

If *f*(*x*) is strictly concave, then optimal x^0 ($x^0 \in Q^0$) is unique. If *g*(*x, y*) is strictly convex, then the optimal y^0 ($y^0 \in Q^0$) is unique as well. This means *the uniqueness of the optimal solution for convex programs*.

If the set $Q^S = \{x > 0, y \in Y \mid g(x, y) < 0\}$ is nonempty, and if *f*(*x*) and *g*(*x*, *y*) are also differentiable in addition to that *f*(*x*) is concave and *g*(*x*, *y*) is convex, and if *Y*= R^m, then any triple (x, y, μ) that satisfies the following Kuhn-Tucker conditions:

$$\begin{aligned} &\frac{\partial L(x, y, \mu)}{\partial x} \leq 0 \perp x \geq 0, \\ &\frac{\partial L(x, y, \mu)}{\partial y} = 0, \\ &\frac{\partial L(x, y, \mu)}{\partial \mu} \leq 0 \perp \mu \geq 0, \end{aligned} \tag{A7}$$

is optimal, where $L(x, y, \mu) = f(x) - \mu g(x, y)$ is the Lagrangian.

Non-convex programs

In mathematics program (A4) or (A5), if *f*(*x*) is non-concave or *g*(*x*) in (A4) or *g*(*x*, *y*) in (A5) is non-convex, then the program becomes a non-convex program. In more general form, a non-convex program reads:

$$\phi = \max\{f(x) \mid x \in Q\}. \tag{A8}$$

Theorem: If $f(x)$ is continuous, the set $X = \{x | f(x) \geq 0, x \geq 0, x \in Q\}$ is nonempty and compact, then the optimum value ϕ for (8A) is non-negative and bounded and the set of *optimal solutions*, $X^0 = \{x | f(x) \geq \phi, x \in Q\}$ is nonempty and compact.

This theorem implies that the *optimal solutions exists if f(x) is continuous and possibly there are more than one solution if there exist.* This implies that the optimal solution does not necessarily exist if *f*(x) is non-continuous for a general non-convex program

APPENDIX B SOME ECONOMIC CONCEPTS

Efficiency and decentralisation

Pareto-efficiency is the most prominent concept for efficiency in economics. An allocation is Pareto-efficient if it is impossible to find another feasible allocation (which is said to be Pareto-superior) that makes at least one consumer better off in terms of his utility without making anyone worse off. The efficiency issue is addressed in the first and second welfare theorem.

The first welfare theorem states: under some assumptions (the production set is nonempty and compact, the utility function is continuous and nonsatiated), the competitive equilibrium allocation is Pareto-efficient. For a welfare program, the welfare optimum with positive welfare weights is Pareto-efficient.

The second welfare theorem states: if a transfer can be mobilised, one can achieve distributional objective from equity perspective while the resulting equilibrium will also be Pareto-efficient, though obviously not superior to the first one.

Decentralisation means that the economic decisions are made through a price system such that the economic agents maximise their objectives. An allocation is efficient if the allocation does not allow for further increase of social welfare, which is an implicit weighted aggregated utility. The great virtue of a competitive market is that each individual (consumer) and each firm (producer) only has to worry about its own maximisation problem. The only facts that need to be communicated among the firms and the individuals are the prices of the goods. Given these signals of relative scarcity, consumers and firms have enough information to make decisions that achieve an efficient allocation of resources. In this sense, the social problems involved in efficiently utilising resources can be *decentralised*, and solved at the individual level (Varian, 1999). An optimal solution to a welfare program would then be efficient.

Externalities

An externality occurs when the production or consumption decisions of one agent affects the utility or production possibilities of another agent in an unintended way, and when no compensation is made by the producer of the external effect to the affected party (Perman, 1999). To qualify as an externality, two conditions must be satisfied: *i*) An externality is present whenever some individual's (A's) utility or production relationships include real (that is, nonmonetary) variables, whose values are chosen by others (persons, corporations, governments) without particular attention to the effects on *A*'s welfare. *ii*) The decision maker, whose activity affects others' utility levels or enters their production functions, does not receive (or pay) in compensation for this activity an amount equal in value to the resulting benefit (or costs) to others (Baumol and Oates, 1988). Externalities make that the decentralised decision-making does no longer results in an efficient outcome. Externalities, therefore, call for internalising externalities such as by means of a Pigouvion tax in a competitive setting. A Pigouvion tax is a fee levied on the generators of the externality by environmental authority, which is equal to the marginal damages accruing to all victims (Baumol and Oates, 1988). If Pigovian taxes are set at the appropriate level, decentralised decision-making can result in efficient allocation.

Public goods

A private good is both rival and excludable. Rivalry says that the consumption by one agent makes the same unit of consumption unavailable for other agents. Excludability refers to the condition that it is possible to exclude some agents from enjoying the benefit physically or legally.

Public goods are the goods that are both non-rival and non-excludable. A good is non-rival when a unit of the good can be consumed by one individual without detracting, in the slightest, from the consumption opportunities still available to others from that same unit. This property is called non-rivalry. A good example is the sunset when views are unobstructed. Non-excludability is the property that it is impossible to exclude people from consumption in physical sense (e.g. to set a fence) and/or in legal sense. A good example for non-excludability is food safety, because people cannot be excluded for consuming food in order to survive. Air pollution is another example for both nonrivalry and nonexcludability. That your suffering from air pollution does not reduce the loss of anybody else from air pollution is the characteristics of non-rivalry. Since you have to breathe therefore you are not excludable from using the polluted air[1]. This is non-excludability. Clean air is a good example for a public good or, polluted air is a 'public bad'.

[1] Only if special helmets are used would it be technically possible to exclude individuals from the free use of air, but this of course is no realistic option.

Another relevant concept is the concept of 'club goods'. Club goods are the goods that are non-rival but excludable. You can exclude people by charging membership fee but for the members the consumption is non-rival because one person' consumption does not diminish others' consumption. The most important property is that club goods are local. It is relevant to spatial issues.

Categories of capital and Sustainability

In the context of the discussion on sustainability, it is common to distinguish three types of capital (see e.g. Costanza and Daly, 1992; Ekins, 2003): a) manufactured capital (e.g. buildings and machinery), b) human capital (skills and knowledge) and c) natural capital (e.g. minerals and fossil fuels). *Manufactured capital* encompasses all material goods generated through economic activity and technological change. *Human capital* refers the stocks of learned skills, embodied in particular individuals. Manufactured capital and human capital are also aggregated into a category of 'human-made capital' or 'man-made capital'. The capacity of the environment to provide materials and energy for production, sink for waste and a habitat for all life on earth constitutes our *natural capital* (*ecological or environmental capital*). Capital theory analyses how the decision-makers use the capital stock portfolio over time. The well-being[2] of present and future generations is highly dependent on how we exploit these types of capital in pursuit of economic growth and expansion (or sustainable development or *sustainability*).

Sustainability is a buzzword and an essentially vague concept (Solow, 2000). There is no universally agreed definition of the concept sustainability. There are many different interpretations for it. Pezzey (1997) claims that there could be five thousand different definitions for sustainability. Hartwick (1977) proposed implicitly 'non-declining consumption over time' as sustainability. Pezzey (1992) defined sustainability as 'non-declining utility of a representative member of society from millennia into future'. A widely quoted one refers to sustainable development as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987). According to this definition, sustainability can be interpreted as intergenerational equity[3].

Strong sustainability and weak sustainability are two relevant concepts. A strong sustainability criterion claims that critical natural capital (e.g. keystone species and keystone processes) cannot be substituted for by human-made capital and must be individually

[2] Well-being or utility could be replaced here by 'advantage', 'pleasure', 'happiness' or 'welfare', without affecting the definition, for utility is effectively defined as whatever people maximise when they make rational choices which economics assumes they always do (Pezzey, 1992).

[3] Sustainability is also interpreted in economic terms as: dynamic efficiency plus intergenerational equity (Stavins *et al*., 2003).

preserved (Turner, 1993 and de Groot *et al*, 2003). Weak sustainability criterion considers natural and human-made capital as substitutable as long as the level of total capital (human-made and natural) remains constant (de Groot *et al*., 2003). The distinctions between strong sustainability and weak sustainability are: *i*) that the former denies to a greater or lesser extent substitutability between natural capital and other capital – human and manufactured capitals; and *ii*) that strong sustainability stresses 'discontinuity' and 'non-smoothness' (or non-convexities) in ecological systems and hence in the economic damages to which ecological impairment gives rise (Pearce *et al*., 1996).

GK (2002) formulate sustainability in terms of a steady state of a dynamic economic model. Formally it is $\tilde{k}_{t+1} = \tilde{k}_t$, where $\tilde{k}_t$ is the vector of initial stock of capital at time t. This is actually consistent with the concept of 'very strong sustainability[4]' (Turner, 1993). Steady state is related to the path followed by the variables (both man-made capital and natural capital) of a dynamic model. In a steady state, both stock prices and levels reproduce until infinity and thus it is interpreted as *sustainable use*. In that case convergence to a steady state in a dynamic path means *sustainability* (see e.g. Gerlagh and Keyzer, 2003 and 2004).

If we consider some substitutability between consumption of human-made capital and natural capital, for example, amenity value of the nature and private consumption (e.g. a house), then we are considering weak sustainability. Strong sustainability is considered if we consider the non-convexities of the natural environment because the dynamics of natural systems can be non-linear, complex and chaotic, subject to abrupt and irreversible 'flip' from one state to another (Mäler and Vincent, 2003).

Convexity of production sets

Competitive general equilibrium models usually assume that the production set of every producer has the 'possibility of inaction' and it is compact and convex. Another assumption on the production set is 'free disposal'. These assumptions assure the existence of equilibrium in a competitive market.

A production vector y describes the net outputs from a production process. A production set Y describes the set of all production vectors that constitute feasible plans for the firm. A production set Y is convex, if $y, y' \in Y$ and $\alpha \in [0,1]$, implies $\alpha y + (1-\alpha) y' \in Y$ (Mas-Collel, 1995). The convexity of the production set is ensured by divisibility. *Perfect divisibility*[5] ensures the convexity of a production set (Keyzer, 2000). Divisibility means that

[4] Sustainability is also distinguished as 'very weak sustainability' (Solow sustainability), 'weak sustainability' (modified sustainability), 'strong sustainability' (ecological economic approach) and 'very strong sustainability' (stationary state sustainability), see Turner (1993) for details.

[5]Although in some literature (e.g. Kuosmanen, 2003) addivitity is mentioned as a necessary condition for the convexity of a production set, divisibility is sufficient for convexity. Additivity is required only for an aggregate

production is viewed as a transformation of an input bundle into an output bundle according to techniques at non-increasing returns to scale (Keyzer, 2000). Divisibility refers to the shrinkability of production scale without decreasing the quality of production. Producers can scale down and up at will. Formally, a production set Y_j satisfies *divisibility* if for all $y_j \in Y_j$, all $\lambda \in (0,1)$, $\lambda y_j \in Y_j$. Informally, we could say that if feasible input-output combinations can always be scaled down, and if the simultaneous operation of several technologies without mutual interference is always possible, then convexity is obtained (Mas-Collel *et al*., 1995). The intuitive meaning of convexity is that you can combine goods or production inputs at will for production within the set of possibilities.

The convexity assumption incorporates two ideas about production possibilities. First, if inaction is possible, convexity implies that production set exhibits non-increasing return to scale (Koopmans, 1957; Mas-Collel, 1995). That is, for any $y \in Y$, $\alpha y \in Y$ for any $\alpha \in [0,1]$. Second, convexity captures the idea that 'unbalanced' input combination is not more productive than 'balanced' one (Mas-Collel, 1995).

The convexity assumption made about supply or production possibilities and about preferences is in some sense *minimum assumptions* ensuring the existence of a price system that permits or sustains compatible and efficient decentralised decision making (Koopmans, 1957). The implication of the assumption of a convex set is to preclude indivisible commodities (Koopmans, 1957) because indivisibility generates discontinuities in the set of feasible allocations (GK, 2002).

Possibility of inaction ($0 \in Y_j$) means that complete shutdown is possible (Mas-Collel, 1995). This gives to each producer the freedom not to produce. This ensures non-negativity of profits (GK, 2002).

'Free disposal' means that extra amount of inputs or outputs can be disposed of or eliminated at no cost.

Possibility of inaction ensures the feasibility of production and convexity ensures constant returns to scale. For example, it pigs and wheat are produced in 'factories' it is possible to shut down (possibility of inaction). Since you can use proper inputs (such as feed and land) for a certain level of production, the production sets of pigs and wheat are then convex. The combination of two assumptions assures the existence of a competitive equilibrium. The allocation can then be decentralised by price signals into the problem of producers maximising profits and consumers maximising utility.

production set (Mas-Collel, 1995). Additivity is relevant to the convexity of a preference set, which is generated by utility function.

APPENDIX C DYNAMIC GENERAL EQUILIBRIUM MODELS

There are two types of infinite-horizon dynamic GE models: dynastic models and Overlapping Generations (OLG) models. Dynastic models deal with welfare distribution and capital transfer over generations. They are 'Ramsey' types of models based on the concept of a central planner who maximises aggregated welfare in present and future periods. In dynastic models, there are a finite number of infinitely lived consumers. Dynastic models describe infinitely-lived families whose generations anticipate each other's utility and leave bequests to future generations or borrow from future generations.

In OLG models, there is infinite number of generations with finitely lived consumers who live G (for example 2 or 3) periods so that G generations coexist in every period t. Each finitely lived consumer faces a lifetime budget constraint. There is an infinite succession of such consumers. We follow GK (2002) to describe the structures of dynastic models and OLG models.

Dynastic model

A dynastic model can be expressed in the form of Negishi welfare program. The formal structure of dynastic model reads:

$$\begin{aligned} &\max \sum\nolimits_i \alpha_i u_{i1}, \\ &x_{it} \geq 0, u_{it}, \text{all}\, i, k_t, \tilde{k}_{t+1} \geq 0, y_t, t = 1, 2..., \end{aligned} \quad \text{(A9)}$$

subject to

$$u_{it} = W_i(x_{it}, u_{i,t+1}), \quad \text{(A10)}$$

$$F(y_t, \tilde{k}_{t+1}, k_t) \leq 0, \quad \text{(A11)}$$

$$k_t \leq \tilde{k}_t \quad \text{(A12)}$$

$$\sum\nolimits_i x_{it} - y_t \leq 0, \ \text{for given}\, \tilde{k}_1, \quad \text{(A13)}$$

where α is the welfare weight, u_{i1} is the utility of consumer i in time period 1, x is the vector of consumption, k is the vector of capital stock, $\tilde{k}$ is the stock of capital available at the end of period, F is the transformation function and y is the vector of net supply of production sectors. Subscript t gives time period.

In the dynastic economy, there is a planner whose objective is to maximise a social welfare function (A9), given the physical constraints of utility function (A10), transformation constraint (A11), stock balance (A12) and commodity balances (A13).

If we introduce the environmental problems into this model, we can take the following approaches. Firstly, use of environmental resources by consumers can be included in the utility function. Secondly, use of environmental resources by producers can be included in transformation functions. Thirdly, balance equations for stocks of environmental resources can also be included.

The dynastic competitive equilibrium is Pareto-efficient, but not necessarily sustainable if we interpret steady state as sustainable use. The path generated by a dynastic model can follow any pattern. It may converge to a steady state, but it may also diverge, cycle or be chaotic. Therefore, equilibrium and steady state are different for the dynastic model. In equilibrium welfare weights are such that budget constraints are satisfied over the infinite horizon. In a steady state, the welfare weights do not refer to the budget because the steady state exists with any positive discount rate, which is independent of the equilibrium welfare weights. The reason is that steady state conditions require that discount factors be constant and common to all consumers while equilibrium condition requires that consumers have different endogenous discount factors.

OLG model

In a pure exchange OLG model, each agent solves his optimisation problems. It is usually started in t = 1, with consumer born in t = 0 coming in with a claim M^0 and a commodity endowment ω_1^0. If M^0 is equal to $p_1 m^0$, where m^0 is a given vector expressed in terms of commodities (a "real" claim). The consumer, who was born in t=0, solves

$$\begin{aligned}&\max u(x_0^0, x_1^0),\\ &x_1^0 \geq 0,\end{aligned} \tag{A14}$$

subject to

$$p_1 x_1^0 \leq p_1 m^0 + p_1 \omega_1^0. \tag{A15}$$

The consumer born in t=1,2… (denoted by superscript t) solves the two-period (period t and t+1) consumer problem:

$$\begin{aligned}&\max u(x_t^t, x_{t+1}^t)\\ &x_t^t, x_{t+1}^t \geq 0,\end{aligned} \tag{A16}$$

subject to

$$p_t x_t^t + p_{t+1} x_{t+1}^t \leq p_t \omega_t^t + p_{t+1} \omega_{t+1}^t. \tag{A17}$$

Markets clear in every period t =1,2,….

$$x_t^{t-1} + x_t^t \leq \omega_t^{t-1} + \omega_t^t \perp p_t \geq 0. \tag{A18}$$

With this model framework, the environmental issues can also be included by representing the environmental resources as part of the consumption goods x.

The equilibrium for this model exists under some assumptions (GK, 2002), but the *efficiency* of this equilibrium is not directly obtained. In OLG economy, consumers make decisions only in terms of their own benefit. Therefore there exists finite (limited) intertemporal substitutability. As such, compensation is difficult and efficiency is hard to obtain. But for the dynamics of the path, a steady state exists because the steady state is ensured by the zero excess demand with a positive price vector (the complementarity condition): no saving or no discounting.

APPENDIX D SOME ECONOMIC MODELS DEALING WITH RESOURCE USE AND ENVIRONMENTAL PROCESSES

The environment is dealt with in economic literature in different ways. Proper economic modelling should pay in-depth attention to the question on how to represent the economic processes and environmental processes and their interactions in model terms. We are interested in whether a model can represent these aspects and address related economic efficiency. Literature on models dealing with environmental problems is diverse; a comprehensive overview is not the main purpose of this section. For an overview on economic modelling of sustainable development, see for example, van den Bergh and Hofkes (1998).

There are different types of models for different types of environmental problems. A classification of the models is needed to understand them and to evaluate their merits and drawbacks. Usually we can classify them in terms of economic model structures such as partial equilibrium models, general equilibrium models and input-output models. We can also classify the models according to the way in which the environmental process is presented. We prefer the latter because we represent the environmental problems by including an environmental process model in economic models. Accordingly we consider four important types of models for illustration:

1) resource (renewable and non-renewable) use models;
2) models for economic growth and environmental quality;
3) climate change models;
4) other biophysical process models (e.g. for soil and water).

The first category contains *resource use models*. These models deal with the optimal allocation of the non-renewable resources over time (Vousden, 1973; Krautkraemer, 1985 and 1986), and renewable resources including efficient pricing and attributing property rights to environmental goods (Clark, 1976; Mourmouras, 1993; Gerlagh, 1998; Keyzer, 2000). This type of models addresses the question of resource depletion and show that substitution technology is needed for sustainable use of non-renewable resources. They also consider the issues of resource regeneration and irreversibility of renewable resources. We are interested in this type of models because they represent the processes of resource regeneration and we study the soil acidification process considering soil fertility as a renewable resource.

The second category contains models for economic growth and environmental quality. Specifically, environmental quality is treated as a process, and the feedbacks of environmental processes on consumers and producers are also specified (e.g. Smulders, 1994; Ayong Le Kama, 2001). We study these models because they deal with the interaction between the economic system and the environment through environmental quality indicators, and this approach is relevant to our analysis. This type of models is, however, often at the macro-level without specifying the detailed economic sectors and agents. They are also often classified as growth models, because they focus on the process of capital formation and technological change.

The third category contains models dealing with emissions of GHGs to the atmosphere and their impacts, such as DICE (Nordhaus, 1993), RICE (Nordhaus and Yang, 1996) or MERGE (Manne *et al.*, 1995). This type of model is used for assessing climate change policy proposals. The model structure is thus on a very aggregated level and focuses on long-term issues related to climate changes. The DICE model has only one aggregated region while RICE has 10 regions and MERGE has five regions. This type of model is of the dynastic structure of dynamic GE models[6]. We discuss these models because a real environmental process model (a climate change model) is included in an AGE model.

The fourth category contains models that represent a biophysical process of emissions to soil and water and their impacts on environmental quality indicators. They are used to determine the optimal level of pollution. They deal with environmental problems at a micro level by integrating a specific environmental process model with an economic model. For example, a soil acidification model is integrated in an economic model to find the optimal reduction of nitrogen emissions in a dynamic context. But the model focuses on the efficient solution based on cost-effectiveness analysis and is not typically a GE model. We discuss these models because we are interested in how to include a detailed environmental process model in an economic model.

The first two types of models are more at the theoretical level, while the last two are more at an applied and empirical level. The first three types of models are basically dynamic GE

[6] Appendix C presents two types of dynamic general equilibrium models, namely the dynastic model and the overlapping generation (OLG) model. Many existing dynamic models in literature belong to these types of models.

models (dynastic models or OLG models) although they are classified as optimisation models, OLG models, AGE models, and growth models and so on. The fourth type of model is described as an optimisation model. In what follows, we give a more detailed description of each type. An overview on their characteristics in terms of model structure, theoretical or empirical, one-agent or multi-agents, and the feedbacks of environment on producers and consumers is given in Table A1.

Resource use models

Natural resources are essential inputs in the production of goods and services. Early work in natural resource economics (e.g. Solow, 1974; Stigliz, 1974; Garg and Sweeney, 1978) has been concerned with the question of how an exhaustible extractive resource is optimally allocated over time. The literature has identified three factors which allow an economy to overcome the scarcity of a non-renewable resource: the substitution of other factors for the resource input, technological progress and increasing return to scale. Some models (e.g. Krautkraemer, 1985; Gerlagh and Keyzer, 2001) also consider the amenity value of the environmental resources. These models assume that the dynamics of the remaining stock is negatively proportional to the extraction of the resources. Since the resources are non-renewable, this assumption is reasonable. With non-renewable resources, sustainability is relaxed (not relevant).

Renewable resources such as forests, fisheries, soils and biodiversity are often used today at an unsustainable rate (Clark, 1997). Clark (1976) provided a simple model for optimal harvest problem of fishery, where the stock of fishery changes as the growth and harvest over time. A simple model looks like:

$$\max \int_{0}^{\infty} e^{-\delta t} p(t) h(t) dt \, , \tag{A19}$$

subject to

$$\frac{dx}{dt} = F(x) - h(t), \tag{A20}$$

$$0 \leq h(t) \leq h_{\max} \, , \tag{A21}$$

where δ is the discount rate, p is the price of harvested fish, h is the harvest level, x is the stock of fish and F is the growth function of fishery. In this model, the stock of resource is regenerated according to a function $F(x)$, expressed by equation (A20). The solution to this model depends on the functional form of fishery growth F. If F is a concave function, then the model has a unique solution of an optimal path.

Keyzer (2000) provided a theoretical valuation framework for renewable resources considering the biophysical processes of the resources. Biophysical process models describe the environmental system in terms of stocks, processes, inflows and outflows. Based on the *capital theory*, the stock adjustment of the environmental resource in a linear form is:

$$k_{t+1} = T(k_t + \omega) - Cd_t, \quad t = 0,\ 1,....$$

where k is a vector of stocks, ω is a vector of inflows, T is a transition matrix that updates the stock at every location from one cycle to the next. Control matrix C indicates how much of the resource is retrieved at time t. *Human intervention* is represented by means of the vector of demand activities with element d_{ht}. This model considers a linear relationship between capital stock, transformation and retrieving of the stock. Therefore a model with such a process model has no difficulty to find an optimal solution.

Models for economic growth and environmental quality

Other studies (Mourmouras, 1993; Smulders, 2000; Li and Löfgren, 2000; Ayong Le Kama, 2001) obtained the steady state from the growth path and optimality of the renewable resources. In those models, resource stock is regenerated or evolving over time and used as input for production, and also for utility. For example, in Smulders' model, the fundamental growth-environment interaction is studied in a dynamic model consisting of a market clearing condition, a macroeconomic production function, a capital stock growth function, a natural resource growth function, and a utility function. The model is written as:

$Y = C + I$ Market equilibrium,

$Y = F(N, P, K, T)$ Production technology,

$\dot{K} = I - \delta K$ Accumulation of human-made capital,

$\dot{N} = E(N) - P$ Natural resource growth,

$W = \int_0^\infty U(C, N)\exp(-\theta t)dt$ Intertemporal utility,

where Y is the aggregate economic activity (production), C is consumption of man-made goods, I is the investment, F(.) is the production function representing the production technology, N is an indicator of environmental quality, P is the use of environmental services in production, K is the stock of man-made capital, T is the state of technology, δ is the depreciation rate of the capital, E(.) is a function of regeneration of the environmental resources indicating the capacity of the environment to absorb pollution, U(.) is the instantaneous utility, and θ is the utility discount rate; all variables depend on time index t.

This model can also be classified as *a dynastic model* where there is one infinitely lived consumer. In this model, the environmental process is indicated as an environmental quality indicator whose dynamics is determined by the capacity function of the environment to absorb pollution and the use of environmental services. This environmental quality indicator enters the utility function for its amenity, and it enters the production function as input. This model approach is appreciated because the environmental functions are well presented. However the solution to this model depends on the relevant functional forms. If the utility function is concave, the production function is concave and the absorption function is convex, there exists equilibrium.

Climate change models

Climate change is one of the big issues for environmental economics. There is vast variety of empirical models that address the environmental problems related to climate change. The environmental process is usually represented in empirical studies by the *damage function approach*. The damage function is a relationship between emission and damage. The examples of the damage function approach are founded in the literature (e.g. Nordhaus, 1993; Manne *et al.*, 1995; Tol, 1996; Hansen, 1998 and van Ierland, 1999). For example, the DICE model (Nordhaus, 1993) considers complex environmental processes of climate change. Firstly, it calculates the CO_2 emissions, which is a linear function of production. Secondly, it calculates the atmospheric concentrations of CO_2, which is a function of CO_2 emissions and concentration in previous periods of time. Thirdly, it calculates the temperature rise caused by the concentration. Fourthly, it calculates the impacts of temperature rise, which will have an impact on production. Fifthly, it analyses emission reduction and its costs. Finally, in the production function, the output is corrected by the climate *damages* and the emission reduction costs.

The MERGE model (Manne *et al.*, 1995) makes similar assumptions about damages of climate change but with relatively more sectors and more details in the energy sector. The three most important anthropogenic greenhouse gases (GHGs)— carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) — are considered. In the energy sector MERGE distinguishes two types of end products, which are the inputs for final product. There are five technologies representing existing sources for electricity supply and nine alternative sources of non-electric energy available in the future.

Since the complex environmental process of climate change and damages are included as extra constraints into a standard economic model, convexity of these constraints need checking because convexity is a basic condition for the existence of the equilibrium. This step seems to be missing in both the DICE and the MERGE model.

Biophysical process (acidification and water pollution) models

Biophysical processes of the environmental or ecological processes receive increasing attention in economic literature (e.g. van Nes *et al.*, 1999; Keyzer, 2000; Schmieman, 2001; Pascual and Barbier, 2003; Sumelius *et al.*, 2003; and Segarra *et al.*, 2003).

Van Nes *et al.* (1999) provide a simple model on water pollution, where total welfare is a weighted sum of welfare of different groups, for determining the optimal level of vegetation abundance in a lake. This is a good illustration on finding the optimal solution by means of a graphical representation, although the optimal solution depends on the parameters chosen.

Schmieman (2001) integrated a dynamic soil acidification model with a dynamic optimisation model for dealing with the environmental problems of acidification. The model was used to analyse dynamic cost-effective abatement strategies. In his model, the dynamic factors related to the reduction of the problem of acidification are driven by economic aspects and aspects related to the process of soil acidification. In order to calculate the emissions and abatement costs, the RAINS model (Alcamo *et al*., 1990) is used. The soil dynamic process is described by a state equation, indicating that a soil quality indicator is a function of emission deposition. The abatement costs are calculated by a national cost curve, which is the cost per unit of emission reduction. The economic model is to find an abatement path by minimising abatement costs subject to the dynamic process of the soil quality. The model is solved by optimal control theory, whose results show the optimal abatement path.

The model considers the natural process of soil acidification to optimise abatement strategies over time. It is a good model for policymaking related to the acidification issue. But the model only looks at the objective of cost-minimisation without considering other aspects of the economy, such as producers and consumers. Since the cost-minimisation problem does not necessarily imply maximisation of total welfare, the efficiency problem is not fully addressed.

Table A1 Overview on some important characteristics of some environmental process models in an economic framework

Process types	Sources	Process representation	Model structure	Objective function	Efficiency
Non-renewable resources	Vousden, 1973	Stock depends on extraction	Optimization model	Present value of utility	Yes
	Krautkreamer, 1985	Stock depends on extraction	Optimal control theory	Intertemporal utility	Yes
Renewable resources	Clark, 1976	Stock depends on growth and harvest	Optimization model	Intertemporal harvest revenue	Yes
	Keyzer, 2000	Stock adjustment depends on inflows and outflows	Optimization model	Value from activity	Yes
Environmental quality	Smulders, 2000	Environmental quality indicator depends on the absorption capacity and use of environment	Dynamic GE (dynastic)	Intertemporal utility	Yes
Climate change (GHGs)	Nordhaus, 1993	Stock of GHGs, atmospheric radioactive forcing, temperature rise	DICE: dynamic AGE model	Intertemporal	Yes
	Manne, 1995	Similar to Nordhaus	MERGE: dynamic AGE model	Global welfare	Yes
Soil acidification	Schmieman, 2001	State as a function of emission	Dynamic optimization model	Total costs	No
Aquatic macrophytes	van Nes *et al.*, 1999	Relation biomass and saturation	Optimization model	Total welfare	Yes

Table A1 (con.)Overview on some important characteristics of some environmental process models in an economic framework

Sources	Agents	Feedback on consumer & producer	Emissions	Damages	Theoretical/ empirical
Vousden, 1973	1 consumer	No	No	No	Theoretical
Krautkreamer, 1985	1 planner	No	No	No	Theoretical
Clark, 1976	1 producer	No feedback on consumer, but through production function on producer	No	No	Theoretical
Keyzer, 2000	1 planner	No	No	No	Theoretical
Smulders, 2000	1 consumer and1 producer	Through production	Input of production process	Through environmental quality indicator	Theoretical
Nordhaus, 1993	1 region (consumer), 1 producer	Through damage function	Output of production process	Damage is a function of temperature rise	Empirical
Manne, 1995	5 region (consumer), 1 producer	Through damage function	Output of production process	Damage is a function of temperature rise	Empirical
Schmieman, 2001	1 decision maker	No	Output of production	No	Empirical
van Nes et al, 1999	1 planner, 2 natural resource users	No	No	No	Conceptual and empirical

Curriculum Vitae

Xueqin Zhu was born on February 24, 1964 in Deqing, Zhejiang province, China. She studied Chemical Engineering at Zhejiang University, China from 1979 to 1983 and got her Bachelor's degree in engineering. After graduation she worked at Zhenjiang Agro-chemicals Plant in China as an engineer for two years. From 1985 to 1987, she studied Chemical Engineering Mechanics for her Master of Engineering degree at Dalian University of Technology, China. After graduation, she worked as a lecturer at the Food Machinery Group, Department of Mechanical Engineering of Wuxi University of Light Industry in China until the end of 1997. From 1998 to 2000, she studied Agricultural and Environmental Economics at Wageningen University, the Netherlands and got her Master degree of economics with the honour of *distinction*. Since 2000, she has been working at the Environmental Economics and Natural Resources Group of Wageningen University as a PhD researcher. Her research topic 'Environmental Economic Assessment of Animal Production and Consumption Chains and Alternative Options' is a project within the research programme 'Protein Foods, Environment, Technology and Society' (PROFETAS) financed by the Netherlands Organisation of Scientific Research (NWO). This thesis contains the main results for the project. The results of this project have also been presented at international conferences, including the 2nd World Congress of Environmental and Resources Economists in Monterey, USA, the 25th conference of International Association of Agricultural Economists (IAAE) in Durban, South Africa, the 6th International Conference on Agricultural Biotechnology (ICAB) in Ravello, Italy, the 12th annual Conference of the European Association of Environmental and Resource Economists (EAERE) in Bilbao, Spain, the International Workshop on Agricultural Transition and Land Use Change in Wageningen, 12th European Workshop on General Equilibrium Theory in Bielefeld, Germany, and the 13th annual Conference of EAERE in Budapest, Hungary. She received an encouragement prize (*aanmoedigingsprijs*) in 2003 in an essay competition organised by AKK (*Stichting Agro Keten Kennis* –an organisation for chain management) for her essay 'Protein Foods and Environmental Pressures: a Comparison of Pork and Novel Protein Foods'. She also received a diploma from the Netherlands Network of Economics (NAKE) in 2002 and a certificate from the Socio-Economic and Natural Sciences of the Environment (SENSE) research school in 2004.

The *Training and Supervision Plan* was completed at the SENSE graduate school and the NAKE programme.

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